Chapter 5: Food Security

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Executive summary

Climate change has complex interactions with food systems, leading to food insecurity through impacts on food availability, access, utilisation and stability, while current food systems contribute to climate change as major emitters of anthropogenic greenhouse gases *(robust evidence, high agreement)*. Food is integral to all people's health on the planet, and food insecurity results in malnourishment in all its forms. Currently 821 million people are undernourished, while 1.3 billion adults are overweight. The activities of the food system (i.e., production, transport, processing, packaging, storage, consumption, loss and waste) emit greenhouse gases that cause climate change and thus exacerbate food insecurity *(robust evidence, high agreement)*. Changes in all parts of the food system can contribute to mitigation and adaptation {5.1.1, 5.1.2}.

Climate change is already affecting food production through changes in temperature, water availability, CO_2 concentrations and extreme events (heatwaves, droughts, inland and coastal flooding), with responses depending on latitude, altitude, and agroecosystem characteristics *(robust evidence, high agreement)*. In some dryland areas, such as Australia, increases in agricultural yields have stagnated despite improvements in technology and management practices. Warming in higher-latitude regions such as Northeast China since the 1980s, along with higher-yielding cultivars and improved management, has led to expanded production areas. In Europe, effects vary across the continent, with agricultural regions in the south faring worse than in the north. Evidence for climate change impacts and adaptation is emerging from local knowledge in highly vulnerable regions of Africa, South America, and mountain areas such as the Hindu-Kush Himalayas {5.2.2}.

Climate change impacts on food production are projected to grow *(robust evidence, high agreement).*

ES Table 5.1 Global crop yield changes (%) per 1°C increase in global temperature

Crop	Low estimate	High estimate
Wheat	-3	-11
Maize	+1	-15
Rice	+4	-8
Soybean	+2	-10

Climate change will increasingly affect water resources for food production through altering rates of precipitation and evaporation, ground water levels, and dissolved oxygen content. Climate change will alter the dynamics of plant and livestock pests, diseases, and pollinators *(robust evidence, high agreement)*. Given increasing frequency and magnitude of extreme weather events and the current state of cross-regional and cross-sectoral interconnectedness, the global food system is at increasing risk of disruption (*medium evidence, medium agreement*) {5.2.3}.

Protein content of plants is affected negatively by higher CO_2 concentrations *(medium evidence, high agreement)* affecting food utilisation. In addition, some micronutrients, like iron and zinc will be less accumulated and less available in food. Higher CO_2 concentrations increase crop growth and yield, especially in crops with C3 photosynthetic pathways, but realisation of these CO_2 direct effects depends on nutrient status *(robust evidence, high agreement)* {5.2.4}.

Climate change will affect food systems through disruption of transport, manufacture, and retail, limiting food access *(medium evidence, high agreement)*. Local availability of food will be impaired by disruptions to food transport networks and storage infrastructure. Since consumption is spatially dislocated from production in many regions, there are many indirect pathways by which climate change can disrupt people's food security. Food prices will be affected due to productivity decreases and impacts on markets and infrastructure {5.2.4}.

By formulating effective adaptation strategies, it is possible to reduce or even avoid some of the negative impacts of climate change on food systems. However, if unabated climate change continues, limits to adaptation will be reached (*robust evidence, high agreement*). Diversification of many components of the food system is a key element for increasing resilience and reducing risks (integrated production systems, agrobiodiversity, indigenous knowledge and local knowledge, local food systems, dietary diversity) *(robust evidence, high agreement)*. Given the site-specific nature of climate change impacts on food system components together with wide variation in agroecosystems and socio-economic conditions, it is widely understood that adaptation strategies must be developed according to environmental and cultural contexts at the regional level (*robust evidence, high agreement)* {5.3}.

The current food system accounts for roughly 40% (30–50%) of total GHG emissions; this estimate includes emissions from crop and livestock activities within the farm gate; from land use and land use change including deforestation and peatland degradation; and from storage, processing, transport, retail, and other supply chain activities *(medium evidence, medium agreement).*

ES Table 5.2 Contribution to GHG emissions from the food system as percentage of total emissions

Activity	**Low estimate***	**High estimate***
Entire food system	30	50
Crop and livestock	7	13
Land use and land use change	5	14
Supply chain	16	20

*Contributions from food loss and waste are included in these estimates and may account for 8-10% of total GHG emissions from all sectors.

Food system emissions are growing globally due to increasing population and demand for food *(robust evidence, high agreement)*. Diets are changing on average toward greater consumption of animal-based foods, vegetable oils and sugar/sweeteners *(robust evidence, high agreement).* GHG emissions are increasing due to greater amounts of animal-based products in diets (*robust evidence, medium agreement*) {5.4}.

Supply-side mitigation practices in the food system can contribute to climate change solutions by sustainably and efficiently intensifying the use of land and sequestering carbon in soils and biomass *(robust evidence, high agreement)*. Supply-side options can be directly applied by farmers, processors, and retailers, etc.), contribute to livelihoods, help countries move towards sustainable land management, and lead to reduction of total emissions under appropriate policy interventions. Options for GHG mitigation in cropping systems include improved land and fertiliser management, biochar applications, breeding for larger root systems, and bridging yield gaps, with a total mitigation potential estimated as 2.0–5.0 $GtCO_2$-eq yr^{-1} by 2030. Options for mitigation in livestock systems include better manure management, improved grazing land management, and better feeding practices for animals (1.8–2.4 $GtCO_2$-eq yr^{-1} by 2050). Reductions in GHG emissions intensity (emissions per unit product) from livestock and animal products can support reductions in absolute emissions in some contexts (e.g., reduction in herd size at constant pasture area, reduction in overall pasture area) (*medium evidence, medium agreement*). Agroforestry mitigation practices include rotational woodlots, long-term fallow, and integrated land use (4.27–21.5 $GtCO_2$-eq yr^{-1}) {5.5.1}.

Demand-side changes, for example, in food choices and consumption, can help to achieve global GHG mitigation targets and improve human health *(robust evidence, high agreement)*. Low-carbon diets on average tend to be healthier and have smaller land footprints. By 2050, mitigation potential of dietary changes ranging from 2.7–3.4 $GtCO_2$-eq yr^{-1} for Mediterranean diets, 3.6–6.4 $GtCO_2$-eq yr^{-1} for healthy diets, 4.3–5.3 $GtCO_2$-eq yr^{-1} for vegetarian diets and 5.2–5.7 $GtCO_2$-eq yr^{-1} for a flexitarian diet with limited meat and dairy products in comparison to business-as-usual food demand projections *(robust evidence, high agreement)*. In high-income industrial countries, there is scope for reducing consumption of animal-sourced foods, particularly processed and red meat, with tangible environmental and health benefits; in developing countries, high meat-based diets are less prevalent and scope for reductions may be more limited. To encourage low-carbon diets, policies such as awareness-raising campaigns, public procurement, and health insurance incentives have been tested in differing contexts {5.5.2}.

Increasing the efficiency of the food system through reduction of food loss and waste lowers GHG emissions and improves food security (*robust evidence, medium agreement,*). Between 1961 and 2011, global food loss and waste has tripled from 540 million tonnes yr^{-1} to 1.6 billion tonnes yr^{-1} and life cycle analysis shows that global food loss and waste resulted in emissions of 4.4 Gt CO_2-eq yr^{-1} in 2011 (8–10% of total anthropogenic greenhouse gas emissions) and costs of about USD 1 trillion per year. Avoiding food loss and waste can compensate for decreases in crop yields due to climate change and lower GHG emissions by reducing the need for agricultural land expansion {5.5.2}.

Practices that create synergies between mitigation and adaptation can lead to low-carbon and climate-resilient pathways for food security and ecosystem health *(robust evidence, medium agreement)*. Many technical interventions known as best agricultural practices can lead to both adaptation and mitigation outcomes and even synergies, although negative adaptation and mitigation outcomes (i.e., trade-offs) are often overlooked. Combining supply-side actions such as efficient production, trade and processing with demand-side interventions such as modification of food habits, both reduce emissions of GHG and enhance climate resilience {5.6}.

Urban and peri-urban agriculture can contribute to improving urban food security, reducing greenhouse gas emissions, and adapting to climate change impacts *(robust evidence, medium agreement)*. With increasing urbanisation and climate change, a growing challenge is to ensure urban food security, mainly for the urban poor and people living in informal settlements. In 2010, around 14% of the global population is nourished by food grown in urban and peri-urban areas. If practiced efficiently, urban and peri-urban agriculture can contribute to reducing carbon footprints by avoiding long-distance food transport. Urban agriculture can contribute to adaptation to heat extremes through evaporative cooling {5.6.5}.

On a regional basis, gender, equity, culture, ethnicity, and access to food and capacity building are important in devising context-specific mitigation and adaptation measures, as well as adoption strategies that ensure food security *(robust evidence, high agreement)*. Sustainable food security is most likely to arise from a mixture of globalised supply chains and local production, not one or the other. However, globalised food systems threaten indigenous knowledge and local knowledge, particularly agro-biodiversity, which are important in providing food security and promoting adaptation and resilience *(robust evidence, high agreement)*. Consumption of locally produced food can be a climate change mitigation option, but emission reduction potential varies across regions and seasons and in some cases may result in increased emissions (*robust evidence, medium agreement*) {5.2.5, 5.3.3, 5.6.4}.

For mitigation and adaptation in food production and supply, enabling conditions are created through markets, policies, institutions, governance, and indigenous/local knowledge (*robust evidence, medium agreement*). Prompt actions that can be taken include incorporating indigenous and local knowledge, and acknowledging women’s role on food systems in regard to climate change mitigation and resilience; optimising the use of natural resources for climate change mitigation and adaptation and food security through agricultural technology transfer and exchange; developing business models and targeted subsidies for climate-friendly production practices; investing in building resilient supply chains and trade networks; incentivising and raising awareness on the co-benefits of healthy consumption patterns; improving access to healthy diets for vulnerable groups through food assistance programs; and implementing policies and campaigns to reduce food loss and food waste {5.7}.

5.1 Framing and context

The *food system* encompasses the activities and actors in the production, transport, manufacturing, retailing, consumption, and waste of food, and their impacts on nutrition, health and well-being and the environment (Figure 5.1). Climate change has complex interactions with food systems, leading to food insecurity through impacts on food availability, access, utilisation and stability, while current food systems contribute to climate change as major emitters of anthropogenic greenhouse gases *(robust evidence, high agreement)*. Many climate change response options in IPCC AR5 (IPCC 2014) address incremental adaptation or mitigation responses separately rather than being inclusive of more systemic or transformational changes in multiple food systems that are large-scale, in depth, and rapid, requiring social, technological, organisational and system responses (Rosenzweig and Solecki 2018; Mapfumo et al. 2017; Termeer et al. 2017) (Figure 5.1). In many cases, transformational change will require integration of resilience and mitigation across all parts of the food system including production, supply chains, social aspects, and dietary choices. Further, these transformational changes need to encompass linkages to ameliorative responses to land degradation, desertification, and water pollution throughout the food-energy-water nexus.

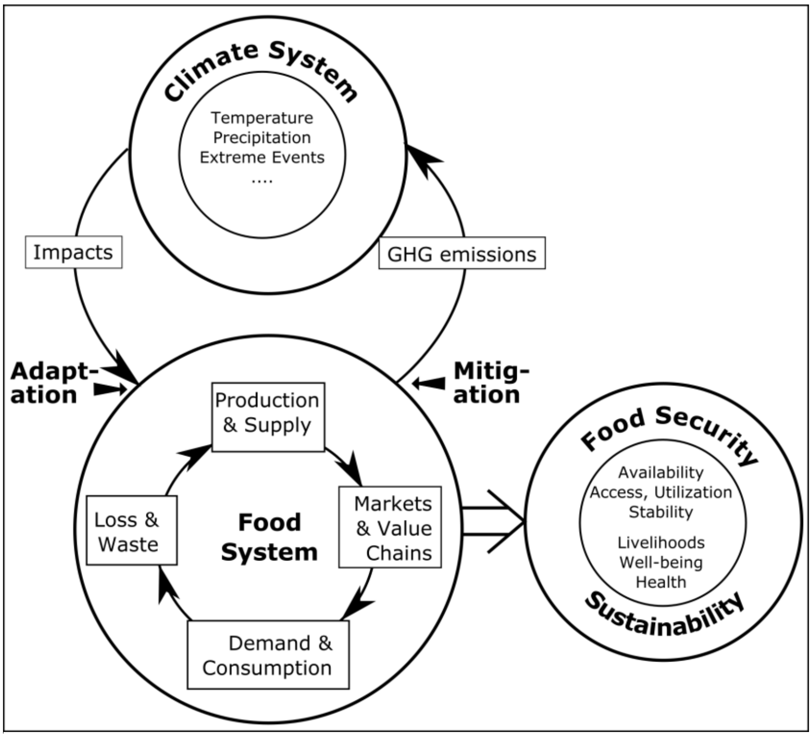

Figure 5.1 Interactions between the climate and food systems, mitigation and adaptation pathways, food security, and planetary health and sustainability

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

5.1.1.1 Definitions

According to FAO (2001), *food security* is a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life. “All people at all times” implies the need for inter-generational equity, and therefore “sustainability” in food production. “Safe and nutritious food …for a healthy life” implies that food insecurity can occur if the diet is not nutritious, including when there is consumption of an excess of calories. In addition to equality between generations, "all people at all times" implies a strong need to address the inequalities in food systems that drive food insecurity both today and in the future.

Food security for people arises as an outcome from their interaction with the food system. Food systems overlap with agricultural systems in the area of food production, but also comprise the diverse set of institutions, technologies and practices that govern the way food is marketed, processed, transported, accessed and consumed (Capone et al. 2014).

As defined by the FAO, undernourishment means that a person is not able to acquire enough food to meet the daily minimum dietary energy requirements, over a period of one year. In addition to the undernourishment meaning insufficient calories (“hunger”), undernourishment occurs in terms of nutritional deficiencies in vitamins (e.g., Vitamin A) and minerals (e.g., iron, zinc, iodine), so-called “hidden hunger”. Whilst countries with high levels of undernourishment tend to have high levels of hidden hunger (Muthayya et al. 2013), this is not always the case (for example, in many parts of the world teenage girls suffer from iron deficiency (Whitfield et al. 2015) and Calcium deficiency is common in Western-Style diets (Aslam and Varani 2016).

Malnourishment (literally “bad nourishment”) includes the concept of “over-consumption”, because it can lead to significant health and morbidity issues (Development Initiatives 2017; GFS 2016). There are associations between obesity and diabetes, dementia, inflammatory diseases (Saltiel and Olefsky 2017), cardio-vascular disease and some cancers. There is a growing recognition of the rapid rise in over-weight and obesity on a global basis and its associated health burden created through the non-communicable diseases) (NCD-RisC 2016a; HLPE 2017) (see Section 5.1.2.1).

As the notion of food security includes access to a diet that underpins a healthy life, there is a relationship between food security and nutrition, or food insecurity and malnutrition. Not all malnourishment arises from food insecurity, as households may have access to healthy diets but choose to eat unhealthily, but in many parts of the world poverty is linked to poor diets (FAO et al. 2018). This may be through lack of resources to produce or access food, lack of resources to access healthy food, with healthier diets generally being more expensive than calorie-dense diets poor in nutrition (Darmon and Drewnowski 2015), or it may be through the availability of food in the “food environment” with retail outlets providing availability of poor diets (Gamba et al. 2015).

Whilst conceptually the definition of food security is clear, the extent to which the definition is operationalised in a way that encompasses all its aspects is less clear. Although there are a range of methods to assess food insecurity they all have some shortcomings. For example, the UN FAO has adopted the Food Insecurity Experience Scale (FIES), a questionannire. This approach is likely to be successful at assessing food insecurity in terms of food insufficiency, and less discriminating where calories are more available than nutrition as the single question on access to a healthy diet requires respondents to assess their own dietary adequacy, which may not match their real access to healthy diets. This may partially explain how different assessments of food insecurity, especially in the developed world, may suggest different prevalences (see Section 5.1.2.1 below).

5.1.1.2 Effects of climate change on the four pillars of food security

Climate change is projected to negatively impacting all aspects of food security – food availability, access, utilisation and stability *(robust evidence, high agreement)* (FAO et al. 2018) (Table 5.1). Since AR5, recent work has strengthened understanding of how climate change affects each of these pillars in a range of ways.

Most studies continue to focus on availability, although more studies are addressing related issues of access, utilisation, and stability as they are affected by a changing climate (Bailey et al. 2015). Low-income producers and consumers are likely to be most affected because of a lack of resources to invest in adaptation and diversification measures (UNCCD 2017; Bailey et al. 2015).

Food aid plays an important role in providing food security and saving lives after climate disasters. In 2015, 14.5 million people were assisted through disaster-risk reduction, climate change and/or resilience building activities (WFP 2018). However, there is no agreement on how to better use emergency food aid and this can come with unintended consequences and different levels (micro, meso, macro) (Barrett 2006). They may include negative dependency of food recipients (Lentz et al. 2005) or price increases, among others. Some authors state that tied food aid provided as "in kind" in the donor country hampers local food production (Clay 2006), although others found no evidence on this (Ferrière and Suwa-Eisenmann 2015). Cash untied aid can be used to buy food locally or in neighbouring countries, which is cheaper and contributes to improve local farmers' livelihood (Clay 2006).

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

Table 5.1 Climate change impacts on the four pillars of food security

Food security pillar	Examples of projected climate change impacts*	References
Availability	• Reduced yields and soil fertility and increased land degradation for some regions and crops • Increased crop and livestock pests and diseases; higher post-harvest losses due to mycotoxins • Disruptions to food storage and transport networks • Indirect impacts due to spatial dislocation of consumption from production for many societies	• (Zhao et al. 2017a; Zimmermann et al. 2017; Smith et al. 2016; Asseng et al. 2015; Challinor et al. 2014; Rosenzweig et al. 2014; FAO 2018a) • (Moretti et al. 2018; Medina et al. 2017; Paterson and Lima 2011; Magan et al. 2011) • (Puma et al. 2015; Wellesley et al. 2017; Rivera-Ferre 2014) • (Morris et al. 2017)
Access	• Loss of agricultural income due to reduced yields and higher costs of production inputs, such as water, limits ability to buy food • Disproportionate impact on low-income consumers, in particular women and girls, due to lack of resources to purchase food • Effects on food supplies due to disruption of transportation infrastructure by increased extreme events • Inability to invest in adaptation and diversification measures to endure price rises	• (FAO et al. 2018; FAO 2016a; Abid et al. 2016; Harvey et al. 2014b) • (FAO et al. 2018; UNCCD 2017; FAO 2016a) • (FAO et al. 2018) • (UNCCD 2017; Vermeulen et al. 2012b)

Utilisation	• Impact on food safety due to effect of increased temperatures on microorganisms, including increased mycotoxins in food and feed	• (FAO et al. 2018; Battilani et al. 2016; Tirado and Meerman 2012)
	• Decline in nutritional quality resulting from increasing atmospheric CO_2	• (Müller et al. 2014; Myers et al. 2014; Smith et al. 2017; Myers et al. 2015)
	• Impact on nutrition resulting from reduced water quantity and quality used to prepare food	• (FAO et al. 2018)
	• Increased burden of diarrheal diseases in low-income regions; risk of flooding may result in an increase in the number of people exposed to diarrheal and other infectious diseases, thus lowering their capacity to utilise food effectively	• (FAO et al. 2018; Aberman and Tirado 2014; Thompson and Cohen 2012)
Stability	• Greater instability of supply due to increased frequency and severity of extreme events, including droughts and heatwaves; disruption to food transport; and instability of incomes from agriculture	• (FAO et al. 2018; FAO 2018a) • (Diffenbaugh et al. 2012; Verma et al. 2014; Willenbockel 2012)
	• Impacts on world market export prices that carry through to domestic consumer prices due to climate shocks	• (Challinor et al. 2018; Hendrix 2018; Selby et al. 2017; Kelley et al. 2017, 2015)
	• Widespread crop failure contributing to migration and conflict	

**See Section 5.2 for detailed explanation.*

5.1.2 Status of the food system, food insecurity and malnourishment

5.1.2.1 Trends in the global food system

The current status of the food system and food insecurity is shown in Figure 5.2 and Table 5.2. With increases in crop yields and production, the global food security situation has been improving during the last five decades. Growing production of animal-sourced food is driving crop use for livestock feed (FAO 2018b). Global trade of crop and animal-sourced food has increased by around 5 times between 1961 and 2011 in terms of calories (FAO 2018b). During this period, global food availability has increased from 2200 kcal/cap/day to 2880 kcal/cap/day, making a transition from a food deficit to a food surplus situation (FAO 2018b; Hiç et al. 2016). Availability of cereals, animal products, oil crops, and fruits and vegetables has mainly grown (FAO 2018b), reflecting shifts towards more-affluent diets. This results in a decrease in prevalence of underweight and an increase in prevalence of overweight and obesity among adults (Abarca-Gómez et al. 2017). During the same period, anthropogenic greenhouse gas emissions associated with agriculture production has grown from 2.8 Gt CO_2-e yr^{-1} to 5.2 Gt CO_2-e yr^{-1}. The increase in emissions is mainly from livestock sector (e.g., enteric fermentation, manure, left on pasture, etc.), use of synthetic fertiliser, and rice cultivation (FAO 2018b).

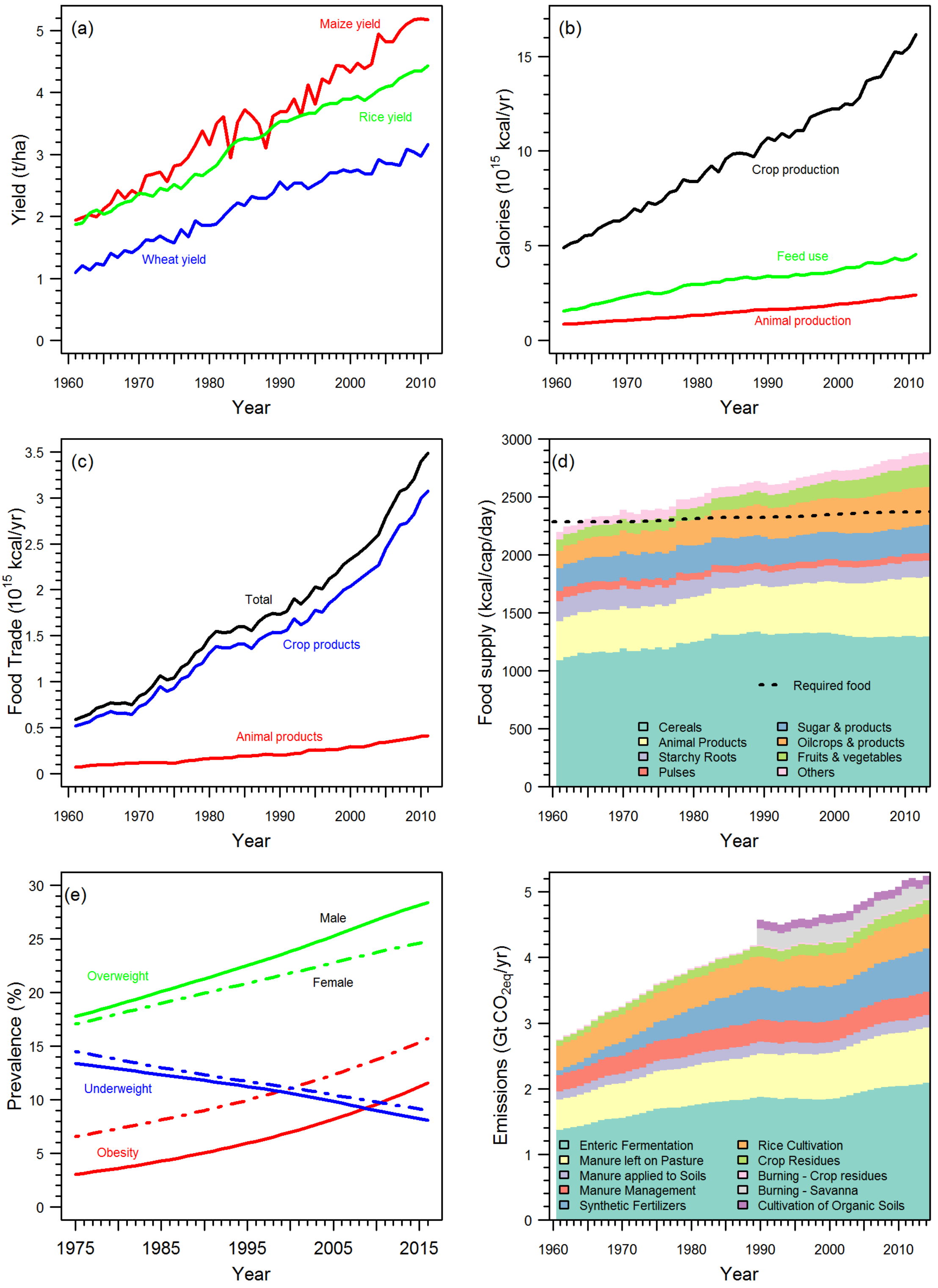

Figure 5.2 Global trends in (a) yields of maize, rice, and wheat (FAO 2018b), (b) production of crop and animal calories and use of crop calories as livestock feed (FAO 2018b), (c) food trade in calories (FAO 2018b), (d) food supply and required from 1961–2012 (FAO 2018b; Hiç et al. 2016), (e) prevalence of overweight, obesity and underweight from 1975–2015 (Abarca-Gómez et al. 2017), and (f) GHG emissions for the agriculture sector, excluding land use change (FAO 2018b). For figures (b), and (c), the data provided on mass units were converted into calories using nutritive factors (FAO 2001b). The data on emissions due to burning of savanna and cultivation of organic soils is provided only after 1990 (FAO 2018b)

5.1.2.2 Status of food insecurity

In addressing food security the dual aspects of malnutrition – under-nutrition and micro-nutrient deficiency, as well as over-consumption, overweight, and obesity – need to be considered (Figure 5.2 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 FAO 2018 report's estimate for undernourished on a global basis is 821 million, up from 815 million the previous year and 784 million the one 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, has been gradually declining, and was 22% in 2017 compared to 31% in 2012 (150.8 million, down from 165.2 million in 2012). 50.5 million (7.5%) of children under 5 were wasted. The food security situation has worsened in particular in parts of sub-Saharan Africa, South-Eastern Asia and Western Asia, and recently Latin America and deteriorations have been observed most notably in situations of conflict and conflict combined with droughts or floods.

In addition, to the prevalence of under-nutrition, estimates of 'hidden hunger' suggests a prevalence of one in three people globally suffering from micronutrient deficiencies (FAO 2013a; Grebmer et al. 2014; Tulchinsky 2010). In the last decades hidden huger (measured through proxies targeting iron, vitamin A deficiency, and zinc deficiencies) became worse in Africa while mainly improved in Asia and Pacific (Ruel-Bergeron et al. 2015).

As globally the availability of inexpensive calories from commodity crops increases, so does per capita consumption of calorie-dense foods (Ng et al. 2014; NCD-RisC 2016a; Abarca-Gómez et al. 2017; Doak and Popkin 2017). As a result, in every region of the world the prevalence of overweight (condition where body mass index ranges between 'normality' and 'obesity', that is weight is more than it should be according to size, but not obese), and obesity is increasing, and there are now more obese adults in the world than underweight adults (Ng et al. 2014; NCD-RisC 2016a; Abarca-Gómez et al. 2017; Doak and Popkin 2017). In 2016, around two billion adults were overweight, including 660 million suffering from obesity (NCD-RisC 2016a; Abarca-Gómez et al. 2017). The prevalence of overweight and obesity has been observed in all age groups. Around 41 million children under five years and 340 million children and adolescents aged 5–19 years were suffering from overweight or obesity in 2016 (NCD-RisC 2016a; FAO et al. 2017; WHO 2017). In many high-income countries, the rising trends in children and adolescents suffering from overweight and obesity have stagnated at high levels; however, these have accelerated in parts of Asia and very slightly reduced in European and Central Asian lower and middle-income countries (Abarca-Gómez et al. 2017; Doak and Popkin 2017; Christmann et al. 2009). There are associations between obesity and diabetes, dementia, inflammatory diseases (Saltiel and Olefsky 2017), cardio-vascular disease and some cancers. There is a growing recognition of the rapid rise in over-weight and obesity on a global basis and its associated health burden created through the non-communicable diseases) (NCD-RisC 2016a; HLPE 2017).

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

As discussed in Section 5.1.1.1, different methods of assessing food insecurity can provide differential pictures. Of particular note is the spatial distribution of food insecurity, especially in higher-income countries. FAO et al. (2018) reports FIES estimates of severe food insecurity in Europe and North America of 1.4% of the population (i.e., about 20 million). However, in the United States, USDA estimates 40 million people are severely food insecure (prevalence about 12%) (Coleman-Jensen et al. 2018). In the UK, estimates from 2017 and 2018 indicate about 4 million adults are moderately to severely food insecure (prevalence 8%) (End Hunger UK 2018; Bates et al. 2017). The UK food bank charity, the Trussell Trust, distributed 1,332,952 three day emergency food parcels to people referred to the charity as being in food crises. Furthermore, a 2003 study in the UK (Schenker 2003) estimated that 40% of adults, and 15% of children, admitted to hospitals were malnourished, and that 70% of undernourishment in the UK was unreported. Given that the USDA and UK survey estimates do not capture food insecurity as chronic exposure to poor diets for low-middle income households, it seems highly likely that the estimates in SOFI are considerable underestimates of food insecurity in high-income countries.

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

Table 5.2 Prevalence of various forms of malnutrition

	HLPE 2017 (UN)	**SOFI 2017 (FAO)**	**SOFI 2018 (FAO)**	**GHI 2018 (IFPRI)**	**GNR2018**
Overweight	1,3 billion				1,34 billion (38,9%)[#]
Overweight under five			38 million		38 million
Obesity	600 million	600 million	672 million		678 million (13,1%) [#]
Undernourishment	800 million	815 million	821 million	20,9% (world)	
Stunting under five			151 million		151 million* (22%)
Wasting under five			50 million		51 million* (7%)
MND (iron)					613 million (32.8%) [Ɨ]
MND (vitamin A) under five	33.3%				
MND (vitamin A) pregnant women	15.3%				
MND (Iodine)	28.5%				
MND (Zinc)	17.3%				

HLPE: High Level Panel of Experts of the committee of world food security; *SOFI*: The State of Food Security and Nutrition in the World; *GHI*: Global Hunger Index; *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 grams per litre at sea level and percentage of non-pregnant women whose haemoglobin level is less than

120 grams per litre at sea level); Vitamin A for year 2005, measured as Serum retinol 0.7umol/L; Iodine deficiency for year 2013, measured as Urine Iodine Concentration < 100umol/L; inadequate zinc intake for year 2005).

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

*UNICEF WHO Joint Malnutrition;

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

5.1.3 Food systems in AR5 and the Paris Agreement

5.1.3.1 Food systems in AR5

The IPCC Working Group II AR5 chapter on Food Security and Food Production Systems broke new ground by expanding its focus beyond the effects of climate change primarily on agricultural production to include a food systems approach as well as directing attention to undernourished people (Porter et al. 2014b). However, it focused primarily on food production systems due to the prevalence of studies on that topic (Porter et al. 2017). It highlighted that a range of potential adaptation options exist across all food system activities, not just in food production, and that benefits from potential innovations in food processing, packaging, transport, storage, and trade were insufficiently researched at that time. The production focus of AR5 highlighted the climate change effects on biophysical aspects of food security but did not assess the climate-related effects on many important social elements of food security and vice versa. AR5 did acknowledge that food security is a complex issue in which climate drivers often aggravate pre-existing factors of food insecurity, and are difficult to separate from other non-climate drivers that affect production and non-production aspects.

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

The IPCC Working Group III AR5 chapter on Agriculture, Forestry and Other Land Use (AFOLU) assessed mitigation potential considering not only the supply, but also the demand side of land uses, by reducing losses and wastes of food, and changes in diets (Smith et al. 2014). However, it did not take a full food system approach to emissions estimates that includes processing, transport, storage, and retail.

5.1.3.2 Food systems and the Paris Agreement

Representatives from 196 countries signed the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement (UNFCCC 2015) in December 2015. The central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. The Paris Agreement requires all Parties to put forward their best efforts through nationally determined contributions (NDCs) and to strengthen these efforts in the years ahead. Many countries have included food systems in their mitigation and adaptation plans as found in their NDCs for the Paris Agreement (Rosenzweig et al. 2017). Richards et al. (2015) analysed 160 Party submissions and found that 103 include agricultural mitigation; and of the 113 Parties that include adaptation in their NDCs, almost all (102) include agriculture among their adaptation priorities. There is much attention to conventional agricultural practices that can be climate-smart (e.g., livestock and crop management), but less to the enabling services that can facilitate uptake (e.g., climate information services, insurance, and credit). Considerable finance is needed for agricultural adaptation and mitigation by lesser developed countries – in the order of USD 3 billion annually for adaptation and 2 billion annually for mitigation, which may be an underestimate due to a small sample size (Richards et al. 2015).

5.1.4 What's new since AR5 and roadmap to Chapter 5

This Chapter builds on the food systems approach followed by AR5 and its focus on climate change and food security, but new work since AR5 has extended beyond production to how climate change will impact the supply chain and demand side of the food system. The analysis of climate change and food insecurity has expanded beyond undernutrition to include the overconsumption of unhealthy mass-produced food high in sugar and fat, which also threatens health in different but highly damaging ways and the role of dietary choices and consumption in greenhouse gas emissions. It takes a farming systems approach, includes agroforestry and aquaculture as well as crop and livestock production, and relates these to the food-energy-water nexus.

New work has shown that transforming the food system can be an important lever to address the complex interactions between climate change and food security. Through acting on mitigation and adaptation in regard to both food demand and food supply it is possible to directly improve both human and planetary health.

The chapter assesses new work on the observed and projected effects of CO_2 concentrations on the nutritional quality of crops and emphasises the role of extreme climate events, price volatility in food systems, social aspects, and dietary choices. Other topics with considerable new literature include impacts on farming systems, food loss and waste, and urban and peri-urban agriculture. Increased demand for food results in intensification systems that support the consumption of resource-intensive food products instead of more efficient, equally nutritious alternatives.

5.2 Impacts of climate change on food systems – Observations and projections

5.2.1 Climate variables important to food systems

Climate variables relevant to food security and food systems include temperature-related, precipitation-related, and integrated metrics that combine these and other variables. Other variables that affect agricultural production, processing, and/or transport are solar radiation, wind, humidity, and (in coastal areas) salinisation and storm surge (Mutahara et al. 2016; Myers et al. 2017). Extreme climate events, such as inland and coastal flooding, can affect the ability of people to obtain and prepare food (FAO et al. 2018). (see Chapter 2 for further discussion of relevant climate variables).

Crop yields are projected to respond to climate change due to changes in the start and length of growing seasons (Urgaya Lemma et al. 2016; Zhao et al. 2015; Fiwa et al. 2014) and the duration and magnitude of heat and water stress (Lobell et al. 2015; Saadi et al. 2015; Schauberger et al. 2017). These abiotic changes influence leaf temperature, soil moisture, and photosynthetic rate and thus phenology and amount of biomass produced and allocated to a crop's storage organs. Growth acceleration due to higher average temperatures results in less radiation interception and less biomass production (Rosenzweig and Hillel 2015). This is distinct from above-optimal temperatures, which directly harm crop physiological processes. For direct effects of CO_2 on crop nutrient status see Section 5.2.4.3.

