Chapter 5: Food Security

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Executive summary

Framing the production, supply, and consumption of food as a system is an important holistic approach through which to address complex issues surrounding climate change, food and nutrition security, land use, as well as public and planetary health *(robust evidence, high agreement)*. The changing climate is impacting the food system and its function to deliver food and nutrition security for all people at all times; food systems also affect climate change through greenhouse gas emissions. It is possible to improve the function of the food system – in efficient and sustainable ways, with low climate impact – through both supply-side and demand-side oriented mitigation and adaptation (5.1, 5.2).

The current food system accounts for 27%-32% of total GHG emissions; 15%-17% from food production, supply, and consumption and 12%-14% from land use change *(robust evidence, high agreement)* (5.3). Increases in population and changing diets are increasing food demand, particularly in terms of animal-based production (*medium evidence high agreement*). Intensification of agriculture may result in reduced GHG emissions intensity, but also in increased emissions due to higher feed and fertiliser inputs, increased consumption, and higher profitability, and expanded activity (*robust evidence, high agreement*).

Supply-side mitigation mechanisms are available to contribute to climate change solutions *(robust evidence, high agreement)*. There are many opportunities to improve the efficiency of crop and livestock systems and reduce GHG emissions intensity (emissions per unit product). For livestock, improving efficiency is an important first step, although reductions in total emissions would require a reduction in herd size coupled with reduction in pasture area. Options differ between regions and systems, but tend to reduce GHG emissions intensity although not necessarily total emissions due to spill over and rebound effects *(medium evidence, medium agreement)*. These options can help countries move toward increased land sparing and sharing, and may contribute under appropriate policy interventions to reduction of total emissions (5.3).

Demand management for food can help to achieve the global GHG mitigation and human health targets *(robust evidence, high agreement)*. In the past decades, diet shifts have occurred across the world towards an increase in the consumption of animal products, vegetable oils, and sugar/sweeteners, which result in excess intake, unhealthy outcomes, and, in the case of meat consumption, a larger carbon footprint (5.2). Low-carbon footprint diets tend to be healthier and have a smaller land footprint *(robust evidence, high agreement)*. Cost savings due to healthy diets can be greater than costs of agriculture mitigation *(limited evidence; medium agreement)* (5.5).

Reducing food loss and waste will have an equivalent GHG abatement throughout the food system and will improve food supply without agricultural expansion *(medium evidence, high agreement)* (5.8). In the last five decades, food loss and waste has increased tremendously, with global average consumer food waste growing from 300 kcalcap^{-1}day^{-1} to 500 kcalcap^{-1}day^{-1} and associated GHG emissions from producing wasted food increasing from 130 Mt CO_{2-}eqyr^{-1} to 530 Mt CO_2eqyr^{-1} between 1961 and 2010. Total carbon footprint of food loss and waste in 2011 was around 4.4 Gt CO_{2e}yr^{-1}, accounting for the lifecycle of lost and wasted food (during production, processing, transport, cooking, etc.) and emissions from deforestation and managed organic soils.

Climate change is affecting food production through changes in temperature, water, CO_2 concentrations and extreme events, with variable responses depending on agroecosystem characteristics, and these impacts are projected to grow *(robust evidence, high agreement)*. Extensive/mixed agroecosystems are higher in diversity and/or more resilient to climate change than highly specialised systems, such as mono-cropping *(high evidence, medium agreement)*. Realisation of CO_2 direct effects depends on nutrient status and will negatively affect nutrient quality of grain yield, affecting food utilisation *(medium evidence, high agreement)*. Additionally, climate change is affecting food systems through disruption of transport, manufacture, and retail; and such disruptions will increase in the future *(medium evidence, high agreement)* (5.6).

There is strong evidence that climate change is likely to change the dynamics of plant and livestock diseases *(high confidence)*. 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)*. Pest and disease pressure is likely to have been intensified due to climate change, causing decreases in both yield and quality *(robust evidence, high agreement)*. Timing mismatch between pollinators and crop flowering will have effects on productivity *(medium evidence, high agreement)* (5.6).

Practices that create synergies between mitigation and adaptation can lead to low-carbon and climate-resilient pathways for food and nutrition security *(high evidence, medium agreement)*. Many technical interventions known as best agricultural practices can lead to both adaptation and mitigation outcomes and even synergies, making them attractive to decision-makers for achieving policy goals. Such adaptation options include maximising the efficient use of agro-climatic and other natural resources, minimising damage and loss due to agro-meteorological disasters, increasing agricultural biodiversity, and preventing desertification and land degradation (5.8).

Urban and peri-urban agriculture can contribute to enhancing urban food and nutrition 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 and nutrition security, mainly for the urban poor and people living in informal settlements (robust evidence, high agreement) (5.9).

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 for food and nutrition security *(robust evidence, high agreement)*. Sustainable food and nutrition security is most likely to arise from a mixture of globalised supply chains and local production, not one or the other. Agricultural technology transfer can help optimise use of natural resources for food and nutrition security in many agricultural regions of the world. Multi-faceted solutions include advancing technology and knowledge, closing yield gaps, reducing waste, and changing diets. No single solution will suffice. Globalised food systems threaten indigenous knowledge particularly agro-biodiversity which is important in providing food and nutrition security and promoting both adaptation and mitigation (5.10).

5.1 Framing and context

Framing the production, delivery, and consumption of food as a system is an important holistic approach through which to address complex issues surrounding climate change, food and nutrition security, land use, and public health. The function of the food system is to deliver food and nutrition security for all people at all times. It is possible to improve the function of the food system – to deliver nutrition for people, in efficient and profitable ways, with low environmental impact – through both supply-side and demand-side oriented climate change interventions, and therefore to achieve both mitigation and adaptation, and food and nutrition security. Improving the functioning of the food system can therefore directly contribute to attaining both planetary and human health (Figure 5.1).

Achieving food and nutrition security and responding to the challenges of climate change are two entwined goals that together contribute significantly to the fulfilment of the UN Sustainable Development Goals (SDGs) set in 2015. Food and nutrition security is also an important component of Nature’s Contributions to People (NCPs), defined as all the positive contributions, or benefits, and occasionally negative contributions, losses or detriments, that people obtain from nature (Díaz et al. 2018; Pascual et al. 2017) Globally, about 800 million people are undernourished and 1.9 billion adults suffer from overweight, of which 600 million are obese (and 41 million children under five are overweight) (HLPE 2017). Policy convergence to address the drivers of and responses to climate change in regard to food production, processing, sale, transport, distribution, and consumption will play an increasingly important role in ensuring sustainable food and nutrition security in the coming decades.

Many aspects of food and nutrition security are potentially affected by projected climate changes, including food access, utilisation, and price stability. At the same time, food systems are significant drivers of climate change and its mitigation for their role in GHG emissions, carbon sequestration, changes in albedo of the land surface and regional hydrological impacts. Many climate change response options in the literature address incremental adaptation or mitigation responses separately rather than being inclusive of more systemic or transformational changes throughout the entire food system that encompass both resilience and reduction in GHG emissions. 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 and desertification.

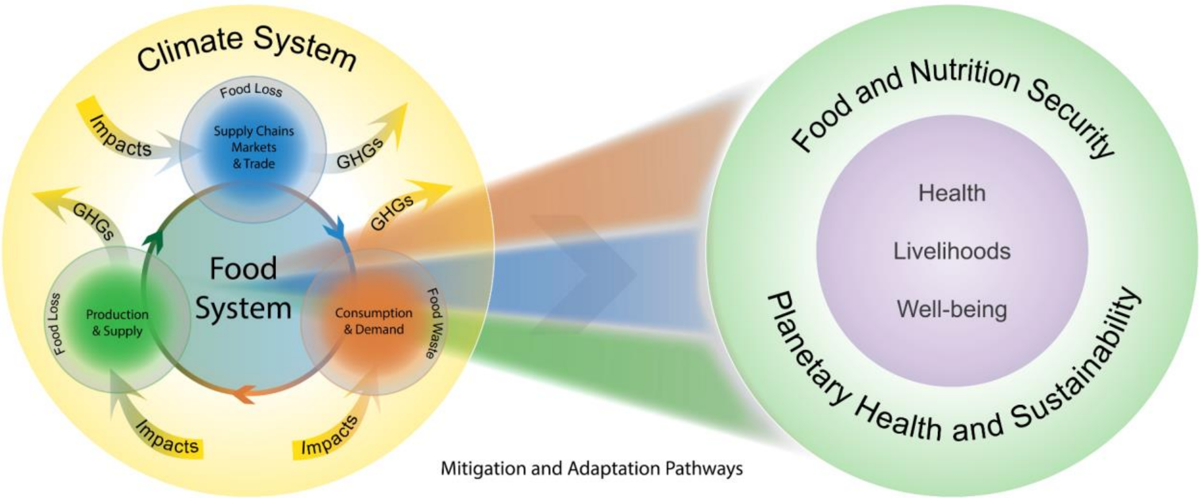


Figure 5.1 Interactions between the climate and food systems, mitigation and adaptation pathways, food and nutrition security, and planetary health and sustainability.

5.1.1 Summary of AR5 Food Systems and AFOLU Chapters

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). AR5 found with high confidence that climate change is projected to undermine food and nutrition security, and climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty. The chapter found with high confidence that all aspects of food and nutrition security are potentially affected by climate change, including access, utilisation, and price stability, although little evidence was available at that time. It also found that global temperature increases of ~4˚C or more above late 20th century levels, combined with increasing food demand, would pose large risks to food and nutrition security globally and regionally, with risks to food and nutrition security generally greater in low-latitude areas. It also highlighted that a range of potential adaptation options exist across all food system activities, not just in food production, but that benefits from potential innovations in food processing, packaging, transport, storage, and trade were insufficiently researched at that time.

Working Group II of AR5 assessed food and nutrition security from the perspective of undernutrition. Here we extend to other forms of food insecurity such as overconsumption, which also threatens health in different but highly damaging ways. The production focus of AR5 highlighted the climate change effects on biophysical aspects of food and nutrition security but did not assess the climate-related effects on many important social elements of food and nutrition security and vice versa. AR5 did acknowledge that food and nutrition security is a complex issue in which climate drivers are often aggravating factors to pre-existing factors of food insecurity, difficult to separate from other non-climate drivers affecting both production and non-production aspects.

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). AR5 WG III AFOLU Chapter found that in terms of emissions the AFOLU sector is responsible for 24% of anthropogenic GHG emissions, mostly from deforestation, livestock, soil and nutrient management. Regarding mitigation potential, options were assessed both considering the supply and demand-side. Improving the efficiency of production could reduce emissions intensity, in absence of rebound effect. Yet, strong importance was given to changes in the demand, which were highlighted as an effective way to reduce emissions. These changes included reducing waste and losses in the supply chain (investments into harvesting, processing and storage technologies, awareness raising, taxation, etc.) and changes in human diets, mainly through the reduction of consumption of animal products. The AR5 WG III Report concluded that agricultural policies need to account for both mitigation and adaptation.

5.1.2 Roadmap to Chapter

This chapter builds on the food systems approach followed by AR5 and its focus on climate change and food and nutrition security. It assesses the risks and opportunities that climate change presents to global and regional land-based food systems and food and nutrition 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. Transforming the food system is an important lever that can be used to address the complex climate change-food and nutrition security nexus (Figure 5.2).

The chapter emphasises the role of extreme climate events, price volatility in food systems, social aspects, and dietary choices. Food and nutrition security and climate change can be linked to sustainable land management to restore areas of the world suffering from land degradation and desertification. The types of agriculture this chapter considers are agroforestry, crop and livestock systems, land-based aquaculture, and urban and peri-urban agriculture. Each has a role to play in mitigation and adaptation of climate change.

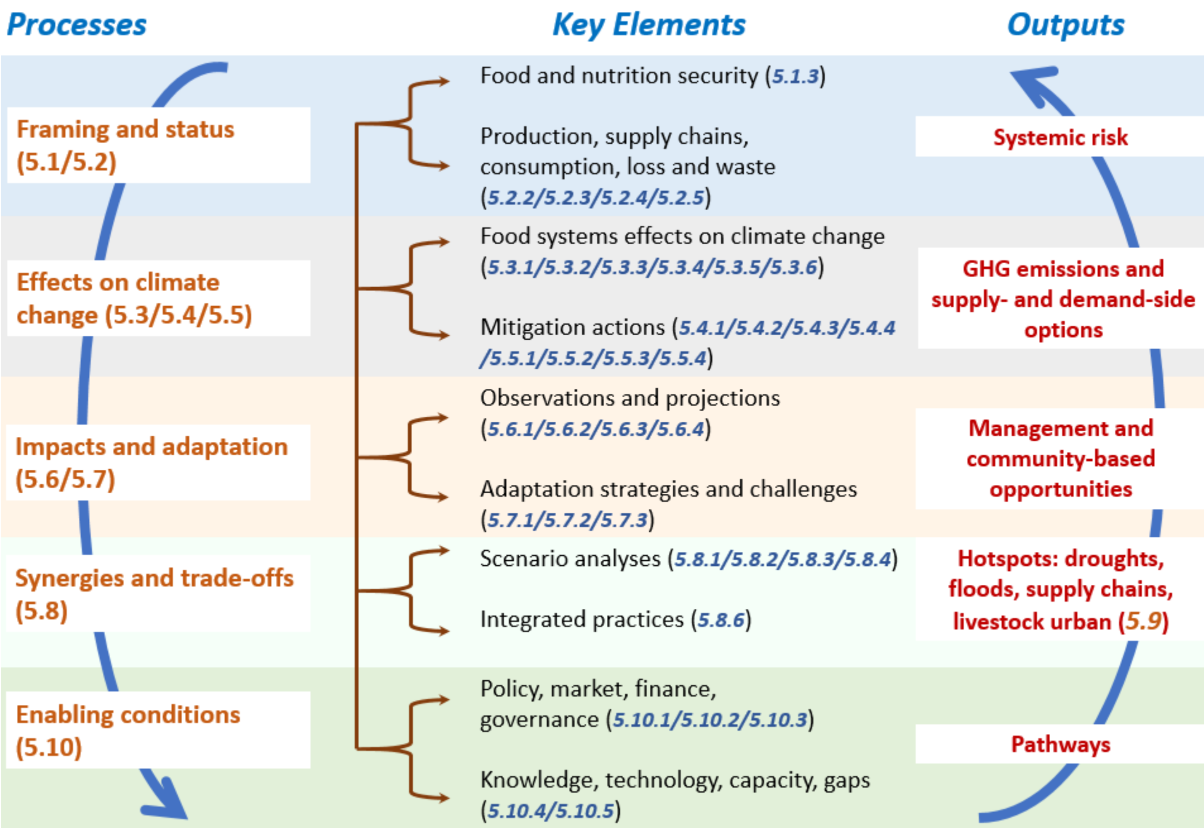


Figure 5.2 Roadmap to Chapter

5.1.3 Food and nutrition security and relation to climate change

Food and nutrition security embraces meeting energy, protein and nutrient needs for healthy life and thus, implicitly, includes the notion of nutrition security (a healthy diet requires providing more than calories), and it also implicitly includes secure access (directly, or indirectly) to water and land to grow the food. The term *food and nutritional security* is generally used to combine the concepts of food and nutrition security and good nutrition (an adequate, well balanced diet combined with regular physical activity (WHO 2017a).

At the same time, the food system is a major driver of climate change through greenhouse gas emissions from many of its components and is also vulnerable to its impacts (Section 5.2.4). Thus, how and what food is produced, processed, transported, and consumed can have significant effects of planetary as well as human health.

The four pillars of food and nutrition security are food availability, access, utilisation, and stability dimensions of food and nutrition security. The additional emphasis on nutrition acknowledges the importance of the key health concerns associated with achieving food and nutrition security (Capone et al. 2014; Micha et al. 2015). The terminology is used to make it clear that food and nutrition security is a precondition to adequate nutrition and that different but complementary actions are needed to achieve both food and nutrition security and good nutrition.

Food and nutrition security action should ensure that food systems provide all individuals with stable access to sufficient, appropriate and safe food, while nutrition-oriented action should ensure that households and individuals have the knowledge and supportive health and environmental conditions necessary to obtain adequate nutritional benefit from the food. The discussion of food and nutrition security is recognising that the food system transformation is needed to provide – in the long-term – access to healthy diets that are sustainably produced (CFS 2012; HLPE 2017).

Measures to enhance food and nutrition security can have consequences for mitigation and adaptation in a changing climate.

5.1.3.1 Effects of climate change on the four pillars of food and nutrition security

According to FAO (2001), food and nutrition 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 that the food system needs to be sustainable, including future generations, and “safe and nutritious food for a healthy life” implies that the food system should not produce malnutrition in any of its forms, including both undernutrition and obesity. According to 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 undernourished (in the sense of “hungry”), undernourishment occurs in terms of nutritional deficiencies in vitamins (e.g., Vitamin A) and minerals (e.g., iron, zinc, iodine), the 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 the UK teenage girls often suffer from iron deficiency).

Finally, 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 5.2). In 2001, chronic diseases contributed approximately 60% of the 56.5 million total reported deaths in the world and approximately 46% of the global burden of disease associated to NCD (WHO/FAO 2003).

Climate change is linked to malnutrition in several ways. Climate change impacts on food production are projected to be severe in developing countries where undernutrition is especially prevalent (See Section 5.3.1.1), and high CO_2 causes declines in nutritional content of grains (See Section 5.5.3.1). On the demand side, dietary choices can lead to varying degrees of greenhouse gas emissions, which are drivers of climate change (See section 5.5).

Food and nutrition security is built on four pillars: availability (supply, production, distribution, and exchange), access (entitlement, affordability, allocation, and preference), utilisation (the body’s ability to metabolise food nutrients, which might be impaired by illness, nutritional value, social value, and food safety) and stability (in the other three pillars) (FAO 2008a). Since AR5, recent work has strengthened understanding of how climate change affects each of these pillars in a range of ways (Table 5.1).

Table 5.1 Climate change impacts on food and nutrition security

Food and Nutrition Security Pillar	Climate Change Impact
Availability	• Reduced yields and soil fertility and increased land degradation (Jobbins and Henley, 2015) • Increased crop and livestock pests and diseases; and higher post-harvest losses (Jobbins and Henley, 2015) • Disruptions to food storage and transport networks (Puma et al. 2015; Wellesley et al. 2017; Rivera-Ferre 2014) • Indirect impacts due to spatial dislocation of consumption from production for many societies (Morris et al. 2017) • Reduced production of fish, livestock, and non-timber forest products.
Access	• Loss of agricultural income due to reduced yields and higher costs of production inputs such as water (Jobbins and Henley, 2015) • Displacement driven by climate extremes and disasters that may affect infrastructure (Jobbins and Henley, 2015) • Disproportionate impact on low-income producers and consumers due to lack of resources to invest in adaptation and diversification measures to endure price rises (UNCCD 2017)
Utilisation	• Impact on food safety due to increased temperatures; impacts on nutrition resulting from reduced water quality and quantity; and climate induced morbidity (Jobbins and Henley, 2015) • Increased presence of mycotoxins in food and feed (Battilani et al. 2016) • Increased burden of diarrheal diseases in low-income regions by approximately 2%–5% by 2020 (Aberman and Tirado 2014)
Stability	• Greater instability of supply due to increased frequency and severity of extreme events, including droughts; and instability of incomes from agriculture (Jobbins and Henley, 2015) • Temporary impacts on world market export prices that carry through to domestic consumer prices (with strong regional effects in parts of Sub-Saharan Africa) due to climate shocks (Diffenbaugh et al. 2012; Verma et al. 2014; Willenbockel 2012) • Widespread crop failure contributing to migration and conflict (Challinor et al. 2018; Hendrix 2018; Selby et al. 2017; Kelley et al. 2017, 2015)

Availability. Food availability or supply is related in part to food production, and the evidence that climate change has affected food production implies some effect on food and nutrition security. Yet quantifying this effect is a difficult task, requiring assumptions about the many non-climate factors that interact with climate to determine food and nutrition security. Impacts of climate change on food availability include reduced rainfall and increased evapotranspiration reducing yields from rainfed agriculture and pastoralism; reduced soil fertility and increased land degradation from increased temperatures, evaporation, and drought; climate change induced crop and livestock pests and diseases; and higher post-harvest losses as a result of climate change (Jobbins and Henley, 2015). In a globalised world, local availability of food may be impaired by disruptions to food transport networks (Puma et al. 2015; Wellesley et al. 2017) and storage infrastructures (Rivera-Ferre 2014). Furthermore, the spatial dislocation of consumption from production for many societies, suggests there are many indirect pathways by which climate change can disrupt people's food and nutrition security (Morris et al. 2017).

Access. Impacts of climate change on access to food include loss of agricultural income due to reduced yields and higher costs of production inputs such as water; climate change impacts on food production could lead to higher global and local food prices; difficulties in accessing food due to displacement driven by climate extremes and disasters that may affect infrastructure (Jobbins and Henley, 2015).

Most studies focus on availability, whereas related issues of stability of supply, distribution, and access may all be affected by a changing climate (Bailey et al. 2015a). Low-income producers and consumers are likely to suffer the most because of a lack of resources to invest in adaptation and diversification measures to endure price rises (UNCCD 2017).

Utilisation. Climate change has been reported as a driver for emerging food and feed safety issues worldwide and its expected impact on the presence of mycotoxins in food and feed is of great concern (Battilani et al. 2016). There is some evidence that climate change will impact food safety due to changes in ambient temperature, salinity, and pH and their impact on the survival, multiplication, and distribution of microorganisms (Tirado and Meerman 2012). Aflatoxins have the highest acute and chronic toxicity of all mycotoxins; hence, the maximal concentration in agricultural food and feed products and their commodities is regulated worldwide. The possible change in patterns of aflatoxin occurrence in crops due to climate change is a may require anticipatory actions (Battilani et al. 2016; Medina et al. 2014). Overall, climate change is projected to increase the burden of diarrheal diseases in low-income regions by approximately 2%–5% in 2020 (Aberman and Tirado 2014).

Impacts of climate change on utilisation of food include impact on food safety due to increased temperatures; impacts on nutrition resulting from reduced water quality and quantity; and climate induced morbidity (Jobbins and Henley, 2015). Diet pathways entail impacts on the nutrient content of the food people grow and eat; health pathways entail food and water safety and diseases and infections that impact the ability of the body to absorb nutrients as well as nutrient requirements (Aberman and Tirado 2014). For instance, the 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. Furthermore, both diet and health interact as undernutrition increases susceptibility to disease, which may decrease productivity and lead to more food insecurity and undernutrition (Aberman and Tirado 2014).

Stability. Impacts of climate change on food stability include greater instability of supply due to increased frequency and severity of extreme events, including droughts; and instability of incomes from agriculture (Jobbins and Henley, 2015). A few recent studies that have studied price volatility (Diffenbaugh et al. 2012; Verma et al. 2014; Willenbockel 2012) have found that climate shocks can have temporary impacts on world market export prices that carry through to domestic consumer prices with strong regional effects in parts of Sub-Saharan Africa. Several studies have considered whether the severe 2007–2010 drought contributed to the conflict in Syria (Kelley et al. 2015, 2017; Challinor et al. 2018; Selby et al. 2017; Hendrix 2018) Most studies conclude that the drought was exceptional, i.e., the worst drought in the instrumental record, and some studies linked the drought to widespread crop failure, but the climate hypothesis has been contested (Selby et al. 2017; Hendrix 2018) (See Section 5.4 for further discussion).

5.1.4 The food system and climate change

A food system encompasses all processes, actors, and infrastructure involved in satisfying a population’s food and nutrition security, that is, the gathering/catching, growing, harvesting (production aspects, see section 5.2), storing, processing, packaging, transporting, marketing, and consuming of food, and disposing of food waste (non-production aspects). It includes food and nutrition security outcomes of these activities related to availability and utilisation of, and access to, food as well as other socioeconomic and environmental factors (Porter et al. 2014b; FAO, 2008). The outcomes also contribute to sustainable environments, livelihoods, and health. Interactions between and within biogeophysical and human environments influence both the activities and the outcomes. Climate change affects multiple aspects of the food system in regard to both impacts and adaptation, as well as mitigation of greenhouse gases.

In addressing the interactions of food systems with climate change, it is important to understand that different type of food systems exist. Throughout the world food is grown for local markets and self-consumption. There is a great variety of specific food systems characterised by production systems (large-scale commercial to smallholder subsistence), supply chains (long vs. short) or trade networks (global, regional, and local markets). Dietary choices influence these elements of food systems and affect greenhouse gases emissions and health (Nelson et al. 2016; Hallström et al. 2017; Drewnowski 2014; Tilman and Clark 2014). Following Ericksen (2008), UNEP groups them into *traditional*, *modern* and *intermediate*. Different food systems present different characteristics in terms of production systems and types of farms/livelihoods from which they rely, they target different markets and offer different choices and type of diets to consumers (UNEP 2016; Drewnowski and Popkin 1997; HLPE 2017), they have different approaches to achieve food and nutrition security.

5.1.4.1 Climate change interactions with the food system

The term *food system* encompasses the entirety of 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).

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).

Climate change affects global agriculture productivity (Porter et al. 2014b; Rosenzweig et al. 2014). At the same time, agriculture is an important contributor to climate change, accounting directly for 10%-12% of anthropogenic greenhouse gas emissions (Frank et al. 2017), and indirectly accounting for 24% through land use change (Tubiello et al. 2015). Understanding the effect of climate variability on food systems and its relation with food and nutrition security and poverty, and identifying effective adaptation measures is imperative to ensure food and nutrition security now and in the future. In Sub-Saharan Africa, climate and price variability currently depress farm household income by about one fifth with productivity losses outweighing price increases with subsequent effects on food availability, access, and stability (Wossen and Berger 2015; Wossen et al. 2018).

Supply chains are disrupted by extreme climate events (Levermann 2014), while they are also large contributors to greenhouse gas emissions through transportation (Avetisyan et al. 2014), waste (Porter et al. 2016; Hiç et al. 2016), and energy use (Mohammadi et al. 2014). Additionally, climate change negatively impacts the quality of food (Müller et al. 2014). In addition there is growing recognition that dietary behaviours, have negative environmental impacts through overconsumption of food, and choice of resource-intensive food types (Tom et al. 2016; Aleksandrowicz et al. 2016a; Bryngelsson et al. 2016; Hedenus et al. 2014; Springmann et al. 2016b; Development Initiatives 2017; Harwatt et al. 2017).

For further discussion on the impacts of food systems on GHG emissions and climate change see Section 5.3, and for observed impacts and projections of climate change on food systems see Section 5.6.

5.1.4.2 Role of social and economic aspects

The interactions of climate change and food systems are highly complex because there is not a unique type of food system. Different types of food systems reflect different perceived functions of agriculture in society (Rivera-Ferre 2012).They result from ecological drivers acting within the context of historical and social conditioning and belief systems (Fieldhouse 1995). (UNEP 2016; Drewnowski and Popkin 1997; HLPE 2017) Whereas economic development has led to improved food security in quantitative terms, adverse health effects of the nutrition transition are many, including growing rates of childhood obesity through low-quality diets (Drewnowski and Popkin 1997).

The selection of the food is influenced by many factors, including price and income levels, but also cultural traditions or preferences, social values, education and health status (Ericksen 2008), as well as by the 'food environment'. Food environment refers to the physical, economic, political and socio-cultural context in which consumers engage with the food system to make their decisions about acquiring, preparing and consuming food (HLPE 2017). Given the connections among all the elements of food systems, consumption decisions will have impacts all the way back along the food chain, both environmental and social.

At the same time, because the globalised food system is increasingly based on long-supply chains and a relatively small number of commodity crops, often incentivised through domestic and international policies, there is a tendency for the food systems of local cultures to become more similar (Claquin et al. 2017).

The ERA-Net SUSFOOD (SUStainable FOOD production and consumption) project includes social and economic aspects in its definition of suitable food systems (italics added): "a food system that supports food and nutrition security, makes optimal use of natural and human resources and respects biodiversity and ecosystems for present and future generations, is *culturally acceptable* and accessible, environmentally sound and *economically fair and viable*, and provides the consumer with nutritionally adequate, safe, healthy and affordable food" (Capone et al. 2014). See also (Eakin et al. 2017; Garnett 2014; Ingram et al. 2008; HLPE 2017) for further discussion of sustainable food systems.

5.1.5 Links to Sustainable Development Goals and Nature's Contributions to People

Two major global policy initiatives interact with the food system and its ability to deliver food and nutrition security under climate change: the Sustainable Development Goals (UNSG 2017) and IPBES (Pascual et al. 2017).

5.1.5.1 Climate change, food and nutrition security, and the SDGs

Sustainable Development Goal 2 (SDG2) aims to end hunger and all forms of malnutrition by 2030; it also commits to universal access to safe, nutritious and sufficient food at all times of the year. SDG 13 calls for urgent action to combat climate change and its impacts. Intra- and inter-linkages of SDG2 to end hunger and all forms of malnutrition by 2030 and SDG13 to take urgent action to combat climate change and its impacts with each other and the other SDGs are shown in Figure 5.3. SDG2 is highly synergistic with many of the other SDGs, but has trade-offs with SDG12 (Responsible Consumption and Production) and SDG15 (Life on Land) (Pradhan et al. 2017). Under the current development paradigm, progress made on ending hunger would have negative consequences on goals related to responsible consumption and production and life on land. Therefore, achieving SDG2 under changing climate conditions will require sustainable food production systems and resilient agricultural practices, equal access to land, effective markets, and international cooperation on investments in infrastructure and technology to sustainably boost agricultural productivity (UNSG 2017).

Past data show mostly trade-offs between SDG13 and other goals based on the limited number of indicators provided for this goal. For example, trade-offs were observed between SDG2 and SDG13 for around 50% of the cases. These large trade-offs highlight the potential need to evolve from current development paradigms that involve lock-in effects in order to protect climate and to achieve food and nutrition security.

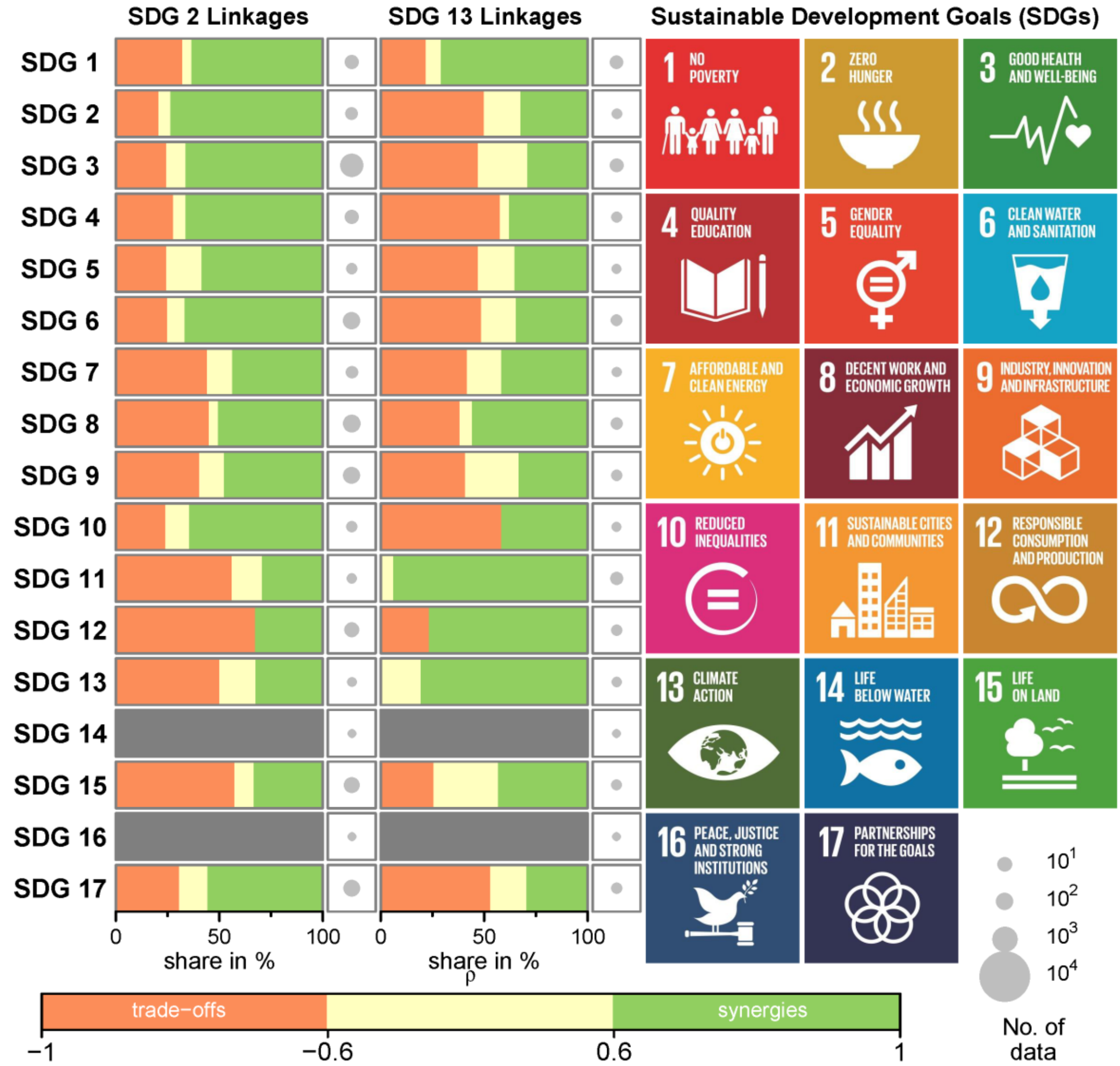


Figure 5.3 Intra and interlinkages of SDG2 to end hunger and all forms of malnutrition by 2030 and SDG13 to take urgent action to combat climate change and its impacts. In past, whilst larger synergies were observed between SDG2 and other SDGs, SDG13 depicted larger trade-offs. We need to leverage synergies and tackle trade-offs to attain the SDGs by 2030. The figure was reproduced following the method of Pradhan et al. (2017) to statistically quantify SDG interactions (Pradhan et al. 2017)

5.1.5.2 Climate change, food and nutrition security, and Nature's Contributions to People

NCPs are all the contributions, both positive and negative, of living nature (diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to people's quality of life

(Díaz et al. 2018). For example, agrobiodiversity is key to improving the sustainability of regional cropping systems, particularly in a context of low external inputs and unpredictable climate change (Costanzo and Bàrberi 2014). A better integration between breeding and management and a clear focus on crop traits related to key NCPs are needed to develop crop types that can contribute resilience to changing climate. Some crop genetic resources are already available that perform relatively well under climate stresses (e.g., high temperature, drought, flooding).

Some of these are under-researched local varieties/breeds of crops and livestock present in a wide range of geographies. There is also potential for improving climate resilience through genetic engineering across species; these techniques are contested due to a range of issues including intellectual property rights and environmental effects. Examples of NCPs related to agroecosystems include weed reduction, nitrogen use efficiency, abiotic stress tolerance, disease and pest reduction and yield and yield stability (Costanzo and Bàrberi 2014). Agrobiodiversity provides other NCPs, such as cultural values.

Genetic diversity in livestock breeds is crucial for agriculture and food production since it allows for the raising of farm animals in a wide range of environments and provides the basis for diverse products and services. Globally, 20% of local livestock breeds, meaning breeds reported in only one country, are at risk of extinction. Another 16% of breeds are stable, and the status of the remaining local breeds is unknown owing to a lack of data. The figures exclude livestock breeds that have already become extinct (UNSG 2017).

5.1.6 Links to desertification and land degradation

Desertification and land degradation can undermine livelihoods related to food systems as a result of an effectively permanent reduction in the provision of NCPs from land (including provisioning, supporting, regulating and/or cultural services) (Pascual et al. 2017; Díaz et al. 2018) (See Chapters 3 and 4). Often, this is due to the undervaluing and consequent loss of natural capital beyond critical thresholds. To reorient food production management pathways away from degradation and towards Sustainable Land Management (SLM) requires natural capital to be sufficiently valued to be maintained above critical thresholds (Reed et al. 2015; Dasgupta et al. 2014). To do this requires internalising the external costs of food production.

New mechanisms may address the economic root causes of land degradation caused by food systems that can benefit both the rich and the poor, and which can sustain food system livelihoods through the continued provision of NCPs across a range of types of land tenure (Reed et al. 2015).

In some regions, higher temperatures and changes in precipitation patterns associated with climate change have affected the process of land degradation, compromising extensive agricultural areas (See Chapter 4). Degradation and desertification increase vulnerability to market volatility and the management of food supply shortages caused by climate change (Porter et al. 2014b). Thus, desertification and land degradation exacerbate the effects of climate change on food and nutrition security. Desertification and land degradation processes (e.g., soil erosion, nutrient depletion) threatened the livelihood of 20% of the global population in 2015, i.e., food and nutrition security for almost one billion people, and reduced national productivity (GDP) in many countries (Siegel 2016).

Desertification and land degradation lead to uncertain crop yields and local food supplies and results in higher risks of landslides and erosion damage. Analyses of land suitability that includes desertification and land degradation can be the basis for projecting potential optimum yield for the current suite of crops and cultivars that comprise agricultural production (Schmidhuber and Tubiello 2007). Land degradation related to agriculture has been proven to be the strongest driver of land productivity loss and forest degradation (Díaz et al. 2018; Pascual et al. 2017). Because all ecosystems have some sort of land degradation due to human influence, land degradation related to agriculture affects 2/3 of the global economic impact (GEP) estimated to be 10% of GEP (Díaz et al. 2018; Pascual et al. 2017). It can be reversed cost effectively using various solutions depending on local context (Schmidhuber and Tubiello 2007).

Land degradation generally means that less food is produced on the land, which has a direct impact on the health and well-being of the residents and nearby communities. The increase in rural populations depending on degrading agricultural land is seen as a major obstacle to poverty reduction strategies (UNCCD 2017). Nutrient depletion of soils combined with accelerated erosion and reduced fallow periods have direct consequences on crop productivity, food production, food and nutrition security and human livelihoods (Erşahin et al. 2017).

Slowing land degradation by agricultural intensification has been identified as a main direction for addressing ecosystem health while supporting food production systems across the globe. Various forms of intensification have been expected to reduce deforestation. But intensification itself has many motivations, many dominated by technology and markets (Byerlee et al. 2014). Byerelee et al (2014) found in some cases that land expansion can be connected to technical change when this happens near the forest frontier. At a global level, technology-driven intensification can be strongly land saving although deforestation in specific regions (Africa, Latin America and South-East Asia) is likely to continue to occur. Market-driven intensification (often steered by agrobusiness), however, is often a major cause of land expansion and deforestation especially for export commodities in times of high prices. Land saving related to intensification has large spectrum of impacts that could be contrary to forest land sparing. The impact on soils (tillage), water (drainage, deep wells) and air (VOCs, air pollution, smoke) can be large.

In Africa, land sparing has often been done at the expense of rural livelihoods (Minang et al. 2015). For example, most reserves and national parks have been taken out of the landscape continuum of local communities. Human-ecosystem interactions through land sharing, where conservation and productive activities are combined with clear set of goals, can include preservation of ecosystem functions.

Forest degradation and the loss of vegetation have made the Himalayan watersheds more vulnerable to erosion, which has led to loss of soil and nutrients required for food production, siltation of rivers and reservoirs, and increases in the incidence and severity of flooding which can damage crops and livestock (Rasul 2014). The Koshi River in Nepal carries an annual load of 119 million cubic meters of silt, which is equivalent to 2 mm of topsoil depth over its entire catchment (Laban 1979). Siltation is not only causing river beds to rise; it is also affecting the water infrastructure, reducing the life of reservoirs and dams for hydropower, irrigation, and flood control, thus affecting energy and food production (Tiwari 2000).

Watershed degradation is also resulting in decreased groundwater recharge and consequent drying up of springs, streams, and other water sources (Tiwari 2000; Tiwari and Joshi 2012a). This has caused shortage of water for drinking, irrigation, and other livelihood activities in the Himalayas.

Land suitability is highly important in regard to adaptation to new climate conditions with variable pressures from changes in temperature, rainfall, and other climate variables and their impacts on functional processes such as timing of pollination. Projections how the potential for a general southward shift in rainfall in the tropics combined with a northward shift in temperate zones leading to a considerable increase in suitable cropland at higher latitudes. However, overall a net decline of > 100 million ha is projected, a massive decline in agricultural prime land (Schmidhuber and Tubiello 2007).

5.2 Status and current trends of the food system under a changing climate

Since World War II, the food system has evolved following the concept that inexpensive food was a public good. This has enabled greater consumption (and thus economic growth), reduced global food insecurity in terms of quantity, and set the conditions for globalised, competitive markets, where price competition takes priority (McKeon 2015). Whilst this has reduced food prices (locally and globally), it has had a number of consequences, including development of industrial agriculture and breadbasket regions, increasing concentration of production in fewer commodity crops, increasingly complex trade networks and mutual embeddedness, increasing homogenisation of global diets, increasing inefficiency of the food system as a whole, including food loss and waste, and increasing systemic risks and adverse health effects. Price reduction has been enabled by the ability to externalise unmeasured costs onto either the environment or health systems, through incentivising (over-) consumption of food that is calorically dense, and inexpensive, over food that is nutritionally dense and more expensive (O'Rourke 2014).

Following the 2007-2008 and 2010-2011 food price spikes (see Sections 5.6.5.1, 5.9.1) there has been increasing recognition of the systemic risks associated with the food system. This recognition is in part driven by the likelihood of extreme weather perturbing its functioning increasing in future. For both 2007-2008 and 2010-2011 there is evidence that extreme weather (Australia and Ukraine/Russian droughts) acted as an initial spark for a price signal that demand and supply were out of balance, however, a range of factors led to the over-amplification of this signal, with the worldwide consequences thereafter (Bailey et al. 2015b; Bellemare 2015; Homer-Dixon et al. 2015; Tadasse et al. 2016; Challinor et al. 2018).

In this section, we review the status and current trends of food and nutrition security and the structure and main components of the food system. For greenhouse gas emissions from the food system and detection and attribution of observed climate change impacts see Sections 5.3 and 5.6 respectively. Trends since 1960 in key elements of the food system and its food and nutrition security outcomes are summarised in Figure 5.4, showing that crop and animal production, trade, food supply, and agricultural emissions are growing, with declines in undernutrition but increases in overweight and obesity. See Supplementary Material 5.11 for further assessment of the status and current trends of the food system and food and nutrition security.

5.2.1 Food and nutrition security

In addressing food and nutrition security the dual aspects of malnutrition – under-nutrition and micro-nutrient deficiency, as well as over-consumption, overweight, and obesity – need to be considered. The UN agencies' *State of Food and nutrition security and Nutrition* 2017 report (FAO et al. 2017) and the Global Nutrition Report 2017 (Development Initiatives 2017) focus on the developing-world hunger challenge and highlighted the increase of the global undernourished population from 777 to 815 million between 2015 and 2016. However, these numbers have been declining on average for the last three decades, though with two periods of upturns (2005-2007, and 2015-2016). These figures may underestimate the trends and the number of undernourished worldwide (Hickel 2016), and at the same time they may significantly under-represent the prevalence of undernourishment in the developed world. For example, a 2003 study in the UK (Schenker 2003a) estimated that 40% of adults, and 15% of children, admitted to hospitals were undernourished, and that undernourishment was significantly under-reported within the UK. This highlights the importance of considering the impact of inequality on food and nutrition security and the way its chronic nature can be obscured by a focus on broader patterns and trends.

Furthermore, interpretation of the state of food and nutrition security depends on how encompassing is its definition. 815 million people are hungry, as many as two billion have some form of nutrient deficiency, and there are more obese adults than underweight. In total, more than half the World's population are underweight or overweight, 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.

5.2.2 Food production system

On a global basis, there are estimated to be 570 million farms. Globally, the distribution of farm sizes varies with geography, but between 51% and 77% of the volume of the major food groups for human consumption – cereals, fruits, pulses, roots and tubers, and vegetables – comes from farms less than 50ha (Herrero et al. 2017). The 570 million farms are estimated to underpin as much of 40% of the total economically active workforce in the world, and for some countries over 50% of labour is in agriculture (FAOSTAT 2015). An estimated 70% of the poorest in the world live in rural areas where agriculture is the dominant activity. Samberg et al. (2016) found that small farmers are crucial both in local and global food security. They support the livelihoods of many of the most marginalised populations and also produce more than 70% of the food calories produced in Latin America, sub-Saharan Africa and South- East- Asia, using only 30% of the agricultural land. Farmers in these densely populated regions are responsible for more than half of the food calories produced globally, as well as more than half of global production of several major food crops.

At the individual level, proper functioning of the food system is necessary for daily life, health, and well-being. Since 1960, total food supply has increased almost threefold as compared to a population growth of two fold. However, while the fight against hunger has progressed over the past 15 years, the prevalence of overweight and obesity is increasing (NCD-RisC 2016a; UNSG 2017).