High temperature causes stress during key growth stages such as flowering (Stratonovitch and Semenov 2015). Growing degree days (McMaster and Wilhelm 1997) are important metrics because crops respond to accumulation of temperature to progress through their growth stages, directly affecting their length of growing period (Matthews et al. 2018). Lack of chilling hours generates deficiencies in flowering and yield in apple (Darbyshire et al. 2017) and olive (Gabaldón-Leal et al. 2017). In regions where agricultural production is currently limited by cold temperatures (e.g., parts of the tropical highlands, high altitudes, and high latitudes) higher temperatures will expand the length of the growing season and potentially lead to improved crop productivity. In areas where rainy periods are diminished, length of growing seasons will also be shortened (Urgaya Lemma et al. 2016; Fiwa et al. 2014). Climate change affects water resources for food production through altering rates of precipitation and evaporation, ground water levels, and dissolved oxygen content (Cruz-Blanco et al. 2015; Sepulcre-Canto et al. 2014; Huntington et al. 2017; Schmidtko et al. 2017) (Figure 5.3). Integrated metrics that combine temperature and precipitation variables are often used to understand effects on pests and diseases, such as 'warm and wet' conditions causing *Erwinia* infection in potatoes and fungi development in onion in The Netherlands (Schaap et al. 2013).

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

Agricultural production also affects climate through feedbacks to the atmosphere related to changes in albedo (Houspanossian et al. 2017), roughness (Shi et al. 2017), and evapotranspiration (Fisher et al. 2017). For impacts of the food system on climate related to greenhouse gas emissions, see Section 5.4.

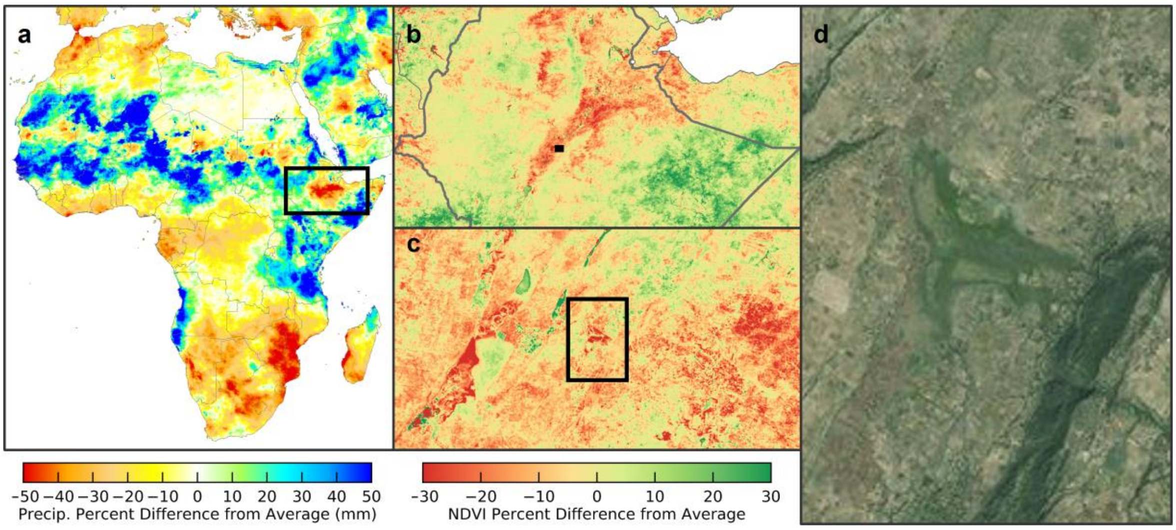

Figure 5.3 (a) Sep 2015–Feb 2016 CHIRPS precipitation anomaly over Africa relative to the 1981–2010 average shows that large areas of Ethiopia received less than half of normal precipitation. Consequently, widespread impacts to agricultural productivity, especially within pastoral regions, were present across

Ethiopia as evidenced by (d) reduced greenness in remote sensing images. (b) MODIS NDVI anomalies for Sep 2015–Feb 2016 relative to 2000–2015 average are shown for the inset box in (a). (c) Landsat NDVI anomalies for Sep 2015–Feb 2016 relative to 2000–2015 average are shown for the inset box in (b). (Huntington et al. 2017)

5.2.2 Observed climate change impacts

5.2.2.1 Detection and attribution

Climate change is already affecting food production through changes in temperature, water availability, CO_2 concentrations and extreme events (heatwaves, droughts, inland and coastal flooding), with responses depending on latitude, altitude, and agroecosystem characteristics *(robust evidence, high agreement)*. Observed impacts of climate change on food security have been noted as a cause of concern, (HLPE 2012). Since the IPCC assessment done on detection and attribution of climate change impacts on food systems in AR5 (Porter et al. 2014b; Cramer et al. 2014), new work has addressed observed climate effects (increasing temperatures, changing in precipitation, and changing frequency and intensity of extreme events) on expanded aspects of the food system, including pastoral systems (Rasul et al. 2019; Abiona et al. 2016), pests, diseases, and pollinators (Prasanna et al. 2018; Ekholm 2017), local knowledge in developing countries (Ifeanyi-obi et al. 2016; Ugochukwu 2018), and adaptation (Li et al. 2017). Surveys of farmer perceptions of climate changes and their impacts are being increasingly utilised for example, (Hussain et al. 2016).

As more studies emerge, it appears that warming may pose a growing threat to agricultural yields and food security in regions at low and mid latitudes (<45º). At high latitudes, warming may increase the yields of some crops because temperatures are not currently above the optimal level for maximum rates of photosynthesis for many crops. However, evidence for observed climate change impacts on agriculture remains not as robust as for other systems or sectors (e.g., ecosystems, cryosphere). Reasons for this are multiple, one being that agriculture is a managed system – and management practices of such systems change over time. Separating the role such practices may have played from observed climate trends is therefore necessary for clear attribution. Because this is an area of research that is still in its nascent stages, we have included both studies with long-term datasets and that utilised IPCC attribution methods (Hegerl et al. 2010) as well as other studies, particularly those that depend on local knowledge from the developing world.

5.2.2.2 Observed impacts on crop production

Since AR5, there have been studies that document trends in crop production and related variables at global and regional scales (Table 5.3).

Global scale. A recent analysis related to global aridity change has found that a drying tendency since 1951–2011 has been dominating the 'global grain production area,' which may be affecting yields of the four major crops (maize, rice, wheat, and soybean) (Wang et al. 2018). Drought spots categorised by severity and frequency were typically located in the north of Eastern Asia, Western Africa, central Southeast Asia, and Central Europe. Another recent study found that drier regions are projected to dry earlier, more severely and to a greater extent than humid regions, with the population of sub-Saharan Africa most vulnerable (Lickley and Solomon 2018). Statistical analyses have shown that climate variation explains a third of global crop yield availability (Ray et al. 2015).

Table 5.3 Observed climate change impacts on regional crop production, data sources, and attribution methods

Region	Time Period	Observed Impacts	Climate Data	Impact Method/Source	Attribution Method (to change in climate, but not anthropogenic forcing)	Reference
Kenya's Lower Tana Basin	1975-2010	None yet, but the authors state that the observed changing climate conditions are threatening to make agricultural zones unsuitable for maize production	Weather Station data	Tana River County subcoutries' agricultural and lifestock extension office	None	{Ketiem 2017}
Soutwest, Nigeria	Prior to 2016	Reduced farmers' income, increased infestation of pests and diseases, the discoloration of crop leaves, the adoption of mixed farming, and lower growth and harvesting yields	No climate data included	Data were collected from 80 traditional crop farmers	None	{Abiona 2016, Arable}
Abia State, Nigeria	Prior to 2016	Declines in yields, reduced soil fertility, uncertanty of planting and harvesting date, stunted growth, increase in decay of planted corns/normels, increased losses during storage in barns	No climate data included	Data was collected using a participatory pair-wise ranking technique from Key cocoyam farmers, village chiefs and Agricultural extension agents in a Focused group discussion and in-depth interview	None	{Ifeanyi-obi 2016}
Anambra State, Nigeria	2015	Adoption of adaptation measures by farmers including mixed cropping, crop rotation and application of fertilizers.	No climate data included	A cross section of two hundred and forty farmers was sampled with the aid of a structured questionaire and analysed using descriptive statistics.	None	{Ubochukwu 2018}
Ebonyi State, Nigeria	Unclear	Women farmers are percieving that irregulatrity of rainfall, increasing temperatures, variability of relative humidity, and high intensity of sunshine all affecting cassava production	None	160 Cassava women farmers selected for structured interviews	None	{Eze 2017}
North China Plain	1954-2014	Reduced maize yields	China Meterological Data Sharing Service System	Wuqiao experimental station	Single Step	{Huang 2018, period}
Heilengjiang Province, China	1980-2009	A 7-17% percent increase in yield in maize per decade	Chinese Meterological Administration	China Agricultural Database	Single Step	{Meng 2014}
Hindu Kush Himalayan Region	Survery given 2011-1012 (questioned asked about last ten years)	More requent incidences of floods, landslides, droughts, livestock diseases, and crop pest, leading to lower farmer incomes	No climate data used in the study, though the authors do cite other studies hat have dcoumented trends in temperature and precipitation in the region	Data from 8083 Households	No formal attribution method used. The article does state that local people have attributed observed impacts to climate change	{Hussain 2016}
India	1981-2009	Reduced yields by about 5.2%	Indian Meteorological Department (IMD)	Indian Harvest Database from the Centre of Monitoring the Indian Economy (CMIE) and the Directorate of Enomomics, Ministry of Agriculture.	The atuhors do establish through regression analysis a relationship between temperature and yield.	{Gupta 2017}
India	1956-2000	Warming over the last 30 years is responsible for 59,300 suicides in India	The National Center for Environmental Protection	Indian Ministry of Agriculture, Indian NCRB	Though no formal attribution method was applied, the study does demonstrate a statistical relationship between suicides and temperatures, and shows that the two are increasing with time. The author also shows a statistical relationship between temperatures and agricultural yieids and shows that the response to agricultural yields mirrors that of suicides.	{Carleton 2017}
Pujab, Pakistan	1980-2014	Change in Phenology in Maize	Pakistan Meterological Department	Punjab Agriculture Department	Single Step	{Abbas 2017, phenology}
Pujab, Pakistan	1980-2016	Change in phenology of sunflowers	Pakistan Meterological Department	Punjab Agriculture Department	Single Step	{Tariq 2018, warming}
Australia	1965-2015	Stalled wheat yields	Australian Bureau of Meterology	Agricultural Commodity Statistics	Single Step	{Hochman 2017}
Czech Republic	1961-2014	Recent warming has had long term impacts on fruiting vegetibles (for 4.9 to 12.2% C-1) but resulted in decreaes in the stability of tradionally grown root vegetibles in the warmest areas of the country.	Czech Hydrometerological Institute (CHMI), 268 climatological stations, and 774 rain gauge stations	A database of 12 field-grown vegetables at the district level as reported by the Czech Statiistical Office.	Associative Pattern	{Potopova 2017}
Europe	1989-2009	Wheat and barley yields have declined by 2.5% and 3.8%, and maize and sugar beet yields have increased.	Terrestrial Precipitation: 1900-2008 Gridded Monthly Time Series Version 2.01. Available at: http://climate.geog.udel.edu/~climate/.	EU Farm Accountancy Data Network (FADN)	Associative Pattern	{Moore 2018}
Great Plains, United States	1968-2013	Up to a quarter of variability in yields explained by climate variability	Global Historical Climatology Network (GHCN) provided by the National Climatic Data Centre of the National Oceanic and Atmospheric Administration	United States Department of Agriculture-National Agriculture Statistics Services	None	{Kukal 2018}
Bolivian Andes	2012-1014	Changes in the viability of native potato varieties, planting and harvesting strategies, and reduced number of planting harvests.	No climate data used, thoug the article states that "agronomists who served as key informants noted a marked change in the rainy season over recent decades."	Data collected via participatory workshops with female farmers and food preparers, semi-structured interviews with local governments, and the authors' cultivation of two native potato plots in 2013-1014 in collaboration with local community organizations.	None	{Saxena 2016}

Australia. In Australia, declines in rainfall and rising daily maximum temperatures based on simulations of 50 sites caused water-limited yield potential to decline by 27% from 1990 to 2015, even though elevated atmospheric CO_2 concentrations had a positive effect (Hochman et al. 2017). However, the 27% climate driven decline was not experienced in recorded national yields due to ongoing improvements in management and technology, which have allowed yields to stay stagnant rather than decline by 25 kg ha^{-1} yr^{-1}.

Asia. There are numerous studies demonstrating that climate change is affecting agriculture and food security in Asia. Observed warming has led to increasing rice area expansion and production in Northeast China (Box 5.1) (Li et al. 2017; Shi et al. 2013; Lin et al. 2005; Liu et al. 2014; Wang et al. 2014; Meng et al. 2014; Huang et al. 2018).

Crop yield studies focusing on India have found that warming has reduced wheat yields by 5.2% from 1981 to 2009, despite adaptation (Gupta et al. 2017); that maximum daytime temperatures have risen along with some night-time temperatures (Jha and Tripathi 2017); and that if India continues to deplete its groundwater impacts of increased climate variability are likely to increase by half (Fishman 2018). A recent study has shown that such crop-damaging temperatures have led to an increase in the rate of suicides among smallholder farmers in India (Carleton 2017), but the suicides may also be related to lack of crop insurance and inability to repay loans taken for high-yield, high-input crops.

Agriculture in Pakistan has also been affected by climate change. From 1980 to 2014, spring maize growing periods have shifted an average of 4.6 days per decade earlier, while sowing of autumn maize has been delayed 3.0 days per decade (Abbas et al. 2017). The authors concluded that these shifts in the maize growing period may have been enabled by adoption of new cultivars (i.e., newly introduced hybrids with altered temperature requirements). A similar study with sunflower showed that increases in mean temperature from 1980 to 2016 were highly correlated with shifts in sowing, emergence, anthesis, and maturity for fall and spring crops (Tariq et al. 2018).

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

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

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

In recent years, yields of staple crops such as maize (*Zea mays*), wheat (*Triticum*), sorghum, and a variety of fruit crops, such as mangoes (*Mangifera indica*), have decreased across Africa, widening food insecurity gaps (Ketiem et al. 2017). Some areas, such as the dryland areas of Kenya, are particularly vulnerable due to low adaptive capacity and highly fragile productive systems. In Nigeria, there have been reports of climate change having impacts on the livelihoods of arable crop farmers (Abiona et al. 2016; Ifeanyi-obi et al. 2016; Ugochukwu 2018). The Sahel region of Cameroon has experienced an increasing level of malnutrition, partly due to the impact of climate change since harsh climatic conditions leading to extreme drought have a negative influence on agriculture (Chabejong 2016).

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

Europe. The impacts of climate change are varied across the continent. Moore and Lobell (2015) showed that climate trends are affecting European crop yields, with long-term temperature and precipitation trends since 1989 reducing continent-wide wheat and barley yields by 2.5% and 3.8%, respectively, and having slightly increased maize and sugar beet yields. Though these aggregate affects appear small, the impacts are not evenly distributed. In cooler regions such as the United Kingdom and Ireland, the effect of increased warming has been ameliorated by an increase in rainfall. Warmer regions, such as Southern Europe, have suffered more from the warming, in Italy this effect has been amplified by a drying, leading to yield declines of 5% or greater. Another study documented positive long-term impacts of recent warming on yields of fruiting vegetables (cucumbers and tomatoes) (from 4.9 to 12% per 1°C increase in local temperature) but decreases in yield stability of traditionally grown root vegetables in the warmest areas of the country (Potopová et al. 2017). There is evidence that climate change has already had impacts on bees and pollinators in the Mediterranean region, including advanced and reduced flowering, decoupling between bees and crops, and spread of diseases (López-i-Gelats and Rivera-Ferre).

North America. A recent study looking at extensive crop yield and climate datasets from 1968–2013 showed a connection between climate variability and variability in crop (maize, sorghum, soybean) yields in the Great Plains of the United States (Kukal & Irmak, 2018). The climate-driven impacts in the region were also shown to be variable across crop types and geographies for a particular crop.

Box 5.1. Expansion of rice in Northeast China due to climate warming and cultivar switching

Rice is one of three major cereals in China and represents a crucial part of the country’s food security (Wu et al. 2014). Located between 115º05’~135º02’ E, 38º40’~53º34’N, Northeast China is the coldest region and the only single-crop rice area located at the highest latitude in China (Shi et al. 2013). It is the northern-most region of rice cultivation in the world (Li et al. 2017), as well as the largest *Japonica* rice-production region. Producing high-quality grain plays an important role in guaranteeing China's national and global food security (Shi et al. 2013). Since the 1980s, Northeast China has experienced the most rapid rate of climate warming in China (Lin et al. 2005): the temperature there has increased by 1.43°C in the past half of century (Shi et al. 2013), about two times higher than the global average level. The observed warming together with the extension of higher-yielding cultivars and improved management has allowed expansion of rice production in this region. It is estimated that the warming had contributed to the increased rice yields in Northeast China at the rate of 0.59% yield per year (Liu et al. 2014; Wang et al. 2014).

With the increasing northward movement of the accumulated temperature belt, all three river basins in the area have become suitable for rice growth. The rice cultivated area has expanded since the 1990s (Lin et al. 2005), and statistics show that there exists a close correlation between significant climate change and the expansion of rice cultivation area in Northeast China during recent decades (Shi et al. 2013). Further analysis has demonstrated that the shifts in the extent and location of rice-cropping areas match the pattern of climate change – the increased temperature has enabled rice planting at higher altitudes and northward and eastward, extending beyond the northern boundary of rice planting (Figure 5.4) (Liu et al. 2014).

The suitable area for rice in the region increased from 47.1% of all Chinese land area in 1980 to 51% in 2010 due to extension of the northern limits of climatically suitable rice production from 48ºN in 1980 to 50ºN in 2010 in Northeast China. Li et al. (2017) found that rice area has increased by approximately 2.4×10^6 ha during the past 30 years at an annual rate of 8.0×10^4 ha, and that most of the increase occurred after 2000. According to Li et al. (2017), the central latitude of the rice area shifted northwards from 46°N to 47°N and moved eastwards from 130°E to 133°E from 1984 to 2013. This occurred mainly in the Sanjiang Plain in Heilongjiang province (Zhang et al. 2017). However, cold stress is still a threat to rice production (Wang et al. 2014).

The expansion of rice-cropping area in Northeast China is a demonstration of taking the opportunity to increase food production, in both amount and nutritional quality, as the *Japonica* rice adopted is also highly nutritious. The share of the region in China's total national rice output increased, with relative contribution going up from 3% to 16.2% (Li et al. 2016). As temperature increased, the early-maturing rice variety, which had been restricted to a limited area due to cool temperatures, was replaced with a more productive longer-duration variety, while the early variety is used in the previous unavailable areas where warming temperature now allows production (Zhang et al. 2013).

However, environmental impacts cannot be neglected. Expansion of rice-cropping land area would reduce biodiversity and affect other regional ecosystem services. Rapid population growth in the region will lead to more demand for food and land resources, in turn bringing deforestation and further land use change from transformation of grasslands and lakes to agriculture (Shi et al. 2013). A further side-effect is that warming would provide a more favourable environment for overwintering and subsequent epidemics of rice pests and diseases. Other environmental consequences are higher degrees of soil salinity and water shortages (You et al. 2011) and lower groundwater levels due to withdrawal for irrigation (Piao et al. 2010). In addition, excessive nitrogen fertilisation can lead to high nitrate accumulation in soil profiles (Ju et al. 2004). Moreover, expansion of cultivated rice land would lead to greater greenhouse gas emissions (Yao et al. 2017).

Expansion of rice cultivaton in Northeast China provides an example of observed agricultural adaptation to climate warming. In some cases, it is possible to take advantage of warming for food security, including maximising utilisation of increased accumulated temperature with new varieties, high-efficiency irrigation and fertilisation, pest and disease control (Liang et al. 2015; Thakur et al. 2016). However, institutional efforts and policy initiatives are needed for GHG emissions reduction and environmental protection at the same time (Liang et al. 2015).

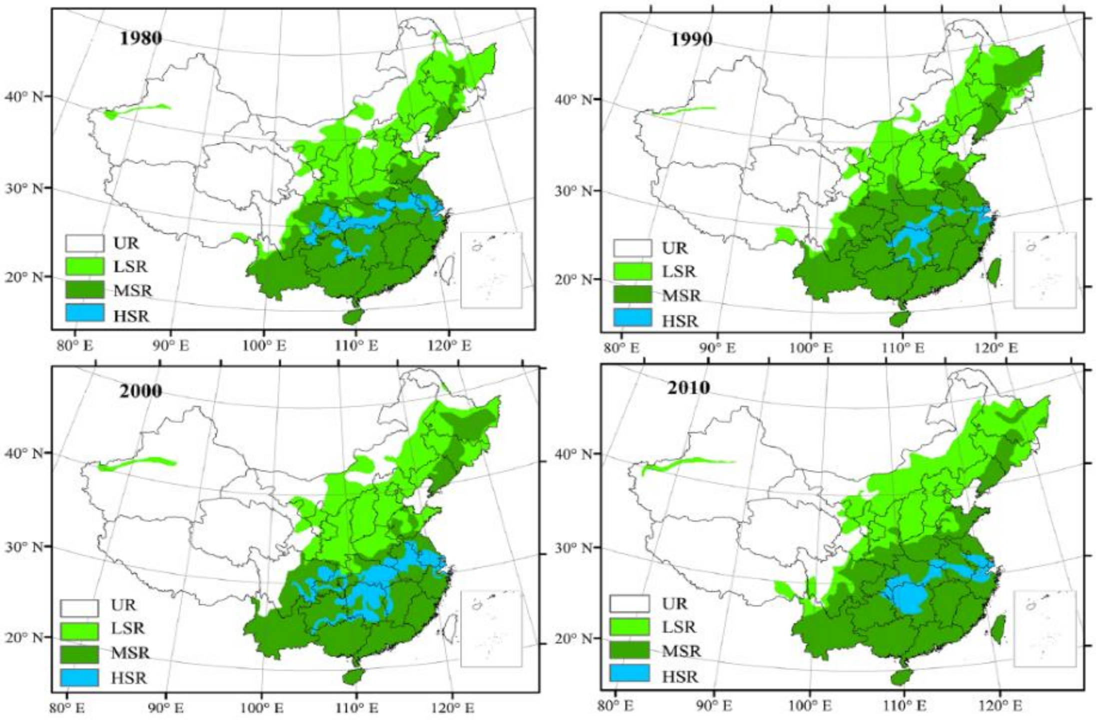

Figure 5.4 Spatial distribution of climatically-suitable rice regions in China (1980 to 2010) (Liu et al. 2014)

5.2.2.3 *Observed impacts on pastoral systems*

Pastoral systems are particularly vulnerable to climate change (Dasgupta et al. 2014). Especially important are those impacts linked to drought and flood, rising temperature and seasonality, although these impacts exacerbate a contextual vulnerability where other non-climate drivers play an important role. Observed impacts 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, increasing conflicts for the access to pasture land (López-i-Gelats et al. 2016). During environmental disasters, livestock holders have been shown to be more vulnerable to food insecurity than their crop-producing counterparts because of limited economic access to food and unfavorable market exchange rates (Nori et al. 2005).

5.2.3 Future climate change impacts

Since AR5, methods for assessment of future climate change impacts on food systems have improved in several areas, providing new insights. These methods include greater number of ensembles of multiple climate, crop, and economic models, with improved characterisation of uncertainty (Wiebe et al. 2015); further comparison of results from process-based crop models and statistical models (Zhao et al. 2017a); advances in regional integrated assessments (Rosenzweig and Hillel, 2015), and new coordinated global and regional studies (Rosenzweig et al. 2017; Ruane et al. 2018). Expanded meta-analyses of free-air carbon dioxide experiments (FACE) have examined effects of high CO_2 on crop nutrients not just on yield (Smith and Myers 2018; Zhu et al. 2018a) (Section 5.2.4). A number of impacts studies utilising a range of these methods responded to the request by the UNFCCC for food system implications of limiting global temperature increases to 1.5°C and 2.0°C above pre-industrial conditions. Recent reviews have confirmed that higher CO_2 concentrations increase crop growth and yield, especially in crops with C3 photosynthetic pathways, but realisation of these CO_2 direct effects depends on nutrient status (Lombardozzi et al. 2018; Toreti et al.) *(robust evidence, high agreement)*. New work has considered future impacts of farming systems, extreme events, fruits and vegetables, rangelands and livestock, and aquaculture, as well as food safety, pests and diseases, and food quality (Section 5.2.4).

Most of the work continues to focus on the major commodities -- wheat, maize, rice, and soybean -- while areas still lagging are multi-model ensemble approaches for livestock and fruits and vegetables. While the current reliance on the four major commodities makes assessment of climate change impacts on them important, there is a growing recognition that more than caloric intake is required to achieve food security for all and that assessments need to take into account how climate change will affect the 2 billion malnourished people in the current climate and food system.

5.2.3.1 Future impacts on crop production

Climate change impacts on food production are projected to grow *(robust evidence, high agreement)*. Climate change effects have been studied on a global scale with a variety of methodological approaches that have recently been compared through meta-analysis. The approaches are global gridded crop model simulations (e.g., Müller et al. 2017), point-based crop model simulations (e.g., Asseng et al. 2015), analysis of point-based observations, and temperature-yield regression models (e.g., Liu et al. 2016). These analyses have focused primarily on wheat, rice, and maize, which provide about two-fifths of the calories and protein globally produced for human consumption (Shiferaw et al. 2013).

Figure 5.5 illustrates the impact of temperature on yields of the four crops at the global scale across the four different methods. These results do not take CO_2 effects, adaptation, and genetic improvement into account. A temperature increase of one degree Celsius will reduce average wheat, rice and soybean yield globally by 6.0 ± 2.9%, 3.2 ± 3.7% and 3.1%, respectively but with large uncertainties for soybean yield (Zhao et al. 2017a). All four methods predict a large negative impact for maize, but with varying magnitudes; loss in yield for each degree Celsius increase in global mean temperature (with multimethod average ±2 SE) of −7.4 ± 4.5% per degree Celsius. Mostly the different methods generated similar results at the global scale, but estimates varied between countries.

The meta-analysis of major methods by Zhao et al. (2017a) found that the impact estimates are consistently negative for four major maize producers, together responsible for two-thirds of global maize production – namely, the United States (−10.3 ± 5.4% per degree Celsius), China (−8.0 ± 6.1% per degree Celsius), Brazil (−5.5 ± 4.5% per degree Celsius), and India (−5.2 ± 4.5% per degree Celsius). The estimated impact on maize crops in France, however, is smaller (−2.6 ± 6.9% per degree Celsius), including a small positive estimate (3.8 ± 5.2% per degree Celsius) from statistical modelling (Zhao et al. 2017a).

Alimitation of Zhao et al. (2017a) is that it is based on the assumption that yield responses to temperature increase are linear to derive the yield impacts per degree Celsius increase. However, the yield response for each degree Celsius warming differs by growing season temperature level. The projected global mean yields of maize and soybean in the end of this century monotonically decrease with warming, whereas those of rice and wheat increase with warming and level off at a warming of about 3ºC (2091–2100 relative to 1850–1900) (Izumi et al. 2017).

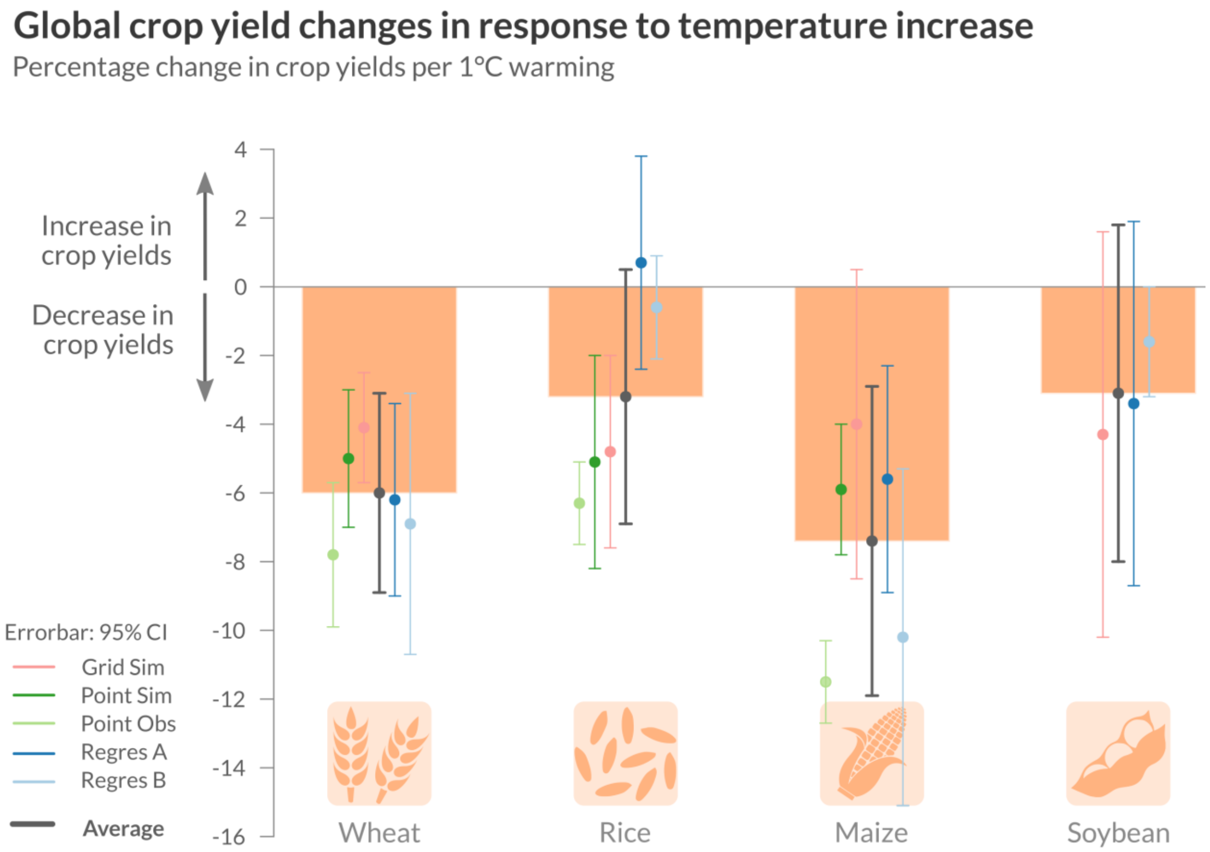

Figure 5.5 Multimethod estimates of global crop yield changes in response to temperature increase. (A) Impacts on crop yields of a 1°C increase in global temper- ature in grid-based simulations (Grid-Sim), point-based simulations (Point-Sim), field-warming experiments (Point-Obs), and statistical regressions at the country level (Regres_A) (9) and the global level (Regres_B) (8). Circles, means of estimates from each method or medians for Grid- and Point-Sim. Filled bars, means of the multimethod ensemble. Error bars show 95% CIs for individual methods (gray lines) and the ensemble of methods (black lines). These results do not take CO_2 effects, adaptation, and genetic improvement into account (Zhao et al. 2017a)

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

Empirical statistical models have been applied widely to both maize and wheat systems, at multiple scales (Tebaldi and Lobell 2018a). Statistical models and global climate model scenarios for maize and wheat found that the RCP4.5 scenario reduced the size of average yield impacts, the risk of major slowdowns, and exposure to critical heat extremes compared to RCP8.5 in the latter decades of the 21st century. These effects were not as great in wheat as in maize because of stronger CO_2 fertilisation effects, based on empirically estimated linear relationships between climate and yields at the global level.

Using a global gridded crop model, Deryng et al. (2014) projected maize to face worsening impacts under a range of RCPs, while spring wheat and soybean improved to the 2080s due to CO_2 fertilisation effects globally. However, parts of the tropics and subtropics could face substantial yield declines. Impacts on crops grown in the tropics are projected to be more negative than in mid- to high-latitudes as stated in AR4 and AR5 and confirmed by Rosenzweig et al. (2014) (Figure 5.6). For example, a review of recent scientific literature found that West Africa is experiencing a rapid climate change with warming, recovery of monsoonal precipitation and increase in extremes in many areas; and projected yield loss the degree of which depends on manifestations of wetter or drier conditions and elevated CO_2 concentrations (Sultan and Gaetani 2016). Faye et al. (2018b) in a crop modelling study with RCPs 4.5 and 8.5 found that climate change could have limited effects on peanut yield in Senegal due to the effect of elevated CO_2 concentrations.

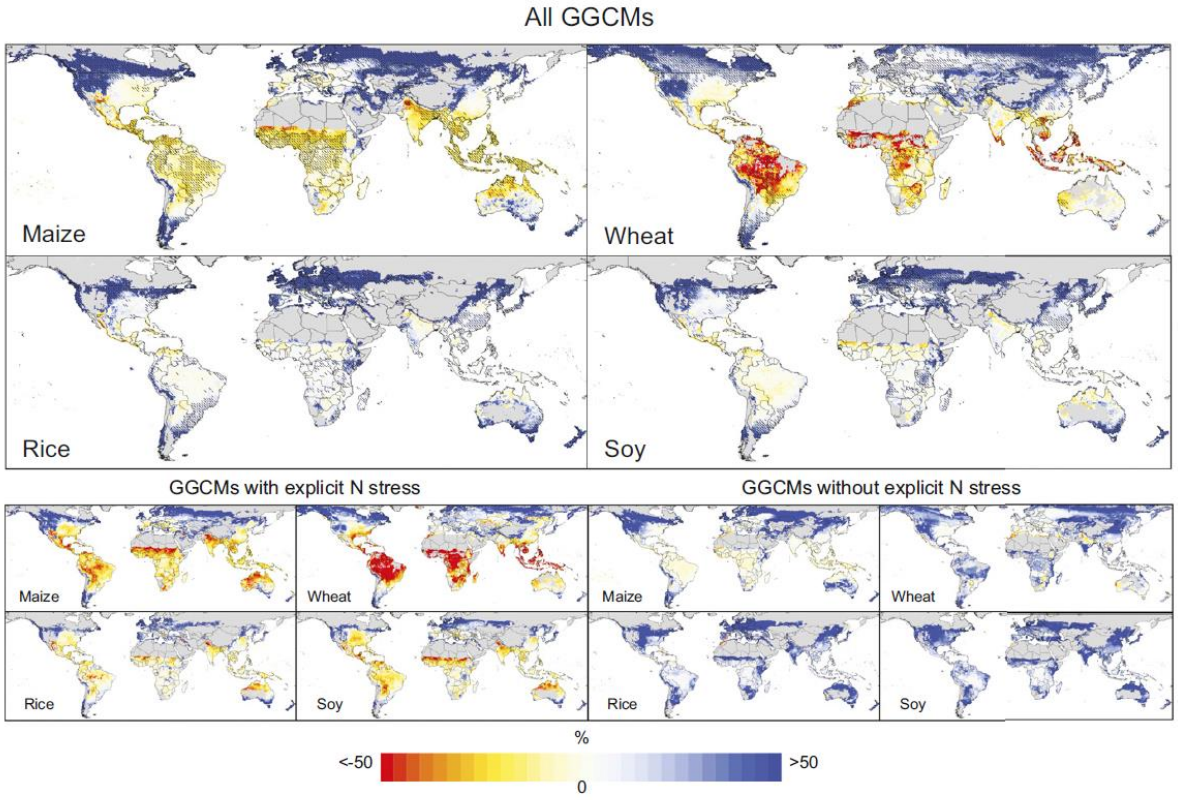

Figure 5.6 Median yield changes (%) for RCP8.5 (2070–2099 in comparison to 1980–2010 baseline) with CO_2 effects over all five GCMs x seven Global Gridded Crop Models (GGCMs) (6 GGCMs for rice) for rainfed maize (35 ensemble members), wheat (35 ensemble members), rice (30 ensemble members), and soy (35 ensemble members). Hatching indicates areas where more than 70% of the ensemble members agree on the directionality of the impact factor. Gray areas indicate historical areas with little to no yield capacity. The bottom 8 panels show the corresponding yield change patterns over all five GCMs x four GGCMs with nitrogen stress (20 ensemble members from EPIC, GEPIC, pDSSAT, and PEGASUS; except for rice which has 15) (Left); and 3 GGCMs without nitrogen stress (15 ensemble members from GAEZ-IMAGE, LPJ-GUESS, and LPJmL)

Crop productivity changes in 1.5°C and 2.0°C worlds. Schleussner et al. (2018) investigated the sensitivity of future crop yield projections with a set of global gridded crop models for four major staple crops at 1.5°C and 2°C warming above pre-industrial levels, as well as at different CO_2 levels determined by similar probabilities to lead to 1.5°C and 2°C, using climate forcing data from the Half a degree Additional warming, Prognosis and Projected Impacts project. For the same CO_2 forcing, they found consistent negative effects of half a degree warming on productivity in most world regions. Increasing CO_2 concentrations consistent with these warming levels have potentially stronger but highly uncertain effects than 0.5°C warming increments. Half a degree warming will also lead to more extreme low yields, in particular over tropical regions. The results indicate that global mean temperature change alone is insufficient to determine future impacts on crop productivity.

Using an empirical model, Tebaldi and Lobell (2018b) showed that the inclusion of CO_2 effects negates benefits of mitigation for wheat and reduced benefits in magnitude for maize yields. They found that for globally-averaged yields for wheat and maize the 1.5°C target does not change substantially the expected impacts on yields caused by warming temperatures of the 2.0°C target.

AgMIP coordinated global and regional assessment (CGRA) results show that at the global scale, there are mixed areas of positive and negative simulated wheat and maize yield changes, with declines in some breadbasket regions, at both 1.5°C and 2.0°C (Rosenzweig et al. 2017). Declines are especially evident in simulations that do not take into account direct CO_2 effects on crops. These projected global yield changes mostly resulted in increases in prices of wheat and maize in two global economic models. Regional simulations for 1.5°C and 2.0°C using site-based crop models had mixed results depending on region and crop. In conjunction with price changes from the global economics models, these productivity declines in the Punjab, Pakistan resulted in an increase in vulnerable households and poverty rate (Rosenzweig et al. 2017).

One assessment of 1.5°C and 2.0°C in West Africa using four crop models found that the maize, millet and sorghum yields were shown to fall in a majority of areas, with increased variability and likelihood of crop failures in others (Parkes et al. 2017). Another study (Faye et al. 2018) assessed impacts of 1.5°C versus 2.0°C on yields of maize, pearl millet and sorghum in the West African Sudan Savanna using two crop models that were calibrated with common varieties from experiments in the region with management reflecting a range of typical sowing windows. With current fertiliser use, results indicated 2% higher losses for maize and sorghum with 2.0°C compared to 1.5°C warming, with no change in millet yields for either scenario. In the intensification case, yield losses due to climate change were larger than with current fertiliser levels. However, despite the larger losses, yields were always two to three times higher with intensification, irrespective of the warming scenario.

Extreme events and production shocks. Using global datasets of maize production and climate variability combined with future temperature projections to quantify how yield variability will change in the world’s major maize-producing and -exporting countries under 2°C and 4 °C of global warming, a new assessment by Tigchelaar et al. (2018) showed rising instability in global grain trade and international grain prices, affecting especially the about 800 million people living in extreme poverty who are most vulnerable to food price spikes. They also underscore the urgency of investments in breeding for heat tolerance. Tesfaye et al. (2017) projected that the extent of heat-stressed areas in South Asia could increase by up to 12% in 2030 and 21% in 2050 relative to the baseline. At a regional scale, they found maize yield declines in 2050 of up to 12% and 14% in rainfed and irrigated maize, respectively.

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

Mean yield declines of these crops were projected for a temperature increase of 4°C by 31.5% (CI 41.4–21.5%) with baseline temperature higher than 20°C but only by 4.9% (CI -47.6% to +37.8%) with baseline temperature equal or below 20°C (Scheelbeek et al. 2018). Rippke et al. (2016) found that 30–60% of the common bean growing area and 20–40% of the banana growing areas in Africa will lose viability in 2078–2098 with a global temperature increase of 2.6°C and 4°C respectively. Tripathi et al. (2016) found fruits and vegetable production to be highly vulnerable to climate change at their reproductive stages and also due to potential for greater disease pressure.

5.2.3.2 *Future impacts on rangelands and livestock*

The impacts of climate change on global rangelands and livestock have received comparatively less attention than the impacts on crop production. Furthermore, there are large uncertainties related to grasslands and grazing lands, especially in regard to net primary productivity (NPP) (Fetzel et al. 2017; Chen et al. 2018). Boone et al. (2017) estimated that the mean global annual net primary production (NPP) may decline by 10 gC m^{-2} yr^{-1} in 2050 under RCP 8.5, but herbaceous NPP is likely to increase slightly (i.e., average of 3 gC m^{-2} yr^{-1}) (Figure 5.7). Results of a similar magnitude were obtained by (Havlík et al. 2015), using EPIC and LPJmL on a global basis.

Boone et al. (2017) identified significant regional heterogeneity in responses, with large increases in annual productivity projected in northern regions (e.g., a 21% increase in productivity in the US and Canada) and large declines in western Africa (-46% in sub-Saharan western Africa) and Australia (-17%). Soil organic carbon is projected to increase in Australia (9%), the Middle East (14%) and central Asia (16%), and decline in many African savannahs (e.g., -18% in sub-Saharan western Africa).

When translating these impacts on forage productivity to impacts on livestock, they found that livestock numbers are projected to decline 7.5–9.6% in 2050. These results suggest that forage production in Africa is sensitive to changes in climate, which will have substantial impacts on the livelihoods of the more than 180 million people who raise livestock on those rangelands.

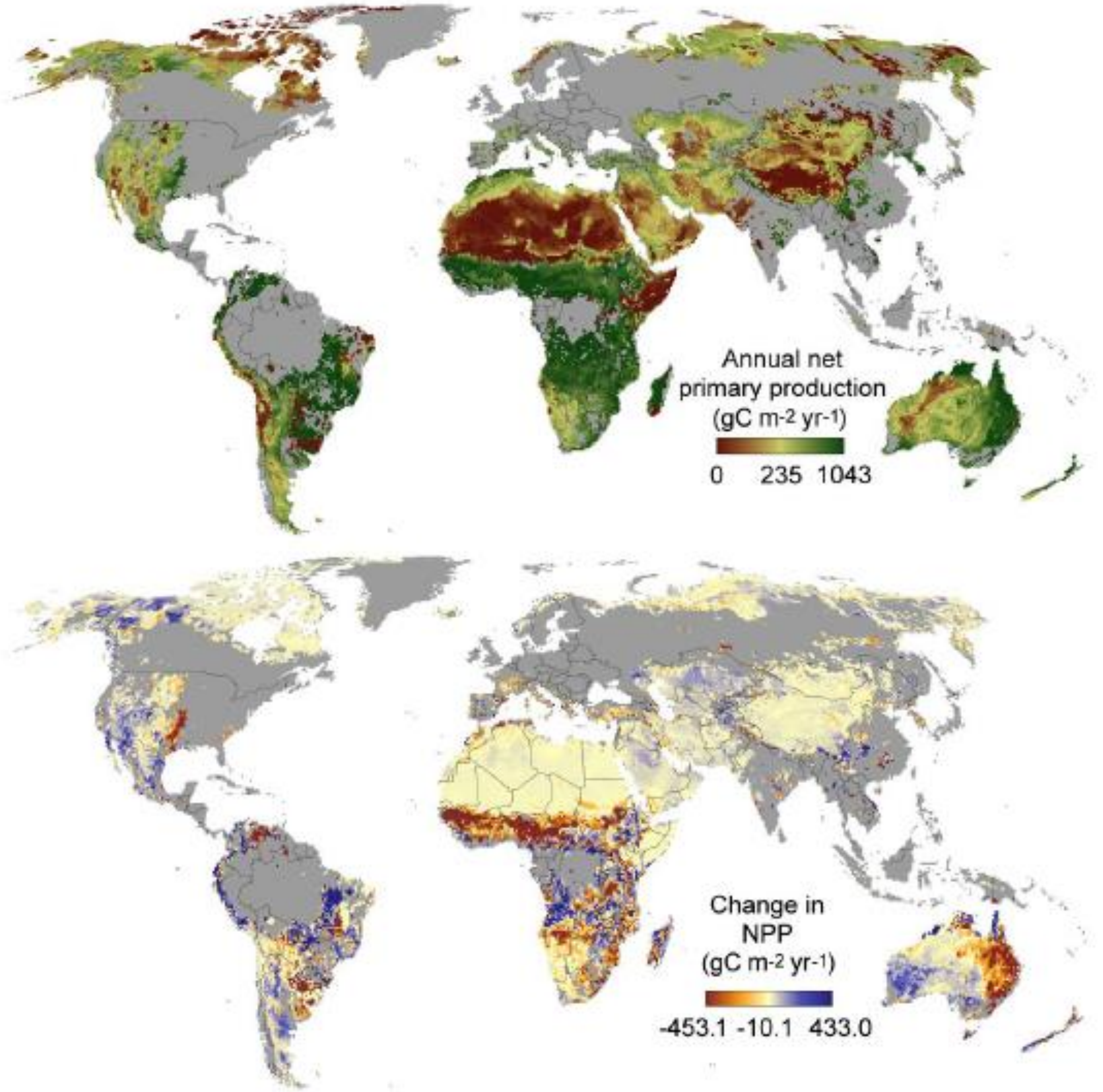

Figure 5.7 Ensemble simulation results for annual net primary productivity of rangelands as simulated in 2000 (top) and their change in 2050 (bottom) under emissions scenario RCP 8.5, with plant responses enhanced by CO_2 fertilisation. Results from RCP 4.5 and 8.5, with and without positive effects of atmospheric CO_2 on plant production, differed considerably in magnitude but had similar spatial patterning, 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)

According to Boone et al. (2017), the composition of rangelands is likely 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 likely 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 increase, albeit at lower productivity and standing biomass.

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. 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.

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

Impacts of climate change on livestock productivity, particularly of mixed and extensive systems, are strongly linked to impacts on rangelands and pastures. This is critical considering the very large areas concerned and the number of vulnerable people affected (Steinfeld 2010; Morton 2007). 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 directly to the animal, 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.

By production system, 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; López-i-Gelats, 2014). Direct impacts of climate change in mixed and extensive production systems are linked to increased water and temperature stress on the animals potentially leading to animal morbidity, mortality and distress sales. Most livestock species have comfort zones between 10ºC–30ºC, and at temperatures above this, animals reduce their feed intake 3–5% per additional degree of temperature. In addition to reducing animal production, higher temperatures negatively affect fertility (HLPE 2012). Indirect impacts to mixed and extensive systems are mostly related to the impacts on the feed base, whether pastures or crops, leading to increased variability and sometimes reductions in availability and quality of the feed for the animals (Rivera-Ferre et al. 2016b). Increased risk of animal diseases is also an important impact to all production systems (Bett et al. 2017).

5.2.3.3 Future impacts on farming systems

New work has developed farming system approaches that take into account both biophysical and economic processes affected by climate change, and multiple activities. Farm households in the developing world often rely on a complex mix of crops, livestock, aquaculture, and non-agricultural activities for their livelihoods (Rosenzweig and Hillel 2015; Antle et al. 2015). By including regional economic models, these methods take into account the potential for yield declines to raise prices and thus livelihoods (up to a certain point) in some cases and for other crops, livestock, and non-farm strategies to be examined. On the other hand, lost income for smallholders from climate change-related declines in, for example, coffee production can decrease their food security.

Farming system methods developed by AgMIP have been used in regional integrated assessments in Sub-Saharan Africa (Kihara et al. 2015), West Africa (Adiku et al. 2015); East Africa (Rao et al. 2015), South Africa (Beletse et al. 2015), Zimbabwe (Masikati et al. 2015), South Asia (McDermid et al. 2015), Pakistan (Ahmad et al. 2015), the Indo-Gangetic Basin (Subash et al. 2015), Tamil Nadu (Ponnusamy et al. 2015), and Sri Lanka (Zubair et al. 2015). The AgMIP approach has developed representative agricultural pathways (RAPs) to be consistent with and complement the RCP/SSP approaches for use in agricultural model intercomparisons, improvement, and impact assessments (Valdivia et al. 2015).

Other work includes a survey of 600 households in Madagascar found that smallholder farmers are particularly vulnerable to shocks owing to their high dependence on agriculture for their livelihoods, chronic food insecurity, physical isolation, and lack of access to formal safety nets (Harvey et al. 2014b). Climate change is expected to disproportionately affect these smallholder farmers by further exacerbating risks of pest and disease outbreaks, extreme weather events (tropical cyclones), and market shocks (Harvey et al. 2014b).

In Central Asia, a study using the bio-economic farm model (BEFM) found large differences in projected climate change impact ranging from positive income gains in large-scale commercial farms in contrast to negative impacts in small-scale farms (Bobojonov and Aw-Hassan 2014). Negative impacts may be exacerbated if irrigation water availability declines due to climate change and increased water demand in upstream regions.

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

5.2.3.4 Future impacts on aquaculture

Climate change impacts on aquaculture can include losses of production and infrastructure arising from extreme events such as floods, increased risks of diseases, parasites and harmful algal blooms. Other impacts can include reduced availability of wild genetic resources, as well as reduced precipitation leading to increasing competition for freshwater. Viet Nam, Bangladesh, the Lao People's Democratic Republic and China are estimated to be the most vulnerable countries in Asia, with Belize, Honduras, Costa Rica and Ecuador the most vulnerable in the Americas, for freshwater aquaculture. Uganda, Nigeria and Egypt were found to be particularly vulnerable in Africa. In the case of brackish water production, Viet Nam, Egypt and Thailand have the highest vulnerabilities. Climate-driven changes in temperature, precipitation, ocean acidification, incidence and extent of hypoxia and sea level rise, amongst others, are expected to have long-term impacts in the aquaculture sector at multiple scales.

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

5.2.4 Climate change impacts on food safety, food quality, pests and diseases

There are many routes by which climate change can impact upon human health (Watts et al. 2018), with respect to food systems, the major routes are via affecting the amount of food (both via direct impacts from weather on yields, and indirect effects on yields via climate change's impacts on pests and diseases, as well as pollination services). Climate change, and changing CO_2 in the atmosphere can affect nutritional quality and, food safety risks during transport and storage can be exacerbated by changing climate. Finally, the direct impacts of changing weather can affect human health through exposure to extreme temperatures for the agricultural workforce. Through changing metabolic demands and physiological stress for people exposed to extreme temperatures, there is also the potential for an interaction with food availability: people may require more food to cope, whilst at the same time being impaired from producing it (Watts et al. 2018).

5.2.4.1 Impacts on food safety and human health

Factors related to climate change that can influence food safety through changing the population dynamics of contaminating organisms include changes in temperature and precipitation patterns, increased frequency and intensity of extreme weather events, ocean warming and acidification, and changes in contaminants' transport pathways, among others, as well as other socio-economic aspects related to food systems such as agriculture, animal production, global trade, demographics and human behaviour which all influence food safety (Tirado et al. 2010). These changes include: changing the activity of mycotoxin-producing fungi, changing the activity of micro-organisms in aquatic food chains that cause disease (e.g., dinoflagellates, bacteria like *Vibrio*), contamination of pastures following flooding, with enteric microbes (like *Salmonella*) that can enter the human food chain. Degradation and spoilage of products in storage and transport can also be affected by changing humidity and temperature outside of cold-chains, notably from microbial decay but also potential changes in the population dynamics of stored product pests (e.g., mites, beetles, moths) (Moses et al. 2015).

Mycotoxin-producing fungi occur in specific conditions of temperature and humidity, so climate change will affect its range, increasing risks in some areas (such as mid-temperate latitudes) and reducing them in others (the tropics) (Paterson and Lima 2010). There is some *strong evidence* from process-based models of particular species (*Aspergillus*/Aflatoxin B1, *Fusarium*/deoxynivalenol) with projections of future climate that show, for example, that aflatoxin contamination of maize in southern Europe will increase significantly (Battilani et al. 2016), and deoxynivalenol contamination of wheat in north-west Europe will increase by up to 3 times (van der Fels-Klerx et al. 2012b,a). Whilst the downscaled climate models make any specific projection for a given geography uncertain (Van der Fels-Klerx et al. 2013), experimental evidence on the small scale suggests that the combination of rising CO_2 levels affecting physiological processes in photosynthetic organisms and temperature changes can be significantly greater that temperature alone (Medina et al. 2014). Whilst there is no overall clear picture of how risks related to aflotoxins may change, they are nonetheless likely to (Vaughan et al. 2016).

In aquatic environments, there is evidence that a range of microbes that can contaminate food products, particularly shellfish – such as *Vibrio* bacteria – are associated with warm-water upwellings. The geographical expansion of *V. parahaemolyticus* outbreaks into Peru (1997) and Alaska (2004) corresponded closely with climate anomalies such as El Niño, which brought large masses of abnormally warm water into these regions (Martinez-Urtaza et al. 2010). The dinoflagellate *Dinophysis* was modelled by (van der Fels-Klerx et al. 2012b) which indicated the potential for greater frequency of algal blooms, with possible increases in shellfish contamination with toxins.

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

Additional routes to human health impacts from climate changing exposures include through changing food plant biology. This may include how crops sequester heavy metals (Rajkumar et al. 2013), or how they respond to changing pest pressure (e.g., cassava produces hydrogen cyanide as a defence against herbivore attack).

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

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

5.2.4.2 Impacts on food quality

Food quality of certain crops is affected by changes in climate through changes in nutrient composition (*medium evidence, high agreement*). Such changes may decrease protein and mineral nutrient concentrations, as well as alter lipid composition (DaMatta et al. 2010). For example, apples in Japan have been exposed to higher temperatures and shown earlier blooming over 3–4 decades. This has led to changes in acidity, firmness and water content, reducing quality. In other fruit, such as grapes, warming-induced changes in sugar composition affect both colour and aroma (Mira de Orduña 2010).

Climate change affects a range of biological processes, including rate of metabolism in plants and ectothermic animals. Changing these processes can change growth rates, and therefore yields, but can also cause organisms to change relative investments in growth vs reproduction, and therefore change the nutrients assimilated. For example, warmer temperatures increase growth rate of Atlantic salmon and faster-growing fish mature earlier – thereby reducing average size of the fish (Jonsson et al. 2012).

As climate change (and CO_2 fertilisation, see next section) can fundamentally affect plant metabolism it can also result in a change of quality for consumers of plants from forage or pasture. The quality of forage for grazers has declined over 22 years in the US, leading to an estimated additional cost of 1.9 billion USD. Whilst there is little evidence about whether changing the protein in forage affects the quality of livestock produce (instead of the yield), there is some evidence in aquatic food chains, where (Rossoll et al. 2012; Bermúdez et al. 2015; Myers et al. 2017) changing temperatures affect the synthesis of long chain polyunsaturated fatty acid leading to reductions in their concentration in harvested fish.

Climate change may affect food quality in other ways (see Section 5.2.4.1 for discussion of changing microbial contamination). For example, changing heat stress in poultry, as well as affecting yields, can affect meat quality (by both altering fat deposition and chemical constituents), shell quality (and hence its function), and the immune system (ability to fight disease) (Lara and Rostagno, 2013).

As with the impacts of climate change on pest and diseases, its impact on food quality can occur through a range of different routes affecting basic biological responses from the base of the food chain to the top. This includes changing the relative ability for basal organisms to compete and therefore the potential for ecosystem impacts to drive effects.

5.2.4.3 Direct CO_2 effects on nutritional quality

Plants require carbon dioxide to form sugar during photosynthesis, and so rising CO_2 levels, all things being equal, enhance the ability to form sugar; a process known as CO_2 fertilisation. Furthermore, increasing CO_2 allows the stomata to be open for a shorter period for gas exchange, reducing water loss through transpiration. However, whilst CO_2 fertilisation is often seen as a positive for yields (e.g., (Yu et al. 2014) and Section 5.2.3), there is now *robust evidence, with high agreement*, that the nutrient content of plants – proteins, minerals, like iron and zinc, and vitamins - is affected negatively by higher CO_2 concentrations. These studies include meta-analyses, modelling, and small-scale experiments (Franzaring et al. 2013; Mishra and Agrawal 2014; Myers et al. 2014; Ishigooka et al. 2017; Zhu et al. 2018a; Loladze 2014).

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

Decreases in protein concentration are related to reduced nitrogen concentration possibly caused by nitrogen uptake not keeping up with biomass growth, an effect called 'carbohydrate dilution' or 'growth dilution', and by inhibition of photorespiration providing most of the energy for assimilating nitrate into proteins (Bahrami et al. 2017). Other mechanisms have also been postulated (Feng et al. 2015; Bloom et al. 2014; Taub and Wang 2008).

Legume and vegetable yields increased with elevated CO_2 concentration of 250 ppm by 22% (CI 11.6–32.5%), with a stronger effect on leafy vegetables than on legumes and no impact was found for changes in iron, vitamin C or flavonoid concentration (Scheelbeek et al. 2018). Together, the impacts on protein availability may take as many as 150 million people into protein deficiency by 2050 (Medek et al. 2017).

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

5.2.4.4 Impacts on pests and diseases

Climate change is likely to change the dynamics of plant and livestock diseases (*robust evidence*, *high agreement*). Such changes are likely to depend on specifics of the local context (including management) but perturbed ecosystems are more likely, on theoretical grounds, to allow pest and disease outbreaks (*low confidence*). Whilst specific changes in pest and disease pressure will vary with geography, farming system, pest/pathogen – increasing in some situations decreasing in others – there is robust evidence, with *high agreement*, that pest and disease pressures are likely to change. Warren et al. (2018) imply that about 50% of insects, which are often pest or disease vectors, will change ranges by about 50%, under current commitments to carbon budgets.

There are many potential biological and ecological mechanisms by which climate change will affect the potential for pests and diseases to affect food production (Canto et al. 2009; Gale et al. 2009; Thomson et al. 2010; Pangga et al. 2011; Juroszek and von Tiedemann 2013; Bett et al. 2017). These include CO_2 and a range of stresses affecting host susceptibility; changes in the biology of pests and diseases or their vectors (e.g., more generational cycles, selection driving evolution); mismatches between pests or vectors and their 'natural enemies'; changes in survival or persistence of pests or disease pathogens (e.g., changes in crop architecture driven by CO_2 fertilisation and increased temperature, providing a more favourable environment for persistence of pathogens like fungi). These are in addition to changes in species distributions accompanying changes in bio-climatic envelopes.

There is some good evidence that pests and diseases have already responded to climate change (Bebber et al. 2014), and many studies have now built predictive models based on current incidence of pests, diseases or vectors which indicate how they may respond in future (e.g., (Caminade et al. 2015; Kim et al. 2015; Kim and Cho 2016; Samy and Peterson 2016; Yan et al. 2017)). We can say with *high confidence* that pests, diseases and vectors (for both crop and livestock diseases) are likely to be changed by climate change. For example, Samy and Peterson (2016) modelled Blue-tongue virus (BTV), which is spread by biting *Culicodes* midges. Their model, coupling a niche-based model of the vectors, parameterised with empirical data, with climate scenarios, indicates that in future, the distribution of BTV was likely to extend, particularly in central Africa, the US and western Russia.

There is some evidence (*medium confidence*) that exposure will, on average, increase (Bebber and Gurr 2015; Yan et al. 2017), and an expectation that, in general, perturbations may increase the likelihood of pest and disease outbreak by perturbing processes that may currently be at some quasi-equilibrium (Canto et al. 2009; Thomson et al. 2010; Pangga et al. 2011).

However, in some places, and for some diseases, risks may decrease as well as increase (e.g., drying out may reduce the ability of fungi to survive) (Kim et al. 2015; Skelsey and Newton 2015). Changes in diseases and their management, as well as changing habitat suitability for pests and diseases in the matrix surrounding agricultural fields, have the ability to mitigate or enhance impacts (Bebber, 2015). For example, changes in water storage and irrigation to mitigate rainfall variation has the potential to enhance disease vector populations and disease occurrence (Bett et al. 2017).

5.2.4.5 Impacts on pollinators

Pollinators play a key role on food security globally. Pollinator-dependent crops contribute up to 35% of global crop production volume and are important contributors to healthy human diets and nutrition. (IPBES 2016). On a global basis, some 1500 crops require pollination (typically by insects, birds and bats) (Klein et al. 2007) and estimates of the global value of pollination services at over £150 billion (2010 prices) (Hanley et al. 2015). As with other ecosystem processes affected by climate change (e.g., changes in pests and diseases), how complex systems respond is highly context-dependent. Thus, predicting the effects of climate on pollination services is difficult (Tylianakis et al. 2008; Schweiger et al. 2010) and uncertain, although there is some evidence that impacts are occurring already (Section 5.2.2.2), and *medium evidence* that there will be an effect.

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

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

However, not all expected impacts of climate change are likely to have undesirable consequences. For instance, the spread of exotic species in some cases could compensate for the decoupling generated between native pollinators and pollinated species.

5.2.5 Socio-economic aspects

5.2.5.1 Gender and equity

Food security and climate change have strong gender and equity dimensions (see Cross-Chapter Box 6: Gender, Chapter 7). Climate change impacts differ among diverse social groups depending on factors such as age, gender, wealth, and class (Vincent and Cull 2014; Kaijser and Kronsell 2014). Risk perception is also influenced by gender (Lebel et al. 2014; Bee 2016). Women and poor people are in general more affected by climate change, because their starting point or contextual vulnerability is higher due to differentiated relative power, roles and responsibilities at the household and community levels (Bryan et al. 2013; Nelson et al. 2002). Poverty, along with socio-economic and political marginalisation, cumulatively put women in a disadvantaged position in coping with the adverse impacts of the changing climate (UNDP 2013). Given their central role in feeding their families, decreasing women's capacity to adapt to the impacts of climate change also decreases that of the household (Bryan et al. 2013).

Gender. Worldwide, women play a key role in food security, although regional differences exist (World Bank 2015). In many rural areas, women often grow most of the crops for domestic consumption and are primarily responsible for storing, processing, and preparing food; handling livestock; gathering food, fodder and fuelwood; managing domestic water supply; and providing most of the labour for post-harvest activities (FAO 2011a). Climate change impacts on livestock keeping are differentiated between the food security of men and women (Table 5.4) (McKune et al. 2015).

Vulnerability and gender norms are aspects of the underlying context that impact behaviours and coping strategies for climate change, affecting all dimensions of the four food security pillars (Aberman and Tirado 2014). At the same time, the four pillars of food security have strong gender dimensions (Thompson 2018). In terms of food availability, women tend to have less access to productive resources, including land. In terms of food access, women intra-household inequity limits their ability to purchase food; in terms of food utilisation, men and women have different nutritional needs (e.g., during pregnancy or breast-feeding), which is also linked to age. In terms of stability, women are more likely to be disproportionately affected by price spikes (Vellakkal et al. 2015; Arndt et al. 2016; Hossain and Green 2011; Darnton-Hill and Cogill 2010; Cohen and Garrett 2010; Kumar and Quisumbing 2013), because when family food is scarse women in some areas reduce food consumption relative to other family members. However, these norms vary according to age, ethnicity, region, and social position, as well as by location in rural or urban areas (Arora-Jonsson 2011; Goh 2012; Niehof 2016).

Water scarcity, as a result of climate change can particularly affect women because they need to spend more time and energy to collect water or may be forced to use unsafe water in the household, increasing risk of diarrheal diseases (Parikh 2009). Furthermore, increased pressure on women’s time in order to gather fuelwood also impacts their ability to appropriately care for infants and children, who require frequent feeding to meet their nutritional requirements, and the elderly (Levinson et al. 2002; Tirado and Meerman 2012; McKune et al. 2015; World Bank 2009; Preet et al. 2010).

Existing gender norms and power inequalities shape the ability of men and women to adapt to climate risks (Rossi and Lambrou 2008). These include participation in decision-making and politics; division of labour, resource access and control, and knowledge and skills (Nelson and Stathers 2009). Migration of young mean to cities, partly related to climate change, has led to the feminisation of agriculture in many parts of the world (FAO 2016a).

Women's adaptive capacity to climate change is diminished because their work often goes unrecognised and they have only limited access to productive (e.g., land, technology, credit) and other resources (infrastructure, health, education), as well as decision-making (Rao 2005; Nelson and Stathers 2009). Rural women often manage complex households and pursue multiple livelihood strategies, but many of their activities are not defined as “economically active employment” in national accounts (FAO 2011a). This non-economic status of women activities implies that they are not included in wider discussions of priorities or interventions for climate change; their unique perspectives are not included; their needs are not met; and thus, interventions, information (including actionable weather and climate forecasts), technologies, and tools promoted are potentially not relevant, and even can increase discrimination (Alston 2009; Edvardsson Björnberg and Hansson 2013; Huynh and Resurreccion 2014).

Table 5.4 A gendered approach to understanding how climate change affects dimensions of food security across a spectrum of livestock-holding livelihood groups (Source: (McKune et al. 2015)

Group	Livelihoods	Health	Nutrition
Pastoral	↑ time demand on *women* for water.fuel collection ↑ time demand on *men* to seek out water sources with herd ↑ productive and reproductive demands on *women* ↓ financial autonomy of *women* due to liquidation of small animal assets	↑ disease risk due to proximity of *women’*s work to disease agents ↑ vulnerability to maternal mortality due to ↑ fertility due to sedentarization ↓ mental and emotional health due to increased stress/loss of social support ↑ vulnerability of newly sedentarized households, particularly women	↑ undernutrition due to ↓ availability of plant and animal foods ↑undernutrition due to separation of from milk-producing animals ↑ undernutrition due to unfavorable trade between animal products and grains ↑ risk of food insecurity due to ↓ production of livestock and ↑ prices
Agro-pastoral	↑ time demand on *women* due to migration of men for herding or wage labor		

	↓ financial autonomy of *women* due to liquidation of small animal assets	Earlier weaning, shortened birth intervals, and risk of maternal depletion	↑ exposure to foods that have become spoiled
	↑ constraints on herd management due to shifts in responsibilities	↑ incidence of anemia and stunting in children	Less varied and less nutritious diets
		↑ susceptibility to infectious diseases that are sensitive to climate change	
	↑ susceptibility to market fluctuations	↑ child mortality rates	↑ malnutrition, including overnutrition
Urban livestock holders	↓ access to inputs	↑infectious diseases (diarrhea, respiratory diseases, malaria)	Shift towards unhealthier dietary patterns
	Urban nutrient cycling of food waste to animal feed	↑ incidences of chronic diseases (e.g., heart disease, diabetes)	↑ affordability, accessibility and availability of processed foods poor in nutrient value

Equity. Decreased yields can impact nutrient intake of the poor and vulnerable by decreasing supplies of highly nutritious crops and by promoting adaptive behaviours that may substitute crops that are resilient but less nutritious (Thompson et al. 2012; Lobell and Burke 2010). In Guatemala, food prices and poverty have been correlated with lower micronutrient intakes (Iannotti et al. 2012). In the developed world, where people's diets typically include more processed food, poverty is more typically associated with calorically-dense but nutrient-poor diets, obesity, overweight, and other related diseases (Darmon and Drewnowski 2015). In case of food price hikes, those more vulnerable, particular poor people, are more affected than wealthier social groups (Uraguchi 2010). This is especially relevant in urban contexts (Ruel et al. 2010), where livelihood impacts are particularly severe for the poor, directly affecting their ability to buy food (Gasper et al. 2011).

In urban areas, the literature increasingly demonstrates that climate change disproportionately impacts individuals and groups that have scarce resources or are socially isolated (Gasper et al. 2011; Revi et al. 2014) (*robust evidence, high agreement*). For instance, urban floods and droughts may result in water contamination increasing the incidence of diarrhoeal illness in poor children (Bartlett 2008). Climate change amplifies urban vulnerability and hampers adaptive capacity especially for the poor, women, the elderly, children and ethnic minorities. These people often lack power and access to resources, adequate urban services and functioning infrastructure. Gender inequality is particularly pervasive in cities contributing to differential consequences of climate change. As climate events become more frequent and intense, this can increase the scale and depth of urban poverty overall (Rosenzweig et al. 2018).

5.2.5.2 Migration and conflict

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

Climate variability and extremes have short-, medium- and long-term impacts on livelihoods and livelihood assets – especially of the poor – contributing to greater risk of food insecurity and malnutrition (FAO et al. 2018). Drought threatens local food security and nutrition and aggravates humanitarian conditions, which can trigger large-scale human displacement and create a breeding ground for conflict (Maystadt and Ecker 2014). There is *some agreement* that existing patterns of conflict could be reinforced under climate change affecting food security and livelihood opportunities, for example, already fragile regions with ethnic divides such as North and Central Africa as well as Central Asia (Buhaug 2016; Schleussner et al. 2016) (Box 5.2).

Challinor et al. (2018) have developed a typology for transboundary and transboundary risk transmission that distinguishes the roles of climate and social and economic systems. To understand these complex interactions, they recommend methods including expert judgement; interactive scenario building; global systems science and big data; innovative use of climate and integrated assessment models; and methods to understand societal responses to climate risk (see Section 5.3.2.1).

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

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

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

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

Box 5.2 Migration in the Pacific region: Impacts of climate change on food security

Climate change-induced migration in the Pacific has received wide attention in the scientific discourse. The processes of climate change and their effects in the region have serious implications for Pacific Island nations as they influence the environments that are their ‘life-support systems’ (Campbell 2014).

Climate variability poses significant threats to both agricultural production and food security. Rising temperatures and reductions in groundwater availability, as well as increasing frequency and severity of disaster events translate into substantial impacts on food security causing human displacement, a trend that will be aggravated by future climate impacts (ADB 2017). Declining soil productivity, groundwater depletion, and non-availability of freshwater threatens agricultural production in many remote atolls.

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

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

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

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

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

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

Beyond sea level rise, effects of increasing frequency and intensity of extreme events such as severe tropical cyclones are likely to affect human migration in the Pacific (Connell 2015; Krishnapillai and Gavenda 2014; Charan et al. 2017; Krishnapillai 2017). While sea-level rise alone is causing adverse impacts, extreme events have a profound impact on the livelihoods of some atoll communities. Although considerable differences occur in the physical manifestations of severe storms, such climate stressors threaten the life-support systems of many atoll communities (Campbell et al. 2014). Failure of these systems resulting from climate disasters may propel vulnerable atoll communities into poverty traps, and low adaptive capacity could eventually force these communities to migrate.

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

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

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

5.3 Adaptation options, challenges, and opportunities

In the food system, adaptation actions involve any activities designed to reduce vulnerability and enhance resilience of the system to climate change. By formulating effective adaptation strategies, it is possible to reduce or even avoid some of the negative impacts of climate change on food systems. In some areas, increased agro-climatic resources, especially heat resources, will alter agro-ecological zones, with opportunity for expansion towards higher latitudes and altitudes, soil and water resources permitting (Rosenzweig and Hillel 2015). However, if unabated climate change continues, limits to adaptation will be reached (*robust evidence, high agreement*). Given the site-specific nature of climate change impacts on food system components together with wide variation in agroecosystems and socio-economic conditions, it is widely understood that adaptation strategies must be developed according to environmental and cultural contexts at the regional level (*robust evidence, high agreement*).

Food security under changing climate conditions requires adaptation throughout the food system – producing more food where needed, moderating demand, reducing waste, and improving governance (Godfray & Garnett, 2014). Besides the direct impacts of climate change on agricultural production, there are complex interactions with other components of the food system, including food storage, transport, processing, and trade as well as consumption, health, livelihoods, cultural contexts, and ecosystem services.

More extreme climatic events are projected to lead to more agro-meteorological disasters with associated economic and social losses. Adaptation responses to extreme events aim to minimise damages, modify threats, prevent adverse impacts, or share losses, thus making the system more resilient (Harvey et al. 2014a).