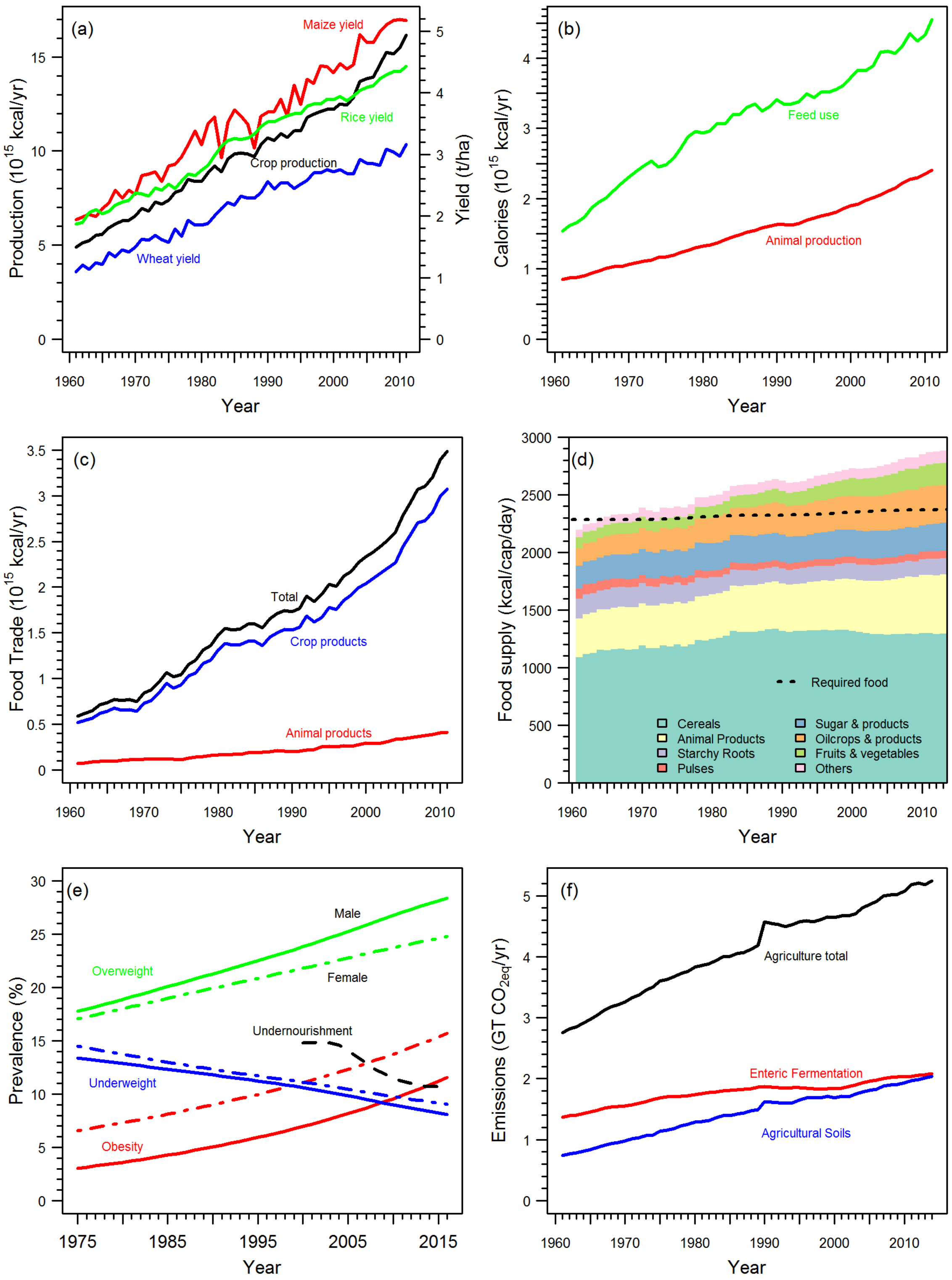


Figure 5.4 Global trends in (a) total crop calorie production and yields of maize, rice, and wheat, (b) production of animal calories and use of crop calories as livestock feed, (c) food trade in calories, (d) food supply from 1961 to 2012, (e) prevalence of undernourishment, overweight, obesity and underweight from 1975 to 2015, and (f) GHG emissions for the agriculture sector. These figures are based on data from FAO (2017), Hiç et al. (2016), and (Abarca-Gómez et al. 2017). For figures (a), (b), and (c), the data from FAO (2017) were converted into calories based on nutritive factors as described in Pradhan et al. (2013a).

5.2.3 Food supply chains, markets, and trade

5.2.3.1 Increasingly complex trade networks and mutual embeddedness

The last decades have seen a global move to liberalise international trade, create global markets, drive innovation, and increase efficiency in production. There is a trend towards increasingly complex networks of trade and interdependence. Global trade (in tonnes of produce) typically flows from regions with very high production to those with lower production (Figure 5.5 data from 2010). As part of this process, agriculturally important nutrients and water are being moved from nutrient-poor regions (e.g., Africa) to nutrient-rich countries by being embedded in food that is being internationally traded. This further exacerbates degradation in the sourcing countries. In 2015, the total trade in agricultural produce was 1.1 trillion USD, with the top five exporters being the US (119 billion USD), Brazil (77 billion USD), Netherlands (57 billion USD), Germany (48 billion USD) then China (47 billion USD), and top five importers being China (120 billion USD), Germany (93 billion USD), US (69 billion USD), Japan (47 billion USD), and the Netherlands (46 billion USD) (Chatham House 2017).

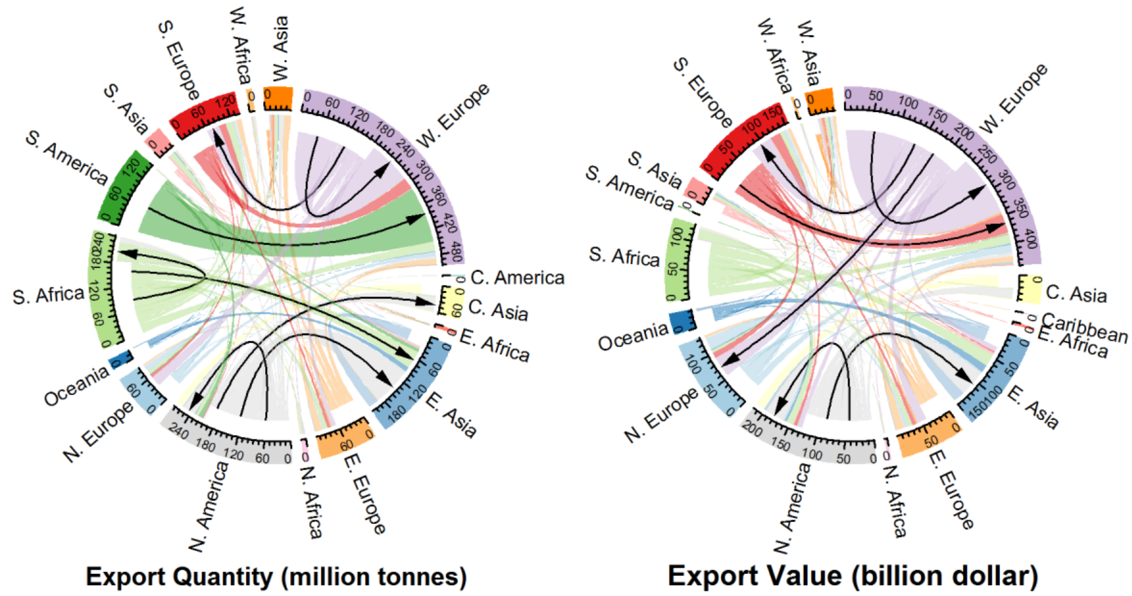


Figure 5.5 Global agricultural exports (in quantity and value) for 2010 on a regional scale based on FAOSTAT (FAO 2018). Total exports of at least one million tonnes or one billion USD are presented. The largest exporter in terms of amount (tonnes) may not necessarily be the largest exporter in terms of dollar value. Discrepancies in trade amount and value also hold for calories, water and nutrient foot prints as reported by (MacDonald et al. 2015)

5.2.3.2 Increasing concentration of production in fewer commodity crops

The presence of the global market, coupled with a supportive environment for agricultural intensification (regulations, policy, subsidy, and infrastructure) and equitable conditions of soil fertility, climate, etc., allows nations with comparative advantage to produce the crops they do best at producing in large amounts. This has helped contribute to concentration of production on fewer crops as each breadbasket area increasingly specialises in production of the global commodity crop it can best produce. On a global basis global calories come from the following crops as a percentage of total production: maize (20.4%), wheat (18.4%), rice (15.5%), palm oil (6.2%), soybeans (5.7%), barley (4.4%), sugar cane (3.6%), potatoes (2.0%) (West et al. 2014). Eight crops provide 74.2% of global calories. Widespread international trade in these crops, coupled with global competition, has driven up yields of these crops and, on average, drove down global prices – at least until the food price spike in 2007-2008.

5.2.3.3 Food prices and price volatility

One impact of the transmission of climatic risks to food and nutrition security is food price volatility (Bailey et al. 2015a). A global food system, which is gradually developing greater global-inter-dependence through more complex trade (Puma et al. 2015), and under gradually increasing pressure from demand and competition for resources (Marianela et al. 2016) can be perturbed by a single climatic event. Such shocks interact with the existing market and its rules to drive price signals, which can be amplified by a range of endogenous factors (Challinor et al. 2018; Tadasse et al. 2016). These responses can also create indirect effects reducing overall vulnerability of the system in the short-term, for example through bringing more land into agriculture (though this may increase long-term climate risk through creating more emissions of GHGs).

Resource-generated risk amplification mechanisms can include properties of the underlying social systems (e.g., functioning of local markets) as well as aggregate responses of social systems to the underlying climate risk (e.g. international financial speculation, or export bans, affecting global markets). To the extent that climate change outpaces natural and human adaptation, or if climate change intensifies a systematic pattern like El Niño Southern Oscillation (ENSO) there would be a climatically-generated long term risk transmission mechanism. Implicit in this discussion of risk transmission (Challinor et al. 2017) is that there are two attribution issues for climate change impact assessment: was a climate event (e.g., extreme weather) influenced by climate change, and, if so, was it contributory, directly or indirectly, to impacts on the food system?

5.2.4 Food consumption and demand

Changing consumption patterns associated with dietary transitions that accompany income growth, urbanisation, market development, and trade liberalisation determine the rate and nature of food demand growth and nutritional levels, and thus is a key determinant of global and local food and nutrition security (Porter et al. 2014b). Changing consumption patterns will directly change GHG emissions (Pradhan et al. 2013b).

For food, there has been a strong relationship between income and demand (Tilman et al. 2011; Bodirsky et al. 2015; Pradhan et al. 2013b; Drewnowski and Popkin 1997). Whatever level of income, as people have become richer they consume more calories, primarily driven by eating more (at very low poverty levels), then eating more livestock produce and producing more food waste (as incomes rise). This requires feed for animals which is converted inefficiently into food for humans (Pradhan et al. 2013a). Other factors for increasing consumption of animal products relate to policies (Rivera-Ferre 2009) providing some opportunities for future dietary changes towards low carbon diets through policy changes.

5.2.4.1 Dietary diversity

Both diets and agricultural systems have been greatly simplified over the past century. Global diet as a whole is becoming more homogenised with a declining intake of nutritious pulses, fruits and vegetables and a predominance of starches such as rice, wheat and maize along with meat and dairy (Bioversity International 2016). General components of healthy diet as defined by the World Health Organisation include fruits, vegetables, legumes, nuts and whole grains (WHO 2015a). These essential elements are provided through food diversity, or the diversity of plants, animals and other organisms used for food, covering genetic resources within species, between species and provided by ecosystems, both cultivated and from the wild. These trends can have both positive and negative local effects. For example, in the Andes, global demand for the alternative seed quinoa has led to dietary changes in importing countries, but also increased production of particular crop varieties and reduced diversity, displacement of alternative uses (such as livestock) and accelerated processes of soil degradation in the producing countries (Hellin and Higman 2005).

However, we are witnessing a reduction of biodiversity globally. As global trade in a relatively small number of crops has increased, the consumption of those crops (and animals able to be reared on them) across nations has led to a narrowing of dietary ranges (Khoury et al. 2014b). Increasingly, people's diets depend on the same narrow range of commodity crops – providing calories from starch, sugar and oil, in a process called nutrition transition, although the number of crop commodities contributing to national food supplies has increased.

The global food consumption habits between 1961 and 2007 can be represented by 16 dietary patterns that differ in terms of calorie content and diet composition. The dietary patterns can be broadly classified as low (fewer than 2100 kcalcap^{-1}day^{-1}), moderate (2100–2400 kcalcap^{-1}day^{-1}), high (2400–2800 kcalcap^{-1}day^{-1}), and very high calorie diets (greater than 2800 kcalcap^{-1}day^{-1}). In general, diet shifts from low and moderate calorie diets to high and very high calorie diets with increase in human development index (HDI) (Pradhan et al. 2013b).

5.2.4.2 Nutrient content, food quality, and food safety

Knowledge on nutrient contents of various crops, livestock and fisheries including their varieties and breeds can be used to select and promote the most nutrient-dense species, varieties and breeds for food and nutrition security. The nutrient composition of numerous wild and indigenous species is higher for many nutrients (micronutrients in particular) than their more widely cultivated counterparts which in selecting for high-yields have reduced their nutrient content (Davis et al. 2004). For example, many indigenous small fish in Bangladesh contain more than the daily requirement of B12 for pregnant women and children whereas more commercial species such as tilapia and carp contain less than 20% of the daily requirement (Bioversity International 2016). Indigenous banana cultivars found in Pacific Islands contain huge amount of carotenoids (antioxidant and precursor of Vitamin A) whereas commercially cultivated Cavendish banana contains almost no carotenoids (Englberger et al. 2003). Significant differences in nutrient content in meat and milk among different breeds of the same animal have also been documented (Barnes et al. 2012; Medhammar et al. 2012). One important attribute of these breeds and varieties is that they are available to poor people since they do not rely on property rights-regime. In that manner, they can play an important role in food and nutrition security in practical terms.

Information about the global structure of agriculture and nutrient production and its diversity is essential to improve present understanding of national food production patterns, agricultural livelihoods, and food chains, and their linkages to land use and their associated ecosystems services (Herrero et al. 2017; Khoury et al. 2014b). Agro-ecological research demonstrates that systems diversity can stimulate long-term productivity, stability, NCPs to and from agricultural lands, and resilience to shocks (e.g., pests and diseases, climate, or price shocks). Trade-offs between maintaining diversity at the field, landscape, or national scale for nutritional, economic, and environmental outcomes, therefore need careful consideration in food-system recommendations (Remans et al. 2015).

Food safety refers to all those hazards, whether chronic or acute, that may make food injurious to the health of the consumer. It is not negotiable (FAO and WHO 2003). Quality includes all other attributes that influence a product's value to the consumer. This includes negative attributes such as spoilage, contamination with filth, discoloration, off-odours and positive attributes such as the origin, colour, flavour, texture and processing method of the food. This distinction between safety and quality has implications for public policy and influences the nature and content of the food control system most suited to meet predetermined national objectives (FAO and WHO 2003). Currently, one in ten people worldwide fall ill due to contaminated food, being children below five the most affected, carrying 40% of the foodborne disease burden (WHO 2015b). In total, 420,000 people die every year after eating unsafe food. Food safety is a complex issue where social (different eating habits and social groups play distinct role) and economic (different types of countries impacted differently both in quantitative and qualitative terms; global trade of food play a key role) aspects are relevant (Uyttendaele et al. 2015)

5.2.5 Food loss and waste

Food loss is considered as the reduction of edible food during primary production, postharvest, processing, and distribution. Discarded food at the consumer and household level is referred as food waste. 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). In absolute terms, a larger amount of per capita food loss and waste occurs in developed countries compared to developing ones (FAO 2011a). Due to variations in definitions and applied methodologies, estimate of food loss and waste differs across studies. Some recent studies also consider over-eating and consumption of resource-intensive animal-based products instead of plant-based alternatives that are nutritionally comparable as food waste (Alexander et al. 2017a; Shepon et al. 2018). The third target of SDG12 (responsible consumption and production) aims to halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses.

Since 2011, considerable effort around the world has been made to improve estimates of food loss and waste, and, so far, while countries and food systems vary, the figure of 20%-30% loss and waste is taken as a reasonable consensus. FAO (2011b) estimated that one-third of the produced food, about 1.3 billion ton per year, was either lost or wasted in 2007 globally, while Kummu et al. (2012) found around one quarter of the produced food supply (614 kcal $cap^{-1}day^{-1}$) is lost within the food supply chain. In the last 50 years, food waste grew from 300 kcal day^{-1} to 500 kcal day^{-1} on the global level, and the associated GHG emissions for producing wasted food increased from 130 Mt CO_2eq yr^{-1} to 530 Mt CO_2eq yr^{-1} (Hiç et al. 2016). The growth in food waste over 50 years shows that food waste has been increasing faster than crop yields (Porter et al. 2016). Total carbon footprint of food loss and waste in 2011 was around 4.4 Gt CO_{2e} yr^{-1}, accounting for the lifecycle of lost and wasted food (e.g., production, processing, transportation, cooking, etc.) and emissions from deforestation and managed organic soils (FAO 2015a, 2013a). 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 production-phase N_2O emissions (more than 200 Gg N_2O-N yr^{-1}) (Reay et al. 2012). When complete avoidance of food loss and wastage is considered, the reduction potential of the N_2O emissions exceed 1 Tg N_2O-N yr^{-1} (Reay et al. 2012).

5.3 Impacts of food systems on climate change – Greenhouse gas emissions from production, supply chains, and consumption

5.3.1 Greenhouse gas emissions from food systems

According to data presented in the AR5, the emissions from agriculture, forestry and land use represented close to 25% (10-12 Gt CO_2 eq yr^{-1}) of global greenhouse gas emissions for the period 2000-2010. Direct non-CO_2 emissions from agricultural activities ranged from 5.0-5.8 Gt CO_2eq, while land use change accounted for 4.3-5.5 Gt CO_2eq. These ranges have changed slightly, but the major sources of emissions remain deforestation, enteric fermentation from livestock, and agricultural emissions from soil and nutrient management. Figure 5.6 shows emission intensity for cattle meat, cow milk, and cereals excluding rice.

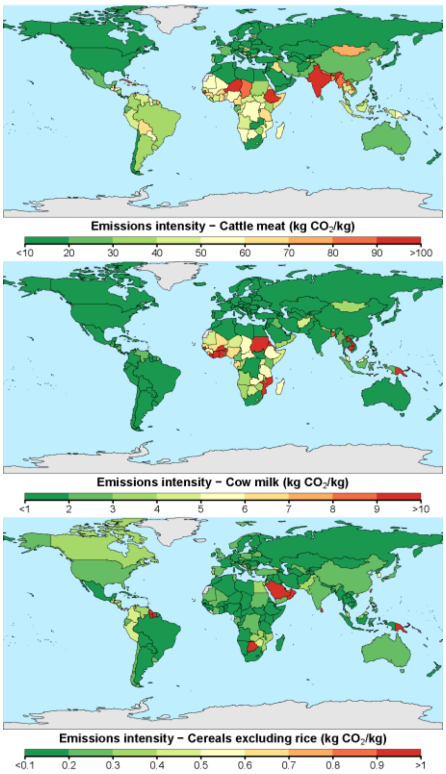


Figure 5.6 Emission intensities of agricultural products varies across countries, presented for cattle meat, cow meat and cereals (excluding rice). The figures were generated based on data from FAOSTAT (FAO 2017).

5.3.2 Greenhouse gas emissions from croplands and soils

Emissions from crops range from 2-3 $GtCO_2eq$ yr^{-1}, and according to Carlson et al. (2017), these are dominated by methane emissions from rice (48%), peatland cultivation (32%) and N_2O from fertiliser applications (20%). Ten crops (rice, maize, wheat, barley, coconut, sugarcane, soybean, oil palm, potato and rapeseed) account for 75% of cropland emissions. Most emissions originate in Asia, with India, China and Indonesia accounting for 51% of cropland emissions. They also found a weak association between production intensity and the respective cropland emissions. Figure 5.7 shows the spatial distribution of emissions from croplands.

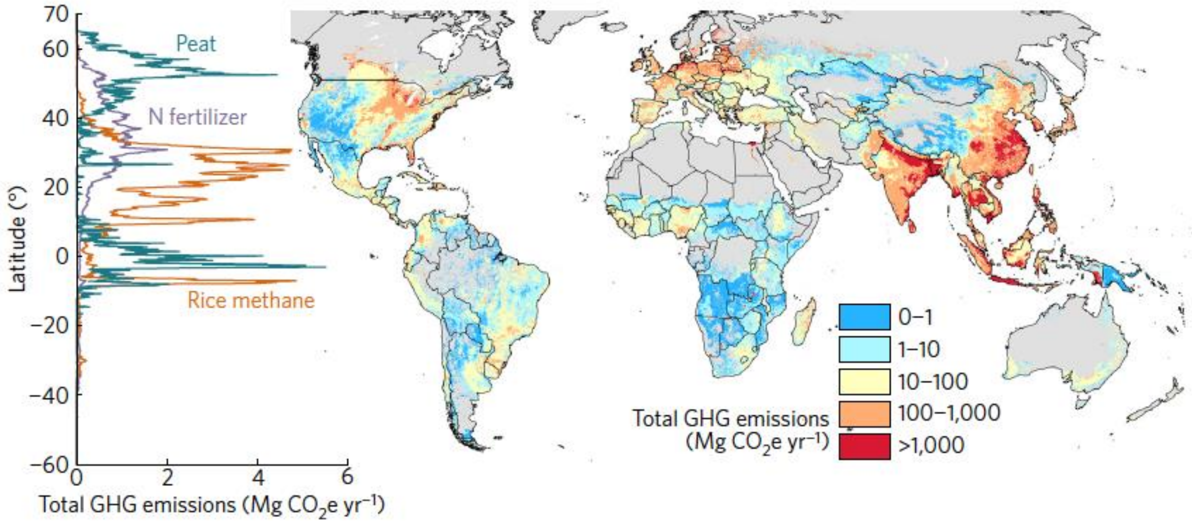


Figure 5.7 Global emissions from cropland (Carlson et al. 2017)

5.3.3 Greenhouse gas emissions from livestock

Figure 5.8 presents the distribution of emissions from livestock. According to Herrero et al. (2016), non-CO_2 emissions from livestock range from 2-3.6 Gt CO_2eq, with the main contributor being enteric fermentation from ruminants. Cattle are the main source of emissions (65%-77%) (FAO, 2013; Herrero et al., 2013). 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. While emissions and emission intensities are heterogeneous throughout the world, mixed crop-livestock systems account for 58% of livestock emissions, while grazing systems account for 19% of sectoral emissions. Industrial systems, dominated by monogastric production, account for the remainder (23%). The livestock sector has reduced emissions intensities by 60% since 1961 (Davis et al. 2015), however products like red meat, are still the most inefficient in terms of emissions per kg of protein produced by a factor of five or more in comparison to milk or pork, eggs and all crop products. Animal numbers remain the main source of variation in total gross emissions of the livestock sector, while at the animal level, feed intake is the main source of variation of emissions and N excretion, followed by diet quality.