Incremental adaptation focuses on improvements to existing resources and management practices, while transformation adaptation explores alternative livelihoods and land use strategies to adopt new farming systems (Termeer et al. 2016). For example, limitations in incremental adaptation among smallholder rice farmers in Northwest Costa Rica led to a shift from rice to sugarcane production due to decreasing market access and water scarcity (Warner et al. 2015). Migration from the Oldman River Basin has been described as a transformational adaption to climate change in the Canadian agriculture sector (Hadarits et al. 2017). If high-end scenarios of climate change eventuate, the food security of farmers and consumers will depend on how transformational change in food systems is managed. An integrated framework of adaptive transition – management of socio-technical transitions and adaptation to socio-ecological changes – may help build transformational adaptive capacity (Mockshell and Kamanda 2018; Pant et al. 2015). Rippke et al. (2016) has suggested overlapping phases of adaptation needed to support transformational change in Africa. Transformation to sustainable and climate-resilient food systems in Africa entails multiple dimensions as shown in Figure 5.8 (Box 5.3).

Box 5.3 Sustainable solutions for food systems and climate change in Africa

With climate change, land degradation and poor farming practices, Africa cannot grow enough food to feed its rapidly growing population. African Agriculture is also by far the largest employment sector (70%) and the food produced comes from the farms and fields of small-holders (AGRA 2017). However, the shortages of food on the continent pose major challenges in terms of availability, access of nutritious food to maintain healthy and active life in Africa.

To face these challenges, profit oriented production systems—driven by external business agents—are increasing in Africa and may influence agricultural livelihoods with extensive environmental externalities. Land degradation, decreasing water tables and quality, loss of biodiversity and the environmental and health impacts of excessive synthetic fertiliser and pesticide use are some of the harms of following the agribusiness models. These impacts to the households, to the agroecosystem, and to food security, nutrition and health are rarely accounted for in the factors market and business models used to design agriculture programs. In conceptualising resilience in food systems, it is essential for Africa to promote strategies to account for the natural capital in financial capital to balance profit with environmental sustainability.

A balanced portfolio of investments in revitalising African agriculture should therefore include investments in shoring up resilient food systems in multifunctional landscapes. Such agricultural landscapes have functions beyond the production of food – the delivery of water, management of disease, especially zoonotic diseases, the delivery of energy, fibre and building materials and of otherwise safe and healthy environments are also important. This will require more investments in improved inputs that couple productivity and production with the ability of such gains to withstand shocks of various kinds - economic, ecological, and climatic. In essence, sustainable food system in Africa entails multiple dimensions as shown in Figure 5.8.

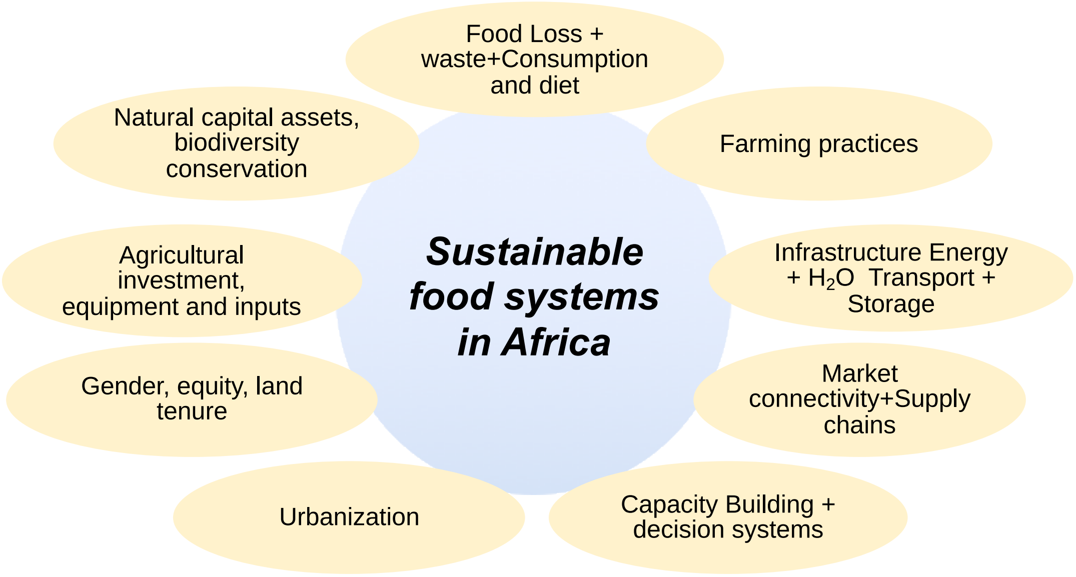

Figure 5.8 Factors influencing sustainable food system in Africa

Feeding Africa sustainably can be consistent with changes of production systems while considering the natural capital that exists as the matrix within which agriculture takes place on farmers' fields, tree crop plantations or pastoral lands.

Recent trends show emerging greater cities from a combination of rapid population growth and immigration; and in the same way, safe and prosperous economies in Africa will need a combination of targeted technologies (e.g., zero-carbon energy, smart irrigation systems, and climate-resilient agriculture). Considering a forward-looking infrastructure plans at various scales will minimise the negative side effect of climate change and unexpected market variability.

Building resilience into productivity and production gains will require paying simultaneous attention to the following six overarching issues:

1) Closing yield gaps through intensification technologies that combine production and preservation of ecosystems essential functions.

2) Identifying appropriate agroecological practices and strategies, including development of underutilised species in favour of biodiversity, conservation, and ecosystem services.

3) Paying attention to the food-water nexus, especially water use and reutilisation efficiency but also management of rain water.

4) Implementing institutional designs toward a dynamic bio-economy focus on youth, job creation including for women, market-based change through improvements in institutions, tenure and governance while considering informal institutions and locally adapted formalisation processes to avoid unintended consequences for example, overlapping land tenure and respective resource conflicts.

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

6) Improving access to agricultural credits and making land reforms to give farmers security of tenure, particularly to vulnerable groups.

These aspects suppose important investments in strengthening infrastructure for storage and transformation and marketing of food, development of post-harvest technologies, enhancing efficient logistics systems as well as provision of the right institutional and policy environment to support production and distribution. The linkage to knowledge for transforming Africa's farming systems entails building the capacity of food system actors such as individual farmers, households, communities, research and advisory services (Morton 2017) to be able to adapt to, respond to and recover from environmental, economic and social shocks that affect their livelihoods.

The challenge for improving Africa's food security is to have systems that are highly climate resilient while supporting the increasing yields needed to feed a growing population. What Africa needs is a genuine working model of how to feed itself without compromising its future. One such model is the 'portfolio' approach that encompasses a diversity of species, lifeforms, livelihoods, value chains and science-based systems as a whole. Initiatives to promote agricultural production can identify what has worked or can work in various ecologies and contexts, what seems to work over the short run but reduces risks for the long term, and what the implications are for food production, livelihoods, food security, resilience and development. This requires a new framing that includes a shift in the narrative and practice of agriculture as part of a "bio-economic system" for present and future needs.

5.3.1 Adaptation options

There are many different climate change adaptation practices that have been proposed and tested. These include optimising and scaling up current agricultural management and breeding practices, diversification, ecosystem-based adaptation, community-based adaptation, and demand-side adaptation.

5.3.1.1 Current agricultural management practices

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

Adaptation also involves use of current genetic resources as well as breeding programs for both crops and livestock. More drought, flood and heat-resistant crop varieties (Atlin et al. 2017; Mickelbart et al. 2015; Singh et al. 2017) and improved nutrient and water use efficiency are needed.

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

5.3.1.2 Diversification

Increasing the resilience of the food system is an effective way to achieve adaptation (*robust evidence, high agreement)*. Diversification of many components of the food system is a key element for increasing resilience and reducing risks (integrated production systems, agrobiodiversity, indigenous knowledge and local knowledge, local food systems, dietary diversity) *(medium evidence, medium agreement)*. The more diverse the food systems are, the more resilient they are in enhancing food and nutritional security in the face of biotic and abiotic stresses. In addition, diverse production systems are important for providing regulatory ecosystem services such as nutrient cycling, carbon sequestration, soil erosion control, reduction of GHG emissions and control of hydrological processes (Chivenge et al. 2015). Further options for adapting to change in both mean climate and extreme events are livelihood diversification (Michael, 2017; Berrang-ford et al. 2015), and production diversity (Sibhatu et al. 2015).

Diversified cropping systems and practicing traditional agro-ecosystems of crop production where a wide range of crop varieties are grown in various spatial and temporal arrangements, making them less vulnerable to catastrophic loss (Zhu et al. 2011). The use of local genetic diversity, soil organic matter enhancement, multiple-cropping or poly-culture systems, and home gardening, agro-ecological approaches were taken to build resilience against extreme climate events (Altieri and Koohafkan 2008).

Evidence also shows that, together with other factors, on-farm agricultural diversity can translate into dietary diversity at the farm level and beyond (Pimbert and Lemke, 2018; (Kumar et al. 2015; Sibhatu et al. 2015). Dietary diversity does not only increases adaptation options, but results in positive health outcomes by increasing the variety of healthy products in people’s diets. Neglected and undertilised species (NUS) can play a key role in increasing dietary diversity (*robust evidence, high agreement*) (Baldermann et al. 2016; van der Merwe et al. 2016; Muhanji et al. 2011) (see Box 5.4). These species can also improve nutritional and economic security of excluded social groups, such as tribals (Nandal and Bhardwaj 2014; Ghosh-Jerath et al. 2015), indigent (Kucich and Wicht 2016) or rural populations (Ngadze et al. 2017). Dietary diversity has also been correlated (*medium evidence*, *medium agreement*) to agricultural diversity in small-holder and subsistence farms (Ayenew et al. 2018; Jones et al. 2014; Jones 2017; Pimbert and Lemke 2018) , including both crops and animals, and has been proposed as an strategy to reduce micronutrient malnutrition in developing countries (Tontisirin et al. 2002).

Box 5.4 Climate change and indigenous food systems in the Hindu-Kush Himalayan Region

Diversification of production systems through promotion of Neglected and Underutilised Species (NUS; also known as understudied, neglected, orphan, lost or disadvantaged crops) offers adaptation opportunities to climate change, particularly in mountains. Farmers in the Rasuwa district, in the mid-hills of Nepal, prefer to cultivate local bean, barley, millet and local maize than commercial crops because they are more tolerant to water stress and extremely cold conditions (Adhikari et al. 2017). Farmers in the high-altitude cold climate of Nepal prefer local barley with its short growing period because of a shorter growing window. Buckwheat is commonly grown in the Hindu-Kush Himalayan (HKH) region mainly because it grows fast and suppresses weeds. In Pakistan, quinoa (*Chenopodium quinoa*) grew and produced well under saline and marginal soil where other crops would not grow (Adhikari et al. 2017).

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

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

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

Internationally, there is rising interest nowadays on Neglected and Underutilised Species (NUS; also known as understudied, neglected, orphan, lost or disadvantaged crops) not only because they present tremendous opportunities for fighting poverty, hunger and malnutrition but also because of their role in mitigating climate risk in agricultural production systems. They play an important role in mountain agro-ecosystems because mountain agriculture is basically low-input agriculture for which many of these NUS are adapted.

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

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

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

5.3.1.3 Ecosystem-based adaptation

There are now many studies of climate change adaptation in many geographical and socio-economic settings. These have documented a wide range of options, including those known as ecosystem-based adaptation (EbA). For example, agroforestry systems can contribute to improving crop productivity while enhancing biodiversity conservation, ecological balance and restoration under changing climate conditions (Paudela et al. 2017; Newaj et al. 2016; Altieri et al. 2015a). Adoption of conservation farming practices such as removing weeds from and dredging irrigation canals, draining and levelling land, and using organic fertilisation were among the popular conservation practices in small-scale paddy rice farming community of northern Iran (Ashoori and Sadegh 2016).

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

Increasing and conserving biological diversity such as microorganisms can achieve high crop yields and sustain the environment (Schmitz et al 2015; Bhattacharyya et al 2016; Garibaldi et al 2017). Biophysical adaptation options also include pest and disease management (Lamichhane et al. 2015) and water soil management (Korbeľová and Kohnová 2017).

The use of non-crop plant resources in agro-ecosystems can improve the conservation of beneficial arthropods and may lead to increased crop productivity (Balzan et al. 2016). Agroecological practices such as soil amendments using bio-char may enhance soil fertility and carbon but limit the effects on functional and structural diversity of soil microbial communities in a temperate agro-ecosystem (Imparato et al. 2016). Nie et al. (2016) argued that while integrated crop-livestock systems present some opportunities such as control of weeds, pests and diseases, and environmental benefits, there are some challenges, including yield reduction, difficulty in pasture-cropping, grazing, and groundcover maintenance in high rainfall zones, and development of chemical-resistant weeds and pests.

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

5.3.1.4 Community-based adaptation

Community-based adaptation operates at the local level in places that are vulnerable to the impacts of climate change (Ayers and Forsyth 2009). It identifies, assists, and implements development activities that strengthen the capacity of local people to adapt to living in a riskier and less predictable climate, while ensuring their food security. Moreover, community-based adaptation generates adaptation strategies through participatory processes, involving local stakeholders and development and disaster risk–reduction practitioners. For example, the study of Scott et al. (2017) revealed that collaborating early and often, and fostering community stewardship were the lessons learnt from implementing integrated water resource management by North Bay-Mattawa Conservation Authority in a First Nations area of Ontario, Canada. Preparedness behaviours by encouraging social connectedness, education, training, messaging and addressing beliefs might improve household preparedness to climate disaster risk (MMWR 2015). Reliance on social networks was also mentioned by Schramski et al. (2017). Yet, community-based adaptation also needs to consider methods that engage with the drivers of perceptions as part of community-based approaches, particularly those unfolding questions of power, culture, identity and practice (Ensor et al. 2018) to avoid maladaptation or exacerbating existing inequalities within the communities (Buggy and McNamara 2016).

In the Pacific Islands, other elements that needed to be considered in a community-based adaptation plan included people's development aspirations; immediate economic, social and environmental benefits; dynamics of village governance, social rules and protocols; and traditional forms of knowledge that could inform sustainable solutions (Remling and Veitayaki 2016). With all these considerations, community based adaptation should be seen as a tool that can help to link local adaptation with international development and climate change policies (Forsyth 2013). In developing community-based adaptation programs, barriers exist that hinder the implementation of the program. These include poor coordination within and between organisations implementing adaptation options, poor skills, poor knowledge about climate change and inadequate communication among stakeholders (Spires et al. 2014). A rights-based approach has been suggested to address issues of equality, transparency, accountability and empowerment in adaptation to climate change (Ensor et al. 2015). Box 5.5 presents the outcomes of a community-based adaptation project in displaced atoll communities in Micronesia.

Box 5.5 Displaced atoll communities and their adaptation strategies

On Yap Island in the Federated States of Micronesia, displaced atoll communities have gained a reputation for growing good-quality vegetables on a degraded land using a locally-adapted pro-poor, pro-woman, pro-nature model (Krishnapillai 2017). Local officials are pleased that people can access more nutritious and reliable food sources.

Climate change is affecting every aspect in lives of atoll communities in Yap due to the islands' small size, their low elevation, and extensive coastal areas. Recurrences of natural disasters and crises threaten food security through impacts on traditional agriculture, causing the forced migration of coastal communities to highlands in search of better living conditions. As many of the projected impacts are unavoidable, implementing some degree of adaptation becomes crucial to enhance food security, strengthen livelihoods, and increase the resilience of coastal communities to future climate risks (Krishnapillai 2018). With support from the US Department of Agriculture and USAID, since 2006 the Cooperative Research and Extension wing of the College of Micronesia-FSM Yap Campus has been providing outreach, technical assistance and extension education to improve the soil and grow community vegetable gardens as well as indigenous trees and traditional crops to regain food security and stability. This program implemented a three-pronged adaptation model to boost household and community resilience under harsh conditions on a degraded landscape (USAID 2017).

Less hunger and more cash from leafy vegetables is a concept adopted at the household level to empower the displaced communities to address the dilemma of malnutrition. Practices include growing a variety of nutritious vegetables as part of a large crop portfolio and using alternative crop production methods such as small-plot intensive farming using container gardening or raised-bed gardening (Krishnapillai and Gavenda 2014). In addition, focusing efforts on increasing sustainable production of staple crops confers significant nutritional benefits. More households in the settlements are consuming vegetables as home gardeners started harvesting regularly and easily sharing their produce with extended families. This spells a healthier future for the settlers.

The location-specific community-based adaptation model was designed to boost household and community resilience, even under harsh conditions on a degraded landscape. In the case of the displaced atoll communities on Yap, resilience is now greater due to improved food security and livelihoods (Krishnapillai 2017). Growing their own food and selling surplus creates a greater confidence about their future.

5.3.1.3 Demand-side adaptation

Recent studies showed that supply-side adaptation measures alone will not be sufficient to sustainably achieve food security under climate change (Bajželj et al. 2014). As noted by Godfray (2015), people with higher income demand more varied diets, and typically ones that are richer in meat and other food types that require more resources to produce. Therefore, both supply-side (production, processing, transport, trade, etc.) and demand-side solutions (changing diets, food loss and waste reduction, etc.)

should be considered in adapting to climate change (Creutzig et al. 2016). Changing diet habit has been suggested for effective food policies (Beheshti et al. 2017).

For example, Hunter & Röös (2016) described factors to motivate consumers to reduce or alter their meat consumption, as well as reducing waste at all points along the entire food chain (Godfray 2015). Reduction in the demand of animal-based food products and increasing proportions of plant-based foods in diets; replacing ecologically-inefficient ruminants and bush-meat with monogastrics, aquaculture, or other more-efficient protein sources are proposed by Machovina et al (2015) as demand-side adaptation measures. Reduction in food loss and waste, 20% reduction in U.S edible food loss would save each year 14 million metric tons of food (about14 MMT), which would equate to two-years of growth in production and would feed millions of people (Dou et al. 2016). Also, replacing beef in the US diet with poultry can meet caloric and protein demands of about120 and about140 million additional people consuming the average American diet (Shepon et al. 2016).

Beheshti et al. (2017) studied food choice behaviors of low-income adults in the US and the results revealed that unhealthy eating behaviors in this population, which is characterised by relatively low consumption of fruits and vegetables and high consumption of fat, are maintained before and after changes in food budgets. Africa has an impressive diversity of edible insect, the use of insects as food and feed has a significant role to play in assuring food security of the African people (Kelemu et al. 2015). Food preference can foster or slow food security goals, for example, a study in Kenya found a significant and positive preference for the cricket-flour-based buns, this may serve as a viable and demand-driven way to increase food security in Kenya in the future (Alemu et al. 2017).

5.3.2 Resilience to increasing extremes and volatility

5.3.2.1 Food price spikes

Under average conditions, global food system markets may function well, and equilibrium approaches can estimate demand and supply with some confidence; however, if there is a significant shock, the market can fail to smoothly link demand and supply through price, and a range of factors can act to amplify the effects of the shock, and transmit it across the world (Box 5.6). Given the potential for shocks driven by changing patterns of extreme weather to increase with climate change, there is the potential for market volatility to disrupt food supply through creating food price spikes. This potential is exacerbated by the interconnectedness of the food system (Puma et al. 2015) with other sectors (i.e., the food system depends on water, energy, transport, digital etc.) (Homer-Dixon et al. 2015), so the impact of shocks can propagate across sectors and geographies (Homer-Dixon et al. 2015). There is also less spare land globally than there has been in the past, such that if prices spike, there are fewer options to bring new production on stream (Marianela et al. 2016). Given the likelihood that extreme weather will increase, in both frequency and magnitude (Hansen et al. 2012; Coumou et al. 2014; Mann et al. 2017; Bailey et al. 2015), and the current state of global and cross-sectoral interconnectedness, the food system is at increasing risk of disruption (*medium evidence, medium agreement*), with large uncertainty about how this could manifest.

Increasing extreme weather events can disrupt production and transport logistics. For example, in 2012 the US Corn Belt suffered a widespread drought; US corn yield declined 16% compared to 2011 and 25% compared to 2009. To the extent that such supply shocks are associated with climate change, they may become more frequent and contribute to greater instability in agricultural markets in the future. Furthermore, analogue conditions of past extremes might create significantly greater impacts in a warmer world. A study simulating analogous conditions to the Dustbowl drought in today’s agriculture suggests that Dust-Bowl-type droughts today would have unprecedented consequences, with yield losses about 50% larger than the severe drought of 2012 (Glotter and Elliott 2016). Damages at these extremes are highly sensitive to temperature, worsening by about 25% with each degree centigrade of warming. By mid-century, over 80% of summers are projected to have average temperatures that are likely to exceed the hottest summer in the Dustbowl years (1936) (Glotter and Elliott 2016).

How a shortfall in production – or an interruption in trade due to an event affecting a logistics choke-point (Wellesley et al. 2017) – of any given magnitude may create impacts depends on many interacting factors (Homer-Dixon et al. 015; Tadasse et al. 2016; Challinor et al. 2018). The principal route is by affecting agricultural commodity markets, which respond to a perturbation through multiple routes as in Figure 5.9. This includes pressures from other sectors (such as if biofuels policy is incentivising food used for production of ethanol, as happened in 2007–2008). The market response can be amplified by poor policies, setting up trade and non-trade barriers to exports, from countries seeking to ensure their local food security (Bailey et al. 2015). Furthermore, the perception of problems can fuel panic buying on the markets that in turn drives up prices. Thus, the impact of an extreme weather event on markets has both a *trigger* component (the event) and a risk *perception* component (Challinor et al. 2016, 2018). Through commodity markets, prices change across the world because almost every country depends, to a greater or lesser extent, on trade to fulfil local needs. Commodity prices can also affect local market prices by altering input prices, changing the cost of food aid, and through spill-over effects; for example, in 2007–2008 the grain affected by extreme weather was wheat, but there was a significant price spike in rice markets (Dawe 2012).

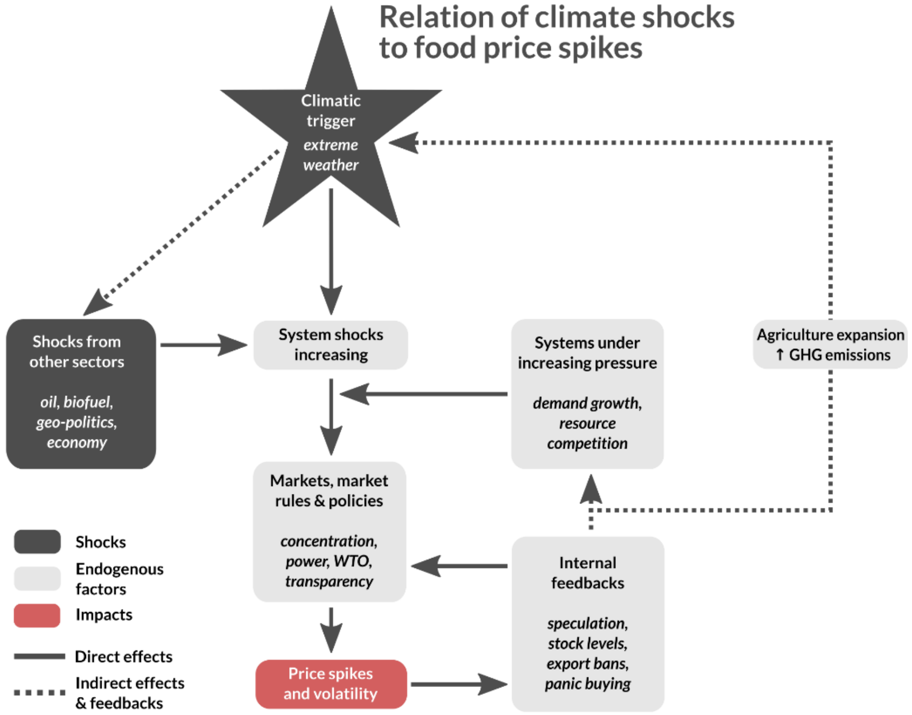

Figure 5.9 Underlying processes that affect the development of a food price spike in agricultural commodity markets (Challinor et al. 2018)

Box 5.6 Causes and consequences of Russian drought (2010-2015)

The 2010–2011 food price spike was initially triggered by the exceptional heat in summer 2010, with an extent from Europe to the Ukraine and Western Russia (Barriopedro et al. 2011; Watanabe et al. 2013; Hoag 2014). The heatwave in Russia was extreme in both temperature (over 40°C) and duration (from July to mid-August in 2010). This reduced wheat yields by approximately one third (Wegren 2011; Marchand et al. 2016). Simultaneously, in the Indus Valley in Pakistan, unprecedented rainfall led to flooding, affecting the lives and livelihoods of 20 million people. Arctic warming influencing atmospheric Rossby waves is likely the underlying causative link (Puma et al. 2015; Mann et al. 2017).

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

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

In the UK, global commodity price inflation influenced local food prices, increasing food-price inflation by about 5x at the end of 2010. Comparing household purchases over the five year period from 2007 to 2011 showed that the amount of food bought declined, on average, by 4.2%, whilst paying 12% more for it. The lowest income decile spent 17% more by 2011 than they did in 2007 (Defra 2012; Tadasse et al. 2016). Consumers also saved money by trading down for cheaper alternatives. For the poorest, in the extreme situation, food became unaffordable: the Trussell Trust, a charity supplying emergency food handouts for people in crisis, noted a 50% increase in handouts in 2010.

5.3.2.2 Risk management

Risk management is an important concept in adapting the food system to increasing frequency and intensity of extreme events. Risk sharing, risk transfer, and spreading resilience are mechanisms. UNEP (2011) proposed the introduction of insurance markets to spread risk in an event of a climate disaster in order to reduce the vulnerability to the hazard, and index-based climate insurance against crop loss is commonly adopted in developing and developed countries. For example, Named Risk Climate Insurance and Multiple Risk Climate Insurance are mostly practised in Canada and USA, Area/Yield Index Insurance is mainly adopted in Brazil, India, and USA, and Livestock Mortality Index adopted in Mongolia; and Flood Insurance in South East Asia (Zhu et al. 2011).

Financial incentives policies used as adaptation options include taxes and subsidies; index-based weather insurance schemes; and catastrophe bonds (Lipper et al. 2017; Linnerooth-bayer and Hochrainer-stigler 2014; Ruiter et al. 2017; Campillo et al 2017). Microfinance, disaster contingency funds, and cash transfers are other mechanisms Ozaki (2016) and Kabir (2016).

5.3.3 Socio-economic aspects

5.3.3.1 Institutional measures

There are a number of adaptation options in agriculture in form of policy, planning, governance and institutions (Lorenz 2017); for example, early spatial planning action is crucial to guide decision-making processes and foster resilience in highly uncertain future climate change (Brunner and Grêt-Regamey, 2016). Awareness about the institutional context within which adaptation planning decisions are made is essential for the usability of climate change projection (Lorenz 2017). Moreover, the effective land use planning would guide current and future decision making and planners in exploring uncertainty to increase the resilience of communities (Berke & Stevens 2016). One of the important policy implications for enhanced food security are the trade-offs between agricultural production and environmental concerns, including the asserted need for global land use expansion, biodiversity and ecological restoration (Meyfroidt 2017).

For example, Nepal has developed a novel multi-level institutional partnership, including collaboration with farmers and other non-governmental organisations in recent years manner (Chhetri et al. 2012). By combining conventional technological innovation process with the tacit knowledge of farmers, this new alliance has been instrumental in the innovation of location-specific technologies thereby facilitating the adoption of technologies in a more efficient manner. In Africa, enhanced transportation networks combined with greater national reserves of cash and social safety nets could reduce the impact of 'double exposure' on food security (Brown et al. 2017b).

5.3.3.2 Cultural beliefs

Cultural dimensions are important in understanding how societies respond to climate change, since they help to explain differences in responses across populations to the same environmental risks (Adger et al. 2013). There are some entrenched cultural beliefs and values that may be barriers to climate change adaptation. For instance, culture has been shown to be a major barrier to adaptation for the Fulbe ethnic group of Burkina Faso (Nielsen and Reenberg 2010). Thus, it is important to understand how beliefs, values, practices and habits interact with the behaviour of individuals and collectivities that have to confront climate change (Heyd and Thomas 2008). Granderson (2014) suggests that making sense of climate change and its responses at the community level demands attention to the cultural and political processes that shape how risk is conceived, prioritised and managed. For a discussion of gender issues related to climate change, see Section 5.2.5.1.

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

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

5.4 Impacts of food systems on climate change

5.4.1 Greenhouse gas emissions from food systems

The current food system accounts for roughly 40% (30–50%) of total GHG emissions; this estimate includes 10% (7–13%) from crop and livestock activities within the farm gate; 10% (5–14%) from land use and land use change including deforestation and peatland degradation; and 18% (16–20%) from storage, processing, transport, retail, and other supply chain activities (Table 5.5) *(medium evidence, medium agreement)*. Food system emissions are growing globally due to increasing population and demand for food *(robust evidence, high agreement)*. Diets are changing on average toward greater consumption of animal-based foods, vegetable oils and sugar/sweeteners *(robust evidence, high agreement)*. GHG emissions are increasing due to greater amounts of animal-based products in diets (*robust evidence, medium agreement*). Contributions from food loss and waste are included in these estimates and may account for 8–10% of total GHG emissions from all sectors.

Table 5.5 Contribution to GHG emissions from the food system as percentage of total emissions

Activity	Low estimate*	High estimate*
Entire food system	30	50
Crop and livestock	7	13
Land use and land use change	5	14
Supply chain	16	20

Emissions from food systems include emissions from crop and livestock activities within the farm gate, typically covered as non-CO_2 emissions under the IPCC GHG inventory sector 'Agriculture'; extend to include relevant components of the CO_2 emissions from 'Land Use, Land Use Change and Forestry (LULUCF)'; and encompass additional emissions, generated beyond the farm gate along multiple food supply chain and consumption patterns, typically reported under non-AFOLU IPCC sectors. Despite the large uncertainties characterising these food-related emissions in general, the first two components described above are well quantified (Smith et al. 2014; Tubiello et al. 2015). For instance, the most updated FAO estimates (FAO 2018b) post-AR5 indicate that global non–CO_2 emissions from crop and livestock activities within the farm gate were 5.2 ± 1.5 Gt CO_2-eq yr^{-1} during 2010-2016; while emissions linked to agriculture, but generated outside the farm gate, such as from deforestation and peatland degradation, added globally during the same period another 4.8 ± 2.4 Gt CO_2-eq yr^{-1} ((Tubiello 2018); assuming 30% and 50% uncertainty respectively for agriculture and LULUCF, as per IPCC AR5 (Smith et al. 2014)).

These two components imply a contribution of agriculture and associated land use activities of 10.0 ± 4.0 Gt CO_2-eq yr^{-1}, or some 20% of total emissions from all economic sectors during the most recent decade—assuming that overall GHG emissions have remained at roughly 50 Gt CO_2-eq yr^{-1} (Smith et al. 2014) and are consistent with previous estimates for the decade 2001-2010 (Tubiello et al. 2015). Adding all relevant production and consumption activities linked to food, including manufacturing, transport and retail, may nearly double these estimates. The IPCC AR5 stated that total food-systems emissions may in fact represent 30–40% of the total from the entire economy. These are impressive numbers, which however have been poorly investigated in post-AR5 literature. Yet even limiting the analysis to non-CO_2 GHG from within the farm gate, it is worth noting that during 2010–2016 agriculture emissions represented roughly 50% of all emitted anthropogenic CH_4 and 75% of all emitted anthropogenic N_2O (Tubiello 2018).

5.4.2 Greenhouse gas emissions from croplands and soils

A few authors have attempted recently to quantify the separate contributions of crops and soils on the one hand, and livestock on the other, to the total non-CO_2 and CO_2 emissions from agriculture and associated land use. Of the total 10.0 ± 4.0 Gt CO_2-eq yr^{-1} reported above, Carlson et al. (2017) estimated emissions from crops to be in the range of 2–3 $GtCO_2$-eq yr^{-1}, including methane emissions from rice, CO_2 emissions from peatland cultivation and N_2O emissions from fertiliser applications. In FAOSTAT, the same emission categories corresponded globally to 3.4 ± 1.2 Gt CO_2-eq yr^{-1} over the period 2010–2016, two-thirds by carbon emissions from peatland degradation, followed by N_2O emissions from synthetic fertilisers and methane emissions from paddy rice fields (Tubiello, 2018). Asia, especially India, China and Indonesia accounted for roughly 50% of the world total. Figure 5.10 shows the spatial distribution of emissions from cropland according to Carlson et al. (2017), not including emissions related to deforestation or soil C stock change.

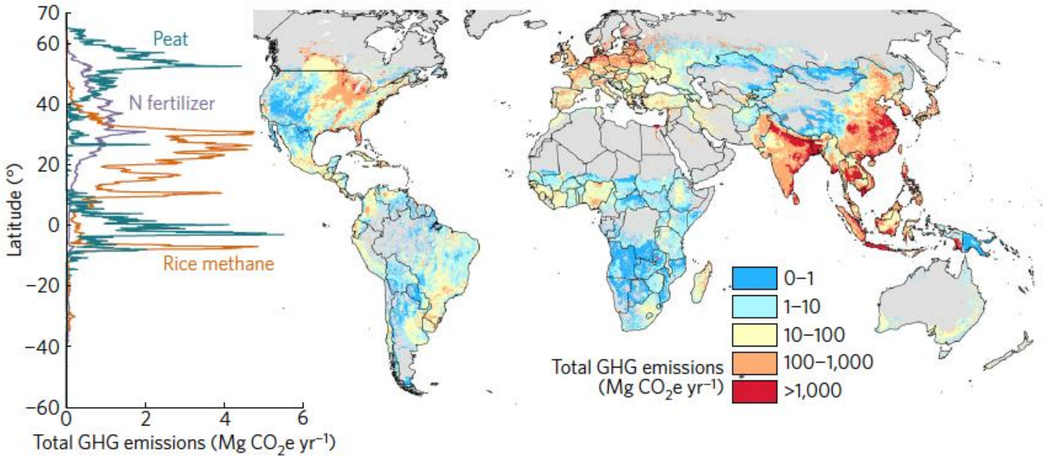

Figure 5.10 Cropland GHGs consist of CH_4 from rice cultivation, CO_2, N_2O, and CH_4 from peatland draining, and N_2O from N fertiliser application. Total emissions from each grid cell are concentrated in Asia, and are distinct from patterns of production intensity. (Carlson et al. 2017)

5.4.3 Greenhouse gas emissions from livestock

Emissions from livestock include enteric fermentation and manure management, as well as emissions from manure deposited on pastures (Smith et al. 2014). Herrero et al. (2016) quantified non-CO_2 emissions from livestock in the range 2.0–3.6 GtCO_2-eq, with enteric fermentation from ruminants being the main contributor. This range is consistent but lower than recent FAO estimates. Using an IPCC Tier 1 approach, FAO estimated global non-CO_2 emissions within the farm gate of 3.6 ± 1.1 Gt CO_2-eq yr^{-1} for the period 2000–2016 (Tubiello, 2018; uncertainty of 30% from IPCC AR5). These estimates increase when considering life-cycle analysis. Using a IPCC Tier 2 approach and adding emissions from relevant land use, energy and transportation to those within the farm gate, FAO estimated livestock emissions in the range 5.3 ±1.6 GtCO_2-eq yr^{-1} circa 2010, with uncertainty of 30% and GWP scaled to IPCC AR5 value (FAO 2014a; Gerber et al. 2013).

Regardless of the estimation approach, in general cattle is the main source of global livestock emissions (65–77%). Livestock in low and middle-income countries contribute 70% of the emissions from ruminants and 53% from monogastrics, and these are expected to increase as demand for livestock products increases in these countries (Figure 5.11). Additionally, the livestock sector has reduced emissions intensities by 60% since 1961 (FAOSTAT, 2018; Davis et al. 2015). Yet products like red meat remain the most inefficient in terms of emissions per kg of protein produced in comparison to milk or pork, eggs and all crop products (IPCC AR5). Animal numbers remain the main source of variation in total gross emissions of the livestock sector, while at the animal level, feed intake, diet regime and quality are the main sources of variation of emissions through their impacts on enteric fermentation and manure N excretion.

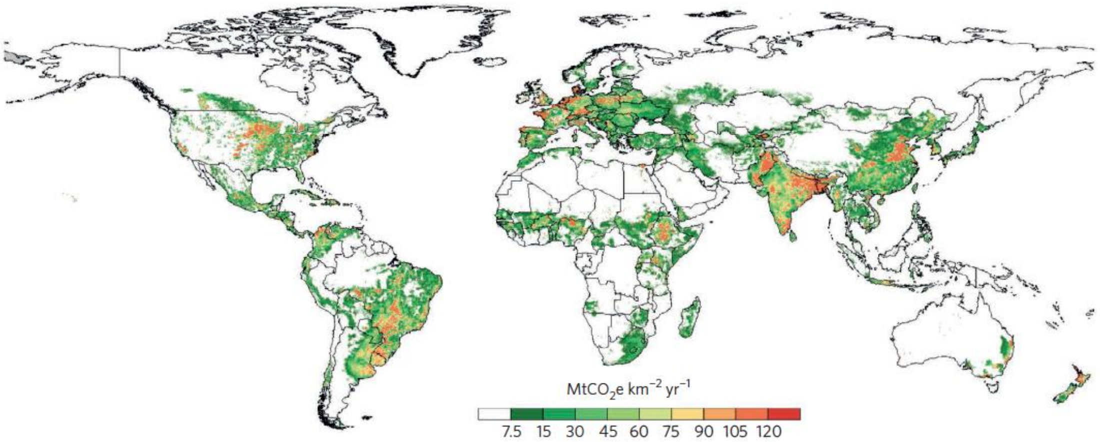

Figure 5.11 Global GHG emissions from livestock for 1995-2005 (Herrero et al. 2016a)

The majority of variation in estimates of N_2O emission factors are due to a) climate, b) soil type and c) N form (Charles et al. 2017; Fitton et al. 2017). It was recently suggested that N_2O soil emissions linked to livestock through manure applications could be 20%-40% lower than previously estimated in some regions, for instance in Sub-Saharan Africa and Eastern Europe (Gerber et al. 2016) and from smallholder systems in East Africa (Pelster et al. 2017). Herrero et al. (2016) estimated global livestock enteric methane to range from 1.6–2.7 Gt CO_2-eq, depending on assumptions on body weight and diet of the animals.

5.4.4 Greenhouse gas emissions from aquaculture

Emissions from fisheries and aquaculture are about 10% of total agriculture emissions, or about 0.55 Gt CO_2-eq yr-1 (Barange et al. 2018) with two-thirds being non-CO_2 emissions from aquaculture (Hu et al. 2013; Yang et al. 2015) and the rest due to fuel use in fishing vessels. Methodologies to measure aquaculture emissions are still being developed (Vasanth et al. 2016). N_2O emissions from aquaculture are partly linked to fertilisers use for feed, and depend on the temperature of water as well as on fish production (Paudel et al. 2015). Hu et al. (2012) estimated the global N_2O emission from aquaculture in 2009 to be 0.028 Gt CO_2-eq yr^{-1}, but could increase to 0.114 Gt CO_2-eq yr^{-1}, that is 5.72% of anthropogenic N_2O–N emission, by 2030 for an estimated 7.10% annual growth rate of the aquaculture industry. Numbers estimated by Williams and Crutzen were around 0.036 Gt CO_2-eq yr^{-1}, and suggested that this may rise to more than 0.179 Gt CO_2-eq yr^{-1} within 20 years for an estimated annual growth of 8.7% (Williams and Crutzen 2010). Barange et al. (2018) assessed the contribution of aquaculture to climate change as 0.38 Gt CO_2-eq yr^{-1} in 2010, around 7% of those from agriculture.

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

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

Apart from the direct and indirect emissions associated with food production, food systems also generate emissions from the pre- and post-production stages in the form of input manufacturing (fertilisers, pesticides, feed production) and processing, storage, refrigeration, retail, waste disposal, catering, and transport. The IPCC AR5 estimated that these emissions may add to direct emissions from agriculture and associated land use another 18–20% of total emissions.

Refrigerated trucks, trailers, shipping containers, warehouses, and retail displays that are vital parts of food supply chains all require energy and are direct sources of global hydrofluorocarbon (HFC) and GHG emissions (Mandyck and Schultz 2015). Upstream emissions in terms of feed and fertiliser manufacture and downstream emissions (transport, refrigeration) in intensive livestock production (dairy, beef, pig meat) can account for 24–32% of total livestock emissions, with approximately 40% arising from energy emissions and 60% from land use emissions (Weiss and Leip 2012), with the proportion of upstream/downstream emissions falling significantly for less intensive and more localised production systems (Mottet et al. 2017a).

Markets and prices indirectly affect emissions. Because the food chain involves land use, infrastructure, transportation, and energy production systems, at each stage, emissions can be influenced by available agricultural and fishing technologies, by actors along the supply chain, by consumers, and by technology choices.

Processing and transport. Recent globalisation of agriculture has favoured creation of breadbasket regions, promoted industrial agriculture, and encouraged processing and more distant transport of agricultural community, all leading to increased GHG emissions. To some extent, processing is necessary in order to make food more stable, safe, easy for conservation, and in some cases, nutritious (FAO, 2007). Globally, agricultural production itself contributes 80–86% of total food-related emissions, with emissions from other processes such as processing and transport being small (Vermeulen et al. 2012a). However, in net food-importing countries where consumption of processed food is common, emissions from other parts of the food life cycle is much higher (Green et al. 2015).

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

Although greenhouse gas-intensive, food transportation plays an important role in food chains: it delivers food from producers to consumers at various distances, particularly to feed people in food shortage zones from food surplus zones.

5.4.6 Greenhouse gas emissions associated with different diets

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

The emissions intensities of red meat mean that it has a disproportionate impact on total emissions (Godfray et al. 2018). For example, in the US 4% of food sold (by weight) is beef, which accounts for 36% of diet-related emissions (Heller and Keoleian 2015). Dietary-related emissions are therefore very sensitive to the amount and type of meat consumed.

There is therefore *robust evidence* (*with low uncertainty*) that the mixture of foods eaten can have a highly significant impact on per capita carbon emissions, driven particularly through the amount of (especially grain-fed) livestock and products. In addition, as many populations around the world consume more foodstuffs than is warranted by dietary needs, over-consumption of foods can be considered as a form of food waste (Heller and Keoleian 2015; Aleksandrowicz et al. 2016). For example, overconsumption in Australia represents about 33% GHG emissions from food (Hadjikakou 2017).

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

Changing dietary patterns towards healthier diets may have some significant benefits for greenhouse gas emissions. For example, in the US replacing beef with beans in the diet could achieve about 50% (46–74% depending on assumptions) of the reductions needed to meet the 2020 GHG target for the US, and so doing would potentially reduce the amount of US cropland by 42% (or 692,918 km^2) (Harwatt et al. 2017). Given higher income countries typically have higher emissions per capita, these results are particularly applicable in such places - though the one study on a non high-income country (India) indicated consistent patterns – that a “meat and rice diet” had emissions about 25% to about 33% higher than other dietary patterns (Green et al. 2018).

In lower-income countries, diets to promote a healthy life should be a priority first and foremost. However, as noted by Springmann et al. (2018) there are locally applicable upper bounds to the footprint of diets around the world, and for lower income countries undergoing a nutrition transition, adopting “Westernised” consumption patterns (over consumption, large amounts of livestock produce, sugar and fat), even if in culturally applicable local context, would increase emissions. This global mitigation potential of healthy but low-emissions diets is discussed in detail in Section 5.5.2.1.

5.5 Mitigation options, challenges, and opportunities

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

Supply side: emissions from land use change, land management, and crop and livestock practices can be reduced and terrestrial carbon stocks can be increased by sequestration in soils and biomass, and emissions from energy production can be saved through the substitution of fossil fuels by biomass.

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

In this chapter, supply-side mitigation practices include land use change and carbon sequestration in soils and biomass in both crop and livestock systems. Cropping systems practices include improved land and fertiliser management, biochar applications, breeding for larger root systems, and bridging yield gaps. Options for mitigation in livestock systems include better manure management, improved grazing land management, and better feeding practices for animals. Agroforestry also is a supply-side mitigation practice. Demand-side mitigation practices include dietary changes, reduction in food loss and waste, and improving efficiency in supply chains.

5.5.1 Supply-side mitigation options

Supply-side mitigation practices in the food system can contribute to climate change solutions by sustainably and efficiently intensifying the use of land and sequestering carbon in soils and biomass *(robust evidence, high agreement*). Options for GHG mitigation in cropping systems include improved land and fertiliser management, biochar applications, breeding for larger root systems, and bridging yield gaps, with a total mitigation potential estimated as 2.0–5.0 GtCO$_2$-eq yr^{-1} by 2030 for mitigation efforts consistent with carbon prices up to 100 USD/tCO$_2$-eq (Smith et al. 2014). Options for mitigation in livestock systems include better manure management, improved grazing land management, and better feeding practices for animals (1.8–2.4 GtCO$_2$-eq yr^{-1} by 2050). Reductions in GHG emissions intensity (emissions per unit product) from livestock and animal products can support reductions in absolute emissions in some contexts (e.g., reduction in herd size at constant pasture area, reduction in overall pasture area) (*medium evidence, medium agreement*). Agroforestry mitigation practices include rotational woodlots, long-term fallow, and integrated land use (4.27–21.5 GtCO$_2$-eq yr^{-1}).

Emissions from food systems can be reduced significantly by the implementation of practices that reduce carbon dioxide, methane, and nitrous oxide emissions from agricultural activities related to the production of both crops and livestock. These include sustainably intensifying the use of land so as to reduce land use change impacts, bridging yield gaps, implementing better feeding practices for animals, and better manure management. Practices that promote soil improvements and carbon sequestration can also play an important role. In Brazil, the reduction of deforestation, restoration of degraded pasture areas, and adoption of agroforestry and no-till agricultural techniques play a major role in the nation's voluntary commitments to reduce GHG emissions in the country's mitigation activities (Box 5.7).

The importance of supply-side mitigation options is that these can be directly applied by food system actors (farmers, processors, retailers, etc.) and if economically feasible, they can contribute to livelihoods and income generation. Recognising these social roles will be crucial to increasing the adoption rates of effective mitigation practices and to build convincing cases for enabling GHG mitigation.

Box 5.7 Towards sustainable intensification in the South America region

Most of the world's agricultural production growth has occurred in South America and Africa regions in the last three decades (FAO-OECD 2015), primarily driven by demands from Asia, Europe, Middle East and Northern Africa for soybeans, meat (poultry, beef and pork) and palm oil. Agricultural expansion in South America has driven profound landscape transformations in the region, particularly between the 1970s and early 2000s, contributing to increased deforestation rates and GHG emissions. High rates of native vegetation conversion occurred in Argentina, Bolivia, Brazil, Colombia, Ecuador, Paraguay and Peru (FAO 2016b; Graesser et al. 2015), threatening ecologically important biomes, such as the Amazon, savannas (Cerrado, Chacos and Lannos), Atlantic Rainforest, Caatinga and Yungas.

In the mid 2000s, governments, food industries, NGOs and international programs joined forces to put in place important initiatives to respond to the growing concerns about the environmental impacts of agricultural expansion (Negra et al. 2014; Finer et al. 2018). Brazil led regional actions by launching the Interministerial Plan of Action for Prevention and Control of Deforestation of the Legal Amazon[1] (PPCDAm), associated with a real-time deforestation warning system. Further, Brazil built capacity to respond to alerts by coordinated efforts of ministries, federal police, army and public prosecution (Negra et al. 2014; Finer et al. 2018). Other countries in the region have also launched similar strategies, including a zero-deforestation plan in Paraguay in 2004 (Gasparri and de Waroux 2015), and no-deforestation zones in Argentina in 2007 (Garcia Collazo et al. 2013). Peru also developed the National System of Monitoring and Control, led by the National Forest Service and Wildlife Authority (SERFOR), to provide information and coordinate response to deforestation, and Colombia started producing quarterly warning reports on active fronts of deforestation in the country (Finer et al. 2018).

Engagement of the food industry and NGOs, particularly through the Soy Moratorium (from 2006) and Beef Moratorium (from 2009) also contributed effectively to keep deforestation at low historical rates in the regions where they were implemented (Nepstad et al. 2014; Gibbs et al. 2015). In 2012, Brazil also created the national land registry system (SICAR), a georeferenced database, which allows monitoring of farms' environmental liability compulsory to access to rural credit. Besides the government programs, funding agencies and the Amazon Fund provide financial resources to assist smallholder farmers in complying with environmental regulations (Jung et al. 2017). Nevertheless Azevedo et al. (2017) argue that the full potential of these financial incentives has not been achieved due to weak enforcement mechanisms and limited supporting public policies.

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

Overall, FAO (2018) shows that deforestation rates in South America declined significantly with a two-folded decrease since early 2000s. However, inconsistent conservation policies across countries (Gibbs et al. 2015) and recent data (Curtis et al. 2018) indicate that deforestation control still requires stronger reinforcement mechanisms. Further, Curtis et al. (2018) and Dou et al. (2018) point out that, although the Amazon deforestation rate decreased in Brazil, it has increased in other regions, particularly in Southern Asia, and with less intensity, in other countries in South America, resulting in a nearly-constant global deforestation rate worldwide.

Despite the constraints on agricultural land availability, agricultural production continues to rise steadily in South America, relying on increasing productivity and substitution of extensive pastureland by crops. The average soybean and maize productivity in the region increased from 1.8 and 2.0 t ha^{-1} in 1990 to 3.0 and 5.0 t ha^{-1}, respectively, in 2015 (FAO 2018b). Yet, higher crop productivity was not enough to meet higher cereal and oilseed demand and cultivation continued to expand, mainly over

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[1] 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.

grasslands (Richards 2015). The reconciliation of this expansion with higher demand for meat and dairy products has been carried out through the intensification of livestock systems (Martha et al. 2012). Nevertheless, direct and indirect deforestation still occurs.

The effort towards sustainable intensification has also been incorporated in agricultural policies. In Brazil, for instance, the reduction of deforestation, the restoration of degraded pasture areas, the adoption of agroforestry integrated systems[2] and no-till agricultural techniques play a major role in the nation's voluntary commitments to reduce GHG emissions in the country's NAMAs (Mozzer 2011) and NDCs (Silva Oliveira et al. 2017; Rochedo et al. 2018). Such commitment under the UNFCCC is operationalised through the Low Carbon Agriculture Plan (ABC)[3], which is based on low-interest credit for investment on sustainable agricultural technologies (Mozzer 2011). Direct pasture restoration and integrated systems reduce area requirements (Strassburg et al. 2014), and increase organic matter (Gil et al. 2015; Bungenstab 2012), contributing to overall life-cycle emissions reduction (Cardoso et al. 2016; de Oliveira Silva et al. 2016). Also, increased adoption of supplementary feed and feedlots, often based on agroindustrial co-products and agricultural crop residues are central to improving productivity and increasing climate resilience of livestock systems (van Zanten et al. 2018; Mottet et al. 2017a).

Despite providing clear environmental and socioeconomic co-benefits, including improved resource productivity, socio-environmental sustainability and higher economic competitiveness, the Brazilian Low Carbon Agriculture Plan implementation is behind schedule (Köberle et al. 2017). Structural inefficiencies related to the allocation and distribution of resources need to be addressed to put the plan on track to meet its emissions reduction targets. Monitoring and verification are fundamental tools to guarantee the successful implementation of the plan.

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

5.5.1.1 Greenhouse gas mitigation in croplands and soils

The mitigation potential of soils and cropland management has been the subject of much research and was well represented in AR5 (Smith et al. 2014). Key mitigation pathways are related to practices reducing nitrous oxide emissions from soils and fertiliser applications, reducing methane emissions from paddy rice, and sequestering carbon or reducing its losses, with practices for improving grassland and cropland management presenting the largest mitigation opportunities. However, better monitoring and reporting systems are still needed for reducing the uncertainties in the application of these practices.

New work since AR5 has charted a pathway for reductions in GHG emissions from agriculture to meet the 2.0°C above preindustrial levels target pledged in the Paris Agreement (Paustian et al. 2016; Wollenberg et al. 2016). Altieri and Nicholls (2017) have characterised mitigation potentials from traditional agriculture. Zomer et al. (2017) have estimated the global sequestration potential of increased

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

[3] FOOTNORE: ABC - *Agricultura de Baixo Carbono* in Portuguese.

organic carbon in cropland soils. For discussion of integrated practices such as sustainable intensification, conservation agriculture and agroecology see Section 5.6.3.

Paustian et al. (2016) developed a decision-tree for studying mitigation practices in cropland and described the features of key practices. They observed that most individual mitigation practices will have a small effect per unit of land; hence they need to be applied widely for their impact to be significant (Figure 5.12). In this study, multiple practices are aggregated for cropland (for example, improved crop rotations and nutrient management, reduced tillage) and grazing land (for example, grazing management, nutrient and fire management, species introduction) categories. Practices that increase net soil C stocks or reduce emissions of N_2O and CH_4 are combined in each practice category. The portion of projected mitigation from soil C stock increase (about 90% of the total technical potential) would have a limited time span of 20–30 years, whereas non-CO_2 emission reduction could, in principle, continue indefinitely. Estimates for biochar application represent a technical potential only, but it is based on a full life-cycle analysis applicable over a 100-year time span. Although global estimates of the potential impact of enhanced root phenotypes for crops have not been published, a first-order estimate of about 1 Pg CO_2-eq yr^{-1} is shown, using the global average C accrual rates (0.23 Mg C $ha^{-1}yr^{-1}$) for cover crops, applied to 50% of the cropland land area. ‘Set aside’ land is arable land, usually for annual crops, that is taken out of production and converted to perennial vegetation (often grassland) and not actively managed for agricultural production, such as conservation reserves. They also identified significant synergies and trade-offs with other ecosystems functions and a broad range of implementation costs, which may influence their adoption.

Co-benefits include ecosystem services from implementation of these practices. Relative costs are provided as examples based on a developed region such as North America and a less developed region such as sub-Saharan Africa; however, a specific option in one region may have a higher cost or be a less feasible option in another region. Potential constraints include factors that might limit or preclude adoption of a specific practice or increase other GHG emissions as a consequence of its adoption. All options require a region-specific full-cost carbon accounting (GHG life-cycle analysis) that considers potential indirect land use effects in order to define specific mitigation potentials.

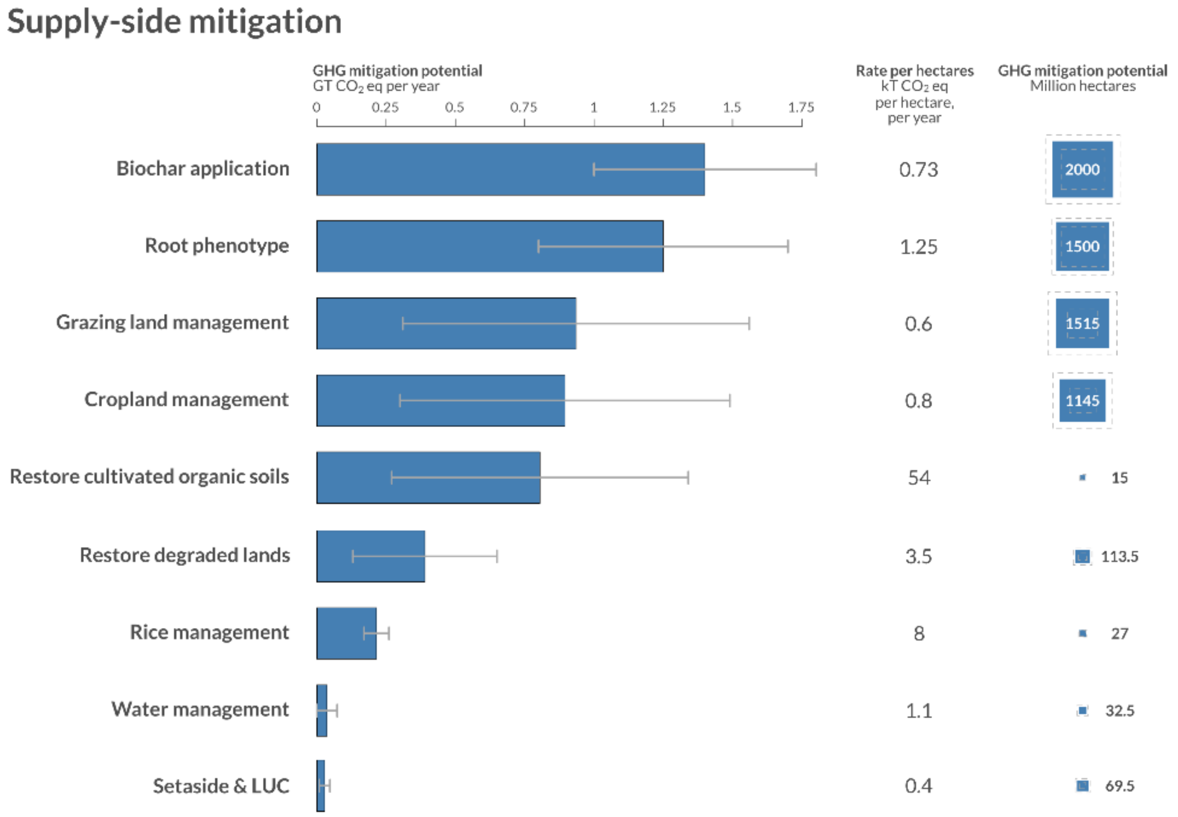

Figure 5.12 Global potential for agricultural-based GHG mitigation practices. Management categories are arranged according to average per hectare net GHG reduction rates and potential area (in millions of hectares) of adoption (note log-scales). Unless otherwise noted, estimates are based on cropland and grassland area projections for 2030. Ranges given in units of total Pg CO$_2$-eq yr^{-1} represent varying adoption rates as a function of C pricing (USD20, USD50 and USD100 per Mg CO$_2$-eq), to a maximum technical potential—that is, the full implementation of practices on the available land base (Paustian et al. 2016)

5.5.1.2 Greenhouse gas mitigation in livestock

The technical options for mitigating GHG in the livestock sector have been the subject of recent reviews (Hristov et al. 2013a,b; Smithers 2015; Herrero et al. 2016a; Rivera-Ferre et al. 2016b). Figure 5.13 synthesises the main alternatives. They can be classified as either targeting reductions in enteric methane; reductions in nitrous oxide through manure management; sequestering carbon from pastures; implementation of best animal husbandry and management practices, which would have an effect on most GHG; and land use practices that also help sequester carbon. Excluding land use practices, (Herrero et al. 2016) found that these options have a technical mitigation potential of 2.4 GtCO$_2$-eq yr^{-1}. These estimates are in the same range as those proposed by FAO (2013, 1.8 GtCO$_2$-eq). Some of the better tested strategies are described below. Different production systems will require of different strategies (Rivera-Ferre et al. 2016b) and this has been the subject of significant research.

Livestock systems are heterogeneous in terms of their agro-ecological orientation (arid, humid or temperate/highland locations), livestock species (cattle, sheep, goats, pigs, poultry and others), structure (grazing only, mixed-crop-livestock systems, industrial systems, feedlots and others), level of intensification, resource endowment and others (Robinson et al. 2011). The AR5 did not include the differentiation of mitigation practices by production system but the implementation of strategies presented in Figure 5.13 is subject to this differentiation. Manure management strategies are more applicable in confined systems, where manure can be easily collected, such as in pigs and poultry systems or in smallholder mixed crop –livestock systems. More intensive systems, with strong market orientation, such as dairy in the US can implement a range of sophisticated practices like feed additives/vaccines, while many market oriented dairy systems in tropical regions can improve feed digestibility by improving forage quality and adding larger quantities of concentrate to the rations. Many of these strategies can be implemented as packages in different systems, thus maximising the synergies between different options (Mottet et al. 2017b).

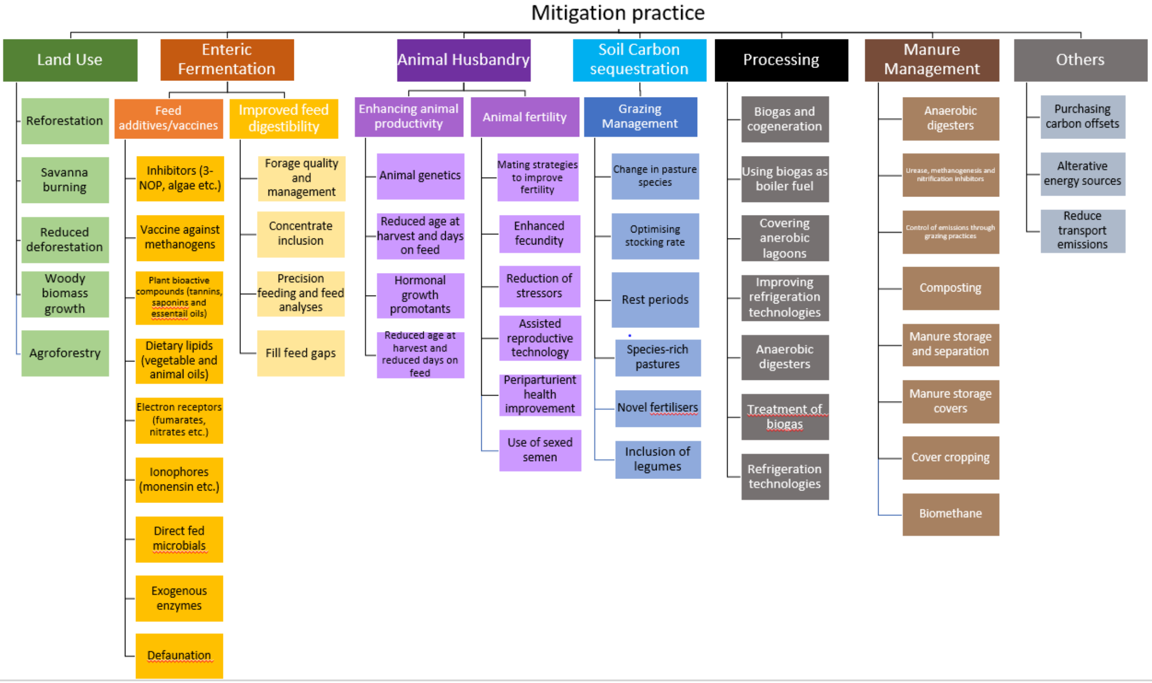

Figure 5.13 Technical supply-side mitigation practices in the livestock sector (adapted from Hristov et al. 2013b; Herrero et al. 2016b; Smith et al. 2014)

Intensification of animal diets. It is well established that feeding better quality diets to animals reduces the amount of GHG produced per unit of animal product (Gerber et al. 2013). This increased efficiency can be achieved through improved supplementation practices or through land use management with practices like improved pasture management (grazing rotation, fertiliser applications, soil pH modification, development of fodder banks, improved pasture species, use of legumes and other high protein feeds, the use of improved crop by-products and novel feeds (i.e. black soldier fly meal, industrially produced microbial protein (Pikaar et al. 2018). When done through increased feeding of grains, transition to improved diets shifts the contributions of different GHG gases to the total emissions. This is due to the fact that the proportion of methane to total emissions reduces (due to lower roughage intake), while the proportion of emissions associated with feed manufacture (energy and land use change) increases. Therefore, CO_2 emissions from land use change increase while methane emissions per unit of output decrease (Gill et al. 2010).

Of the available livestock GHG mitigation options, improved feeding systems are relatively easy to implement at the farm level. A pre-requisite for these options to work is that the livestock systems need to be geared towards market-orientated production, as otherwise there is little incentive to improve feeding systems. Examples of where this option could be applicable are smallholder dairy-crop mixed systems in Africa and Asia, dual-purpose and dairy production in Latin America and beef cattle operations, where significant mitigation opportunities exist. Other options include manipulation of rumen microflora, breeding for lower methane production, and the use of feed additives (Hristov et al. 2013).

The largest GHG efficiency gaps are observed in livestock systems where the quality of the diet is the poorest (i.e., grassland-based and some arid and humid mixed systems in the developing world). The highest marginal gains of improving animal diets through simple feeding practices, both biologically and economically, are in these systems (FAO, 2013; Herrero et al. 2013).

Control of animal numbers, shifts in breeds, and improved management. Increases in animal numbers are one of the biggest factors contributing directly to GHG emissions (EPA 2012; Thornton and Herrero 2010). Regions with intensive animal production, such as concentrated animal feeding operations (CAFOs), can control animal numbers, conduct breeding programs for efficient animals, and improve feeding management. In the developing world, many low-producing animals could be replaced by fewer but better-fed cross-bred animals of a higher potential, with improved grazing management (i.e., attention to feed, herbage availability, and allowances) playing an important role. In both developed and developing countries these practices are able to reduce total emissions while maintaining or increasing the supply of livestock products, and can be effective in carbon-constrained markets. Improvements in animal health can also significantly reduce emissions intensity by improved yields and fertility per animal and reductions in mortality (ADAS 2015).

Changes in livestock species. Switching species to better suit particular environments is a strategy that could yield higher productivity per animal for the resources available. At the same time, structural changes in the livestock sector from ruminants to monogastrics could lead to reduced methane emissions and higher efficiency gains (e.g., from beef to pig or poultry production). These practices could lead to reductions in land use change and its associated emissions (Havlik et al. 2014; Frank et al. 2018).

Managing nitrous oxide emissions from manure. In the developing world, large amounts of nutrients are lost due to poor manure management. The opportunistic nature of many feeding systems means that large amounts of nutrients and carbon are lost before manure is stored (Herrero et al. 2013). In many places in Africa and Latin America, pig manure is not recycled; considered a waste, it is often discharged to water bodies or left to accumulate unused. Yet these farming systems can be highly N and P limited. This practice creates serious problems especially in urban and peri-urban systems by contributing to water and air pollution. Research in intensive African ruminant livestock systems has shown that up to 70% of the manure N can be lost within six months of excretion when manure is poorly managed (Tittonell et al. 2009).

Options to manage emissions in the livestock sector are not easy to design because they require systems thinking and awareness of key driving factors in different livestock systems. Reducing N emissions starts with feeding livestock balanced diets so that excreta are not rich in labile N, which is easily lost as ammonia and enters the N cascade (Bouwman et al. 2013). In intensive systems, mineral N can be captured effectively using bedding material, which has been increasingly excluded from livestock facilities to reduce operational costs. In intensive livestock systems, manure is increasingly handled as slurry in tanks or anaerobic lagoons, which may reduce direct nitrous oxide emissions during storage but can increase methane and ammonia loss and also increase the risk of emissions during land spreading (Velthof and Mosquera 2011). However, optimising land spreading of manures (in terms of timing or placement) to maximise N and P replacement value can minimise ammonia losses while also displacing mineral fertiliser (Bourdin et al. 2014). In extensive systems, emissions of ammonia and nitrous oxide can be managed by spatially shifting livestock pens or the facilities where they overnight. Other options in more intensive grazing systems also include nitrification inhibitors, stand-off pads, delayed manure spreading collected in milking sheds.

Carbon sequestration. The opportunities for carbon sequestration in grasslands and rangelands is modest according to recent literature (Garnett et al. 2017; Herrero et al. 2016a; Henderson et al. 2015). Henderson et al. (2015) found that the economic potential of these practices is lower than 200 MtCO$_2$-eq yr^{-1}. Carbon sequestration can occur in situations where grasslands are highly degraded, however the carbon accumulation is not continuous and reaches a saturation point (Garnett 2016). Carbon sequestration could be considered a co-benefit of well-managed grasslands rather than a main objective.

5.5.1.3 Greenhouse gas mitigation in agroforestry

Agroforestry can curb GHG emissions of CO_2, CH_4, and N_2O in agricultural systems in both developed and developing countries. Soil carbon sequestration is enhanced through agricultural lands management practices used by large-scale and smallholder farmers, such as increased application of organic manures, use of intercrops and green manures, incorporation of trees within farms or in hedges (manure addition, green manures, cover crops, etc.) promote greater soil organic matter (and thus soil organic carbon) content and improve soil structure (Mbow et al. 2014b) (Table 5.6). CO_2 emissions are lessened through lower rates of erosion due to better soil structure and more plant cover in diversified farming systems than in monocultures. There is great potential for increasing above ground and soil C stocks, reducing soil erosion and degradation, and mitigating GHG emissions. These practices can improve food security through increases in productivity and stability since they contribute to increased soil quality and water-holding capacity.

Table 5.6 Carbon sequestration potential for agroforestry (Mbow et al. 2014b)

Source	**Carbon sequestration (Mg C ha yr^{-1}) (range)**	**C stock (Mg C ha) (range)**	**Max rotation period (years)**
Dominant parklands	0.5 (0.2–0.8)	33.4 (5.7–70.8)	50
Rotational woodlots	3.9 (2.2–5.8)	18.5 (11.6–25.5)	5
Tree planting-windrows-home gardens	0.6 (0.4–0.8)	19.0	25
Long term fallows, regrowth of woodlands in abandoned farms	2.24 (0.22–5.8)	15.7	25
Integrated land use	3.12 (1.0–6.7)	77.9 (12–228)	50
Soil carbon	0.9 (0.25–1.6)	5.7 (13–300)	-

Meta-analyses have been done on carbon budgets in agroforestry (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 to be: semi-arid = 2.6 Mg Cha^{-1} yr^{-1}; temperate = 3.9 Mg Cha^{-1} yr^{-1}; sub-humid = 6.1 Mg Cha^{-1} yr^{-1}; and humid = 10 Mg Cha^{-1} yr^{-1}. (Montagnini and Nair 2004) estimated potential C sequestration rates from 1.5 to 3.5 Mg Cha^{s} yr^{-1} for smallholders in the tropics.

Data from several countries suggest that agroforestry systems can partially offset CH_4 emissions, while conventional high-input cropping systems can exacerbate CH_4 emissions (Montagnini and Nair 2004). Agroforestry can mitigate N_2O and CO_2 emissions from soils and increase methane sink strength compared to annual cropping systems (Mutuo et al. 2005; Rosenstock et al. 2014). Because smallholder biodiverse farms use less energy, pesticides and fertilisers, their emissions avoidance is achieved through (Niggli et al. 2008) lower N_2O emissions (due to lower nitrogen input). It is usually assumed that 1–2% of the nitrogen applied to farming systems is emitted as N_2O.

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 that will help to reduce GHG emissions. These include several strategies that help decoupling livestock from land use. One of these strategies is feeding livestock on leftovers (waste from food supply chains) or in land with low opportunity costs, which is not suitable for crop production. If this strategy was implemented, the synthesis by (van Zanten et al. 2018) demonstrates that 7–23 g of animal protein per capita per day could be produced without livestock competing for vital arable land. This would imply a contraction of the livestock sector, but also a more efficient use of resources, and would lead to land sparing and emissions reductions. Pikaar et al. (2018) also demonstrated that producing microbial protein as a feedstuff from sewage streams is feasible and has started to be implemented in livestock feeding as a replacement for soybean production. The technical potential of this novel practice could replace 10–19% of the feed protein required, and would reduce cropland demand by 6% and emissions from crop production by 7%. These practices, while promising are still not economically feasible or upscalable to large numbers of animals or regions. Identifying ways to increase their feasibility will demand a great understanding of biomass and leftover value chains, and mechanisms for reducing the transport and processing costs of these materials.