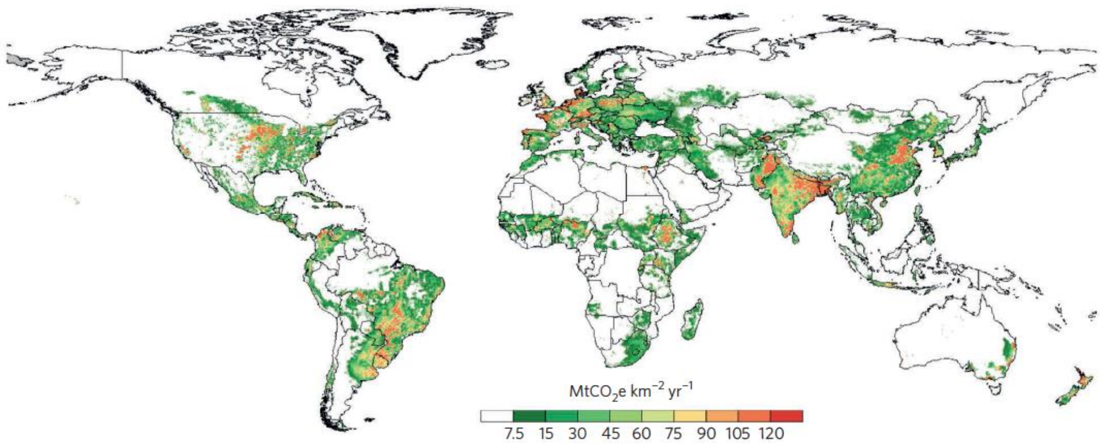


Figure 5.8 Greenhouse gas emissions from global livestock circa 2005 (Herrero et al., 2016)

Novel studies have tried to improve the accuracy of these estimates. (Gerber et al. 2016) suggest that N_2O emissions from soils could be 20%-40% lower than expected for Sub-Saharan Africa and Eastern Europe, when taking into account non-linearities in fertiliser and manure response curves, while Pelster et al. (2017) also found lower soil and manure emissions from smallholder systems in East Africa. The majority of variation in N_2O emission factors are due to a) climate, b) soil type and c) N form (Charles et al. 2017; Fitton et al. 2017). Herrero et al. (2016) found that global livestock enteric methane estimates range from 1.6-2.7 Gt CO_2eq and that these depend on the method of estimation, and assumptions on body weight and diet of the animals. Niu et al. (2018) also found that IPCC Tier 2 methods overestimated enteric methane emissions by 22% when compared against experimental data from European and North American dairy cattle. Taking these into account, the range of non-CO_2 emissions from agriculture would increase from the AR5 estimation of 5.0-5.8 Gt CO_2eq to 4.0-6.6 Gt CO_2eq. Emissions from deforestation remain consistent with the AR5 estimates.

5.3.3.1 Limitations in monitoring, recording, and verification of GHG emissions from livestock

Comparisons of GHG emissions from livestock production between countries are confounded by countries due to the use of different methods (e.g. default IPCC Tiers 1 and 2, and different specific Tier 3 models or emission factors). A number of countries have moved to Tier 2/3 for methane and nitrous oxide in order to a) reduce uncertainties associated with emissions and b) to incorporate mitigation technologies into inventories (feed inputs to reduce methane, inhibitors to reduce N_2O for example). This will result in different emissions associated with the same given activity level depending on the country. Indeed, Charles et al. 2018 reported 422 different emission factors for N_2O arising from the input of organic amendments alone. For example, the Tier 1 default EF3, the N_2O emission factor for N deposition on pasture, range and paddock, is 2% of applied N. However, for New Zealand, EF3 is 1% for urine N and 0.25% for dung (Luo et al. 2009). Differences in higher Tier EF's from country to country are generally based of differences between feed type and animal breeds (methane) and N form, soil type and climate (for N_2O). As a result, GHG emissions associated with lower income countries which use Tier 1 EF's or have poor recording of activity data (animal numbers, land use, etc.) will have a much higher degree of uncertainty and emissions may be grossly over- or under-estimated.

5.3.4 Greenhouse gas emissions from aquaculture

Global emissions of aquaculture are an under-researched field, but play a considerable role in greenhouse gases emissions, mostly through N_2O emissions (Hu et al. 2013), primarily in intensive aquaculture, and CH_4 (Yang et al. 2015). Yet, methodologies to measure emissions are still being developed (Vasanth et al. 2016) and thus, current numbers can suffer changes in the future. N_2O emissions from aquaculture 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 9.30×10^{10} g, but could increase to 3.83×10^{11}g, 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 0.12 Tg N_2O–N yr^{-1}, and suggested that this may rise to more than 0.6 Tg N_2O-N yr^{-1} within 20 years for an estimated annual growth of 8.7% (Williams and Crutzen 2010)

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

Vermeulen et al. (2012b) estimated that 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. These emissions account for 18%-20% (1.5- 2.2 $GtCO_2eq$) of the emissions generated by food systems. For example, in intensive crop systems, fertiliser manufacture alone can account for up to 20% of the emissions intensity of production.

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 32%-24% 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. 2017).

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.

5.3.6 Greenhouse gas emissions associated with different diets

There is now an extensive literature on the relationship between food products and emissions (Figure 5.9). Nelson et al. (2016) updated 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. A similar hierarchy from roots to beef was found in another recent review focussing exclusively on GHG emissions (Clune et al. 2017).

The emissions intensities of red meat mean that it has a disproportionate impact on total emissions. 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.

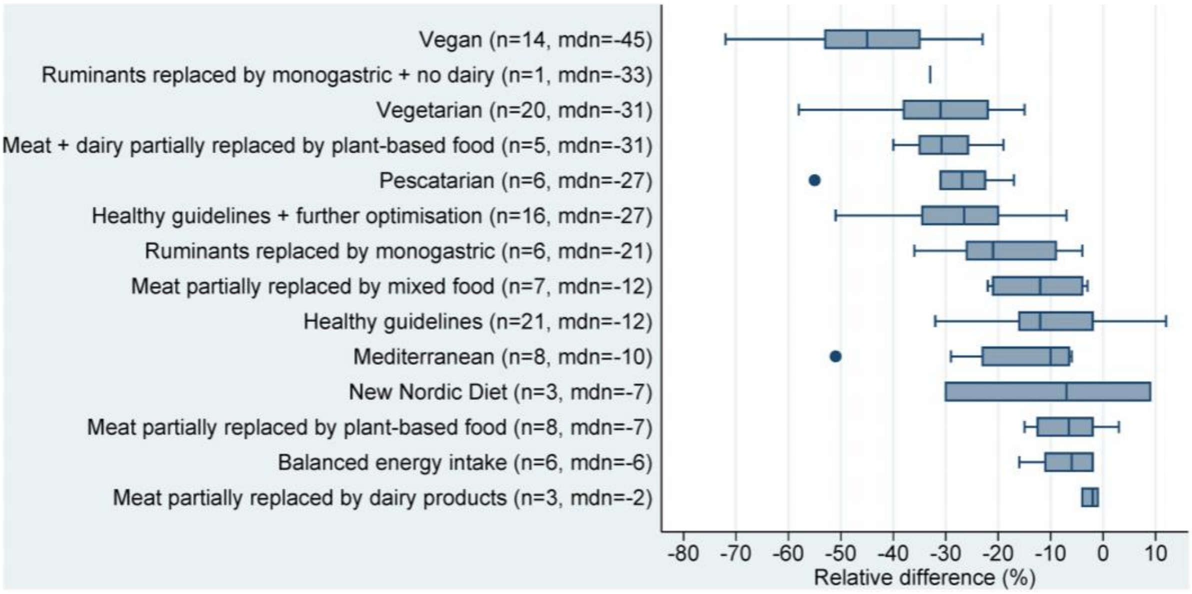


Figure 5.9 Relative differences in GHG emissions (kg CO_2eq capita^{-1}yr^{-1}) between current average diets and sustainable dietary patterns from a systematic review charting 210 scenarios from 63 studies (Aleksandrowicz et al. 2016b). Note: n = number of studies; mdn = median.

There is therefore strong 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 loss (Heller and Keoleian 2015; Aleksandrowicz et al. 2016b). 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 mitigates greenhouse gas emissions also reduce the burden of ill health? 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”.

5.4 Supply-side mitigation options

AR5 WG III ranked mitigation measures from simple interventions such as land use, land management and livestock sector interventions (Kunreuther 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 WGII AFOLU chapter (Clarke 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.

This section considers supply-side options related to crops and soils, livestock, and agroforestry individually and then presents novel and integrated approaches and economic potentials. It then assesses greenhouse gas emissions associated with supply chains such as transport costs and other post-production activities, and GHG emissions from food loss and waste throughout the food system. The following section assesses demand-side mitigation options including dietary pathways.

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.

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.

5.4.1 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. The key mitigation pathways are related to practices reducing nitrous oxide emissions from soils and fertiliser applications, reducing methane emissions from soils, and sequestering carbon or reducing its losses. According to AR5, the combined technical mitigation potential of these practices is 5.3 Gt CO_2eq, with practices for improving grassland and cropland management presenting the largest mitigation opportunities (Paustian et al. 2016; Wollenberg et al. 2016). However, better monitoring and reporting systems are still needed for reducing the uncertainties in the application of these practices. See Supplementary Material 5.11for assessment of cropland productivity improvement mechanisms.

Paustian et al. (2016) developed a decision-tree for studying mitigation practices in cropland (Figure 5.10) and described the features of key practices (Table 5.2). 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. They also identified significant synergies and trade-offs with other ecosystems functions and a broad range of implementation costs, which may influence their adoption (Figure 5.11).

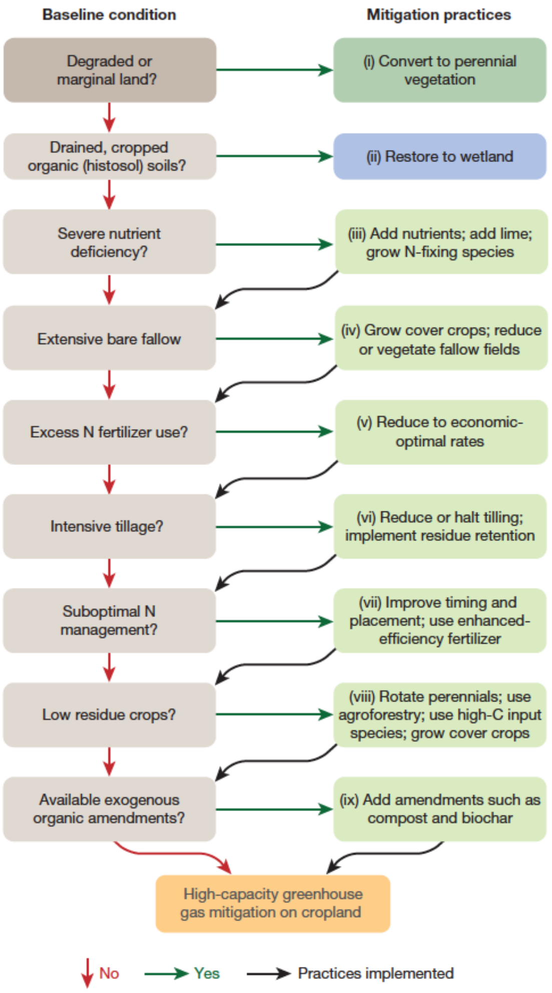


Figure 5.10 Decision-tree for cropland mitigation practices (Paustian et al. 2016)

Table 5.2 Co-benefits, relative costs and constraints for soil mitigation practices (Paustian et al. 2016)

Mitigation practices	Practice co-benefits	Relative cost		Constraints and caveats
		Developed	Less developed	
Convert to perennial vegetation	↓ Soil erosion ↑ Biodiversity ↑ Water quality	$$	$$	Alternate land/livelihood for subsistence farmers; opportunity cost of removing land potential for leakage (that is, land use change impact)
(ii) Restore to wetland	↑ Biodiversity ↑ Water quality	$$$	$$$	High opportunity cost of lost crop production; potential increase in methane emissions; potential for leakage (that is,

				land use change impact)
(iii) Add nutrients; add lime; grow nitrogen fixing species	↑ Food security ↑ Water quality	$	$$	Availability or access to fertiliser; potential increase in nitrous oxide emissions
(iv) Grow cover crops; reduce or vegetate fallow fields	↓ Soil erosion ↑ Water quality ↑ Soil health ↑ Food security	$	$$	Limited applicability in dry areas
(v) Reduce to economic-optimal rates	↑ Water quality	$	$	Risk of crop production loss
(vi) Reduce or halt tilling; **implement residue retention**	↓ Soil erosion ↑ Water quality ↑ Soil health	$	$$	Limited applicability in cold climates; potential increased equipment cost; increased herbicide use
(vii) Improve timing and **placement; use enhanced-efficiency fertiliser**	↑ Water quality	$$	$$	Availability or access to enhanced efficiency fertiliser
(viii) Rotate perennials; use agroforestry; use high carbon input **species; grow cover crops**	↑ Biodiversity ↑ Water quality ↑ Soil health	$$$	$$	Less applicability in dry areas and shallow soils; potential opportunity costs of lost crop
(ix) Add amendments such as compost and biochar	↑ Soil health ↑ Food security	$$$	$$	Dependent on life-cycle emissions of producing the amendment
(x) Use as feedstock for biorefining or anaerobic digestion	Reduced fossil fuel Food security	$$$	$$$	Only applicable in middle-high income countries, may compete with food security if food energy is consumed in this process

Co-benefits include non-GHG NCPs 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.

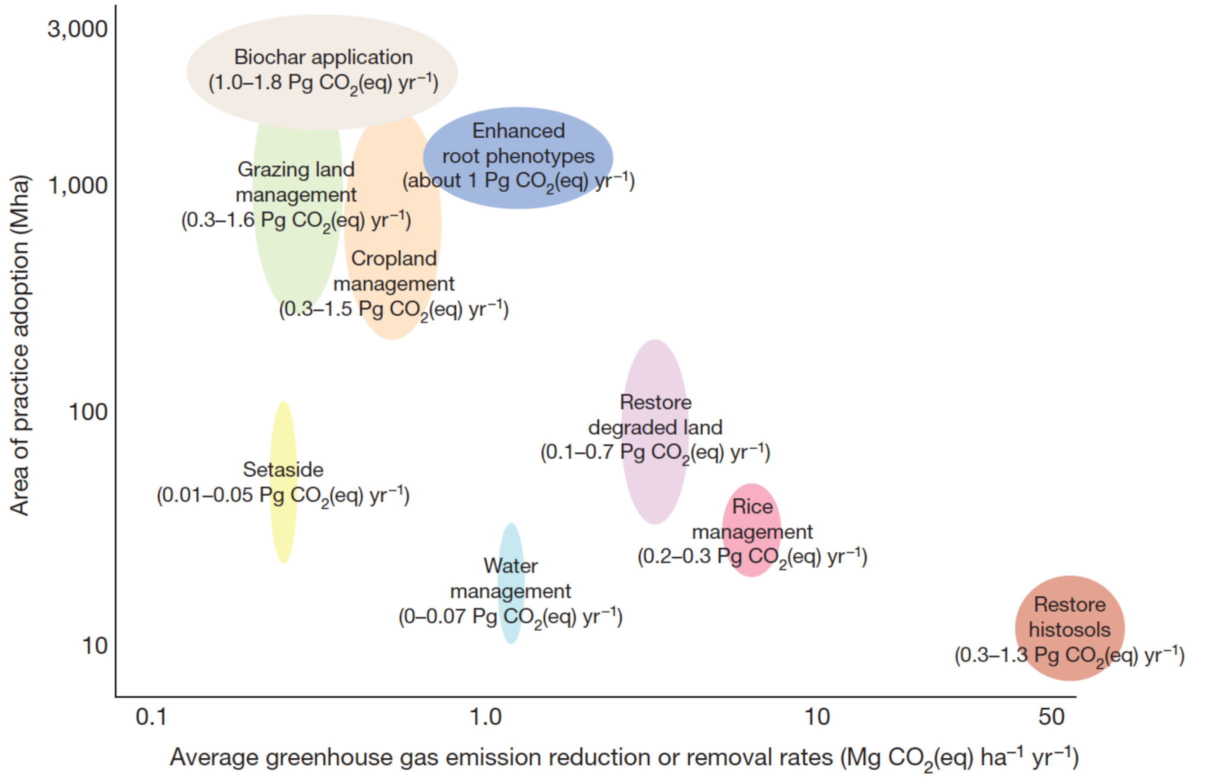


Figure 5.11 Global potential for agricultural-based GHG mitigation practices. Management categories are arranged according to average per hectare net GHG reduction rates and potential area (in millions of hectares) of adoption (note log-scales). Unless otherwise noted, estimates are based on cropland and grassland area projections for 2030. Ranges given in units of total Pg CO_2eq yr^{-1} represent varying adoption rates as a function of C pricing (USD20, USD50 and USD100 per Mg CO_2eq), to a maximum technical potential—that is, the full implementation of practices on the available land base. 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 to 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_2eqyr^{-1} is shown, using the global average C accrual rates (0.23 Mg Cha^{-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 (Paustian et al. 2016)

5.4.2 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 5.12 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

$GtCO_2eq\ yr^{-1}$. These estimates are in the same range as those proposed by FAO (2013, 1.8 $GtCO_2eq$). Some of the better tested strategies are described below. Different production systems will require of different strategies (Rivera-Ferre et al. 2016b).

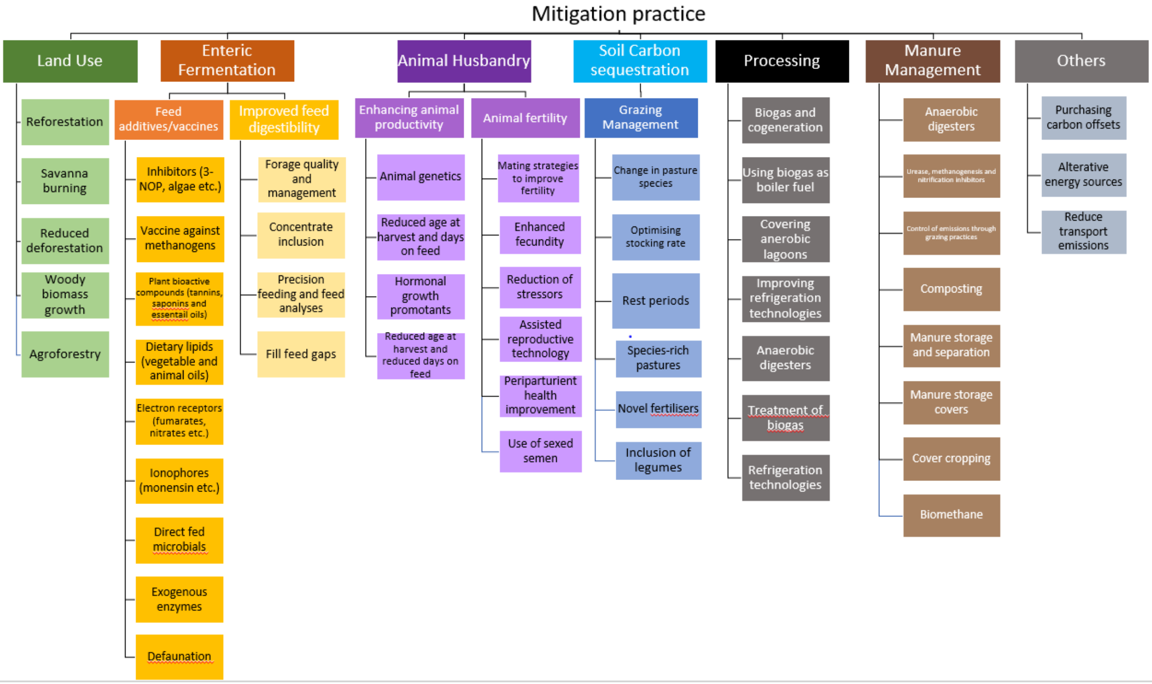


Figure 5.12 Technical supply-side mitigation practices in the livestock sector (adapted from Hristov et al. 2013b; Herrero et al. 2016b; Smith et al. 2014)

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. 2011). 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 others) and the use of improved crop by-products. 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), 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 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 (Gill et al. 2010).

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). In the developing world, many low-producing animals could be replaced by fewer but better-fed animals of a higher potential, with improved grazing management (i.e., attention to feed, herbage availability, and allowances) playing an important role. 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).

Shifts 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.

5.4.3 Greenhouse gas mitigation in agroforestry

The potential of agroforestry for aiding in the curbing of GHG emissions is not limited to carbon sequestration. 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). Data from several countries suggests that agroforestry systems can partially offset CH_4 emissions, while conventional high-input cropping systems can exacerbate CH_4 emissions (Montagnini and Nair 2004). At the same time, soil carbon sequestration is enhanced through agricultural lands management practices used by traditional 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 (Table 5.3).

Table 5.3 Carbon sequestration potential (Mbow et al. 2014)

Legend	Description (source)	C sequestration (Mg. C ha yr^{-1}) (range)	C stock (Mg. C ha) (range)	Max rotation period (year)
A	Parklands dominate AFS (Faidherbia)	0.5 (0.2-0.8)	33.4 (5.7-70.8)	50
B	Rotational woodlots	3.9 (2.2-5.8)	18.5 (11.6-25.5)	5
C	Tree planting-windrows-home gardens	0.6 (0.4-0.8)	19.0 (ns)	25
D	Long term fallows, regrowth of woodlands in abandoned farms	2.24 (0.22-5.8)	15.7 (ns)	25
E	AFS and integrated land use	3.12 (1.0-6.7)	77.9 (12-228)	50
F	Soil C in AFS	0.9 (0.25-1.6)	5.7 (13-300)	ns

Because traditional 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. 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.

In a review of 42 studies, (Ramachandran Nair et al. 2009) estimated that the C sequestration potential of differing agroforestry systems was: i) semi-arid = 2.6 Mg Cha^{-1} yr^{-1}; ii) temperate = 3.9 Mg Cha^{-1} yr^{-1}; iii) sub-humid = 6.1 Mg Cha^{-1} yr^{-1}; and iv) humid = 10 Mg Cha^{-1} yr^{-1}. (Montagnini and Nair 2004) estimated potential C sequestration rates range from 1.5 to 3.5 Mg Cha^{s} yr^{-1} for smallholders in the tropics. 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 farm were increasing in tree cover in semi-arid ecosystems due to natural regeneration and that the increased application of agroforestry systems were supporting production and reducing GHG emissions.

5.4.4 Integrated approaches to crop and livestock mitigation

5.4.4.1 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. If this strategy was implemented, (van Zanten et al. 2018) demonstrate 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%.

5.4.4.2 Waste streams into energy

Waste streams from manures and food waste can also be used for energy generation in terms of biogas or biomethane production (De Clercq et al. 2016). 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 (Figure 5.13) (Nguyen et al. 2017).

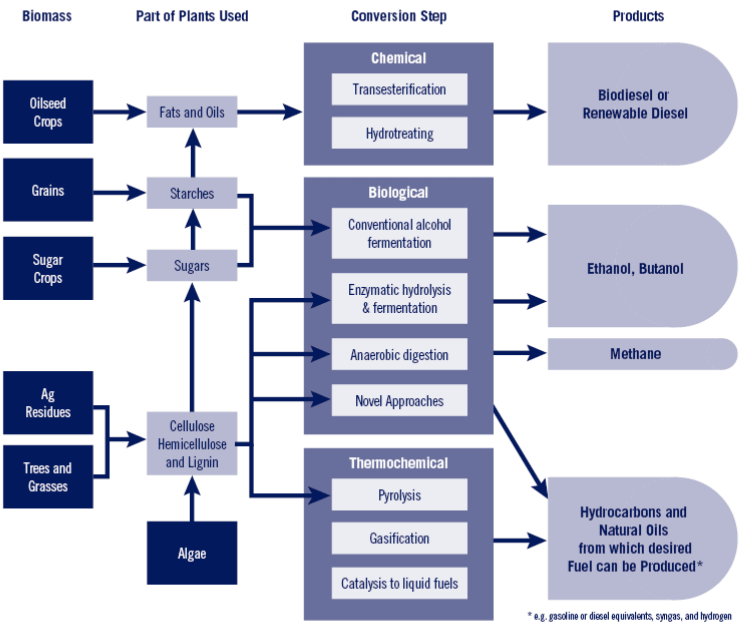


Figure 5.13 Second-generation process by which biorefineries generate hydro-carbons from agricultural residues, grass and woody biomass that do not compete with food and can generate biofuel (Peña 2008).

5.4.4.3 Technical measures

Novel strategies to reduce methanogenesis include supplementing with antimethanogenic agents (e.g. chemical inhibitors such as chloroform) or supplementing with electron acceptors (e.g. nitrate) or dietary lipids. However, 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).

For crop and soil management practices, it is estimated that 1-1.5 $GtCO_2eq$ 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. 2013a; Wollenberg et al. 2016). For the livestock sector, these estimates range from 0.125-0.250 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 $GtCO_2e$ (Figure 5.14). A similar analysis is shown for CO_2 emissions from land use options up to 2030 in Figure 5.15.

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 reductions in consumption caused by food price increases. The individual practices implemented can be seen in Figure 5.14. Key to the achievement of this mitigation potential lied 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).

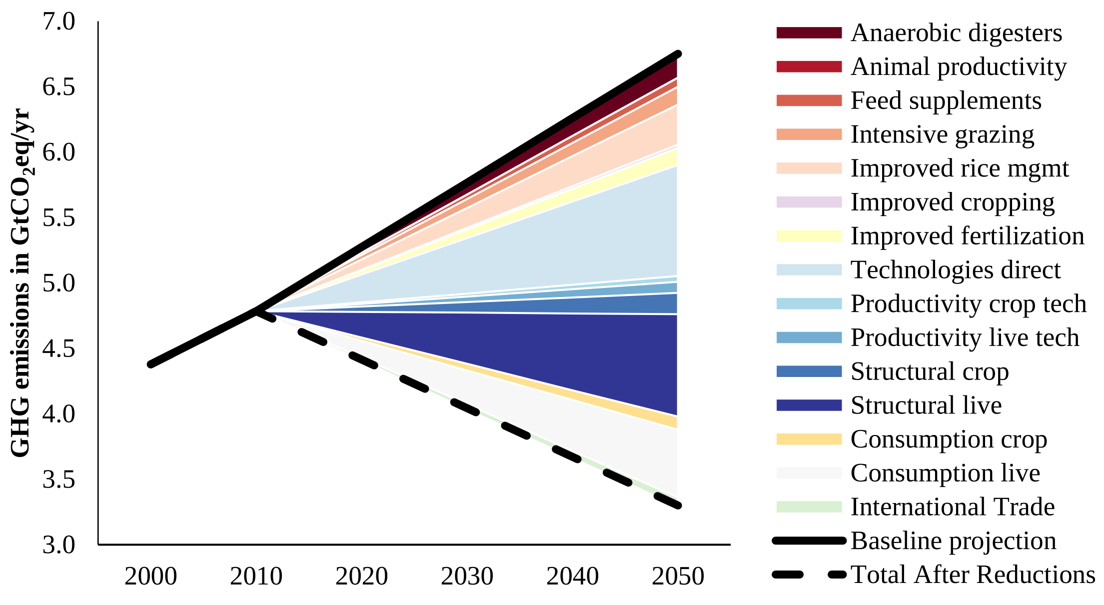


Figure 5.14 Greenhouse gas mitigation wedges for the crop and livestock sectors to 2050 at a carbon price of USD $100tC^{-1}$ (this study, data from (Frank et al. 2018). Mitigation options include consumption changes to price signals; structural options such as livestock and crop system transition, reallocation of production through intra and international trade; and technical options (anaerobic digesters, animal supplements such as antibiotics, bovine somatotropin, propionate precursors, and anti-methanogen vaccination, improved rice management in terms of different combinations of water, residue, and fertiliser management, improved cropping practices such as no tillage and residue incorporation, and improved fertilisation practices such as nitrogen inhibitors and optimal fertiliser application) (Frank et al. 2018)

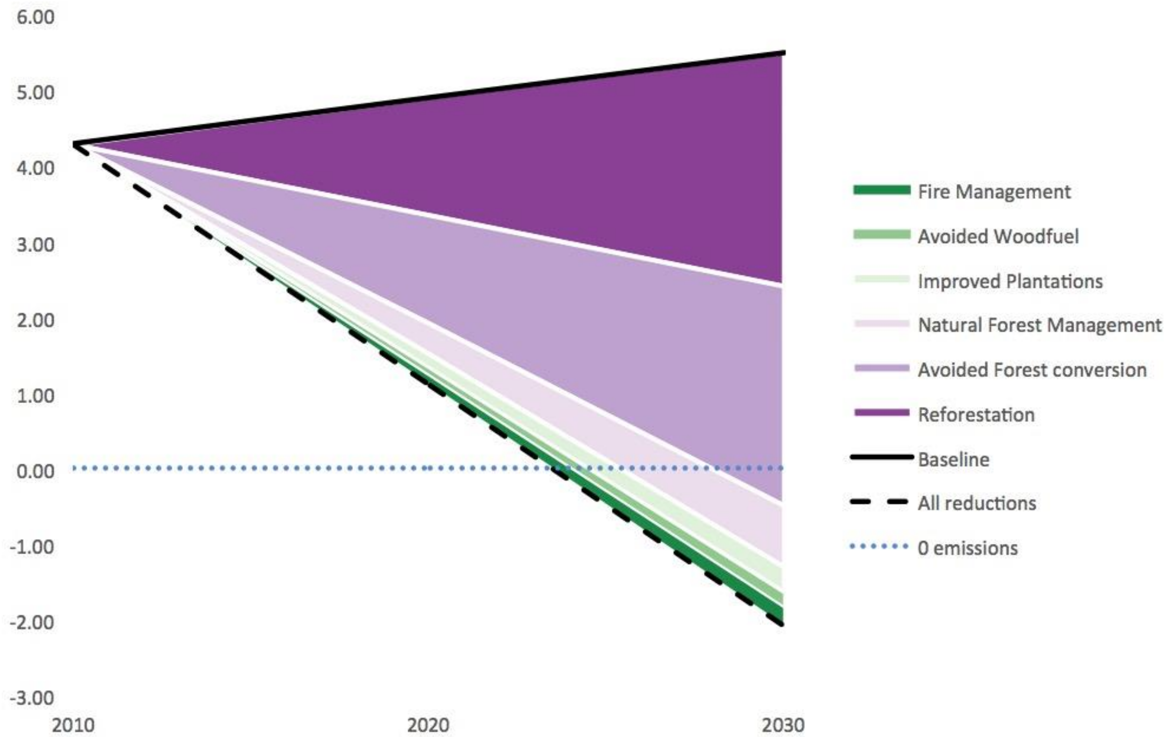


Figure 5.15 CO_2 emissions from land use to 2030. Baseline values are lower and upper bounds of emissions from AR5. Data are from (Griscom et al. 2017). Prices are the same as for the wedge figure above, but analysis goes only to 2030

5.5 Demand-side mitigation options – Locally produced food, dietary pathways

5.5.1 Locally produced food

Encouraging consumption of locally produced food and enhancing efficiency of food processing and transportation can in some cases minimise food loss, contribute to food and nutrition security, and also reduce 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 of such fruits and vegetables offers considerable emissions savings. They also highlighted that in the situation that imports are necessary, importing from Europe instead of the Global South can help make considerable GHG emissions savings i.e. 9.96 $kgCO_2eq\ kg^{-1}$.

5.5.2 Role of dietary preferences

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.

However, consumers' choice and dietary preferences are guided by social, cultural and traditional factors as well as economic growth. In general, animal-based diets have higher environmental footprint than plant-based diets (Hamerschlag 2011) and ruminant meat has a higher environmental footprint than white meat. Therefore, minimising consumption of ruminant meat where possible may help achieve food and nutrition security without brining additional land into cultivation (Harwatt et al. 2017). This will help reduce GHG emissions by curbing additional deforestation on the one hand but also allowing forest regeneration on land that is spared, all contributing to climate change adaptation and mitigation (Soret et al. 2014; Song et al. 2017). By reducing beef consumption between 2005 and 2014, Americans avoided approximately 271 million metric tons (MMT) of climate-warming pollution based on NRDC's calculations (NRDC 2017). See section 5.5.3 for quantitative analysis.

Gender differences have been observed in food consumption in cities, e.g., women do 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 and nutrition 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 can be promising.

With malnutrition due to overweight and obesity increasing significantly as diets change, examining what a lower demand for food would mean for human health, land use and GHG emissions has been the subject of significant research since the AR5. These studies assess the mitigation potential of consumption patterns including eating less and eating differently, particularly through less consumption of livestock and livestock products (Garnett et al. 2017). 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).

5.5.3 Demand-side scenarios of different diets

Figure 5.16**Error! Reference source not found.** 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_2eq 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_2eq yr^{-1} in the Healthy Diet scenario, and 5.8 and 6.4 CO_2eq yr^{-1} for the No Ruminant Meat and No Meat scenarios, respectively.

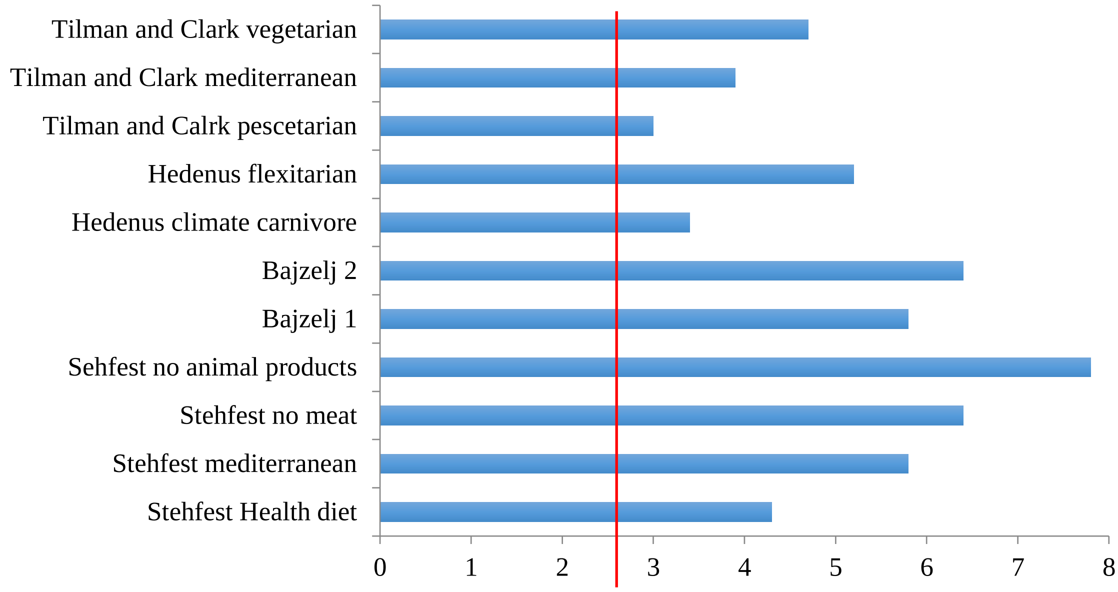


Figure 5.16 The mitigation potential of changing diets according to a range of scenarios examined in the literature (Herrero et al. 2016a). For comparative purposes, the red bar represents the supply side mitigation potential of 2.4 Gt.

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_2eq yr^{-1} for additional variants including low or high-yielding bioenergy, 4.6 Gt CO_2eq 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_2eq 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_2eq yr^{-1} in the Climate Carnivore scenario, and 5.2 Gt CO_2eq 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 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_2eq 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 to 2.4 Gt CO_2eq yr^{-1}.

Their study also 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 5.17**Error! Reference source not found.**). Relatively similar results were obtained by (Springmann et al. 2016b,a).

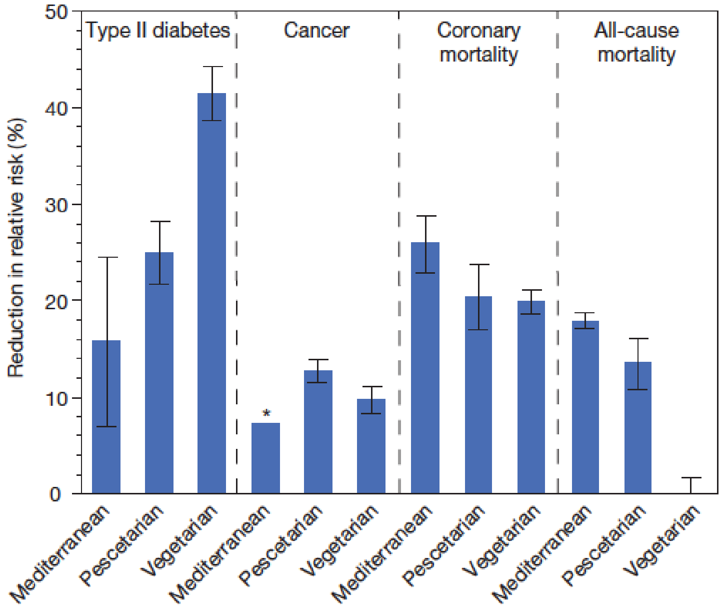


Figure 5.17 Diet and health effects of different consumption scenarios (Tilman and Clark 2014)

Other studies have defined dietary shift as e.g., 20kg per person per week CO_2eq for Mediterranean diet, vs 13kg per person per week CO_2eq for Vegan (Castañé and Antón 2017; Rosi et al. 2017) developed seven-day diets in Italy for about 150 people defined as Omnivore 3.9593 ± 0.9758; Ovo-lacto-veggie 2.5983 ± 0.619; and Vegan 2336.1 ± 0.4968 kg CO_2eq pc pd.

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.

5.5.4 Dietary shifts, health impacts, and GHG emissions

Two key questions arise in regard to the role of diet as a mechanism for GHG reduction. They are 1) Are diets that minimise GHG also healthy? and 2) Can dietary shifts mitigate climate change at large-enough scales to make a difference?"

Are diets that minimise GHG also 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 is associated with lesser environmental impact (GHG and energy, land, and water use) than is the current average US diet (Nelson et al. 2016). Another study (Van Mierlo et al. 2017) shows via linear programming, that it is possible for nutritionally equivalent diets to substitute plant-based foods for meat, and saving in GHG emissions.

There are several studies (e.g., Van Dooren et al. 2014) that estimate "health adequacy" and "sustainability" and conclude that sustainable healthy diets are possible (in the Netherlands in this example). Another study of this kind concludes that halving the 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. In addition, the dietary changes would also lower health risks. (Westhoek et al. 2014). In China, GHG-friendly diets were designed that met dietary guidelines and created significant savings in agri-food GHG (between 5% and 28% depending on the scenario) (Song et al. 2017).

A range of studies are starting to estimate both health and environmental savings from dietary shifts. For example, (Farchi et al. 2017) estimate health (cancer, CVD) and GHG savings of low meat diets in Italy. In US (Hallström et al. 2017) found that adoption of healthier diets reduced the 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 by 222–826 kg CO_2eq/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). Note that (Hallström et al. 2017) show that the GHG savings are not insignificant from reduced healthcare costs of changing diets (as well as GHG emissions from the food system).

Changing diets can also mitigate non-dietary related health issues caused by emissions of air pollutants. Changing diet has been shown to be a means of mitigating PM2.5 in China (Zhao et al. 2017b).

Can dietary shifts mitigate climate change at large-enough scales to make a difference? Several studies highlight that current dietary trends lead to approximately 20Gt CO_2eq by about 2050; this is inconsistent with a climate-equitable pathway (Pradhan et al. 2013b; Bajželj et al. 2014; Hedenus et al. 2014; Bryngelsson et al. 2017).

Many studies now indicate GHGs savings of dietary shifts. 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).

In the agricultural sector, changes in livestock management practices, promoting healthy diets including reduced beef and dairy consumption, and reductions in food waste have been promoted as ways to mitigate emissions. These have been shown to have the potential to provide large societal benefits (USD 50-150 billion per year). Increases in methane emissions may have offset much of the societal benefits from a slowdown in the growth rate of carbon dioxide emissions (Shindell et al. 2017).

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

5.6.1 Climate variables, including extremes, important to food systems

Climate variables relevant to food and nutrition security and the food system include temperature-related, precipitation-related, and integrated metrics. Other climate variables that affect agricultural production, processing, and transport include 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. See Chapter 2 for further discussion of climate variables and Section 5.9 in this chapter for assessment of climate 'hotspots' for the food system.

Temperature-related metrics include extreme heat days (T_{max}>35˚C); length of frost-free period (days from last spring frost to first autumn frost; frost = Tmin<0˚C); growing degree days (GDD5) with base of 5˚C (cumulative positive difference: T_{avg} – 5˚C) (e.g., a day where Tavg = 10˚C →5 GDD); and vernalisation degree days (VDD) with cap of 0˚C (cumulative negative difference: T_{avg} – 0˚C) (e.g., a day where T_{avg} = -5C →5 VDD). Growing degree days are important metrics because crops respond to accumulation of temperature to progress through their growth stages (Matthews et al. 2018). Precipitation-related metrics include simple daily precipitation intensity index (SDII = total precipitation / #wet days; wet days could be days were P>1mm); monsoon intensity (range of monthly mean precipitation/mean annual precipitation); and annual maximum five-day precipitation total (RX5day). Integrated metrics include Palmer Drought Severity Index (PDSI) and heat index (combines temperature and relative humidity). Remote sensing data of precipitation are useful in understanding effects of drought on agricultural production (Figure 5.18).

Aerosols and ozone are two atmospheric components that affect agricultural production. Anthropogenic climate changes are a result of both global emissions of long-lived greenhouse gases (LLGHGs) and other short-lived climate pollutants (SLCPs). Two potent SLCPs, tropospheric ozone and black carbon, have direct effects on crop yields beyond their indirect effects through climate (Burney and Ramanathan 2014). Ghude et al. (2014) quantified, for the first time the potential impact of ozone on district-wide cotton, soybeans, rice, and wheat crops in India for the first decade of the 21st century. Wheat is the most impacted crop with losses of 3.5 ± 0.8 million tons (Mt), followed by rice at 2.1 ± 0.8 Mt, with the losses concentrated in central and north India. On the national scale, this loss is about 9.2% of the cereals required every year (61.2 Mt) under the provision of the recently implemented National Food Security Bill (in 2013) by the Government of India. The nationally aggregated yield loss is sufficient to feed about 94 million people living below poverty line in India.

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.

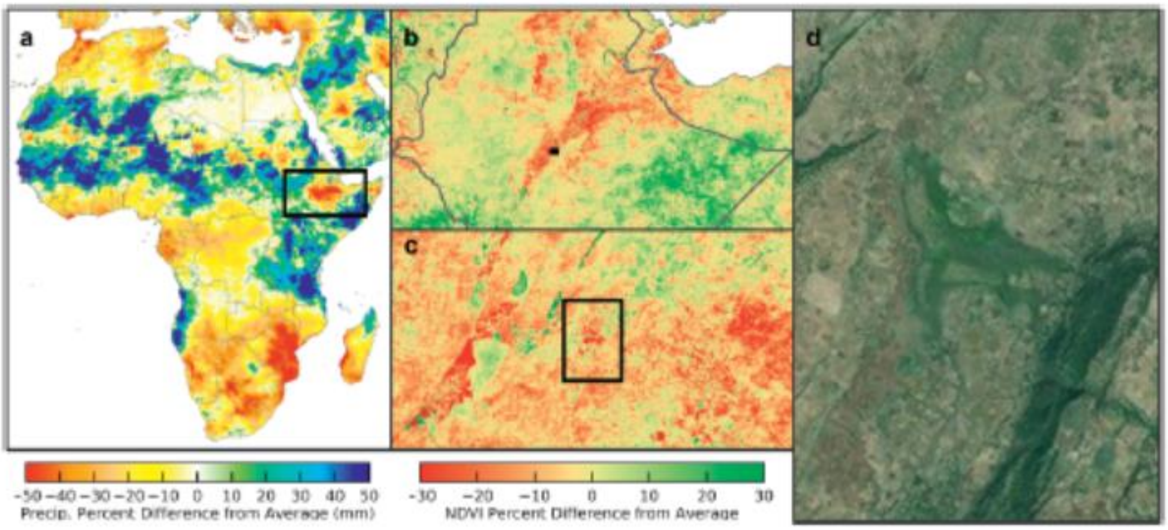


Figure 5.18 Precipitation anomaly as measured by CHIRPS over Africa from September 2015 to February 2016 with widespread impacts on agricultural productivity, especially in pastoral regions in Ethiopia.