Waste streams into energy. Waste streams from manures and food waste can also be used for energy generation in terms of methane production (De Clercq et al. 2016) or for the production of microbial protein (Pikaar et al 2018). Also, second-generation biorefineries can generate hydro-carbon from agricultural residues, grass and woody biomass that do not compete with food and can generate, along with biofuel, high value products such as plastics (Nguyen et al. 2017). Second-generation energy biomass from residues constitutes a complementary income source for farmers that can increase their incentive to produce. The use of CHP (combined heat and power) or gas turbines for biofeed, and specific fuel obtention technologies like obtention of bio-diesel, bio-pyrolysis, torrefaction of biomass, production of cellulosic bio-ethanol and of bio-alcohols produced by other means than fermentation, and the production of methane by anaerobic fermentation, must be considered (Nguyen et al. 2017).

Technical measures. Novel strategies to reduce methanogenesis include supplementing with antimethanogenic agents (e.g., 3NOP, algae, chemical inhibitors such as chloroform) or supplementing with electron acceptors (e.g., nitrate) or dietary lipids. Two notable examples, already in the market but with increasing potential for commercialisation are *Asparogopsis taxiformis* algae, developed by CSIRO, which has shown reductions of 60–80% in methane production in cattle when fed at rates of 2–3 g per day (CSIRO, 2018). This would be useful for confined animals, like in smallholder systems, or in feedlots or dairy operations. The other compound is 3-nitrooxypropanol (3-NOP),which can decrease methane by up to 40% when incorporated in diets for ruminants (Hristov et al. 2015). These two examples could potentially get rid of large amounts of methane, but the land footprint of ruminants and the CO_2 and N_2O emissions from ruminants will remain.

Whilst these strategies are very effective at reducing methane (30–75%), they can be expensive and also impact on animal performance and/or welfare (Llonch et al. 2017). The use of novel fertilisers and/or plant species that secrete biological nitrification inhibitors also have the potential to significantly reduce N_2O emissions from agricultural soils (Subbarao et al. 2009; Rose et al. 2018).

Economic mitigation potentials of crop and livestock sectors. Despite the large technical mitigation potential of the agriculture, livestock and land use sector, its economic potential is relatively small in the short term (2030) and at modest carbon prices (less than USD 20 tC^{-1}). For crop and soil management practices, it is estimated that 1–1.5 $GtCO_2$-eq could be a feasible mitigation target at a carbon price of USD 20/tonne of carbon (Frank et al. 2018, 2017; Griscom et al. 2016; Smith et al. 2013; Wollenberg et al. 2016). For the livestock sector, these estimates range from 0.125–0.250 $GtCO_2$-eq at similar carbon prices (Herrero et al. 2016b; Henderson et al. 2017).

Frank et al. (2018) recently demonstrated that the economic mitigation potential of non-CO_2 emissions from agriculture and livestock to 2030 could be up to four times higher than the AR5 estimates, if structural options such as switching livestock species from ruminants to monogastrics, or allowing for flexibility to relocate production to more efficient regions were implemented, at the same time as the technical options such as those described above. At higher carbon prices (up to USD 100tC^{-1}), they found a mitigation potential of supply-side measures of 2.6 $GtCO_2$-eq. However, switching from ruminants to monogastrics may have socio-cultural implications, including gender, because large livestock often belong to men and small livestock to women.

In this scenario, technical options would account for 38% of the abatement, while another 38% would be obtained through structural changes, and a further 24% would be obtained through shifts in consumption caused by food price increases. Key to the achievement of this mitigation potential laid in the livestock sector, as reductions in livestock consumption, structural changes and implementation of technologies in the sector had some of the highest impacts. Regions with the highest mitigation potentials were Latin America, China and Sub-Saharan Africa. These findings are consistent with (Havlik et al. 2014).

5.5.1.5 Greenhouse gas mitigation in aquaculture

Barange et al. (2018) provide a synthesis of effective options for GHG emissions reduction in aquaculture including reduction of emissions from production of feed material, replacement of fish-based feed ingredients with crop-based ingredients; reduction of emissions from feed mill energy use, improvement of feed conversion rates, improvementof input use efficiency, shift of energy supply (from fossil fuel to renewables), and improvement of ish health. When these approaches are combined, there is a potential reduction of 21% in CO_2 emissions per tonne of fish production.

5.5.1.6 Cellular agriculture

Cultured meat (CM), also called in-vitro meat, synthetic meat and hydroponic meat, is part of the so-called cellular agriculture, which includes production of milk, egg white and leather from industrial cell cultivation (Stephens et al. 2018). CM is produced from muscle cells extracted from living animals, isolation of adult skeletal muscle stem cells (myosatellite cells), placement in a culture medium which allow their differentiation into myoblasts and then, through another medium, generate myocytes which coalesce into myotubes and grow into strands in a stirred-tank bioreactor (Mattick et al. 2015). The current technology allows creating beef hamburgers, nuggets, steak chips or similar products from meat of other animals, including wild species. It also has advantages such as reduction of zoonotic and food born diseases, reduce GHG emissions, reduce land use, support animal rights, allowing bioengineering from the manipulation of the stem cells and nutritive culture, reducing harmful fatty acids and creating new products (Bhat et al. 2015; Kumar et al. 2017).

There is no reported technology yet to produce a high-end steak with all other biological structures, such as connective and vascular tissues. Another current technological challenge is that, typically, the cells culture is nourished by serum made from animal blood. Serum-free sources have been developed, but it requires modification of the myoblasts to be nourished from such culture and productivity is not well defined (Alexander et al. 2017). The precise methods vary between labs and companies and there is still a lot of industrial confidentiality on the processes (Stephens et al. 2018).

Most of the available environmental impact analysis of cultured meat assume serum-free medium (Tuomisto and Teixeira de Mattos 2011; Alexander et al. 2017; Mattick et al. 2015) . Tomisto & Mattos (2011) made optimistic technological assumptions, relying on cyanobacteria hydrolysate nutrient source, and produced the lowest estimates on energy and land use. Tomisto & Mattos (2011) lifecycle assessment indicate cultured meat could have less than 60% of energy use and 1% of land use of beef production of beef and it would have lower GHG emissions than pork and poultry as well. Newer estimates (Alexander et al. 2017; Mattick et al. 2015) indicate a tradeoff between industrial energy consumption and agricultural land requirements of conventional and cultured meat and possibly higher GWP than pork or poultry due to higher energy use.

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

5.5.2 Demand-side mitigation options

Population growth will drive global food demand and the resulting environmental burden, but demand-side management of the food system could be one of the solutions to curb climate change. Avoiding food waste during consumption, reducing over-consumption and changing dietary preferences can contribute significantly to provide healthy diets for all as well as reduce the environmental footprint of the food system.

Demand-side changes, for example, in food choices and consumption, can help to achieve global GHG mitigation targets and improve human health *(robust evidence, high agreement)*. Low-carbon diets on average tend to be healthier and have smaller land footprints. By 2050, mitigation potential of dietary changes ranging from 2.7–3.4 GtCO$_2$-eq yr^{-1} for Mediterranean diets, 3.6–6.4 GtCO$_2$-eq yr^{-1} for healthy diets, 4.3–5.3 GtCO$_2$-eq yr^{-1} for vegetarian diets and 5.2–5.7 GtCO$_2$-eq yr^{-1} for a flexitarian diet with limited meat and dairy products in comparison to business-as-usual food demand projections *(robust evidence*, *high agreement)*. In high-income industrial countries, there is scope for reducing consumption of livestock produce with tangible environmental benefits; in developing countries, high meat-based diets are less prevalent and scope for reductions may be more limited. To encourage low-carbon diets, policies such as awareness-raising campaigns, public procurement, and health insurance incentives have been tested in differing contexts.

5.5.2.1 Demand-side scenarios of different diets

Figure 5.14 shows the mitigation potentials of scenarios of alternative diets examined in the literature. Stehfest et al. (2009) were some of the first to examine these questions. Under the most extreme scenario, where no animal products are consumed at all, adequate food production in 2050 could be achieved on less land than is currently used, allowing considerable forest regeneration, and reducing land based greenhouse gas emissions to one third of the reference "business-as-usual" case for 2050, a reduction of 7.8 Gt CO_2-eq yr^{-1}. This defines the upper bound of the technical mitigation potential of demand side measures. Stehfest et al. (2009) also examined a range of scenario variants. "No animal products", "No meat", "No ruminant meat", and "Healthy diet" compared to a reference case based on FAO assumptions. Reduction in animal protein intake was assumed to be fully compensated by higher intake of pulses. They found emissions reductions of 4.3 Gt CO_2-eq yr^{-1} in the Healthy Diet scenario, and 5.8 and 6.4 CO_2-eq yr^{-1} for the No Ruminant Meat and No Meat scenarios, respectively.

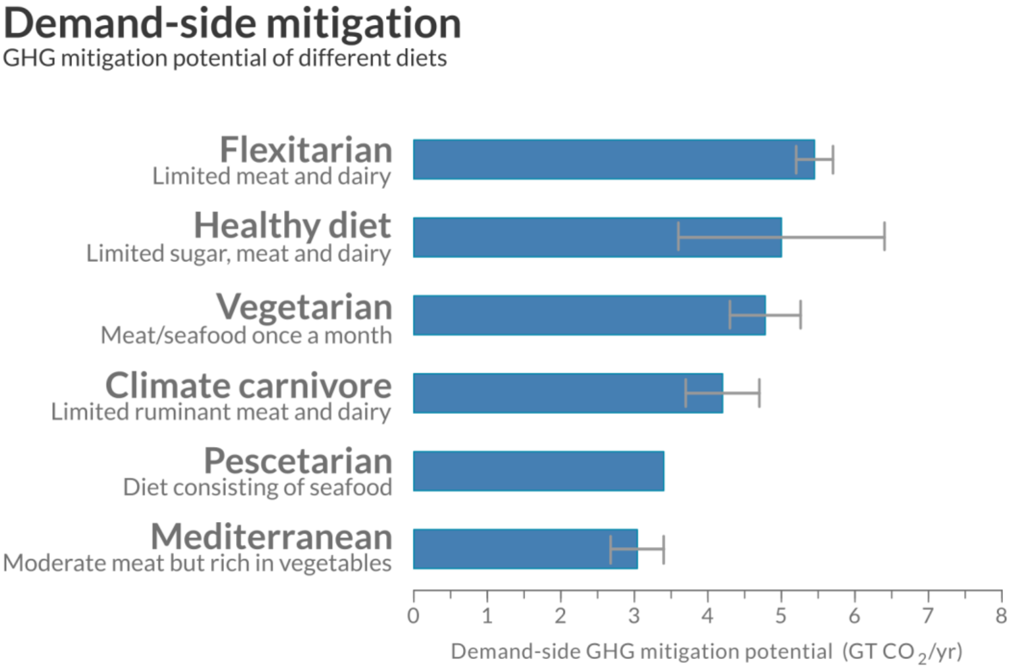

Figure 5.14 The mitigation potential of changing diets according to a range of scenarios examined in the literature (Herrero et al. 2016a)

In their study, changes in the agricultural and livestock sectors, like the reduction of livestock production, lead to changes in N_2O, CH_4 and CO_2 emissions. While CH_4 and N_2O emissions are mostly coupled to the production process and the total amount of production, CO_2 emission/uptake from land use change is mostly coupled to a change in agricultural area. As a consequence, reduction potentials in CH_4 and N_2O emission are rather stable in time, while changes in the CO_2 balance of land use are only temporary. When the transition to a low-meat diet reduces the agricultural area required, land is abandoned and the re-growing vegetation can take up carbon until a new equilibrium is reached. This is known as the land-sparing effect.

In another study, Smith et al. (2013) analysed a dietary change scenario that assumed a convergence towards a global daily per-capita calorie intake of 2800 kcal cap^{-1} day^{-1} (11.7 MJ cap^{-1} day^{-1}), paired with a relatively low level of animal product supply, while the reference scenario largely follow the FAO projections (Alexandratos and Bruinsma 2012). Their range of mitigation was 0.7–7.3 Gt CO_2-eq yr^{-1} for additional variants including low or high-yielding bioenergy, 4.6 Gt CO_2-eq yr^{-1} if spare land is afforested.

Bajželj et al. (2014) developed different scenarios of farm systems change (expansion or intensification), waste management, and dietary change on GHG emissions with the metric being efficiency of land use. Their dietary scenarios were based on a target kilocalorie consumption levels and reductions in animal product consumption. Their scenarios were “Healthy Diet”, implemented on top of two reference cases (one with low waste, one with low waste and high yields); Healthy Diet with 2500 kcal cap^{-1} day^{-1} in 2050; while reference cases have 2520–3027 kcal cap^{-1} day^{-1}, depending on the region. Their emissions reductions were 5.8 and 6.4 Gt CO_2-eq yr^{-1} depending on the reference chosen.

Hedenus et al. (2014) explored further dietary variants based on the type of livestock product. “Climate Carnivore”, in which 75% of the baseline-consumption of ruminant meat (beef, lamb) and dairy was replaced by pork and poultry meat (on kcal basis), and “Flexitarian”, in which 75% of the baseline-consumption of meat and dairy was replaced by pulses and cereal products (on kcal basis). Their emissions reductions were 3.4 Gt CO_2-eq yr^{-1} in the Climate Carnivore scenario, and 5.2 Gt CO_2-eq yr^{-1} in the Flexitarian scenario by 2050. These potentials are relative to a supply-side mitigation scenario, which incorporates mitigation effects from increased livestock productivity and technical interventions (e.g., improved manure management technology).

In contrast to these scenarios, Tilman and Clark (2014) used stylised diets as variants of a reference diet that matched the FAO projections. Their variants included “Pescetarian”, “Mediterranean”, “Vegetarian”, compared to a reference diet. Vegetarian diet is based on reference 37, the Pescetarian diet was modified from the vegetarian diet, including one serving of fish per day, but reduced milk, egg and cereal demand; the Mediterranean diet is derived from nutritional recommendations. Demand for the reference diet in 2050 is calculated based on a relationship between GDP and consumption. Their direct emissions reductions were 1.2, 1.9 and 2.3 Gt CO_2-eq yr^{-1} excluding land use change, for the Mediterranean, Pescetarian and Vegetarian Diet, respectively. Reduction in global cropland by about 450, 580 and 600 million ha, avoiding about 1.8–2.4 Gt CO_2-eq yr^{-1}.

More recently, Springmann et al. (2018) developed another set of dietary change scenarios, with the objective of identifying the types of measures that would prevent the world food systems from transgressing the planetary boundaries of GHG emissions, and land use N and P and water use. Their results confirm that for achieving progress towards reducing the environmental burdens on the food system in the future, both supply and demand side measures would need to be implemented simultaneously. They found that a combination of a flexitarian diet (mostly plant based but with small additions of animal source foods, including fish), together with waste reduction and implementation of technical measures would achieve the desired results.

All these studies, still examine the technical potential of changing diets. The feasibility of how to create transitions to more sustainable and healthy diets is still the subject of more research.

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

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

5.5.2.2 Dietary shifts, health impacts, and GHG emissions

Two key questions arise from the potentially significant mitigation potential of dietary change: 1) Are ‘low-emission diets’ likely to be beneficial for health (and so could concerns for a healthy diet drive adoption of, or avoidance of, high emissions diets)? and 2) Would changing diets at scale provide a large enough benefit that might overcome social and political constraints?

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

There are several studies (e.g., for the Netherlands, Van Dooren et al. 2014) that estimate health adequacy and sustainability and conclude that sustainable healthy diets are possible. Another study found that halving consumption of meat, dairy products and eggs in the European Union would achieve a 40% reduction in nitrogen emissions, 25–40% reduction in greenhouse gas emissions and 23% per capita less use of cropland for food production, with dietary changes lowering health risks. (Westhoek et al. 2014). In China, diets were designed that met dietary guidelines and created significant reductions in GHG emissions (between 5% and 28% depending on scenario) (Song et al. 2017). Changing diets can also mitigate non-dietary related health issues caused by emissions of air pollutants; for example, changing diet has been shown to be a means of mitigating PM2.5 in China (Zhao et al. 2017b).

A range of studies are starting to estimate both health and environmental benefits from dietary shifts. For example, (Farchi et al. 2017) estimate health (cancer, cardio-vascular disease) and GHG reductions of low meat diets in Italy. In US (Hallström et al. 2017) found that adoption of healthier diets reduced relative risk of coronary heart disease, colorectal cancer, and type 2 diabetes by 20–45%, US health care costs by USD 77–93 billion per year, and direct GHG emissions by 222–826 kg CO_2-eq/capitayr^{-1} (69–84 kg from the health care system, 153–742 kg from the food system). Similar conclusions come (with some caveats) in the Netherlands (Biesbroek et al. 2014); and from the UK (Friel et al. 2009; Milner et al. 2015).

Tilman and Clark (2014) demonstrated significant benefits in terms of reductions in relative risk of key diseases: type II diabetes, cancer, coronary mortality and all causes of mortality (Figure 5.15). Similar results were obtained by (Springmann et al. 2016b,a). (Hallström et al. 2017) show that reductions in GHG emissions due to changing diets can ensue from reduced healthcare operations as well as reduced GHG emissions from the food system.

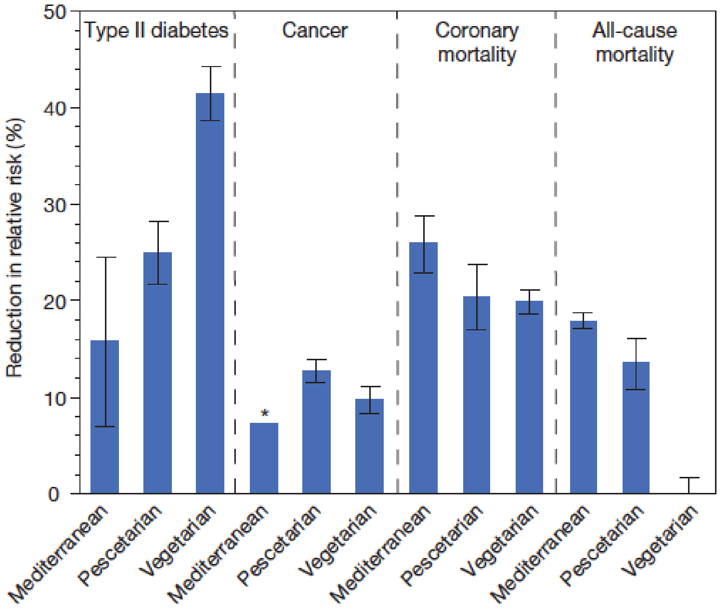

Figure 5.15 Diet and health effects of different consumption scenarios (Tilman and Clark 2014)

Can dietary shifts provide significant enough benefits to overcome constraints? Several studies highlight that current dietary trends lead to approximately 20Gt CO_2-eq by about 2050 and that this would make achieving the Paris Agreemet targets (Pradhan et al. 2013; Bajželj et al. 2014; Hedenus et al. 2014; Bryngelsson et al. 2017). Many studies now indicate that dietary shifts can significantly reduce GHG emissions. In the US, a shift in consumption towards a healthier diet, combined with meeting the USDA and Environmental Protection Agency's 2030 food loss and waste reduction goal could increase per capita food-related energy use 12%, decrease blue water consumption 4%, decrease green water use 23%, decrease GHG emissions from food production 11%, decrease GHG emissions from landfills 20%, decrease land use 32%, and increase fertiliser use 12% (Birney et al. 2017). Similar studies have been conducted, for China (Li et al. 2016a) and India (Green et al. 2017; Vetter et al. 2017).

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

5.5.2.3 Role of dietary preferences in mitigation

Consumers’ choice and dietary preferences are guided by social, cultural and traditional factors as well as economic growth. As suggested by Springmann et al. (2018), per capita dietary emissions will translate into different realised diets, according to regional contexts (including cultural norms). Gender differences have been observed in food consumption in cities, for example, women more often buy seasonal and local products and organic food. Moreover, women and men have different preferences in terms of food: men tend to eat more meat, while women eat more vegetables, fruits and dairy products. Due to their central role in family care responsibilities and food security, and the higher public awareness to climate change that women hold with respect to men in specific regions (McCright 2010), specific measures addressed to women and changing diets could be promising. Preferences have also been shown to change over time. For example, by reducing beef consumption between 2005 and 2014, Americans avoided approximately 271 million metric tonnes (MMT) of greenhouse gas emissions (NRDC 2017). See Section 5.5.2.1 for quantitative analysis.

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

Increasing the efficiency of the food system through reduction of food loss and waste lowers GHG emissions and improves food security (*robust evidence, medium agreement,*). Between 1961 and 2011, global food loss and waste has tripled from 540 million tonnes yr^{-1} to 1.6 billion tonnes yr^{-1} and life cycle analysis shows that global food loss and waste resulted in emissions of 4.4 $GtCO_2$-eq yr^{-1} in 2011 (8-10% of total anthropogenic greenhouse gas emissions) and costs of about USD 1 trillion per year. Avoiding food loss and waste can compensate for decreases in crop yields due to climate change and lower GHG emissions by reducing the need for agricultural land expansion.

Food loss and waste impacts food security by reducing global and local food availability, limiting food access due to increase in food price and decrease of producers' income, and affecting future food production due to unstainable use of natural resources (HLPE 2014). During the last 50 years, the global food loss and waste increased from around 540 Mt in 1961 to 1630 Mt in 2011 (Porter et al. 2016). The amount of food currently wasted is enough to nourish around 1–1.4 billion people (Kummu et al. 2012; Hiç et al. 2016). The economic costs associated with the food loss and waste reach around USD 1 trillion and environmental and social costs are around USD 700 billion and USD 900 billion, respectively (FAO 2014b). The environmental cost is related to environmental impacts during production of the lost/wasted food. The effects of the environmental impacts on people's well-being and livelihoods are estimated in the social cost. A large share of produced food is lost in developing countries due to poor infrastructure, while a large share of produced food is wasted in developed countries (Godfray et al. 2010). Changing consumer behaviour to reduce per capita overconsumption offers substantial potential to improve food security by avoiding related health burdens (Alexander et al. 2017; Smith 2013) and reduce emissions associated with the extra food (Godfray et al. 2010). Changing consumer behaviour to reduce per capita overconsumption offers substantial potential to improve food security by avoiding related health burdens and reduce emissions associated with the extra food.

In 2007, around 20% of the food produced was lost in Europe and North America, while around 30% of the food produced was lost in sub-Saharan Africa (FAO 2011b). In the European Union, 80 kg yr^{-1} of food was lost per person in 2013, which is associated with the cost of around 143 billion euros (Stenmarck et al. 2016). Nine percent of food was lost during harvest and storage in China in 2010 (Liu et al. 2013b). A meta-analysis reveals that variation in estimation of post-harvest losses in sub-Saharan Africa is mainly due to inadequacies of applied methodologies that do not account for the interaction of various loss agents and omit social, cultural, economic, and ecological factors in loss assessment (Affognon et al. 2015). In 2016, post-harvest losses in sub-Saharan Africa for cereals ranged between 2% and 20% (APHLIS 2018). In Europe, 23.6 Mt of fresh fruit and vegetables were lost, resulting in production phase emissions of 5.1 Mt CO_2-eq between 1989 and 2015 due to deliberate withdrawal and destruction of fresh fruit and vegetables under the Common Agriculture Policy of the European Union (Porter et al. 2018a). Similarly, production phase emissions of 22.5 Mt CO_2-eq yr^{-1} are associated with food loss due to cosmetic standards in Europe (Porter et al. 2018b).

In the last 50 years, food waste grew from 300 kcal $cap^{-1}day^{-1}$ to 500 614 kcal $cap^{-1}day^{-1}$ on the global level, and the associated agricultural GHG emissions for producing wasted food increased from 130 Mt CO_2-eq yr^{-1} to 530 Mt CO_2-eq yr^{-1} (Hiç et al. 2016). At the consumer level, per capita food wasted is around 95–115 kg yr^{-1} in Europe and North America, while it is only 6–11 kg yr^{-1} in sub-Saharan Africa and South/Southeast Asia (FAO 2011b). Seven percent of food is wasted at the consumer level in China (Liu et al. 2013b). In the European Union, 90 kg yr^{-1} of food is wasted per person, resulting in total household waste of around 47 million tons (Stenmarck et al. 2016). For Europe, livestock products contribute to 27% and 14% of the total food waste in the retail and household sectors, respectively (Bellarby et al. 2013). Emissions associated with production of livestock products in Europe which is wasted both in Europe and outside Europe is up to 56–115 Mt CO_2-eq yr^{-1} (Bellarby et al. 2013).

In 2011, the food waste and loss resulted in 4.4 Gt CO_2-eq yr^{-1} emissions (i.e., around 8–10% of the total anthropogenic greenhouse gas emissions) throughout the life cycle of the lost and wasted food, considering various phases of the food supply chain and land use change (FAO 2015a, 2013b). At a global scale, loss and waste of milk, poultry meat, pig meat, sheep meat, and potatoes is associated with 3% of the global agricultural N_2O emissions (more than 0.06 Gt CO_2-eq yr^{-1}) in 2009 (Reay et al. 2012). For the United States, 35% of energy use, 34% of blue water use, 34% of GHG emissions, 31% of land use, and 35% of fertiliser use related to an individual's food-related resource consumption were accounted for as food waste and loss in 2010 (Birney et al. 2017).

Alexander et al. (2017) found that due to cumulative losses, the proportion of global agricultural dry biomass consumed as food is just 6% (9.0% for energy and 7.6% for protein), and 24.8% of harvest biomass (31.9% for energy and 27.8% for protein). The highest rates of loss are associated with livestock production, although the largest absolute losses of crop biomass occur prior to harvest. Losses of harvested crops were also found to be substantial, with 44% of crop dry matter (36.9% of energy and 50.1% of protein) lost prior to human consumption. Consumption above nutritional needs can be seen as a form of food waste (Alexander et al. 2017), and at a global level is as significant as household-related food waste. In Australia, overconsumption accounts for about 33% GHGs associated with food (Hadjikakou 2017). If human overconsumption, defined as food consumption in excess of nutritional requirements, is included as an additional inefficiency, 48.4% of harvested crops were found to be lost (53.2% of energy and 42.3% of protein). Over-eating was found to be at least as large a contributor to food system losses as consumer food waste (Alexander et al. 2017). Similarly, food losses associated with consuming resource-intensive animal-based products instead of nutritionally-comparable plant-based alternatives is defined as 'opportunity food losses.' These were estimated to be 96, 90, 75, 50, and 40% for beef, pork, dairy, poultry, and eggs, respectively, in the US (Shepon et al. 2018).

In low-income countries, the majority of food is lost during production, post-harvest, processing and transportation phases. These losses are often due to a lack of infrastructure including cold-chain refrigeration, processing facilities and reliable transportation to bring crops to market. As a result, crops may spoil before they can be fully utilised (FAO 2011b). A lack of available drying technologies or improper storage can also contribute to losses due to aflatoxins, poisonous carcinogens produced by molds in staple crops under high-moisture, high-temperature conditions. Opportunities to minimise food loss and waste in low-income countries include expansion of transportation, processing and preservation infrastructure including cold chain, drying technologies and increased market opportunities (FAO 2011b), though many of these may result in increased use of energy or resources.

In high-income countries, most food is wasted at the retail and consumption levels (FAO 2013b; Blanke 2015). Opportunities to reduce food waste in retail include changing consumer perceptions about food appearances, reducing over- stocking, reducing portion sizes in restaurants, utilising packaging and processing technologies that help keep food fresh for longer, and clarifying the meaning of sell-by and use-by dates for consumers (Blanke 2015; Schanes et al. 2018; Wilson et al. 2017). Prevention of consumer food waste must consider complex human behaviors (Quested et al. 2013) but might involve consumer acceptance of 'ugly' products, increased planning and preparation for cooking, better storage techniques and food sharing (Blanke 2015).

Reduction of food loss and waste can contribute to feeding undernourished people by enhancing local, national and regional food self-sufficiency (Pradhan et al. 2014), however, this is debatable and needs to be systematically explored (Chaboud and Daviron 2017). In developing countries, food security of poor households can be improved by reducing food loss and waste, for example by using steel silos for storage (Gitonga et al. 2013; Chaboud and Daviron 2017; Okawa 2015). FAO and LEI (2015) also highlights the differential impacts across producers and consumers of reducing food loss and waste in the European Union which can reduce food prices in sub-Saharan Africa, benefiting consumers but forcing local producers to cut their food price and profits. Similarly, reduction of food loss and waste can have the differential impacts across exporters. For example, reduction in waste of dairy products may increase exports of the United States that exports to developing countries, while decrease the exports of the European Union and New Zealand that export considerably to developed countries (Okawa 2015)

Avoiding food loss and waste will also contribute to reducing emissions from the agriculture sector. When complete avoidance of food loss and wastage is considered, the reduction potential of the current N_2O emissions exceed 0.3 Gt CO_2-eq yr^{-1} (i.e., around 15% of the global agricultural production-phase N_2O emissions) (Reay et al. 2012). By 2050, GHG emissions associated with food waste may increase tremendously to 1.9–2.5 Gt CO_2-eq yr^{-1} (Hiç et al. 2016). By 2050, GHG emissions associated with food waste may increase tremendously to 1.9–2.5 Gt CO_2-eq yr^{-1} (Hiç et al. 2016). Compared to the baseline scenarios (Bajželj et al. 2014) halving the food waste reduces the global need for cropland area by around 14% and GHG emissions by 22–28% (4.5 Gt CO_2-eq yr^{-1}), limiting the need for agriculture expansion and subsequent emissions from land use change . The emission mitigation potential of food loss and waste reduction would further increase when emissions throughout the life cycle of the lost and wasted food are accounted for.

Food loss and waste can be reduced using a wide range of approaches across the food supply chain, including technical and non-technical solutions (Lipinski et al. 2013). However, technical solutions include additional cost (Rosegrant et al. 2015) and may have impacts on local environment (FAO 2017). Additionally, the objective of food loss and waste reduction can only be achieved when all the parts of the food supply chain become effective (Lipinski et al. 2013). Together with technical solutions, approaches to changes in behaviours and attitudes of a wide range of stakeholders across the food system will play an important role in reducing food loss and waste.

In summary, reduction of food loss and waste can be considered as a climate change mitigation and adaptation measure that provides synergies with food security and land use (m*edium agreement, robust evidence*). Avoiding food loss and waste can be seen as an adaptation option for decreased crop yields due to climate change, as well as a mitigation option by reducing agricultural GHG emissions and agricultural expansion for producing excess food. However, the beneficial effects of reducing food loss and waste will vary between producer and consumers, and across regions.

5.5.2.5 Shortening supply chains

Encouraging consumption of locally produced food and enhancing efficiency of food processing and transportation can in some cases minimise food loss, contribute to food security, and reduce GHG emissions associated with energy consumption and food loss. For example, Michalský and Hooda (2015), through a quantitative assessment of GHG emissions of selected fruits and vegetables in the UK, reported that increased local production offers considerable emissions savings. They also highlighted that when imports are necessary, importing from Europe instead of the Global South can contribute to considerable GHG emissions savings, (i.e., 9.96 $kgCO_2$-eq kg^{-1}).

In other cases, environmental benefits associated with local food can be offset by inefficient production systems with high emission intensity and resource needs, e.g., water, due to local conditions. Avetisyan et al. (2014) reported that regional variation of emission intensities associated with production of ruminant products have large implications for emissions associated with local food. They showed that consumption of local livestock products can reduce emissions due to short supply chains in countries with low emission intensities, however, this reduction could be lower than emissions growth due to increase in locally produced food in countries with high emission intensities (see Section 5.5.1).

In addition to improving emission intensity, efficient distribution systems for local food are needed for lowering carbon footprints (Newman et al. 2013). Emissions associated with food transport depend on the mode of transport, for example, emissions are lower for rail rather than truck (Brodt et al. 2013). Tobarra et al. (2018) reported that emissions saving from local food may vary across seasons and regions of import. They highlighted that in Spain local production of fruits and vegetables can reduce emissions associated with imports from Africa but imports from France and Portugal can save emissions in comparison to production in Spain. Additionally, local production of seasonal products in Spain reduces emissions, while imports of out-of-season products can save emissions rather than producing them locally Tobarra et al. (2018). In summary, consumption of locally produced food is a climate change mitigation option, whose emission reduction potential varies across regions and seasons, but in some cases may also result in increase in overall emissions (*robust evidence, medium agreement*).

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

Food systems will need to adapt to changing climates, but also, where possible, to reduce their greenhouse gas (GHG) emissions and sequester carbon if Paris Agreement targets are to be met (van Vuuren et al. 2014). The synergies and trade-offs between the food system mitigation and adaptation options described in Sections 5.3 and 5.5 are of increasing interest in both scientific and policy communities because of the need to ensure nutritious food for the growing population while responding to climate change (Rosenzweig and Hillel 2015) (Figure 5.16). A special challenge involves interactions between non-food system mitigation, such as negative emissions technologies, and food security. Synergies and trade-offs are being analysed in a range of integrated agricultural pratices. The roles of women's empowerment and urban agriculture in mitigation and adaptation are also being examined. Interactions within and between SDGs are another focus of synergies and trade-offs.

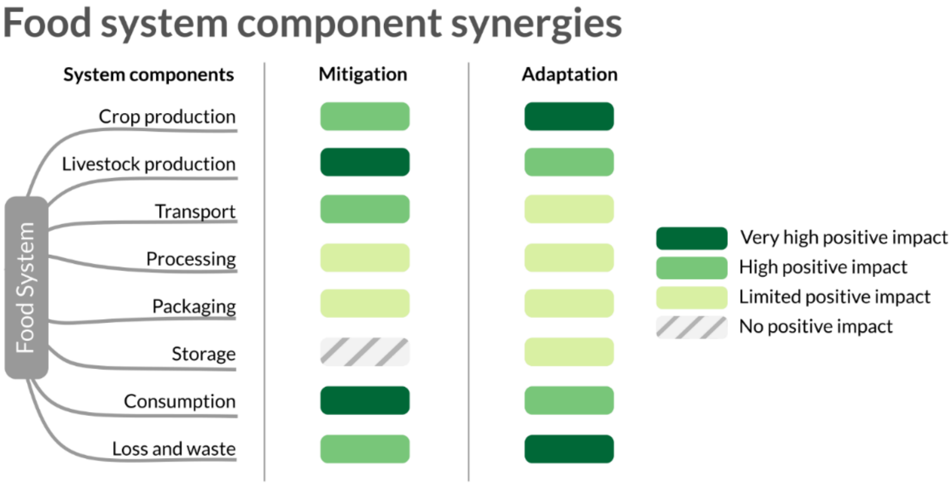

Figure 5.16 Food system components and their impacts on mitigation and adaptation. Many food system components offer significant potential for both mitigation and adaptation

5.6.1 Negative emission technologies

Negative emission technologies (NETs) are expected to play a major role in avoiding unacceptable climate change (SR15C). Among the available NETs, carbon dioxide removal (CDR) technologies are receiving increasing attention. CDR technologies include afforestation and reforestation (AR), biomass energy with carbon capture and storage (BECCS) and biochar (BC) production. Among them, BECCS is the least mature as they face challenges similar to fossil fuel CCS. Most of the literature on global mitigation potential relies on CDRs, particularly on BECCS, as a major mitigation action (Kraxner et al. 2014; Larkin et al. 2018). The effectiveness of large-scale BECCS to meet Paris Agreement targets has, nevertheless, been questioned and other pathways to mitigation have been proposed (Anderson and Peters 2016; van Vuuren et al. 2017; Hoegh-Guldberg et al. 2018).

Atmospheric CO_2 removal results from the balance between photosynthesis and respiration, which generates net organic carbon accumulation in plant biomass (Kemper 2015). AR, BECCS and BC differ particularly on the use and storage of plant biomass. In BECCS, the biomass carbon is used in industrial processes (e.g., plants for electricity, hydrogen, ethanol, and biogas generation), releasing CO_2 which is then captured and geologically stored (Greenberg et al. 2017). AR stores carbon in plant biomass, including below-ground biomass, which remains a sink while plant growth occurs, typically decades for forests (in contrast to thousands of years for geological C storage (Smith et al. 2016)). Biochar results from controlled thermal decomposition of biomass in absence of oxygen (pyrolysis), producing biochar, combustible oil and combustible gas in different proportions. Biochar is a very stable carbon form, with storage on, at minimum, centennial timescales (Lehmann et al. 2006). It can be applied to soil leading to improved water-holding capacity, nutrient retention, and microbial processes (Lehmann et al. 2015).