5.6.2 Observed climate change impacts

5.6.2.1 Detection and attribution

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 advanced multi-factor methodological approaches (e.g., Kelley et al. 2015, 2017; Werrell et al. 2015; Challinor et al. 2018). These in particular have addressed systemic risks to food and nutrition security that result from cascading impacts triggered by droughts and floods.

Several studies have explored the causal links among climate change, drought, impacts on agricultural production, livelihoods, and civil unrest in Syria, but without agreement as to the role played by climate in subsequent migration (see e.g., Selby et al. 2017). 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). 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).

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; they recommend other 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.

5.6.2.2 Observed impacts on crops

Observed impacts of climate change on food and nutrition security have already been noted as a cause of concern, and assessments have begun to examine how climate change might affect systems and sectors related to agricultural production (HLPE 2012). Here, we focus on studies documenting perceived changes in crop yields associated with changes in climate. Since AR5, there have been a number of studies that document observed climate impacts on differing aspects of the food system, as well as climate-related indices. Related to the climate indices, a recent analysis from 1951-2011 found that a drying tendency 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 hot spots categorised by severity and frequency were typically located in the north of Eastern Asia, Western Africa, central Southeast Asia, and Central Europe. High drought frequency was observed in Western Africa, Northern Africa, Northern Europe, and Southern Asia. Central Eastern Asia, Northern America, and Western Asia were identified to have low drought frequency and few severity areas Accordingly, developing countries and regions are generally more susceptible to extreme droughts and suffered more losses than developed countries and regions (Wang et al. 2018). However, some developed countries, have also been adversely affected. Australia, for instance, has experienced stalled wheat yields since 1990 because of climate trends (Hochman et al. 2017).

A recent study has shown that such crop-damaging temperatures have led to an increase in the rate of suicides in India (Carleton 2017). Across all states and all years since 1980, a cumulative total of 59,300 suicides can be attributed to warming (Carleton 2017). Other studies focusing on India have found that combinations of local air pollution and warming have reduced wheat yields by 5.2% from 1981 to 2009 (Gupta et al. 2017); and increase in night temperature in southern states in India is affecting yield of paddy adversely (Jha and Tripathi 2017). Irrigation water has been used to mitigate some of the impacts of climate change, but if India continues to deplete its groundwater the impacts of increased variability are likely to increase by half (Fishman 2018). North of India, maximum temperature has also adversely affected wheat production in Pakistan for the period 1989 to 2015 (Ali et al. 2017).

One large geographic area that appears vulnerable is the Hindu-Kush Himalayan region, which encompasses four river sub-basins stretching across Pakistan, India, Nepal, and China. Such mountain peoples are particularly vulnerable to food insecurity related to climate change because of their poor infrastructure, limited access to global markets, physical isolation, their farmland's low productivity, and vulnerability to hazards (Rasul 2010; Tiwari and Joshi 2012b; Huddleston et al. 2003; Ward et al. 2013; FAO 2008b). In the Hindu-Kush Himalayan region, there has been changes in precipitation patterns, hydrological imbalances, rises in temperature, increases in temperature, more frequent floods, as well as an overall degradation of agriculture lands, rangelands and forests (Nautiyal et al. 2007). The unusually large rainfall has also contributed to the increase in Glacial Lake Outburst Floods (GLOFs) in these mountain areas (Din et al. 2014). In terms of water availability, the region appears to be experiencing an increase in extremes, with farmers facing more frequent floods as well as prolonged droughts, with negative impacts on their agricultural yields and increase in food insecurity (Hussain et al. 2016). Crop damages related to changes in precipitation have been corroborated to changes in weather in some cases, such as an analysis which showed that after 2000-2001, the frequency and magnitude of floods in the Upper Indus has increased due to intense rainfall in the Indus catchment and increase in snowmelt (Manzoor et al. 2013).

To determine how these climate-related changes have affected food and nutrition security, local adaptation strategies in the Hindu-Kush Himalayan region were analysed from 8083 households across the four river sub-basins in Pakistan, India, Nepal, and China. For the majority of households, there is a perception that floods, landslides, droughts, livestock diseases and crop pests are all increasing; the households are also attributing these changes to alterations in climate. These changes have led to lower agricultural productivity and income, particularity in the Eastern Brahmaputra basin where all staple and cash crops are reported by households as declining in productivity, leading to very low farm income (Hussain et al. 2016). These declines have occurred in the last 10 years despite advances in agricultural techniques (Hussain et al. 2016). To adapt to the increase in climate risks, it has been recommended that farmers switch to more climate-resilient crops and abandon raising sheep and larger animals, which are vulnerable to water and fodder stress, and instead raise goats, which appear more adaptable to climate extremes (Hussain et al. 2016).

Also in the region, a study focusing on Nepal found that shifts in climate were in agreement with farmers' perception of the changing climate, and that farming communities appear to be negatively affected by such alterations in climate (Shrestha and Nepal 2016). The perceived changes were erratic rainfall, increased drought and flood frequency, and increases in insect pests, weeds, and diseases. Though the farmers have altered their traditional cropping practices and planting calendar, utilised different crop varieties, and increased the use of fertilisers and pesticides, agricultural productivity in the area continues to decline and only one third of all households are food secure. Adaptive measures, at the household level, which have helped families adapt to the changes in climate including rainwater harvesting, mulching, adjusting planting dates, and seeking off-farm employment (Shrestha and Nepal 2016).

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, then, have had important implications for the agriculture, human health, and biodiversity of the region (Saxena et al. 2016). Data collected through mixed methods and qualitative fieldwork from 2012 to 2014 suggests that in Colomi, Bolivia climate change is affecting crop yield and causing farmers to alter the timing of planting, their soil management strategies, and the use and spatial distribution of crop varieties. Though the study is limited in terms of quantitative data, it does suggest that further work should be conducted to document and analyse the threat climate change is posing to food and nutrition security in the high mountains of South America. Experimental evidence has also concluded that climate change will result in severe economic losses due to crops yield declines and food insecurity in the tropical Andes (Tito et al. 2018).

Along with high mountain communities, dryland settlements are another geographical area perceived as vulnerable to climate change with regard to food and nutrition 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. A study examined rainfall and temperature trends, from weather stations, in Kenya's Lower Tana Basin to decipher if the climate was changing in relation to declines in crop yields (Ketiem et al. 2017). Since 1975, there has been a general increase in the both the minimum and maximum mean temperature, with the increase in the minimal temperature being more pronounced. Along with the correlated changes in yield, the observed significant increase in the minimum temperature may be a reason of concern because it could increase the percent probability of the prevalence of Tsetse fly, which is the vector for the trypanosomes that cause human sleeping sickness (Ketiem et al. 2017). Rainfall anomalies also revealed an increase in extreme droughts and floods, with extreme drought events occurring every two or less years. According to the study, the changing climate has affected maize production, and it is recommended that farmers cultivate other crops such as mangoes and cassava that are likely to minimise future food and nutrition security risks due to their greater climate resilience (Ketiem et al. 2017).

Elsewhere in Africa, 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). In Ebonyi State, Nigeria, Eze (2017) reported major manifestations of climate change effects in cassava production as hotness of weather, variability in relative humidity, and frequency of flood. Work on adaptation indicators has found that in Nigeria the principal constraints to climate change adaptation in cassava production are lack of institutional support, inadequate socio-cultural attitude, and poor managerial skill (Eze 2017).

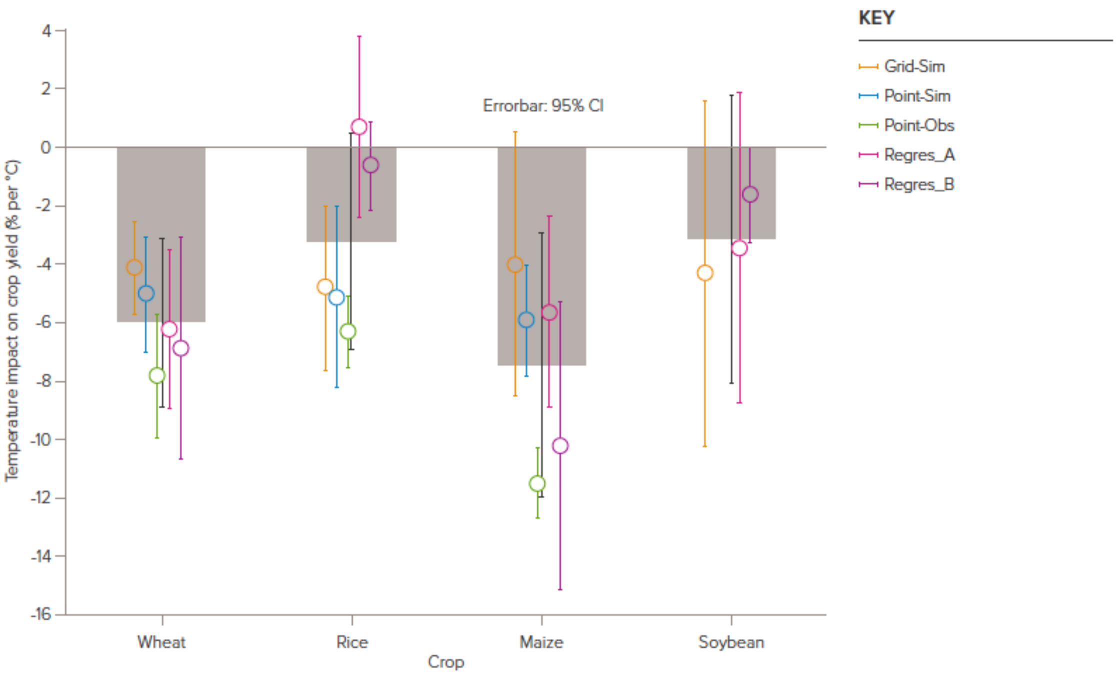
5.6.3 Projected climate change impacts

5.6.3.1 Projected impacts on crops

Effects of climate change on food security are manifested in the first instance through its biophysical effects on crops, livestock and farming system productivity. Changes in mean temperature and precipitation and their variability have already had demonstrable and varying effects on agricultural production around the globe (Lobell et al. 2011), leading to more price and income fluctuations. In general, higher average temperatures will accelerate the growth and development of plants mostly leading to reduced yield. For example, each degree day above 30ºC is projected to reduce maize yield by 1.7% under drought conditions (Thornton and Cramer 2012). However, rising temperatures are not uniformly bad; they will lead to improved crop productivity in parts of tropical highlands and high altitude where low temperatures are currently constraining crop growth. Higher temperatures are also associated with higher ozone concentrations, which are harmful to crops especially soybeans, wheat, oats, green beans, peppers, and some types of cottons.

Globally, crop yields are projected to change in particular due to changes in the start and length of the growing season, CO_2 fertilisation and the duration and magnitude of heat and water stress. These abiotic changes influence leaf temperature, soil moisture, and photosynthetic rate and thus phenology and the amount of biomass produced and allocated to a crop's storage organ. These have been studied with a variety of methodological approaches (Zhao et al. 2017a) (Figure 5.19).

Global crop yield changes in response to temperature increase.



Impacts on crop yields per 1°C increase in global temperature are shown for a range of estimation methods (Grid-Sim, Point-Sim, Point-Obs, Regres_A, Regres_B). Filled bars represent the means of all methods. The bars indicate that the yields of wheat, rice, maize and soybean will decrease in response to global temperature increase. Full caption can be found in the supplementary information. Data were published by Zhao *et al* in 2017. © PNAS.

Figure 5.19 Impacts on crop yields per 1°C increase in global temperature.

Impacts on crops grown in the tropics are more negative than in mid- to high-latitudes as stated in AR4 and confirmed by Rosenzweig et al. (2014) (Figure 5.20). This study, using ensembles of seven global gridded crop models and 20 CMIP5 climate scenarios for RCP8.5 found that maize yields in mid-to high latitude change by -10% to +15% and -15% to +30% with global warming of 2°C and 4°C, respectively compared to maize yield changes in the low latitudes of -30% to +5% and -45% to +5% with global warming of 2°C and 4°C, respectively. Global wheat production from crop model ensembles is estimated to decrease by 6% (10^{th}-90^{th} percentile is 3%-8%) for every °C increase in global temperature (Asseng et al. 2015). Similar studies for four different production sites revealed that maize and rice can decline by 3.4% to 9.8% (25^{th}-75^{th} percentile) and 2% to 11% for every °C increase in global temperature, respectively (Bassu et al. 2014; Li et al. 2015). Note that studies did not use the same standard in reporting median impacts and confidence intervals, so they might not be comparable.

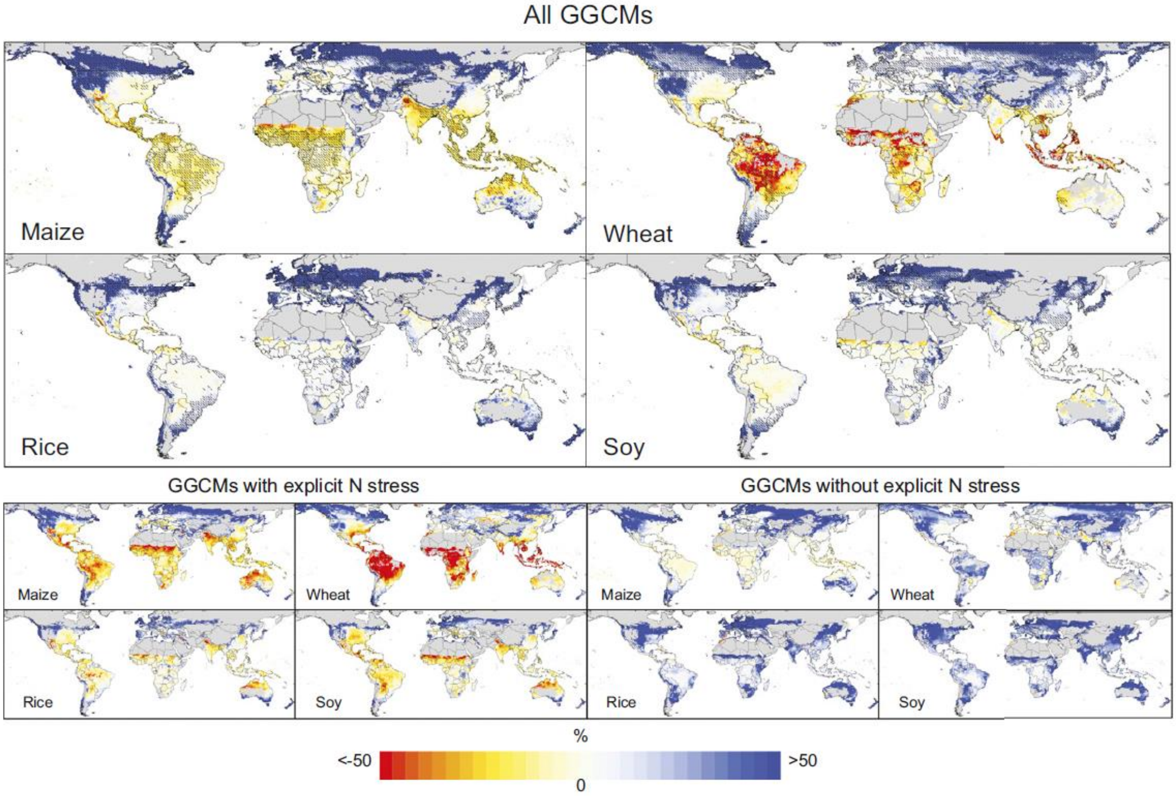


Figure 5.20 Median yield changes (%) for RCP8.5 (2070–2099 in comparison to 1980–2010 baseline) with CO_2 effects over all five GCMs x seven Global Gridded Crop Models (GGCMs) (6 GGCMs for rice) for rainfed maize (35 ensemble members), wheat (35 ensemble members), rice (30 ensemble members), and soy (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)

Climate change impacts on food, feed and cash crops other than cereals, grown in smallholder systems or family farms are less often studied although impacts can 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. (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 experience 10 or more years with crop suitability below the viability threshold in 2078-2098 with a global temperature increase of 2.6°C and 4°C respectively. Studies for vegetables are very limited (Bisbis et al. 2018).

Elevated CO_2 concentration stimulates crop growth due to higher stomatal conductance and water use efficiency in plants (Ainsworth and Long 2005) leading to 17% higher yield on average in wheat but only when nitrogen is not limiting plant growth. At the same time, the nutrient concentration in the edible portions of crops grown under elevated atmospheric CO_2 concentrations (550-580 ppm) will decrease. In a meta-analysis from seven Free-Air Carbon dioxide Enrichment (FACE) 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 peas, soybeans and C4 crops such as sorghum and maize were small or insignificant. 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).

Wheat, rice, maize, and soybean provide two-thirds of human caloric intake. Assessing the impact of global temperature increase on production of these crops is therefore critical to maintaining global food supply, but different studies have yielded different results (Zhao et al. 2017a). Figure 5.19 illustrates the impact of temperature on yields of the four crops at the global scale. The loss in yield for each degree celsius increase in global mean temperature is largest for maize (with multimethod average ±2 SE) of −7.4 ± 4.5% per degree celsius. All four methods predict a negative impact for maize, but with varying magnitudes. Mostly the different methods generated similar results at the country scale, but estimates varied between countries. 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).

The Agricultural Model Intercomparison and Improvement Project (AgMIP) has developed novel methods for Coordinated Global and Regional Assessments (CGRA) of agriculture and food and nutrition security in a changing world (Rosenzweig et al. 2017). This effort responds to the request by the UNFCCC for the implications of limiting global temperature increases to 1.5°C and 2.0°C above pre-industrial conditions. AgMIP protocols for the 1.5°C/2.0°C assessment establish explicit and testable linkages across disciplines and scales, connecting outputs and inputs from the SSPs, Representative Agricultural Pathways (RAPs), HAPPI and Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble scenarios, global gridded crop models, global agricultural economic models, site-based crop models, and within-country regional economic models (Rosenzweig et al. 2017).

The CGRA consistently links disciplines, models, and scales in order to track the complex chain of climate impacts and identify key vulnerabilities, feedbacks, and uncertainties in managing future risk (Rosenzweig et al. 2017). 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. 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).

A second AgMIP CGRA study (Ruane et al. 2018) showed that global mitigation using a carbon tax is much more disruptive to land use and crop prices than projected production changes from direct climate change impacts. This is especially true for the 1.5°C World, as large portions of croplands and grasslands would need to be converted to biofuel production. For regional farming systems, direct biophysical impacts can be substantially larger in both positive and negative directions. Local price changes can counteract or exacerbate the net effects on farm returns to a greater extent than in the global aggregate. Regional farmers can buffer negative effects or take advantage of new opportunities via price increases, mitigation incentives, and farm management technologies. Primary uncertainties in the CGRA framework include CO_2 effects on diverse cropping systems, the need for enhanced dietary and farm intensification mitigation scenarios, and more accurate spatial datasets to enable improved crop and economic model configuration (Ruane et al. 2018).

5.6.3.2 *Projected impacts on rangelands*

The impacts of climate change on global rangelands have received comparatively less attention than the impacts on crop production. 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 gCm^2 yr^{-1}) (Figure 5.21**Error! Reference source not found.Error! Reference source not found.**). 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) (Figure 5.22). When translating these impacts on forage productivity to impacts on livestock, they found that livestock numbers are projected to decline 7.5% to 9.6%, which equates to an economic loss of from USD 9.7 to USD 12.6 billion. 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.

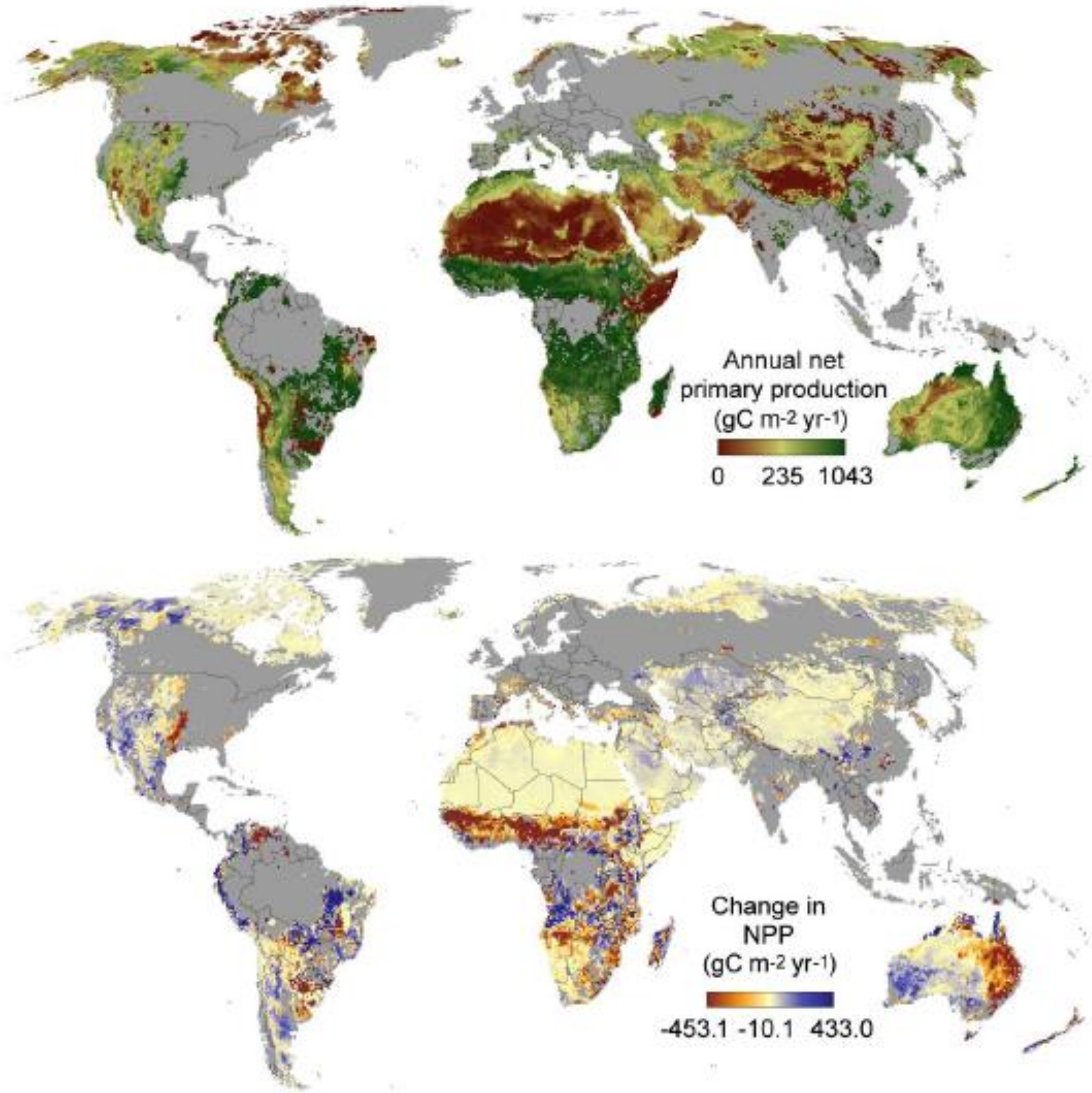


Figure 5.21 Changes in net primary productivity of rangelands under RCP8.5 (Boone et al. 2017)

According to Boone et al. (2017), the composition of rangelands is likely to change as well. 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.