CDRs require high biomass-producing crops. Since not all plant biomass is harvested (e.g., roots and harvesting losses), it can produce co-benefits related to soil carbon sequestration, depending on previous use of the soil and its management, and also improvements in air quality (Smith et al. 2016; Portugal-Pereira et al. 2018). However, CDRs effectiveness varies widely depending on type of biomass, crop productivity, and emissions offset in the energy system and its benefits can be easily lost due to land-use change interactions (Harper et al. 2018).

Major challenges of BECCS, AR and biochar are the large investments and abrupt changes in land use needed to accomplish its expected contribution to the 1.5°C target. Existing scenarios estimate the global area required for BECCS alone in the range of 109°990 Mha (IPCC 2018), most commonly around 380–700 Mha (Smith et al. 2016). Most scenarios assume very rapid deployment between 2030 and 2050, reaching rates of expansion in land use exceeding 20 M ha yr^{-1}, which are unprecedented for crops and forestry reported in the FAO database from 1961 (FAO 2018b). In comparison, the sum of worldwide rates of expansion in harvested areas of soybean and sugarcane did not exceed an average of 3.5 M ha yr^{-1} and, at that rate, they have been the source of major concerns about environmental impacts and food security (Boerema et al. 2016; Popp et al. 2014).

Most land stocks available for CDRs are covered by meadows and pastureland, estimated as 3300 M ha, which currently have low average food productivity and often offer opportunities for sustainable intensification (SI) (Cohn et al. 2014; Strassburg et al. 2014). SI of pasture would produce co-benefits through increasing soil carbon stocks as well as mitigating livestock emissions (de Oliveira Silva et al. 2016). However, grasslands often occur in marginal areas of intensive cropping regions with higher slopes, shallow soils, higher climate risks such as periodicflooding or in less developed regions at agricultural frontiers. These regions, often border primary vegetation and have little infrastructure for the transportation and processing of enormous quantities of biomass related to CDR.

There is *low agreement* about what are the most competitive regions of the world for CDRs. Smith et al. (2016) and Vaughan et al. (2018) indicate that major investments would take place in relatively poor countries in Latin America, Africa and Asia (except China and India), while others indicate those regions may be more competitive for food production, placing Europe as a major BECCS exporter (Muratori et al. 2016). Economically feasible CDR investments are forecast to be directed to regions with high biomass production potential, demand for extra energy production, low leakage potential for deforestation and low competition for food production (Vaughan et al. 2018). Latin America and Africa, for instance, although having high biomass production potential, still have low domestic energy consumption (589 and 673 mtoe – 24.7 and 28.2 EJ, respectively), with about 30% of energy from renewable sources (reaching 50% in Brazil). Therefore, considering competition with expansion of renewable energy, particularly solar, wind and hydro-power, it is likely that BECCS implementation may be constrained by lack of energy demand in those regions. As an illustration, replacing 30% of the current energy consumption in Africa and Latin America with energy production of 250 GJ at a carbon sequestration rate of 0.02 t Ceq/MJ would allow for a contribution of around 0.3 Gt Ceq, i.e. 10% of the estimated potential contribution of BECCS.

There is *high agreement and strong evidence* that deployment of BECCS will require ambitious investments and policy interventions (Peters and Geden 2017) with strong regulation and governance of bioenergy production for protection of forests and food security (Vaughan et al. 2018), and that such conditions may be challenging for developing countries. Increased value of bioenergy puts pressure on land and the prices of agricultural commodities, including food (*robust evidence, high agreement*). There is *medium agreement and medium evidence* for the impact of CDR technologies on increased food prices and reduced food security, as it depends on several assumptions, but those impacts could be strong, with food prices doubling under some model x scenario combinations (Popp et al. 2017).

Most integrated assessment models (IAMs) lack regional data from on-the-ground BECCS projects. Compared with aspirations, very little BECCS implementation has been done to date (Lenzi et al. 2018). There is *high agreement* that BECCS require support for regional, bottom-up studies of biomass potentials, socio-economic consequences (including on food security), and environmental impacts in order to validate global assessments and calibrate expectations (IPCC 2018).

5.6.2 Mitigation, food prices, and food security

Food prices have been traditionally seen as the result of supply, demand and trade relations. Earlier studies (e.g., (Nelson et al. 2009)) demonstrated that climate impacts that reduced crop productivity led to higher prices and higher trade of commodities between regions. Most affected regions in previous studies have been Sub-Saharan Africa and parts of Asia, but there is significant heterogeneity between countries. Relocation of production somehow buffers these impacts, as well as the assumptions of crop and livestock technical change but nevertheless, these relations are robust across modelling frameworks and well accepted by the climate change and agriculture communities.

A newer, less studied impact on prices and their impacts on food security is the level of mitigation necessary to stabilise the global temperature increases. Hasegawa et al. (2018) (Figure 5.17) using an ensemble of seven global economic models across a range of greenhouse gas emissions pathways and socioeconomic trajectories. They selected SSPs: ‘sustainability’ (SSP1), ‘middle-of-the-road’ (SSP2) and ‘regional-rivalry’ (SSP3); climate change impacts on crop yields corresponding to 2°C and 2.7°C increases by 2100 from the pre-industrial level (Representative Concentration Pathways RCP2.6 and RCP6.0); and climate change mitigation efforts: ambitious climate mitigation policies of a 2°C scenario (reducing emissions down to RCP2.6 emission levels) versus no climate action. Results demonstrated that the level of mitigation effort to reduce emissions can have a more significant impact on prices than the climate impacts on reduced crop yields. This occurs because taxing GHG emissions leads to higher crop and livestock prices, while land based mitigation leads to less land availability for food production, potentially leading to lower food supply, and therefore also to food price increases. Price increases in turn lead to reduced consumption, especially by vulnerable groups, or to shifts towards cheaper food items, that are often less nutritious. This leads to significant increases in the number of malnourished people. These results have been confirmed by Frank et al. (2017) and Fujimori et al. (2017) for the

1.5°C mitigation scenario using Globiom and ensembles of global economic models, respectively. While the magnitude of the response differs between models, the results are consistent between them.

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

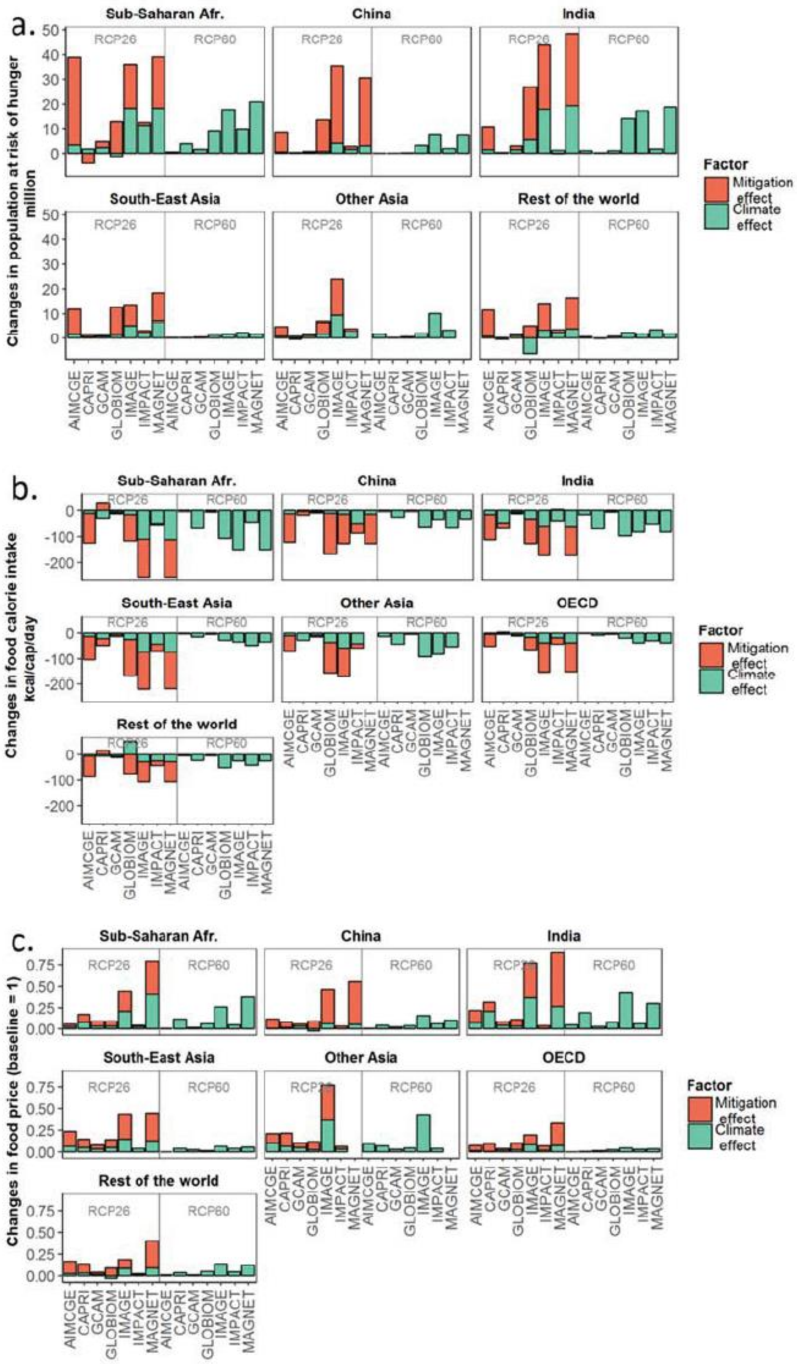

Figure 5.17 Regional impacts of climate change and mitigation on a) undernourishment, b) mean calorie intake and c) food price in 2050 under intermediate socio-economic scenario (SSP2). Values indicate changes from no climate change and no climate change mitigation scenario. MAgPIE is excluded due to inelastic food demand. The value of India includes that of Other Asia in MAGNET (Hasegawa et al. 2018)

5.6.3 Integrated agricultural practices

A range of integrated agricultural systems have been developed and are now being tested that can create synergies between mitigation and adaptation and lead to low-carbon and climate-resilient pathways for food security and ecosystem health *(robust evidence, medium agreement)*. These include agroecology (FAO et al. 2018; Altieri et al. 2015), climate smart agriculture (FAO 2011c; Lipper et al. 2014;

Aggarwal et al. 2018), conservation agriculture (Aryal et al. 2016; Sapkota et al. 2015), and sustainable intensification (Godfray 2015). These have been tested in various production systems around the world (Dinesh et al. 2017; Jat et al. 2016; Sapkota et al. 2015; Neufeldt et al. 2013). Many technical innovations, e.g., precision nutrient management (Sapkota et al. 2014) and precision water management (Jat et al. 2015) can lead to both adaptation and mitigation outcomes and even synergies; although negative adaptation and mitigation outcomes (i.e., trade-offs) are often overlooked.

5.6.3.1 Agroecology

Agroecological practices that enhance on farm diversity (genetic, species and ecosystem diversity), and the wider landscapes (GIAHS, FAO), promote soil conservation, protect watersheds, re-localise food systems, and enable fair access to healthy food (Pimbert and Lemke 2018) contributing to climate change adaptation. Indeed, agroecology has been proposed as to play a key role in building climate resilience (FAO et al. 2018; Altieri et al. 2015).

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

5.6.3.2 Climate-smart agriculture

Some have put forward a ‘climate-smart’ approach to tackle current food security and climate change challenges (FAO 2011c; Lipper et al. 2014; Aggarwal et al. 2018). This is designed to be a pathway towards development and food security built on three pillars: increasing productivity and incomes, enhancing resilience of livelihoods and ecosystems and reducing and removing GHG emissions from the atmosphere.

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

Increasing food production by using more fertilisers in agricultural fields could maintain crop yield in the face of climate change, but may result in greater overall GHG emissions. But maintaining the same level of yield through use of site-specific nutrient/water management based approach could contribute to both food security and climate change mitigation (Sapkota et al. 2017a). Mixed farming system by integrating crops, livestock, fisheries and agro-forestry, on the other hand, could maintain crop yield in the face of climate change, help the system to adapt to climatic risk and minimise GHG emissions by increasingly improving the nutrient flow in the system (Mbow et al. 2014a; Newaj et al. 2016; Bioversity International 2016). Such systems help diversify production or income, build local seed/input system and extension services and support efficient and timely use of inputs thus contributing to increased resilience.

Studying barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe, Long et al. (2016) revealed that incompatibility between existing policies and climate-smart agriculture objectives as well as the adoption of technological innovations. In addition, Dominik et al. (2017) indicated that intensification and simplification of farmed areas into homogeneous monocultures can lead to biodiversity loss and a reduction of associated ecosystem services such as natural pest regulation. Moreover, according to Morrison-Whittle et al. (2017), farm management significantly affects communities in soil, plant structures, and the crop growth in subtle but importantly different ways in terms of number, type, and abundance of species. Adaptation potential of ecologically intensive systems includes crop diversification, maintaining local genetic diversity, animal integration, soil organic management, water conservation and harvesting the role of microbial assemblages, etc.

Climate-smart agriculture, if it is to address resilience and adaptive capacity, must address these underlying socio-economic factors in access to technologies, practices, etc. that can enhance biophysical aspects of agriculture, increase productivity, and reduce emissions. Approaches are needed to address unequal access or ensure equal access to resources such as information and extension services.

5.6.3.3 Conservation agriculture

Conservation agriculture (CA) is based on the principles of minimum soil disturbance and permanent soil cover combined with appropriate crop rotation (Jat et al. 2014). Intensive agriculture during the second half of the 20th century led to soil degradation and loss of natural resources and contributed to climate change. Therefore, sustainable soil management practices can address both food security and climate change challenges faced by agricultural systems. For example, sequestration of soil organic carbon (SOC) is an important strategy to improve soil quality and to mitigation of climate change (Lal 2004). CA has been reported to increase farm productivity by reducing cost of production (Aryal et al. 2015) and increasing yield (Sapkota et al. 2015).

CA brings favourable changes in soil properties which affect the delivery of NCPs including climate regulation through carbon sequestration and GHG emissions (Palm et al. 2013; Sapkota et al. 2017a). However, by analysing the tropical datasets, Powlson et al. (2014, 2016) argued that the rate of SOC increase and resulting GHG mitigation in CA systems, from zero-tillage in particular, was overstated.

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

CA adoption in Africa has been low despite more than three decades of implementation, This calls for a better understanding of the social and institutional aspects around CA adoption, Indeed, (Brown et al. 2017a) found that institutional and community constraints constrained the financial, physical, human and informational resources to implement CA programs. Gender is another variable to consider since at intra-household level, decision-making and benefits distribution, CA interventions have implications for labour requirements, labour allocation and investment decisions, all of them impacting the role of men and women, their resources and their aspirations (Farnworth et al. 2016).

5.6.3.4 Sustainable intensification

Expansion of agricultural land to produce more food required to feed increasing population comes at the price of a significant GHG load with climate change implications as well as biodiversity impacts. Land conversion for agriculture is responsible for an estimated 10–15% of all anthropogenic GHG emissions. The calls for sustainable intensification are based on the premise that damage to public goods including the environment through extensification outweighs any benefits of the extra food produced on new lands (Godfray 2015). However, increasing net production area by restoring already degraded land may contribute to increase production on one hand and increase carbon sequestration on the other (Jat et al. 2016). Sustainable intensification, by improving nutrient-, water- and other input-use-efficiency, not only helps to close yield gaps and contribute to food security (Garnett et al. 2013), but also reduces the loss of such production inputs and associated emissions (Sapkota et al. 2017b; Wollenberg et al. 2016). Closing yield gaps is a way to become more efficient in use of land per unit production. Integrated systems (e.g., mixed crop-livestock, crop-aquaculture) are also a strategy to produce more products per unit land, which in terms of food security becomes highly relevant.

Sustainable intensification acknowledges that enhanced productivity needs to be accompanied by maintenance of other ecosystem services and enhanced resilience to shocks (Vanlauwe et al. 2014). Sustainable intensification in intensively farmed areas may require a reduction in production in favour of increasing sustainability in the broad sense (Buckwell et al. 2014) (see Cross-Chapter Box 5: Agricultural Intensification). Hence, moving towards sustainability may imply lower yield growth rates than those maximally attainable in such situation. For areas that contain valuable natural ecosystems, such as the primary forest in the Congo basin, intensification of agriculture is one of the pillars of the strategy to conserve forest. Intensification in agriculture is recognised as one of the pathways to meet food security and climate change adaptation and mitigation goals (Sapkota et al. 2017b). However, sustainable intensification does not always confer co-benefit in terms of food security and climate change adaption/mitigation.

For example, in the case of Vietnam, where intensified production of rice and pigs reduced GHG emissions in the short term through land sparing, but after two decades, the emissions associated with higher inputs were likely to outweigh the savings from land sparing. Intensification needs to be sustainable in all components of food system by curbing agricultural sprawl, rebuilding soils, restoring degraded lands, reducing agricultural pollution, increasing water use efficiency and decreasing the use of external inputs (Cook et al, 2015).

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

Sustainable intensification has been criticised for considering the food security issue only from the supply side whereas global food security requires attention to all aspects of food system (Godfray 2015). Others, who accept the necessity to focus on supply-side intervention, argue that adoption of high-input forms of agriculture under the guise if simultaneously improving yields and environmental performance will attract more investment leading to higher rate of adoption and the environmental component of SI will be quickly abandoned.

Cross-Chapter Box 5: Agricultural intensification: land sparing, land sharing and sustainability

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Introduction

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

Agroecosystems which maintain or improve the natural and human capital and services they provide may be defined as sustainable systems, those which deplete these assets are unsustainable (Pretty and Bharucha 2014). Producing more food, fuel and fibre without the conversion of additional non-agricultural land while simultaneously reducing environmental impacts requires what has been termed sustainable intensification (Godfray et al. 2010); see Cross-Chapter Box 5: Figure 1). Sustainable intensification (SI) may be achieved through a wide variety of means; from improved nutrient and water use efficiency via plant and animal breeding programs, to the implementation of integrated soil fertility and pest management practices, as well as by smarter land use allocation at a larger spatial scale: for example, matching land use to the context and specific capabilities of the land (Benton et al. 2018). The precise definition of SI is contested for a number of reasons (Garnett et al. 2013; Benton 2016; Pretty et al. 2018). For example, it is broader than simply increasing the technical efficiency of agriculture ("doing more with less"), it sometimes may require a reduction of yields to raise sustainability, it can be dependent on place and scale of implementation. (Pretty et al. 2018), following (Hill 1985), highlights three elements to SI: (i) increasing efficiency, (ii) substitution of less beneficial or efficient practices for better ones, and (iii) system redesign to adopt new practices and farming systems (see Cross-Chapter Box 5: Table 1).

Under a land sparing strategy, intensification of land use in some areas, generating higher productivity per unit area of land, can allow other land to provide other ecosystem services such as increased carbon sequestration and the conservation of natural ecosystems and biodiversity (Balmford et al. 2018). Conversely under a land sharing strategy less, or no, land is set aside, but lower levels of intensification are applied to agricultural land, providing a combination of provisioning and other functions such as biodiversity conservation from the same land (Green et al. 2005). The two approaches are not mutually exclusive and the suitability of their application is generally system-, scale- and/or location specific (Fischer et al. 2014). One crucial issue for the success of a land sparing strategy is that spared land is protected from further conversion: as the profits from the intensively managed land increase, there is an incentive for conversion of additional land for production (Byerlee et al. 2014). Furthermore, it is implicit that there are limits to the sustainable intensification of land at a local and also planetary boundary level (Rockström et al. 2009). These may relate to the "health" of soil, the presence of supporting services, such as pollination, local limits to water availability, or limits on air quality. This implies that it may not be possible to meet demand “sustainably” if demand exceeds local and global limits.

Cross-Chapter Box 5, Table 1 Approaches to sustainable intensification of agriculture.

Approach	Sub-category	Examples/notes
Improving efficiency	Precision agriculture	High and low-technology options to optimise resource use.
	Genetic improvements	Improved resource use efficiency through crop or livestock breeding.
	Irrigation technology	Increase production in areas currently limited by precipitation (sustainable water supply required).
	Farm size scale-up	Increasing farm scale can lead to greater efficiency per unit input – e.g. due to mechanisation, facilitating precision techniques (including co-operative schemes).
Substitution	Green fertiliser	Replacing chemical fertiliser with green manures, compost, biosolids and digasete (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.
System redesign	System diversification	Implementation of alternative farming systems: organic, agroforestry, intercropping.
	Pest management	Implementing integrated pest and weed management to reduce the quantities of inputs required.
	Nutrient management	Implementing integrated nutrient managing by using crop and soil specific nutrient management – guided by soil testing.
	Knowledge transfer	Using knowledge sharing and tech platforms to accelerate the uptake of good agricultural practices.

Improved efficiency – example of precision agriculture

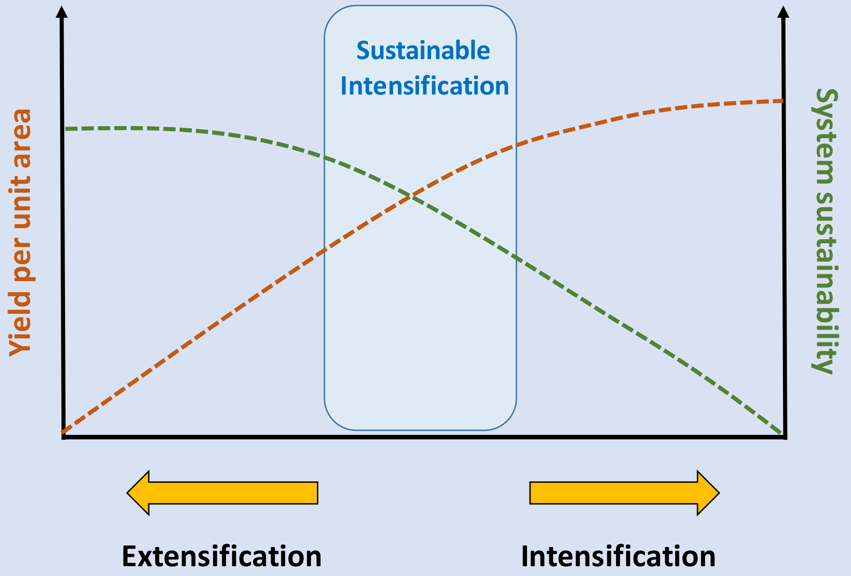
Precision farming usually refers to optimising production in fields through site-specific choices of crop varieties, agrochemical application, precise water management (e.g. in given areas or threshold moistures) and management of crops at a small scale (or livestock as individuals) (Hedley 2015). This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

High-tech precision agriculture

High-tech precision agriculture is a technologically advanced approach that uses continual monitoring of crop and livestock performance to actively inform management practices, often replacing manual labour with technology. 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 rape seed, 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 (Srbinovska et al. 2015). Controlled traffic farming, where farm machinery is confined to permanent tracks, using automatic steering and satellite guidance, increases yields by minimising soil compaction. However, barriers to the uptake of many of these high-tech precision agriculture technologies remain. In what is described as the 'implementation problem', despite the potential to collect vast quantities of data on crop or livestock performance, applying these data to inform management decisions remains a challenge (Lindblom et al. 2017).

Low-tech precision agriculture

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



Cross-Chapter Box 5, Figure 1 Sustainable intensification – there is a need to balance the increasing demands for food, fuel and fibre with long term sustainability of land use. Sustainable intensification can, in theory, offer a window of opportunity between intensification of land use without causing degradation. This potentially allows the sparing of land to provide other ecosystem services, including carbon sequestration and the protection of biodiversity

Sustainable intensification through farming system redesign

SI requires equal weight to be placed on the sustainability and intensification components (Benton 2016; Garnett et al. 2013), Cross-Chapter Box 5: Figure 1, outlines the trade-offs which SI necessitates between the intensity of land use against long-term sustainability. One approach to this challenge is through farming system redesign including increased diversification.

Diversification of intensively managed systems

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

Diversification of production systems

Agroforestry systems combine the cultivation of woody perennials (trees, shrubs, palms, bamboos, etc.) with agricultural crops and/or livestock on the same unit of land. These systems can promote regional food security and provide many additional ecosystem services when compared with monoculture crop systems. Co-benefits include increased carbon sequestration in soils and biomass, improved water and nutrient use efficiency, the creation of favourable micro-climates as well as contributing to many SDG's (Waldron et al. 2017). Silvopasture systems, which combine grazing of livestock and forestry, are particularly useful in reducing land degradation where soil erosion risk is high (Murgueitio et al. 2011). Crop and livestock systems can also be combined to provide multiple services. Research on perennial grains, particularly perennial wheat derivatives, shows very promising results of integrating cereal and livestock production while sequestering soil carbon (Ryan et al. 2018). Research in Australia has shown that perennial wheat derivatives produced both high quality forage and substantial volumes of cereal grains (Newell and Hayes 2017). A key feature of diverse production systems is the provision of multiple income streams for farming households, providing much needed economic resilience in the face of fluctuation of crop yields and prices which will be exacerbated by climate change.

Landscape Approaches

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

- Intensification needs to be achieved sustainably – or the short term becomes the enemy of the long term. This requires a balance to be struck between productivity today and future potential.

- Improving efficiency of agriculture systems and can increase production per unit of land and through greater resource use efficiency – with co-benefits for mitigation.
- Improving efficiency of agriculture systems and can increase production per unit of land and through greater resource use efficiency – with co-benefits for mitigation.
- To achieve SI some already intensively managed agricultural systems may have to be diversified as they cannot be further intensified without land degradation.
- A combination of land sparing and sharing options can be utilised to achieve SI – their application is most likely to succeed if applied using a landscape approach.

5.6.4 Women's empowerment

Empowering women can bring enormous synergies with both adaptation and mitigation options for food security, as well as household food security (Alston 2014) (see Cross-Chapter Box 6: Gender, Chpater 7). Research shows that women appear to be less adaptive because of financial or resource constraints, male domination in receiving information and extension services, lack of access to the social networks and institutions that allocate resources needed for adaptation, and because available adaptation strategies tend to create higher labour loads for women (Jost et al. 2016; Smucker and Wangui 2016; Quaye et al. 2016).

When women have access to decision making and bargaining power, they can contribute to both adaptation and mitigation while ensuring food security of their households, as shown in Western Kenya. Here, widow women in their new role as main livelihood providers, invested in sustainable innovations like rain water harvesting systems and agroforestry, and worked together in formalised groups of collective action (Gabrielsson and Ramasar 2013) to ensure food and water security. Women's empowerment have been shown to have a positive impact on stunted and underweight children in rural India (Imai et al. 2014). In Nepal, women's empowerment had a positively impact in maternal nutrition, mitigating the negative effect of low production diversity on maternal and child dietary diversity (Malapit et al. 2015).

Integrated nutrition and agricultural programs have been shown to increase women decision-making power and control over home gardens and their produce in Burkina Faso (van den Bold et al. 2015). Targeting men is also important in integrated agriculture programs with nutrition concerns. Participatory methods and involving male leaders help to change gender norms with positive outcomes in malnutrition (Kerr et al. 2016). Group-based approaches have been shown to improve women's assets to manage risk (Ringler et al. 2014).

5.6.5 Role of urban agriculture

Urban and peri-urban agriculture can contribute to improving urban food security, reducing greenhouse gas emissions, and adapting to climate change impacts *(robust evidence, medium agreement)*. With increasing urbanisation and climate change, a growing challenge is to ensure urban food security, mainly for the urban poor and people living in informal settlements. In 2010, around 14% of the global population is nourished by food grown in urban and peri-urban areas. If practiced efficiently, urban and peri-urban agriculture can contribute to reducing carbon footprints by avoiding long-distance food transport. Urban agriculture can contribute to adaptation to heat extremes through evaporative cooling.

Cities are an important actor in the food system in regard to both demand for food for urban dwellers and production of food in urban and peri-urban areas. Both the demand side and supply side roles are important relative to climate change mitigation and adaptation. Cities concentrate more than half of the world's population, and a minimal proportion of the production; thus, they are important drivers for the development of the complex food systems in place today, in regard to supply chains and dietary preferences. Furthermore, studies have shown that the urban poor mostly living in informal settlements across the world suffer from food and nutrition insecurity (Maitra and Rao 2015; Crush and Caesar 2014; Acquah et al. 2014), in some cases to a larger extent than rural households (Kimani-Murage et al. 2014; Walsh and van Rooyen 2015). Therefore, the vulnerability of urban poor to food and nutrition insecurity needs to be taken into account in climate change responses.

The global systems of packaging, storage and food transport is estimated to contribute up to 37% of the total emissions of the food-processing national systems in urbanised countries (Heller and Keoleian 2015; Amate and de Molina 2013). Furthermore, the increasing separation of the urban and rural populations with regard to territory and culture is one of the factors favouring the nutrition transition towards urban diets. These are primarily based on a high diversity of food products, independent of season and local production, and on the extension of the distances that food travels between production and consumption (Weber and Matthews 2008; Neira et al. 2016). This transition of traditional diets to more homogeneous diets has also become tied to consumption of animal protein, which has increased GHG emissions.

Cities are becoming key actors in developing strategies of mitigation to climate change, in their food procurement and in sustainable urban food policies. These are being developed by big and medium-sized cities in the world often integrated within climate change policies (Moragues et al. 2013; Calori and Magarini 2015). A review conducted for 100 cities across the world shows that urban food consumption is one of the largest sources of urban material flows, urban carbon footprints, and land footprints (Goldstein et al. 2017).

5.6.5.1 Urban food security

With increasing urbanisation, a growing challenge is to ensure urban food security, mainly for urban poor and people living in informal settlements (*high agreement and robust evidence*). Porter et al. (2014a) reported increasing food imports for Canberra, Copenhagen, and Tokyo since 1965 due to expanding population and reduction in local and regional food self-sufficiencies. Such import dependency makes urban consumers vulnerable to food price increases, resulting in reduction in food affordability, as they are more likely to consume staple foods derived from tradable commodities (Porter et al. 2014a).

Rural urban migration is an important driver for urban food and nutrition insecurity (Brown 2014) as rural poor mostly migrated to informal settlements, e.g., in Windhoek-Namibia (Nickanor et al. 2016). Studies show differences in food security between urban migrant and non-migrant. For example, Crush (2013) reported that urban non-migrant households are more food and nutrition secure than urban migrant households for 11 African cities.

Urban food and nutrition insecurity is a growing concern due to the combination of high rates of urban population growth and urban poverty, high dependencies on food supplied by markets, limited urban agriculture and rural-urban food transfer, and food price changes (Crush and Caesar 2014; Birhane et al. 2014; Smit 2016). Frayne and McCordic (2015) reported that urban food security depends on social and physical infrastructure beyond income, calling for better urban planning. Few cases also show improvement on food security for people living in informal settlements in the recent years, for example, Johannesburg, South Africa (Naicker et al. 2015).

5.6.5.2 Urban and peri-urban agriculture

Urban and peri-urban agriculture can contribute to enhance urban food security, reduced greenhouse gas emissions, and to adapt to impacts of climate change (*medium agreement and medium evidence*). In 2010, around 14% of the global population is nourished by food grown in urban and peri-urban areas (Kriewald et al.). Urban and peri-urban agriculture within 20km of urban extents consist of 11% and 60% of the global irrigated croplands and 5% and 35% of the global rain-fed croplands, respectively (Thebo et al. 2014). Globally, around 100–200 million farmers are involved in urban agriculture providing the city markets with fresh horticultural goods (Orsini et al. 2013). One third of the global urban area can provide required vegetables for global urban inhabitants (Martellozzo et al. 2014). Urban and peri-urban agriculture is carried out in many forms, for example, gardening on backyard, roof-top, balcony, , urban-fringe agriculture, hydroponics, aquaponics, livestock grazing in open spaces, vertical farming, etc. (Gerster-Bentaya 2013). Mainly, urban agriculture provides food at the urban household level, while, peri-urban agriculture can produce larger quantities and follow broader distribution pathways (Opitz et al. 2016).Urban and peri-urban agriculture is increasingly practiced and considered as beneficial to human health of urban inhabitants both in the North and the South due to its potential to improve dietary diversity (Gerster-Bentaya 2013; Poulsen et al. 2015; Warren et al. 2015). Additionally, urban agriculture plays an important role in urban livelihoods for alleviating hunger and poverty and employment generation (Lee-Smith 2010; Salome C. R. Korir 2015), mainly in cities of developing and emerging economy countries, for example, Zambia (Smart et al. 2015), Kenya (Onyango et al. 2017), Malaysia (Rezai et al. 2016), Zimbabwe (Admire 2014), and Sierra Leone (Lynch et al. 2013).

However, urban and peri-urban agriculture has limited potential for provision of complete household food security for the urban inhabitants (Frayne et al. 2014) and to be food self-sufficient because it is not possible to produce all the required food for all communities in urban and peri-urban areas. This food self-sufficiency varies across regions mainly due to availability and fertility of agricultural land and volume of urban demand, for example urban and peri-urban agriculture could supply higher shares of food demand (60–100%) of the cities in South and South East Asia while lower shares (less than 20%) in North America cities in 2010 (Kriewald et al.). Hence urban inhabitants may still need to rely on retailing (supermarkets, specialised shops, farmers' markets) and the informal sector to access food (Crush et al. 2011). Additionally, some studies have also cautioned that urban agriculture can be responsible for harbouring and vectoring pathogenic diseases, urban soils can be contaminated, and that exposure to urban air pollution can affect food quality and grower health (Hamilton et al. 2014). Nevertheless, these negative effects of urban farming can be alleviated by choosing right agriculture practices, preventing open standing water, and reducing urban pollution. For example, Ercilla-Montserrat et al. (2018) did not find an increased heavy metal contamination due to air pollution in food produced in Barcelona using hydroponics.

Urban and peri-urban agriculture is multifunctional in that it provides a variety of environmental, social and economic functions (Aubry et al. 2012; Lin et al. 2015; Zasada 2011), including agro-tourism (Yang et al. 2010). A review study on sub-Saharan Africa shows that urban and peri-urban agriculture also contributes to climate change adaptation and mitigation (Lwasa et al. 2014, 2015). Urban and peri-urban agriculture reduces carbon footprints by avoiding long distance food transport and limits GHG emissions by recycling organic waste and wastewater that would otherwise releases methane from landfill and dumping sites (Lwasa et al. 2014). Urban and peri-urban agriculture also contributes in adapting to climate change including extreme events for example, by reducing urban heat island effect, increasing water infiltration and slowing down run-offs to prevent flooding, etc. (Lwasa et al. 2014, 2015). For example, a scenario analysis shows that urban gardens reduces the surface temperature up to 10°C in comparison to the temperature without vegetation (Tsilini et al. 2015).

Urbanisation has benefited some farmers due to proximity to the nearby urban market, whereas, others has been displaced due to farmland loss and increased land fragmentation (Pribadi and Pauleit 2015). Additionally, urban and peri-urban agriculture is exposed to climate risks and urban growth that may undermine its long-term potential to address urban food security (Padgham et al. 2015). Therefore, there is a need to better understand the impact of urban sprawl on peri-urban agriculture; the contribution of urban and peri-urban agriculture to food self-sufficiency of cities; the risks posed by pollutants from urban areas to agriculture and vice-versa; the global and regional extent of urban agriculture; and the role that urban agriculture could play in climate resilience and abating malnutrition (Mok et al. 2014; Hamilton et al. 2014). Globally, urban sprawl is projected to consume 1.8–2.4% and 5% of the current cultivated land by 2030 and 2050 respectively, leading to crop calorie loss of 3–4% and 6–7%, respectively (Pradhan et al. 2014; Bren d’Amour et al. 2017). Kriewald et al. shows that the urban growth has the largest impacts in most of the sub-continents (e.g., Western, Middle, and Eastern Africa) while climate change will mostly reduce potential of urban and peri-urban agriculture in Southern Europe and Northern Africa.