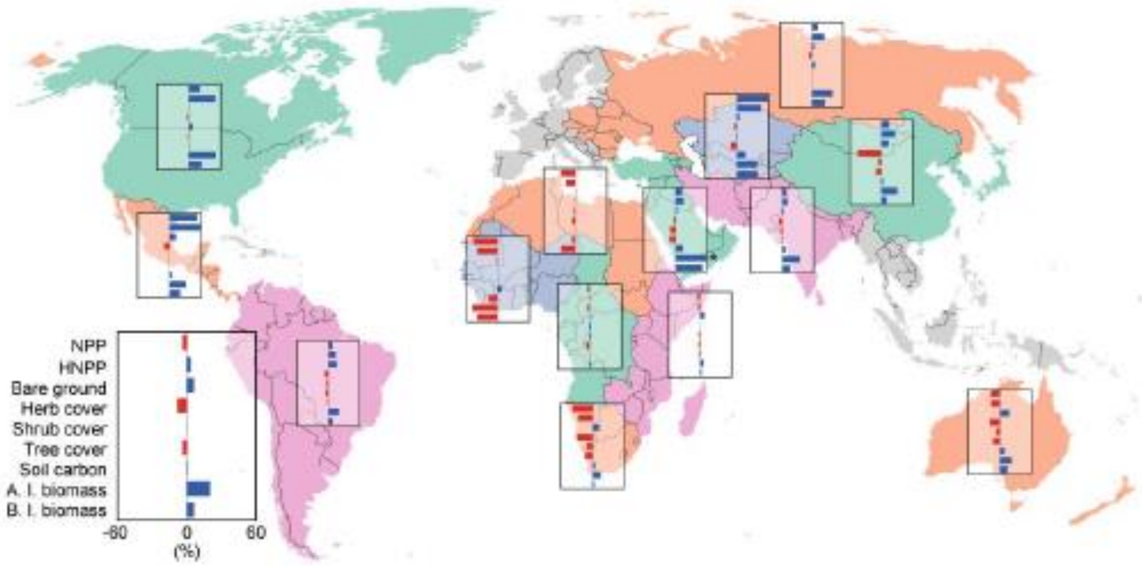


Figure 5.22 Regional distribution of climate impacts on rangeland productivity (RCP8.5)

Vulnerability of societies to climate change impacts in fisheries and agriculture under RCP6.0. Changes in marine fisheries and terrestrial crop production (Rosenzweig et al. 2018) are expressed as $\log_{10}$ (projected/baseline) production, where a value below zero indicates decreases and above are increases. Fisheries and agriculture dependency estimates calculated from employment, economy and food and nutrition security. Circle size represents total dependency on both sectors and green to blue colour scale reflects the balance between land and sea with white indicative of equal dependence. The dependence indices were calculated using publicly available online data from FAO, the World Bank and a recent compilations of fisheries employment data (Teh and Sumaila 2013). Each panel a-d) represents the four Human Development Index (HDI) categories (low, medium, high and very high) and open diamonds indicate no data for agricultural and fisheries dependency.

5.6.3.3 Projected impacts on livestock

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 causality, 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). Mixed and extensive production systems direct impacts of climate change 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 10-30ºC, 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.

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

5.6.4.1 Impacts on food safety

There are a range of routes by which climate change can affect food safety (Tirado et al. 2010), for which significant evidence exists in the literature. These 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 of products in storage and transport can also be affected by changing humidity and temperature outside of cold-chains. Factors related to climate change that can influence food safety 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). 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 may change, they are nonetheless likely to (Vaughan et al. 2016).

Foodborne pathogens in the terrestrial environment typically come from enteric contamination (from humans or animals), and can be spread by wind (blowing contaminated soil) or flooding – the incidence of both of which are likely to 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 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 the biology of food plants, and the way they sequester heavy metals (Rajkumar et al. 2013). The role of multiple abiotic stresses also has potential to alter exposure (for example, cassava is a more resilient crop to climate change than many) (Burns et al. 2010; Lobell et al. 2011), and part of its resilience comes from producing hydrogen cyanide as a defence against herbivore attack. There is a risk that as climate changes, farmers are more likely to utilise cassava and risk exposure to cyanide contamination through poor processing.

Finally, climate change affecting agriculture can affect human health directly. 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).

All of these different 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 their abundance and availability in soils; polycyclic aromatic hydrocarbons in foods following changes in long-range atmospheric transport and deposition into the environment; marine biotoxins in seafood following production of phycotoxins by harmful algal blooms; and the presence of pathogenic bacteria in foods following more frequent extreme weather conditions, such as flooding and heat waves (Miraglia et al. 2009).

5.6.4.2 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 include decreased protein and mineral nutrient concentrations, as well as altered lipid composition (DaMatta et al. 2010).This is for instance the case in wine, whose quality is being reduced due to warming-induced changes in sugar composition, affecting both colour and aroma (Mira de Orduña 2010).

Climate change affects a range of biological processes, including the rate of metabolism in ectotherms. Plants require carbon dioxide to form sugar, and so rising CO_2 levels also act as a fertiliser. Changing these processes can change growth rates, and therefore yields, but can also cause organisms to change relative investments in growing vs reproducing, and therefore change the nutrients laid down.

So, whilst CO_2 fertilisation is often seen as a positive for yields (e.g. (Yu et al. 2014) and Section 5.6.4.3) (both for plants and for other ectotherms like salmon (Jonsson et al. 2012)), there is now *strong evidence, with high confidence*, that protein content of plants 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). In addition, some micronutrients, like iron and zinc will be less accumulated and less available in food (Myers et al. 2014). Together, the impacts on protein availability may take as many as 150m people into protein deficiency by 2050 (Medek et al. 2017).

As CO_2 and changing heat change plant metabolism fundamentally they also result in a change of quality for those that eat plant products, such as pasture. This applies both in terrestrial systems where 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 CO_2 and temperatures affect the synthesis of long chain polyunsaturated fatty acid leading to reductions in their concentration in harvested fish.

Climate change may affect the quality of food in other ways (see also “food safety” for discussion of changing microbial contamination). For example, changing heat stress in poultry, as well as affecting yields, can affect the meat quality (by both altering fat deposition and the meat’s chemical constituents), affect the quality of the shell (and hence its function), and the immune system of the animal (affecting its 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 the 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. So, whilst we cannot predict with great certainty specific effects (other, perhaps than a general reduction in protein in C_3 crops), there is strong evidence that there will be impacts.

5.6.4.3 Direct CO_2 effects on nutritional quality

High atmospheric CO_2 has been shown to have negative effects on the nutrient content of crops (Porter et al. 2014a; Myers et al. 2014). Currently, the C3-crops – wheat, rice and soybean – provide almost 40% of the world's food calorie supply (as well as significant shares of iron, zinc and proteins) (Müller et al. 2014). Under climate change, production quantities are projected to decline (Rosenzweig et al. 2014), leaving a calorie production gap to be filled by intensification, cropland expansion and trade. CO_2 fertilisation can reduce the negative climate change effects considerably so that they are comparable to climate change impacts in a cooler world low in CO_2. Assuming a linear decline of the minerals iron and zinc, as well as protein, with rising atmospheric CO_2 concentrations, production compensation leads to significant decreases in nutritional values (Müller et al. 2014).

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, causing a loss of 63 million life-years annually. 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. Global maps of increased risk show significant heterogeneity (Myers et al. 2015). 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).

5.6.4.4 Impacts on pollinators

On a global basis, some 1500 crops require pollination (typically by insects, birds and bats) (Klein et al. 2007). Whilst most major commodity crops are wind (or mainly wind) pollinated, animal-pollinated crops include many fruit and vegetables and make up about 3%-8% of production by biomass (Aizen et al. 2009). Their importance to nutritional security is therefore perhaps under-rated by valuation methodologies, which, nonetheless, include estimates of the global value of pollination services at over £150 billion (2010 prices) (Hanley *et al.*, 2015).

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.

As with other ecosystem processes affected by climate change reviewed here (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 thus uncertain, although there is medium evidence that there will be an effect.

5.6.4.5 Impacts on pests and diseases

There is strong evidence (*high confidence*) that climate change is likely to change the dynamics of plant and livestock diseases. 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).

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” that may keep them under control; changes in the 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 the persistence of fungus). 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. 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. through drying out reducing 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).

5.6.5 Socio-economic aspects – Food price spikes, gender, equity, and migration

5.6.5.1 Climate change and food supply chain disturbances

The global food system depends on a well-functioning market, as it is typically the private sector that determines the movement of production, from where it is produced to where it is consumed. Increasingly, the world is becoming more interconnected in space (Puma et al. 2015) and more interconnected across sectors (i.e., the food system depends on water, energy, transport, digital etc.) (Homer-Dixon et al. 2015). There is also less spare land, such that if prices spike, there are fewer options to bring new production on stream (Marianela et al. 2016). Climate change, through exacerbation of extreme weather events, can perturb food production and transport (Figure 5.23).

For example, the US Corn Belt suffered a widespread drought in 2012. US corn yield in 2012 was 16% lower than in 2011 and 25% lower than in 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 (Chavas et al. 2014). Furthermore, analogue conditions of past extremes might create significantly greater impacts in a warmer world. In 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. 2015; Tadasse et al. 2016; Challinor et al. 2018). The principal route is by affecting agricultural commodity markets, which respond to a perturbation through multiple routes as in (Figure 5.23). 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. 2015a). 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).

Given the likelihood that extreme weather will increase, in both frequency and magnitude (Hansen et al. 2012; Coumou et al. 2014; Bailey et al. 2015a; Mann et al. 2017), and given the current state of global and cross-sectoral interconnectedness, there is medium evidence that the food system is at increasing risk of disruption, but with high uncertainty about how this could manifest.

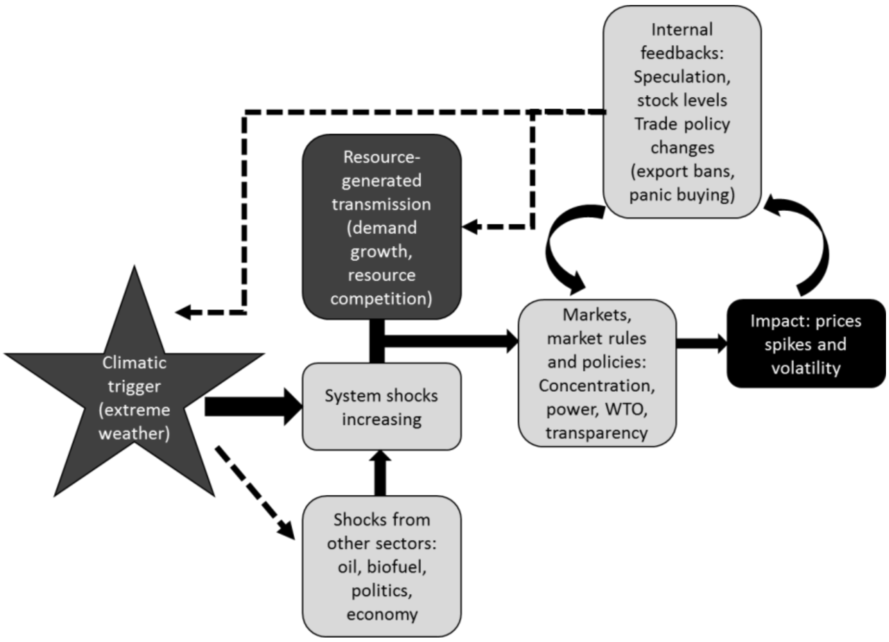


Figure 5.23 Underlying processes that affect the development of a food price spike in agricultural commodity markets (Challinor et al. 2018)

5.6.5.2 Gender and equity

It is well-recognised that food and nutrition security and climate change have strong gender and equity dimensions (Bryan et al. 2013; Nelson et al. 2002). Climate change impacts differently diverse social groups depending on factors such as age, gender, wealth, and class (Vincent and Cull 2014). Women and poor people are in general more affected by climate change because their starting point (or contextual) vulnerability is higher and because of gender-differentiated relative powers, roles and responsibilities at the household and community levels. Worldwide women play a key role in food and nutrition security at different scales, although regional differences exist. Nevertheless, existing gender norms and power inequalities shape the ability of men and women to adapt to climate risks (Rossi and Lambrou 2008). These include: (i) participation in decision-making and politics; (ii) division of labour, (iii) resource access and control, and (iv) knowledge and skills (Nelson and Stathers 2009). Several authors have shown the importance of women's education and gender equality to address child undernutrition (Smith and Haddad 2015) or the global burden of chronic and hidden hunger (Gödecke et al. 2018).

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 and nutrition security pillars (Aberman and Tirado 2014). At the same time, the four pillars of food and nutrition security have strong gender dimensions (Thompson 2018). In terms of availability, women tend to have less access to productive resources; in terms of access, women intra-household inequity limits their ability to purchase food; in terms of 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 and the poor are more likely to be disproportionately affected by price spikes. Still, context specificities need to be considered in regard to gender and climate change (Arora-Jonsson 2011), and different implications will be determined in part by age, ethnicity, region, and social position, as well as by location in rural or urban areas.

In rural areas women often grow most of the crops for domestic consumption and are primarily responsible for storing, processing, and preparing food. They also handle livestock; gather food, fodder and fuelwood; and manage the domestic water supply. In addition, they provide most of the labour for post-harvest activities (FAO 2011c). Yet women's work often goes unrecognised and they have only limited access to production resources (e.g., land, technology, credit, infrastructure, education), which can reduce their adaptation capacity to climate change (Rao 2005; Nelson and Stathers 2009).Although women make up more than 40% of the overall agricultural labour force in the developing world (ranging from 20% in Latin America to 50 percent or more in parts of Africa and Asia), they own between 10%-20% of the land (FAO 2011c). 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).

Water scarcity, as a result of climate change can particularly affect women. Decreased supply of safe water can also increase the labour burdens of those women living in rural areas and developing countries, particularly in Africa and Asia (Parikh 2009). Thus, 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. Furthermore, increased pressure on women's time 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). Households adapt their nutrition habits after shocks affect their food and nutrition security.

Reduction in food availability due to climate change may result in change in dietary intake (Lamichhane et al. 2015; Lobell and Burke 2010). Decreased yields can impact nutrient intake of the poor and vulnerable by possibly 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). Reducing meal intakes during food shortages is a common practice especially among women in some parts of the world (Goh 2012) but not in others (Niehof 2016). 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 (Darmon and Drewnowski 2015).

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) (*strong evidence, high agreement*). For instance, floods and droughts may result in water contamination increasing the incidence of diarrhoeal illness in poor children (Bartlett 2008).

This differentiated impact has also differentiated consequences in terms of food and nutrition security, both at the household and individual levels. At the household level, women in most parts of the world are in charge of feeding their families. They play a key role in all dimensions of food and nutrition security (World Bank 2009), and climate change impacts will affect their capacity to ensure the food and nutrition security of the family. Rural women often manage complex households and pursue multiple livelihood strategies. Their activities typically include producing agricultural crops, tending animals, processing and preparing food, working for wages in agricultural or other rural enterprises, collecting fuel and water, engaging in trade and marketing, caring for family members, and maintaining their homes. Many of these activities are not defined as "economically active employment" in national accounts, but they are essential to the well-being and food and nutrient security of rural households (FAO 2011c).

At the individual level, women's food and nutrition security can be more affected by climate change due to gender norms in different contexts, or because they are initially in poor health or are pregnant, adding to their initial contextual vulnerability. In developing contexts, firewood and water collection is largely done by women and girls on foot, and thus, climate-induced scarcity of natural resources can diminish food and nutrition security by further constraining the time available to women (World Bank, 2009; (Preet et al. 2010). In case of food price hikes, those more vulnerable, particularly women and 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).

5.6.5.3 Migration

Between 2008 and 2015, an average of 26 million people were displaced annually by climate or weather-related disasters (United Nations 2016). Individuals and countries experience climate change in two main ways; either as a change in average climate conditions (often referred to as slow onset change), or as an increase in sudden, extreme events. Gradual or slow environmental change includes processes such as desertification, reduction of soil fertility, coastal erosion and sea level rise. Environmental degradation occurs when these processes negatively affect human livelihoods and the NCPs on which a community depends. Exacerbated by climate change, these phenomena are often also provoked or aggravated by unsustainable forms of development. These processes have a medium- to long-term impact on existing livelihood patterns and systems of production. They may trigger different types of migration. When environmental degradation becomes severe or irreversible, migration becomes permanent and requires relocation of affected populations, either internally or in another country (Box 5.1).

There has been a surge in international migration in recent years, with around five million people migrating permanently in 2016 (OECD 2017). A World Food Program study (WFP 2017) reveals food and nutrition security is one of the critical factors impacting international migration. 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 was found to be 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.

Policy-makers view the potential link between climate change, migration and conflict as a security issue (Burrows and Kinney 2016). However, considerable ambiguity remains regarding the role of climate variability and change play among the many drivers of migration and conflict. Although climate variability and change bring the risk of serious negative impacts on environmental and human systems, including extreme events, there is a disagreement as to whether migrants relocate due to the environmental damage or due to social aspects such as loss of land and property (Burrows and Kinney 2016). The emphasis on environmental factors as drivers of migration has been found to be selective and inconsistent with some migration literature (Brzoska and Fröhlich 2015).

While it is agreed that climate change will not alone cause conflict, it is almost universally acknowledged that it has 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. The “neo-Malthusian” concept argues that as populations continue to increase, competition for resources will also increase, and that resources will become even scarcer due to climate change (Hendrix and Glaser 2007).

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). Nawrotzki et al. (2015) observed that international migration, especially from rural Mexico, is influenced by a set of well-known socio-demographic factors coupled with climate change impacts. In Mexico, in regions lacking social networks, rainfall deficits reduce migration propensities, reflecting constraints in the ability to engage in migration as a coping strategy (Hunter et al. 2013). In rural Ecuador, adverse environmental conditions consistently prompt out-migration, although households respond to environmental challenges in diverse ways resulting in complex migratory responses (Gray and Bilsborrow 2013).

In Pakistan, heat stress consistently increased long-term migration of men driven by a negative effect on farm income (Mueller et al. 2014). Elsewhere in Asia, the economic viability of the population in the Sundarbans is threatened due to decline in food and nutrition security and the lack of developmental choices in the face of migration from coastal areas triggered by climate variability (Guha and Roy 2016). In Nepal, Craven and Gartaula (2015) investigated the impact of out-migration on local perceptions of agricultural and residential land and the meaning given to food and nutrition security. The value changes associated with large-scale outmigration have the potential to make the agricultural sector at the point of origin more vulnerable, unproductive, unsustainable or unattractive, leaving a longer-term impact on food and nutrition security. However, studies carried out by Schwilch et al. (2017) found no evidence of negative impact of out-migration on land degradation.

In Bangladesh, the impacts of climate change are more intense and damaging and have been on the rise throughout the last three decades (Rabbani et al. 2015). Natural disasters have been on the rise leaving citizens with few options to earn an adequate living to sustain themselves and their families. As a result, migration has been increasing, with large numbers of people, mostly men, travelling to other regions in search of a better life and livelihood. This leaves women to stay behind usually with children, not only to cope with increasing effects of natural disasters, but also the increasing patterns of migration by male family members.

Box 5.1 Migration in the Pacific region: Role of climate change and food and nutrition security

Climate change-induced migration in the Pacific has received wider attention in the scientific discourse than elsewhere in the world. The processes of climate change and their effects in the region have serious implications for Pacific Island nations as it influences the environments that are their ‘life-support systems’ (Campbell 2014). First, climate changes, including sea level rise, affect their land security, which is the physical presence on which to live and sustain livelihoods; second, they impinge on livelihood security (especially food and nutrition security) of island communities where the productivity of both subsistence and commercial food production systems is reduced; and third, the effects of climate change are especially severe on small-island environments since they result in declining ecological habitat (Campbell et al. 2014). The effects on island systems are mostly manifested in atolls through erosion and inundation, and on the human populations through migration. Two categories of migrants are defined: climate change induced, and climate change forced. Both types are considered to be forms of climate change adaptation.

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 factors (cultural, religious, economic or social).

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. Despite sea level rise, a net increase in land area of 73.5 ha has been reported. The findings suggest islands are dynamic features that will persist as sites for habitation over the next century presenting alternate opportunities for adaptation that embrace the heterogeneity of island types and their dynamics. Farbotko (2010) and (Farbotko and Lazrus 2012), on the other hand, 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 are visualisations by cosmopolitans.

In Shishmaref (Alaska) and Nanumea (Tuvalu), forced displacements and voluntary migrations are not separated but are complex decisions made by individuals, families and communities in response to discourses of 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).

However, there are equally but lesser-known human migrations in the Pacific owing to a myriad of climate change-induced impacts (Connell 2015; Krishnapillai and Gavenda 2014; Charan et al. 2017; Krishnapillai 2017). While sea-level rise alone is causing adverse impacts, combinations of extreme events have a profound impact on the livelihoods of some atoll communities. Although considerable variations occur in the physical manifestations of climate variability and change, climate stressors threaten the life-support systems of many atoll communities (Campbell et al. 2014). Failure of these systems resulting from climate shocks and disasters propel vulnerable atoll communities into poverty traps. Low adaptive capacity will eventually force these communities to migrate.