Urban development is another driver of emissions. Conversion of agricultural, forested, or otherwise undeveloped land to urban use, and unsustainable harvesting of wood fuels to supply large urban and industrial markets, contribute significantly to forest degradation. By 2050, urbanisation might consume around 5% of the global agriculture land, resulting in crop calorie losses of 6–7% (Pradhan et al. 2014).

5.6.6 Sustainable Development Goals

The 2030 development agenda includes 17 goals and 169 targets including zero hunger and climate action (United Nations 2015). The second goal (*Zero hunger* – SDG 2) aims to end hunger and all forms of malnutrition by 2030 and commits to universal access to safe, nutritious and sufficient food at all times of the year. SDG 2 consists of eight targets with fourteen indicators. SDG 13 (*Climate action*) calls for urgent action to combat climate change and its impacts and consists of five targets with seven indicators. In some aspects, SDGs overlap or interact: When progress in SDG one goal or target benefits another goal or target, the interaction is called synergies; trade-offs are defined as hurdles created to another goal or target (Nilsson et al. 2016; Pradhan et al. 2017; Neumann et al. 2018; International Science Council 2018; Weitz et al. 2018). The trade-offs are mainly due to economic focus of the traditional development paradigm in cost of human welfare and environmental sustainability. Nevertheless, SDGs can be achieved by leveraging synergies and tracking trade-offs. This implies a worldwide change in traditional production and consumption approaches and in human behaviour that are sustaining unsustainable economic institutions and ways of life (Shove et al. 2012).

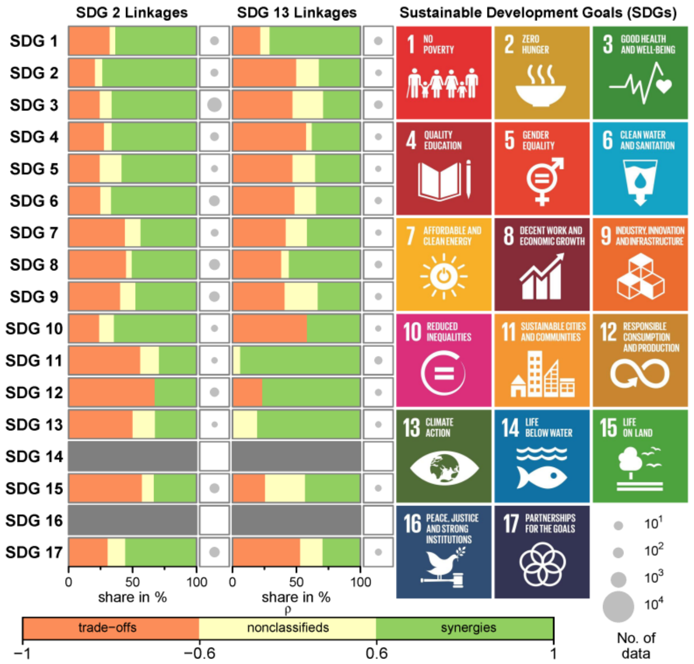


Figure 5.18. Intra and inter-linkages for SDG 2 (*Zero hunger*) and SDG 13 (*Climate action*) at the global level using the official indicators of Sustainable Development Goals (United Nations Statistics Division 2016) and applying a statistical approach (Pradhan et al. 2017). Pradhan et al. (2017) defined synergy and trade-offs as significant positive ($\rho > 0.6$, red bar) and negative ($\rho < -0.6$, green bar) spearman correlation between a pair of SDG indicators, respectively. The ρ between 0.6 and -0.6 is considered as nonclassifieds (yellow bar). At the global level, intra-linkages of SDGs are quantified by the percentage of synergies, trade-offs, and nonclassifieds of indicator pairs belonging to the same SDG (here, SDG 2 and SDG 13) for all the countries. Similarly, SDG interlinkages are estimated by the percentage of synergies, trade-offs, and nonclassifieds between indicator pairs that fall into two distinct goals for all the countries. The grey bar shows insufficient data for analysis. The number of data pair used for the analysis is presented by the area of the circle

Intra- and inter-linkages of SDG 2 and SDG 13 are shown in Figure 5.18. Ensuring food security (SDG 2) shows positive relations (synergies) with most goals (Pradhan et al. 2017; International Science Council 2018) but has trade-offs with SDG 12 (*Responsible Consumption and Production*) and SDG 15 (*Life on Land*) under current development paradigm (Pradhan et al. 2017). Sustainable transformation of traditional consumption and production approaches can overcome these trade-offs based on several innovative method. For example, sustainable intensification and reduction of food waste can minimise the observed negative relations between SDG 2 and other goals (Obersteiner et al. 2016). Doubling productivity of small holder farmers and halving food loss and waste by 2030 are targets of SDG 2 and SDG 12, respectively (United Nations Statistics Division 2016). Similarly, efficient irrigation practices can reduce water demand for agriculture that could improve health of the freshwater ecosystem (SDG 6 and SDG 15) without reducing food production (Jägermeyr et al. 2017).

Climate action (SDG 13) shows negative relations (trade-offs) with most goals under the current development paradigm (Figure 5.18). The targets for SDG 13 have a high focus on climate change adaptation and the data for the SDG 13 indicators are limitedly available. SDG 13 shares two indicators with SDG 1 and SDG 11 (UNSG 2017) and therefore, has mainly positive linkages with these two goals. Trade-offs was observed between SDG 2 and SDG 13 for around 50% of the case (Pradhan et al. 2017). Transformation from the current development paradigms breaking these lock-in effects can protect climate and achieve food security in future. For example, sustainable agriculture practices can provide climate change adaptation and mitigation synergies, linking SDG 2 and SDG 13 more positively (International Science Council 2018).

5.7 Enabling conditions and knowledge gaps

For mitigation and adaptation in food production and supply, enabling conditions are created through markets, policies, institutions, governance, and indigenous/local knowledge (*robust evidence, high agreement*)**.** On a regional basis, gender, equity, culture, ethnicity, and access to food and capacity building are important in devising context-specific mitigation and adaptation measures, as well as adoption strategies that ensure food security *(robust evidence, high agreement)*. Sustainable food security is most likely to arise from a mixture of globalised supply chains and local production, not one or the other. However, globalised food systems threaten indigenous knowledge and local knowledge, particularly agrobiodiversity, which are important in providing food security and promoting adaptation and resilience *(robust evidence, high agreement)*.

Prompt actions that can be taken include incorporating indigenous and local knowledge, and acknowledging women's role on food systems in regard to climate change mitigation and resilience; optimising the use of natural resources for climate change mitigation and adaptation and food security through agricultural technology transfer and exchange; developing business models and targeted subsidies for climate-friendly production practices; investing in building resilient supply chains and trade networks; incentivising and raising awareness on the co-benefits of healthy consumption patterns; improving access to healthy diets for vulnerable groups through food assistance programs; and implementing policies and campaigns to reduce food loss and food waste.

5.7.1 Areas for policy intervention

Here we highlight some of the major policy areas with respect to responding to climate change challenges within the food system. Although two families of policy – agriculture and trade – have been instrumental in shaping the food system in the past, there is scope for a wider group of policy instruments to be deployed in order to reconfigure the food system to be climate-responsive in a sustainable way.

The food system that exists today is a product of a range of policies (agricultural policy, including productivity-related research; trade-policy). The scale of the challenges from climate change and malnutrition in all its forms, as well as the externalisation of costs onto the environment, suggests significant changes in the policy environment are needed. Addressing these challenges requires action across the food system to enhance synergies and co-benefits and minimise trade-offs among multiple objectives of food security, adaptation and mitigation (Sapkota et al. 2017c; Palm et al. 2010; Jat et al. 2016; Sapkota et al. 2015), as well as broader environmental goods exemplified by some of the goals within the SDG framework such as water, air-quality, soil health and biodiversity (Obersteiner et al. 2016; Pradhan et al. 2017). This requires greater policy alignment and coherence between traditionally separate policy domains. For example, aligning the policy goals of sustainable land management for the purposes of managing both food security and biodiversity (Meyfroidt 2017; Wittman et al. 2017).

There are a range of ways that policy can intervene to stimulate change in the food system – through agriculture, its research and development, via food standards, manufacture and storage, changing the food environment and access to food, changing practices to encourage or discourage trade, and providing novel incentives to stimulate the market, including through reduction in waste or changes in diets to gain benefits for health and sustainability (Benton et al. 2018; Pomeranz et al. 2018; Hasegawa et al. 2018; Springmann et al. 2016c; Ezzine-de-Blas et al. 2016; Chalak et al. 2016; Arno and Thomas 2016; Ross et al. 2014; Jones et al. 2013; Neumayer 2001) (Table 5.7). As with SR1.5 (IPCC 2018), there is no single solution that will address food, climate change, and health, but instead the need to deploy many solutions simultaneously. For example, Springmann et al. (2018) indicate that maintaining the food system within climate targets for the mid-century requires increasing the production and resilience of agricultural outputs, reducing waste, and changing diets. Such changes can have significant co-benefits for public health.

Table 5.7 Potential policies related to food and health for adaptation and mitigation of climate change

Type	Goal	Intervention	Example
Supply-side efficiency	Increasing production efficiency	Agricultural R&D	Investment of public money in research, innovation and knowledge exchange
		Precision agriculture	Agricultural engineering, robotics, big data, remote sensing
		Farmer training via extension services, online access, field schools	Development of on-line resources
		Land tenure, access to credit and resources	Land reform, banking services
	Sustainable land use	Land use planning	Zoning, protected area networks, multifunctional landscape planning
		Integrated agricultural projects	Agroecology, climate smart agriculture, conservation sustainable intensification
		Payment for ecosystem service schemes	Carbon sequestration programs
	Lower market impacts	Mandated reporting of company externalised costs in supply chains	Carbon and natural capital accounts
	Response to shocks	Market-led, or government-subsidised, insurance products	Crop insurance programs
	Trade	Liberalising trade flows	WTO rules, green trade agreements
Raising profitability not yields	Markets for higher- quality goods	Nutritious, GHG-efficient local food programs	Standards
Modifying demand	Reduce waste	Instruments for reducing food waste	Guidelines, regulations and taxes
		Awareness campaigns/education	Global initiatives
		Investments in shelf life	Long shelf life varieties; packaging/processing to reduce contamination; cold chain

		Circular economy programs to use waste	Biofuels, waste feed for livestock, charities
	Reducing consumption of excess food	Changing food choice	Education campaigns
		Changing food environments	Planning
		Promotion of healthier and more sustainably produced foods	Subsidies, standards, mandates, regulations, carbon taxes
		Preventative health care incentives	Health insurance reductions through better diets
		Personalised nutrition	Incentivising eating less by highlighting the personal impact on health
		Creating transparency of food impacts as means of changing consumption	Food labelling via public standards; blockchain ledgers for production and climate methodology
		Nutrition and sustainability education and awareness campaigns	In schools; public awareness campaigns
		Investment in disruptive technology to encourage less meat, more vegetable protein (e.g. cellular agriculture)	Tax breaks for R&D; industrial strategies
		Public procurement for health and climate	School feeding programs

5.7.1.1 Trade

Trade is often seen to be a critical mechanism to stabilise demand and supply under climate change and under a diverse set of economic futures. Its role in prices is also significant and it performs a key function of balancing food security between different regions. However, there are strong opposing narratives surrounding trade in that some see trade as an opportunity to enhance food security while others see trade as a threat (Clapp 2016).

Clapp (2016) showed that trade (supported by high levels of subsidy support to agriculture in some countries) can put downward pressure on world prices and reduce incomes for other agricultural exporters. Lower food prices that result from subsidy support may benefit urban consumers in importing countries, but at the same time they may hurt farmers' incomes in those same countries. The outmigration of smallholder farmers from the agriculture sector across the Global South is significantly attributed to these trade patterns of cheap food imports (Wittman 2011; McMichael 2014; Akram-Lodhi and others 2013). Food production and trade cartels, as well as financial speculation on food futures markets, affect low-income market-dependent populations (Reuter 2015), and the new concept of food sovereignty is being developed to conceptualise these issues (Reuter 2015).

Global trade is essential for achieving food security under climate change because it provides a mechanism for reducing the sensitivity of food availability to local changes in weather. However, this potential will only be realised if trade is managed in ways that maximise the benefits of broadened access to new markets while minimising the risks of increased exposure to international competition and market volatility (Brown et al. 2017b; Challinor et al. 2018). Trade acts to buffer exposure to climate-risks whilst the market works well; under certain conditions – such as unprecedented shocks, or the perception of a shock, coupled with a lack of food stocks, or the lack of transparency of stocks (Challinor et al. 2018; Marchand et al. 2016) – the market can fail and trade can expose countries to food shocks.

Furthermore, trade creates long-distance supply chains and significant GHG emissions associated with transport, storage and processing (Michalský and Hooda 2015) (Box 5.8). Hence, there is an unresolved question about the balance of locally produced vs imported food (and feed) that minimises climate risks and emissions into the future (see Section 5.5.2.5).

Box 5.8 Mitigation and adaptation in large-scale commercial food systems in Europe

Europe is an example of large-scale commercial food systems with long supply chains. Long supply chains are often associated with high-income countries, well integrated into global markets. Such food systems can be characterised by a reliance on trade, diets that are calorically dense (and often nutrient poor), leading to a high prevalence of overweight and obesity forms of malnutrition, and increasing levels of food loss and waste.

The main food security issues for Europe are a strong reliance on imports; inequality driving lack of food access (e.g., immigrant communities, elderly people, low-income groups), and concentration on obesogenic diets (in the poor). Hence there is lack of access to healthy food creating growing obesity and NCDs; significant waste on farms (due to rejection of "imperfect produce") and in home and food outlets (EASAC 2017).

Climate mitigation issues include sustainable intensification, reduction of livestock farming (RISE 2018), development of a circular bioeconomy, reduction in waste, and reduction of obesogenic diets (EASAC 2017). There is potential for mitigation via change in demand, especially with respect to systemic emissions (including overseas' footprints). Scherer et al. (2018) found opportunities for sustainable intensification in Europe on 34% of the arable land.

Westhoek et al. (2014) estimated that halving the consumption of animal products in the European Union, which at present consumes 70% more animal protein than recommended by the WHO, would deliver a 40% reduction in nitrogen emissions, 25–40% reduction in GHG emissions and 23% per capita less use of cropland for food production, while at the same time leading to a reduction in cardiovascular diseases and some cancers.

Climate adaptation issues include significant impacts expected for European productivity (e.g., (Hawkins et al. 2013)), especially through heat stress; increasing unpredictability of weather, including extremes and variability of jet stream creating highly variable climate (Francis and Vavrus 2015; Mann et al. 2017), with impacts on domestic productivity creating a need for greater resilience in farming. There is growing vulnerability of imports from geopolitical and climate risk (see Section 5.3.2.1 on food price spikes), and there is a need to build resilience and transparency in trade networks and relationships to ensure continuity in supply (Macfadyen et al. 2015; Thornton et al. 2014; Kent et al. 2017; Coumou and Rahmstorf 2012).

Adaptation measures need to consider the specificities of different countries in Europe since climate change will affect them differently (e.g., Mediterranean and Atlantic regions, Northern and Southern regions). Nevertheless, Iglesias et al. (2012) advanced water use efficiency as a critical response to climate risks and a more effective extension service in Europe as general strategies.

5.7.1.2 Health-related policies

There is an increasingly large literature that argues the key to sustainable land management is not in land management practices but in, for example, the factors that determine the demand for products from land (such as food) and the potential for public health policy to affect dietary choice and thus demand for different amount of, and sorts of, food. Thus, for example, Obersteiner et al (2016) show that increasing the average price of food is an important policy lever that, by reducing demand, reduces food waste, pressure on land and water, impacts on biodiversity and through reducing emissions, mitigates climate change and potentially helps actions towards multiple SDGs. Whilst such policy responses – such as a carbon tax applied to goods including food – has the potential to be regressive, affecting the poor differentially (Frank et al. 2017; Hasegawa et al. 2018), and increasing food insecurity – further development of social safety nets can help to avoid the regressive nature (Hasegawa et al. 2018). Hasegawa et al. (2018) point out that such safety nets for vulnerable populations could be funded from the revenues arising from a carbon tax.

The co-benefits arising from mitigating climate change through changing dietary patterns, and thus demand, have potentially important economic impacts. The gross value added from agriculture to the economy (GVA) was USD 1.9tn (in 2013 (FAO 2015b)), from a global agriculture economy (GDP) of USD 2.7tn (in 2016). In 2013, the FAO estimated an annual cost of USD 3.5tn for malnutrition (FAO 2013a). However, this is likely to be an underestimate of the economic health costs of our food systems several reasons: (1) a lack of data – for example there is little robust data in the UK on the prevalence of malnutrition in the general population (beyond estimates of obesity and surveys of malnourishment of patients in hospital and care homes, from which estimates over 3 million people in the UK are undernourished (BAPEN 2012)), (2) lack of robust methodology to determine, for example, the exact relationship between overconsumption of poor diets, obesity and non-communicable diseases like diabetes, cardio-vascular disease, a range of cancers or Alzheimer’s disease (Pedditizi et al. 2016), (3) unequal healthcare spending around the world. In the US, the economic cost of diabetes, a disease strongly associated with obesity and affecting about 23 million Americans, is estimated at USD 327bn in 2017 (American Diabetes Association 2018), with direct healthcare costs of USD 9,600 per person. By 2025, it is estimated that globally there will be over 700 million people with diabetes (NCD-RisC 2016b), over 30 times the number in the US. Even if a global average cost of diabetes per capita was a quarter of that in the US, the total economic cost of diabetes would be approximately the same as global agricultural GDP. Finally, (4) the role of agriculture in causing ill-health beyond dietary health.

5.7.2 Governance and institutions

In the governance of climate change, several differences exist between mitigation and adaptation. This is important because food systems require integrated policies addressing both challenges at multiple scales. Huitema et al. (2016) emphasised that mitigation requires global agreements and national policies while adaptation requires local and regional considerations. However, in the case of food systems mitigation measures require of local actions e.g., at the farm level, while adaptation actions may require measures at global and national levels, such as emergency food aid for climate disasters and food safety nets. The leading concepts in mitigation are specific and often quantifiable (e.g., reduction of GHG emissions), while in adaptation they are either generic (e.g., increase resilience) or very domain-specific (e.g., productivity of farming systems). In food systems, mitigation measures in crop or livestock farming, for instance, can target individual farms through technical innovations, for example, dietary supplements to ruminants.

Governance of food systems is a major challenge because it is only recently that this approach has been embraced by policy-makers. Apart from the processes which are specific to climate change, food systems have their own specificities in terms of governance. Termeer et al. (2018) developed a diagnostic framework with five principles to assess which governance options are more appropriate to food systems: 1) a system-based problem framing to deal with interlinked issues, drivers and feedback loops; 2) connectivity across boundaries to span siloed governance structures and include non-state actors; 3) adaptability to flexibly respond to inherent uncertainties and volatility; 4) inclusiveness to facilitate support and legitimacy; and 5) transformative capacity to overcome path dependencies and create adequate conditions to foster structural change. Termeer et al. (2018) applied this framework to selected South African governance arrangements; (Rivera-Ferre et al. 2013) proposed seven principles for food systems management considering them as complex socioecological systems: learning, flexibility, adaptation, scale-matching, participation, diversity enhancement and precaution.

For climate change, the definition of a global common pool regime embedded in a polycentric approach is suggested, that is, different food systems and different problems may require different policy and institutional approaches, but common principles based on resilience and social-ecological justice are needed to address both climate change and food security. Ostrom (2009, 2010) proposed polycentric systems for coping with climate change to address both mitigation and adaptation, and (Rivera-Ferre et al. 2013) suggested it as one of the management options for food systems. The food system perspective and the integration of different departments (education, agriculture, environment, welfare, consumption, economic, health, equality, among others) are key. One option proposed for land management that could be equally adopted in food systems implies the creation of government entities or ministerial units responsible for coordinating among ministries, cutting across different administrative levels (Orr et al. 2017).

Quite recently the socio-technical literature has been adopted in agricultural research to address just transitions to sustainability and propose frameworks that can help facilitate the development of viable institutional designs and explicitly transformative strategies that include climate change (Wiskerke 2004; Ortiz et al. 2018; Pant et al. 2014; Isgren et al. 2017; Hinrichs 2014). According to this frame, a new conceptualisation of agricultural goals stresses the harnessing of local ecological capacities. Using this framework, Pant et al. (Pant et al. 2014) found that agricultural sustainability transitions in Karnali Mountains of Nepal required of different management systems (transition management and adaptive management) in order to make new and improved technologies more accessible and adaptable to smallholders while developing local capacity to adapt to changes. Isgren et al. (2017) use it to analyse lock-in elements of just agricultural transitions in Uganda.

5.7.3 Knowledge, capacity building, technology and innovation

Addressing climate change-related challenges and ensuring food security requires all types of knowledge (formal/non-formal, scientific/indigenous, women, youth, technological). Miles et al. (2017) stated that a research and policy feedback that allows transitioning to sustainable food systems must have at first a whole system approach. Currently, in developing and using knowledge for food security and land sustainability under climate change there are three major approaches: (1) public technology transfer with demonstration (extension agents); (2) public and private advisory services (for intensification techniques) and; (3) Non-formal education with variants such as Farmers Field schools (organised by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)), Rural Resource Centers (organised by the World Agroforestry Centre (ICRAF)) and Facilitation Extension where front-line extension agents primarily work as “knowledge brokers” in facilitating the teaching–learning process among all types of farmers (including women and rural young people), or where farmers act themselves as knowledge transfer and sharing actors.

In analysing the potential role of rural advisory services and national level agricultural research in climate change in Africa, Morton (2017) found resource constraints of rural advisory services which limited their capacity of action, disconnects between advisory policy and climate policy, the importance of advisory services adopting commodity/value chain approaches and remaining open to engagement in input supply, new opportunities presented by ICTs, and the importance of mutual learning between multiple stakeholders.

Recent discourse has a strong orientation towards scaling-up innovation and adoption by local farmers. However, autonomous adaptation, indigenous knowledge and local knowledge are both important for agricultural adaptation (Biggs et al. 2013). All these require the promotion of farmer participation in governance structures, including research, to designing systems for the generation and dissemination of knowledge and technology so their needs and knowledge can be taken into consideration.

5.7.3.1 Capacity-building

Capacity building is a cross-cutting issue that covers over all the aspects of climate change adaptation and mitigation. Capacity building is therefore a diverse set of activities with vaiable objectives. Risk mapping is widely recognised as a first step to clarify the priority issues for climate change adaptation. Capacity for climate risk analysis related to food production is high, but is lower in regard to markets and trade, and lacking in regard to food accessibility, utilisation, transportation, and processing. There is an imbalanced capacity of early-warning systems between the developed and developing countries. While communities in poverty have almost no capacity for early-warning systems, some efforts have been made to enhance the insurance for the risk transfer. Ecological restoration practices have been carried out to increase agricultural resilience, while systematic summaries of methodology and guidelines are limited. Planning capacity has increased as public awareness is improved, while monitoring and evaluation capacity for the adaptation to climate change is still very weak.

The areas of capacity building that are relevant to climate change and sustainable food systems involves many aspects. Each aspect of capacity building for climate change can be linked to two domains: innovation and transformation towards sustainability:

1. *System thinking and co-design* with stakeholders to agree on main outcomes first (e.g., innovations needed to increase production; transformation to achieve value-addition and loss reduction). Capacity needs are sustainable approaches to high productivity.

2. *Innovation for managing inputs and services* for sustainable and yield-enhancing food systems (seeds, fertiliser, animal breeds, feed, machinery, etc.) for higher-quality agricultural products. Capacity needs are stable delivery of key inputs, resources and services.

3. *Commercial sector development* of agricultural processors; dealers, entrepreneurs, and investors. Capacity needs are to rationalise standards and regulations for predictable and optimal food outcomes

4. *Technologies for GHG emissions monitoring, reporting, and verification (MRV)*. Capacity needs are improving the ability of countries to conduct inventories of emissions and mitigation options.

5. *Policies related to land tenure, credit, sciencet, technology and innovation*. Capacity building needs are empowering rural communities, safeguarding and promoting ownership, responsibility and accountability in the food value chain.

6. *Institutional capacity for research and development, extension services, input providers, and the dealers*. Capacity needs are to develop financial institutions to provide micro-credit for small/medium farming enterprises and support producers’ organisations (farmers and herders)

7. *Governance and leadership*. Capacity needs are to strengthen local, regional, and national government institutions, as well local and indigenous leaders.

8. *Consumer education to improve nutrition*. Capacity building in adaptation and mitigation of climate change for food security needs to address consumers as well as producers. Education and information programs specific to regional and cultural contexts are needed.

5.7.3.2 Knowledge, science and technology

Mixed and diverse technologies are required for adaptation and mitigation of food systems under climate change.

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

Early warning systems. Early warning systems plays an important role in food systems adaptation by giving adequate warning so people can take appropriate coping measures to minimise impacts on production, supply chains, and consumption (Downing et al. 2004). Mainstreaming early warning systems in adaptation planning could present a significant opportunity for climate disaster risk reduction (Zia and Wagner 2015). Enenkel et al. (2015) suggested that the use of smartphone applications that concentrate on food security could help with more frequent and effective monitoring of food prices, availability of fertilisers and drought-resistant seeds, and could help to turn data streams into useful information for decision support and resilience building. Aghakouchak et al. (2015) showed that systematic monitoring and satellite observations provide opportunities to improve early drought warning. Waldner et al. (2015) demonstrate that cropland mapping can enable strategic food security monitoring and modelling. New approaches to improve forecasts, prediction, projection and downscaling of climate scenarios; such as high-resolution regional climate downscaling approaches are used to improve projections of changes in extreme events, and climate variability (Cheng et al. 2017; Nolan et al. 2017; Abhik et al. 2016).

Transport technology. Improved transport technology is also important to improve food security in developing counties. In Africa, enhanced transportation networks combined with greater national reserves of cash and social safety nets could reduce the impact of ‘double exposure’ of climate change and poverty on food security (Brown et al. 2017b).

5.7.3.3 Indigenous and local knowledge

The role of indigenous knowledge and local knowledge (ILK) in climate change adaptation has been widely recognised (Mapfumo et al. 2016; McLean and Nakashima 2018) and its greater inclusion in IPCC reports has been proposed (Ford et al. 2016). Despite decades of marginalisation as compared to scientific knowledge, evidence has shown the relevance of ILK given its local nature and cultural responsiveness (Leonard et al. 2013).

I&LK for climate change adaptation and food security includes all ancient and localised knowledge that directly or indirectly deals with the four pillars of food security, as well as all activities of food systems. Most reported ILK deals with agrobiodiversity conservation and associated management, including seed conservation, as well as management (cultivars, intercropping, rotations, integrated systems). These can enhance food availability, food stability and food use through diverse diets. In India, ILKinspired food systems have enabled small and marginal farmers to reclaim their livelihoods across the country (Gregory et al. 2017). Other ILK for food security important under climate change conditions relates to soil and water management (Rivera-Ferre et al. 2016a). ILK has been assessed to play a key role on pollinators through biodiversity management (IPBES, 2016). Less studied is the role of ILK in food conservation, which can contribute to food access under crop and infrastructure failure; and in food preparation, which is required for healthy and diverse diets. Important traditional knowledge also relates to maternal child feeding (Bezner Kerr et al. 2008). In promoting the use of ILK for climate change adaptation, it is important to take a gendered approach, since men and women hold different knowledge, expertise and transmission patterns (Díaz-Reviriego et al. 2017).

The potential role that local knowledge can play at the local level depends on local power relations and its interactions with government strategies (Naess 2013). In relying on local knowledge for adaptation to climate change it is also important to understand the structural constraints to its use across scales, and its threat by climate change, which may put pressure on some of the indicators used in ILK for adapting to climate change (Mapfumo et al. 2016). The multiple cultural, legal, risk-benefit and governance contexts of knowledge exchange also need to be considered (Williams and Hardison 2013).

Mobilisation of local knowledge. Klenk et al. (2017) found that mobilisation of local knowledge can inform adaptation decision-making and may facilitate greater flexibility in government-funded research. As an example, rural innovation in terrace agriculture developed on the basis of a local coping mechanism and adopted by peasant farmers in Latin America may serve as an adaptation option or starting place for learning about climate change responses (Bocco and Napoletano, 2017). Clemens et al. (2015) found that an open dialogue platform enabled horizontal exchange of ideas and alliances for social learning and knowledge-sharing in Vietnam. Improving local technologies in a participatory manner, through on-farm experimentation, farmer-to-farmer exchange, consideration of women and youths, is also relevant in mobilising knowledge and technologies.

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

5.7.4 Knowledge Gaps

Knowledge gaps around options and solutions and their (co-)benefits and trade-offs are increasingly important now that implementation of mitigation and adaptation measures is scaling up. The need for forecasts is reduced if the systems are more resilient to change. The questions guiding this section are where research attention should be focused going forward, what knowledge would have the biggest impacts, what do we need to know to move towards a sustainable and food-secure future. Research is needed on how a changing climate and interventions to respond to it will affect all aspects of food security, including access, utilisation and stability, not just availability. These gaps are one of the barriers hindering mitigation and adaptation to climate change in the food system and its capacity to deliver food security.

5.7.4.1 Key areas for climate change, food systems, and food security research

Climate risk information at regional scales. Knowledge gaps exist on both global and regional scales as reported in AR5, but are especially prevalent at regional scales. Shackleton et al. (2015) recognised climate uncertainty, high levels of variability, lack of information on the frequency and intensity of extreme events, and poor predictive capacity at a local scale as knowledge barriers in the adaptation process. Wirsenius et al. (2015) noted the difficulties related to identification of appropriate and sustainable community-based adaptation options in livestock production systems, especially if they are to address climate risk. Information on the intensity and frequency of climate events and poor predictive capacity at the local scale affect not only the local farmer but also the general adaptation process especially at the regional level. A study conducted by Shackleton et al. (2015) on climate change adaptation among small-holder farmers in Ethiopia and South Africa found that limited knowledge on risk perceptions and the willingness to accept change by farmers make adaptation so challenging in sub-Saharan Africa.

Improved GHG emissions inventory techniques. On the mitigation side, knowledge gaps include food consumption-based emissions at national scales, embedded emissions (overseas footprints) of food systems, comparison of GHG emissions per type of food systems (e.g., smallholder and large-scale commercial food system), and GHG emissions from land-based aquaculture. An additional knowledge gap is the need for more socio-economic assessments of the potential of various integrated practices to deliver the mitigation potential estimated from a biophysical perspective. While studies often project how much CO_2 could be sequestered in soil, for instance, there is not yet discussion of the potential for this to be effectively implemented, once barriers and incentives to adoption of the techniques, practices, and technologies are considered.

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

Crop and livestock genetics. Advances in plant breeding are crucial for enhancing food security under changing climate for a wide variety of crops including fruits and vegetables as well as staples. Genetics improvement is needed in order to breed crops and livestock that can both reduce greenhouse gas emissions, increase drought and heat tolerance (e.g., rice), and enhance nutrition and food security. Animal breeding for GHG emission reductions and increase in drought and heat tolerance is needed as well. Linkage of genomics data and simulation models for crop and livestock is critical to scaling up advances. On the production side, leading adaptation measures to climate extreme events and volatility include recovery, development and use of climate stress-tolerant crop varieties (Fisher et al. 2015; Prohens, 2015), heat-tolerant animals (Rout et al. 2017), comprising both new and autochthonous breeds, and salt-resistant crops (Hanin et al. 2016; Das et al. 2015). Phenomics-assisted breeding appears to be a promising tool for deciphering the stress responsiveness of crop and animal species (Papageorgiou 2017; Kole et al. 2015; Lopes et al. 2015; Boettcher et al. 2015).

Food supply chains. The expansion of the cold chain into developing economies means increased energy consumption and GHG emissions at the consumer stages of the food system, but its net impact on GHG emissions for food systems as a whole is complex and uncertain given the prevalence of low processing technologies and potential to reduce food loss and waste (Heard and Miller 2016). Further understanding of negative side effects in intensive food processing systems are still needed. These side effects include increased access, and likely greater consumption, of meat, dairy and pre-packaged or frozen ready-made foods; shifts to larger, supermarket-style shopping patterns; and may in fact result in greater food waste if changes in consumer purchasing patterns facilitate overbuying (Heard and Miller 2016).

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

5.7.4.2 Food-Energy-Water Nexus

Emerging interdisciplinary science efforts are providing new understanding of the interdependence of food, energy, and water systems and these interdependencies are beginning to take into account climate change, food security, and AFOLU assessments (Scanlon et al. 2017; Liu et al. 2017). These science advances, in turn, provide critical information for coordinated management to improve the affordability, reliability, and environmental sustainability of food, energy, and water systems. Despite significant advances within the past decade, there are still many challenges for the scientific community. Key challenges are the need for interdisciplinary science related to the food-energy-water nexus; ground-based monitoring and modelling at local-to-regional scales (Van Gaelen et al. 2017); incorporating human and institutional behaviour in models; partnerships among universities, industry, and government to develop policy-relevant data; and systems modelling to evaluate trade-offs associated with food-energy-water decisions (Scanlon et al. 2017). The food-energy-water nexus offers a framework to integrate sectors, but also to address issues of resource equity. It also implies consideration of trade-offs about the intertwined feedback loops, leading to unintended consequences and negative externalities (Mwale and Mirzabaev 2015).

Frequently Asked Questions

FAQ 5.1 How does climate change affect food security?

Climate change is projected to negatively impact all aspects of food security. This includes availability (supply, production, distribution, and exchange), access (entitlement, affordability, allocation, and preference), utilisation (the body’s ability to metabolise food nutrients) and stability (in the other three pillars). Currently 821 million people are undernourished, while 1.3 billion adults are overweight. Climate change will affect food availability and utilisation by reducing yields and nutritional quality for some regions and crops; increasing crop and livestock pests and diseases; and disrupting food storage and transport networks. Climate change will affect food access by reducing agricultural income because of higher costs of production inputs, such as water; disrupting transportation infrastructure by increased extreme events; and impacting farmers' ability to invest in adaptation and diversification measures to endure price rises. Climate change will affect food utilisation by impacting food safety due to effects of increased temperatures on microorganisms; reducing water quantity and quality used to prepare food; and increasing the burden of diarrheal diseases in low-income regions due to increased risk of flooding. Climate change will affect food stability by increasing instability of supply due to increased frequency and severity of extreme events, including droughts and heatwaves; impacting world market export prices that carry through to domestic consumer prices due to climate shocks; and causing widespread crop failure contributing to migration and conflict.

FAQ 5.2 How can changing diets help address climate change?

Globally, diets are changing toward a greater consumption of animal-based foods, vegetable oils and sugar/sweeteners. Greenhouse gas emissions are increasing due to higher animal-based products in diets. Changes in food choices and consumption can simultaneously help to achieve global greenhouse gas mitigation targets and improve health outcomes. Low-carbon footprint diets on average tend to be healthier and have a smaller land footprint, with mitigation potential of dietary changes ranging from 2.7–3.4 GtCO$_2$-eq yr^{-1} for Mediterranean diets, 3.6–6.4 GtCO$_2$-eq yr^{-1} for healthy diets, 4.3–5.3 GtCO$_2$-eq yr^{-1} for vegetarian diets and 5.2–5.7 GtCO$_2$-eq yr^{-1} for a flexitarian diet with limited meat and dairy products in comparison to business-as-usual food demand projections. Health policies and education programs can lead to pathways for low-carbon, healthy diets. In high-income industrial countries, there is scope for reducing meat consumption with tangible environmental benefits; in developing countries, high meat-based diets are not as prevalent and the scope for reductions may be limited.

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