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 and nutrition security due to lost labour lost and changing attitudes towards traditional ways of life among community members (Craven 2015).

5.7 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. Adaptation responses in the food system are targeted towards minimising losses, modifying threats, preventing impacts, or sharing losses, thus making the system more resilient (Harvey et al. 2014). 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. Given the site-specific nature of climate change impacts on food system components together with wide variation in agro-ecologies and socio-economic conditions, it is widely understood that adaptation strategies must be developed according to regional contexts.

In some areas, increased agro-climatic resources, especially heat resources, would alter agro-ecological zones, with opportunity for expansion towards higher latitudes and altitudes, soil and water resources permitting (Rosenzweig and Hillel 2015). On the other hand, more extreme climatic events are projected to lead to more agro-meteorological disasters with associated economic and social losses. 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 trading as well as consumption, livelihoods, cultural contexts, and NCPs. These interconnections may contribute to negative cascades, social disruption, and conflict (Challinor et al. 2018).

There are different pathways to adapt to climate change corresponding to different climate risk factors. These include optimising the use of agro-climatic resources (such as taking advantage of increased heat resources due to warming); minimising loss and damage due to more frequent and intense agro-meteorological disasters; increasing agricultural biodiversity to enhance resilience, especially to desertification and land degradation; and adjusting policies and strengthening institutional capacity (Rosenzweig and Hillel 2015). AR5 WGII found that taking a risk management approach to adaptation and resilience can help to avoid adverse food system outcomes due to climate change.

5.7.1 Adapting to mean climate changes, increasing extremes, and volatility

Various adaptation and risk management options, typically technological and biophysical measures, have been proposed and documented in recent literature to address increasing climate extremes and volatility. Water-smart agriculture as proposed by Naresh et al (2017), through efficient irrigation system is one option (Gunarathna et al. 2017; Chartzoulakis and Bertaki 2015). 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.

Adaptation measures can offset negative impacts on crop yields but previous meta-analyses have shown that crop yields decline considerably regardless of the positive effect of adaptation and CO_2 fertilisation when global warming exceeds 2°C. Among the often-studied adaptation measures are low-technology, on-farm practices such as irrigation water management (Jägermeyr et al. 2016); soil management; 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); and breeding for more drought, flood and heat-resistant crop varieties (Atlin et al. 2017; Mickelbart et al. 2015; Singh et al. 2017). 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) (Box 5.2).

Box 5.2 Expansion of rice in North 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 and nutrition 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), and the largest *Japonica* rice-production region. Producing high-quality grain, it is plays an important role in guaranteeing national and global food and nutrition 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). For example, Shi et al. (2013) found that temperature in Northeast China has increased by 1.43˚C in the past century, which is two times higher than the global average level. The increase of heat resources together with expansion of higher-yielding cultivars has allowed expansion of rice production in this region (Liu et al. 2014). Wang et al. (2014) showed that climate had contributed to the increased rice yields in Northeast China at the rate of 0.59 % yield per year.

With increasing northward movement of the accumulated temperature belt, all three river basins in the area became favourable to rice growth, and the rice cultivated area expanded beginning in the 1990s (Lin et al. 2005). Shi et al. (2013) found a close correlation between statistically significant climate change and expansion of rice cultivation area in Northeast China during recent decades. Further, Liu et al. (2014) showed that the shifts in the extent and location of rice-cropping areas match the pattern of climate change: The increased temperature enabled rice planting northward and eastward and at higher altitudes in northeast China. Liu et al. (2014) also demonstrated that climate warming has extended the northern limit of rice cropping and expanded the potential area for rice production. According Li et al. (2017), the central latitude of the rice area shifted northwards from 46 to 47°N and moved eastwards from 130 to 133°E from 1984 to 2013 (Figure 5.24**Error! Reference source not found.**). Liu et al. (2014) showed that the suitable area for rice in the region increased from 47.1% in 1980 to 51% in 2010, as a result of the movement of the northern limits of climatically suitable rice production from 48ºN in 1980 to 50ºN in 2010 (Figure 5.24).

Li et al. (2017) found that rice area 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. In addition, there has been a significant expansion of paddy rice areas in Northeast China in the latitude band of 45–48°N and a longitude band of 120~134°E. This is mainly located in the Sanjiang Plain in Heilongjiang province (Zhang et al. 2017). On the other hand, as rice planting expanded northward and upward in the northeast, cold stress is still a threat to rice production (Wang et al. 2014).

As temperature increased, the early-medium rice variety, which had been restricted to a limited area due to cool temperatures, was replaced by a more productive medium-late variety, while the early variety is used in the previous unavailable areas where warming temperature now allows production (Zhang et al. 2013).

The expansion of rice-cropping area in Northeast China is a demonstration of an opportunity for adaptation to increase food production, in both amount and nutritional quality. The share of the region in total national rice output increased, with relative contribution going up from 3% to 16.2% (Li et al. 2016b). *Japonica* rice is also highly nutritious.

However, environmental impacts cannot be neglected. The rice-cropping land expansion would reduce biodiversity and affect regional NCPs. Rapid population growth in the region will lead to more demand for food and land resources, in turn bringing deforestation and land reclamation from grasslands and lakes (Shi et al. 2013). Moreover, expansion of cultivated rice land would definitively lead to more greenhouse gas emissions (Yao et al. 2017). Another side effect is that warming climate would provide a better environment for overwintering and subsequent epidemics of rice pests and disease.

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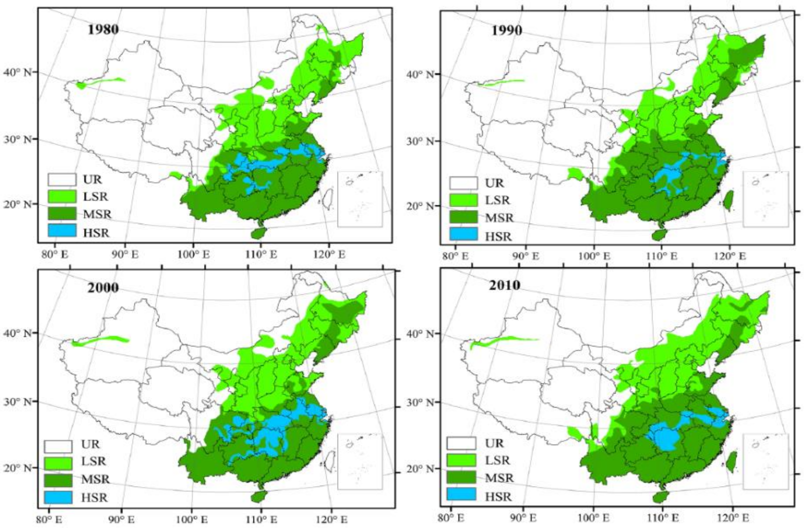


Figure 5.24 Spatial distribution of climatically-suitable rice regions in China (1980 to 2010) (Liu et al. 2014)

5.7.2 Ecosystem-based adaptation

There are now plentiful 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. 2015). 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 the common and preferred conservation agriculture techniques were based on local traditional knowledge, including crop rotation, no or minimum tillage, mulching, and cover crops. Moreover, cover cropping and no-tillage improved soil health in a highly commercialised arid irrigated cropping system in California's San Joaquin Valley, US (Mitchell et al. 2017b). Biofertilisers from *Rhodopseudomonaspalustris* strains enhance rice yields (Kantachote et al., 2016). In addition, 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 biochar 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 related to it, 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. According to Morrison-Whittle et al. (2017), these types of farm management significantly affect communities in soil, plant structures, and crop growth in subtle but importantly different ways in terms of number, type, and abundance of species.

5.7.3 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. 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). Box 5.3 presents the outcomes of a community-based adaptation project in displaced atoll communities in Micronesia.

Box 5.3 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 and nutrition 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 and nutrition 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 and nutrition 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 and nutrition security and livelihoods (Krishnapillai 2017). People can access more nutritious and reliable food sources, and they are growing their own food and selling their surplus, creating greater confidence about their future.

5.7.4 Cultural beliefs

There are some entrenched cultural beliefs and values that are inimical to climate change adaptation. In some communities, societal norms restrict women from access to land, resources, or adopting different methods of food production. Murphy et al. (2016) concluded that culture and beliefs play an important role in adaptive capacity but are not static. In the context of changing beliefs, adaptive capacity should be influenced by how different belief systems co-exist and how epistemological and intergenerational frictions are negotiated. There is evidence that innovation and subsequent adaptive responses may be suppressed if the dominant culture disapproves of departure from the 'normal way of doing things'.

In some rural communities in Africa in particular, women's ideas are not supported because their opinion may not be valued or given much weight or their preferences may be ranked lower than men's. Poor recognition of gender and other social differences could prevent certain people, often the most vulnerable, from adapting, as was the case in the Central Africa Republic in relation to a REDD+ program. This was further demonstrated by Ravera et al. (2016) who concluded that, despite the evidence of the growing impact of climate and other socio-economic drivers, there is little recognition of geographically determined and gender-sensitive preferences and adoption of options related to ecosystem-based management. In the work done by Elum et al. (2017) in South Asia about farmers perception of climate change, they concluded that perceptions and beliefs often have negative effects on adaptation options.

5.7.5 Policy, planning, and governance

There are a number of adaptation options in agriculture in form of policy, planning, and governance; it is believed that early spatial planning action is crucial to guide decision-making processes and foster the 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 projections (Lorenz 2017). In Nepal, enhancement of representation, democratic and inclusive governance, as well as equity and fairness are suggested for improving climate change adaptation policy processes and outcomes (Ojha et al. 2015).

Food, nutrition and health policy adaptation options such as social safety nets and social protection have been implemented in India, Pakistan, Middle East and North Africa (Devereux 2015; Mumtaz and Whiteford 2017; Narayanan and Gerber 2017). Also, food banks and distribution of food surplus, food recovery, and food aid (Silvasti 2015; Baglioni et al., 2017) have been instituted, as well as water and sanitation and public health services (Watts et al. (2015), Fuller et al. (2015), and Hadwen et al. (2015)).

Financial incentive policies used as adaptation options include taxes and subsidies; index-based weather insurance schemes; catastrophe bonds (Lipper et al., 2017; Linnerooth-Bayer and Hochrainer-Stigler 2014; Ruiter et al., 2017; Campillo et al 2017). In addition, microfinance, disaster contingency funds, and cash transfers can be adaptive measures (Ozaki (2016) and Kabir (2016)). Planning and trade regulations relative to drought-tolerant maize for the US Corn Belt have recently been released to deal with new adaptive hybrids (Mckersie, 2017). Other adaptation policies studied are property rights and land tenure security (Knudsen & Mertz (2016) and Brandt et al. (2017)).

To build disaster-resilient societies against water-related disasters such as floods and droughts that affect food and nutrition security, Grobicki et al. (2015) suggested an integrated policies and practices based on stakeholder's perspectives and a partnership approach. In Malaysia, Vaghefi et al. (2016) indicated that increasing the fertiliser subsidy and increasing price support could be a very good policy option to improve rice production and enhance the food and nutrition security.

Nepal has developed a novel multilevel institutional partnership, including collaboration with farmers and other non-governmental organisations in recent years. By combining a conventional technological innovation process with enhanced climate change knowledge of farmers, this new alliance has been instrumental in the innovation of location-specific technologies thereby facilitating the adoption of resilient technologies in a more efficient manner (Chhetri et al. 2012).

5.7.6 Knowledge, science and technology

Development and use of climate stress-tolerant crop varieties (Fisher et al., 2015; Prohens, 2015), heat-tolerant animals (Rout et al., 2017), and salt-resistant crops (Hanin et al., 2016; Das et al., 2015) are leading adaptation measures to climate extreme events and volatility. Fenomics-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).

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 drone applications, such as drones, for 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 provide opportunities to improve early drought warning. Waldner et al. (2015) found that cropland mapping allows strategic food and nutrition security monitoring and climate modelling.

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

Mainstreaming early warning systems in adaptation planning could present a significant opportunity for climate disaster risk reduction (Zia and Wagner 2015). Enenkel et al. (2015) suggested that the use of smartphone applications that concentrate on food and nutrition security could help with more frequent and effective monitoring of food prices, availability of fertilisers and drought-resistant seeds, and could help to turn data streams into useful information for decision support and resilience building.

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. 2017b; Nolan et al. 2017; Abhik et al. 2016).

Improved transport technology is also important to improve food and nutrition 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 and nutrition security (Brown et al. 2017).

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

The synergies and trade-offs between mitigation, adaptation, food and nutrition security, and land use in the food system are of increasing interest in both the scientific and policy communities because of the need to ensure food and nutrition security for a growing population while reducing GHG emissions and adapting to changing climate conditions (Rosenzweig and Hillel 2015). Special challenges involve the interactions within and between supply and demand-side mitigation techniques; between food loss and waste, food and nutrition security and land use; and between mitigation and adaptation, such as the effects of specific interventions such as BECCS.

Assessing the impacts of climate change on agriculture presents researchers and policy makers with a difficult challenge: how can we evaluate all of the potential economic, environmental, and social outcomes of complex, nonlinear systems under recently observed conditions as well as under conditions that may be observed in the distant future? To address this challenge, multidisciplinary teams of scientists have been working together, utilising many kinds of data and quantitative models and investigating methods to create plausible future scenarios. The resulting simulation experiments are designed to quantify the likely impacts of climate change on agriculture and to assess adaptation options that could help farmers reduce adverse impacts and take advantage of favourable impacts (Antle and Stöckle 2017).

Scenarios describe possible future developments. They can be used in an exploratory manner or for a scientific assessment in order to understand the functioning of an investigated system (Carpenter et al. 2005). In the context of the IPCC assessments, scenarios are directed at exploring possible future emissions pathways, their main underlying driving forces and how these might be affected by policy interventions (Fisher and Nakicenovic 2007).

In this section, we highlight the Shared Socio-economic Pathways (SSPs). SSPs are part of a new scenario framework, established by the climate change research community in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation (Riahi et al. 2017). The pathways were developed over the last years as a joint community effort and describe plausible major global developments that together would lead in the future to different challenges for mitigation and adaptation to climate change (Riahi et al. 2017).

SSP scenarios. The SSPs address many aspects of sustainability but do not address the interactions between healthy diets and food and nutrition security. Additional work has created dietary pathways for use in scenario analyses (see section 5.5.3). See Chapters 1 and 2 for descriptions of the SSPs.

1.5°C scenarios. Representatives from 196 countries signed the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement (UNFCCC 2015) in December 2015, setting a goal to limit global mean temperature rise below 2ºC above pre-industrial levels, with nationally-determined commitments (NDCs) aiming to reach a stabilisation at +1.5ºC above pre-industrial conditions. Reduction of GHGs through the agricultural sector is included in the NDCs of many countries, and agricultural impacts are a major source of vulnerability and prime focus of National Adaptation Plans (NAPs) as well (Rosenzweig et al. 2017). The Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI) provides a framework for the generation of climate data describing how the climate, and in particular extreme weather, might differ from the present day in worlds that are 1.5°C and 2.0°C *warmer* than pre-industrial conditions (Mitchell et al. 2017a).

Limitations and caveats. Limitations and knowledge gaps include lack of appropriate modelling frameworks with gaps related to representative consumer behaviour and social dynamics. There is also lack of evidence on climate impacts on nutrients, and not enough coverage of key food groups and consumption data. Current analytical and quantitative modelling capabilities fall short of being able to capture all 17 SDGs and their targets. Even highly ambitious and optimistic pathways currently used in research, such as SSP1/SSP1-2.6, do not meet all SDGs (sustainability gaps) and fail to provide information on some of them (knowledge gaps) (Zimm et al. 2018).

5.8.1 Production, prices, and trade

Given currents trends in dietary patterns, feeding a world population of 9.1 billion people in 2050 would require increasing overall food production by some 60% between 2005 and 2050, production in developing countries would need to increase by 77% (Alexandratos and Bruinsma 2012). Annual cereal production, for instance, would have to grow by almost one billion tons and meat production by over 200 million tons to a total of 470 million tons in 2050; 72% of which in the developing countries (High Level Expert Forum 2009). Presently, global livestock production is the largest user of agricultural land. Further, dietary shifts towards livestock products imply that much of the additional crops, mainly coarse grains and oilseeds, production will be used for livestock feeding. The share of the global crop calories used as livestock feed may increase to 48% and 55% between 2000 and 2050 (Pradhan et al. 2013a) under a business-as-usual scenario.

The annual growth of world agricultural production is projected to fall from 2.2% over the last decade to 1.3% over the period to 2030 and 0.8% from 2030 to 2050 (

Table 5.4). It should, however, be noted that incremental quantities involved are considerable: by 2050 annual cereal production would increase by 940 mt (+46%) and meat production by almost 200 mt (+76%) (Alexandratos and Bruinsma 2012).

Table 5.4 Agricultural production growth rates (percent per annum).

	1961-2007	1987-2007	1997-2007	2005/2007-2030	2030-2050
World	2.2	2.2	2.2	1.3	0.8
Developing countries	3.3	3.5	3.1	1.6	0.9
idem, excl. China and India	2.9	3.0	3.3	1.8	1.2
Sub-Saharan Africa	2.6	3.2	3.1	2.5	2.1
Latin America and the Caribbean	2.9	3.3	3.8	1.7	0.8
Near East / North Africa	3.0	2.7	2.4	1.9	1.3
South Asia	2.9	2.7	2.4	1.9	1.3
East Asia	4.0	4.2	3.3	1.3	0.5
Developed countries	0.9	0.2	0.5	0.7	0.3
44 countries with over 2700 kcal/person/day in 2005/2007*	2.6	2.9	2.0	1.1	0.5

*Accounting for 57 percent of the world population in 2005/2007.

Source: (Alexandratos and Bruinsma 2012).

“Business as usual” projections (those based on past trends and projecting forwards) allow the decomposition of growth into an annual rate of increase. Over the last two decades, yield growth for cereals has averaged about 1.25%. If this is continued to 2050, this equates to a 50%-60% increase compounded. Doubling of yields from 2014 would require about a 1.9% annual increase.

A different analysis, based on different crops, and using smaller scale census data up to 2008, identifies that recent yield growth rates increasing yields by 67%, 42%, 38%, and 55% for maize, rice, wheat and soybean production by 2050 (Ray et al. 2013).

All things being equal, improving the yield of a plant requires location-specific agricultural management strategies and inputs that include more nutrients and more water, and typically arises from greater intensification (Pradhan et al. 2015; Mueller et al. 2012). Whilst there is discussion about how to make intensification sustainable, much of the discussion is focused on increasing efficiency. However, in intensively farmed agricultural areas, “sustainable intensification” may require a reduction in production in favour of increasing sustainability in the broad sense (Buckwell et al. 2014). Hence, moving towards sustainability may imply lower yield growth rates than those maximally attainable.

Bajželj et al. (2014), took recent estimates of yield growth (Ray et al. 2013) for different crops, FAO food demand projections, and models this spatially explicitly as biomass flows, using 2009 as a baseline. If demand exceeds supply, land is taken into agriculture. Under “business as usual” assumptions (current dietary trends, waste etc.), the principle conclusions are that meeting global demand in 2050 would require *120% more water; 42% more cropland and loss of 14% more forest, and GHG emissions would increase 77%. The total emissions for agriculture would, if maintained, create close to 2 degrees of global warming. In addition, continuing trends of diet-related ill-health, would place increasing burdens on health care.* In other words, if the SDGs and Paris Climate Agreement goals operationally define "sustainability," business as usual trends are unsustainable.

Trade is a critical mechanism to stabilise demand and supply under climate change and under a diverse set of economic futures, as those described in the SSPs. Its relation to prices is also significant and a key aspect of how to balance food and nutrition security between different regions.

Current evidence suggests that agricultural trade will increase under climate change under all SSP and RCP scenarios, but with the impacts on consumers changing significantly depending on associated changes in prices, the commodities traded and the mitigation efforts to minimise global temperature increases.

Highest volumes of trade are projected in scenarios with highest climate impacts on crops and livestock (RCP5.6 and 8.5) and socio-economic scenarios that promote unsustainable population growth, regionalisation (SSP3), inequality (SSP4) or high fossil fuel use (SSP5). The higher the mitigation effort, especially if associated with land use, the higher the reduction in land available for crop and particularly for the production of red meats (Hasegawa et al. 2017; van Meijl et al. 2018). Net importers of food in most cases remain Sub-Saharan Africa, while depending on the scenario Asia could become an importer or an exporter (Hasegawa et al. 2017; Popp et al. 2017). NAM, LAC and Europe remain exporter of primary commodities, but volumes of exports in LAC remain dependent on the magnitude of the mitigation efforts.

5.8.2 Supply and demand

The impacts of climate change on food supply and demand have received significant attention recently. This has been done by implementing ensembles of integrated assessment frameworks including global economic models, climate and crop and livestock models. Popp et al. (2017) summarised the results of the marker quantifications of the SSP scenarios for different RCPs. Figure 5.25 shows the changes in the global demand for crops and livestock products from their study.

According to Popp et al. (2017), in general terms, for the baseline without climate change, the demand for crops and livestock is lowest, and reasonably stable by 2050 in SSP1, a scenario geared towards sustainability criteria, where population growth rates are lower and consumption of more sustainable diets is desired. In the SSP2 baseline scenario, current population trends in population, income and consumption are projected. As a consequence, global demand for crop and livestock products increases moderately in SSP2 with the highest shares and increases in demand over time in Asia. In SSP3, very high population increases, but low economic growth drives increases in global demand for crops to higher levels than in SSP2, and to similar levels as in SSP2 for livestock products. Compared to SSP2, SSP4 shows relatively low increases in demand of both crops and livestock products, despite having global population growth very similar to SSP2.

This difference in demand is because the increase in population in SSP4 is mainly in low-income regions such as MAF with limited access to markets, and even more importantly because the GDP growth in these already poor regions is even slower under SSP4 than under SSP2. The high demand for crops in MAF and Asia is met with both local production and imports from OECD and LAM. SSP5 reaches similar levels of crop demand as SSP2, but much higher demand for livestock products occurs in SSP5, especially in the middle of the century (plus 354 million t DM in 2070) due to unhealthy diets with high animal shares and high shares of food waste. Part of the crop demand increases in SSP5 are associated with intensified livestock production systems and higher feed crop use. In the strongly globalised world of SSP5, agricultural products are not necessarily produced domestically with Asia becoming an important exporter.

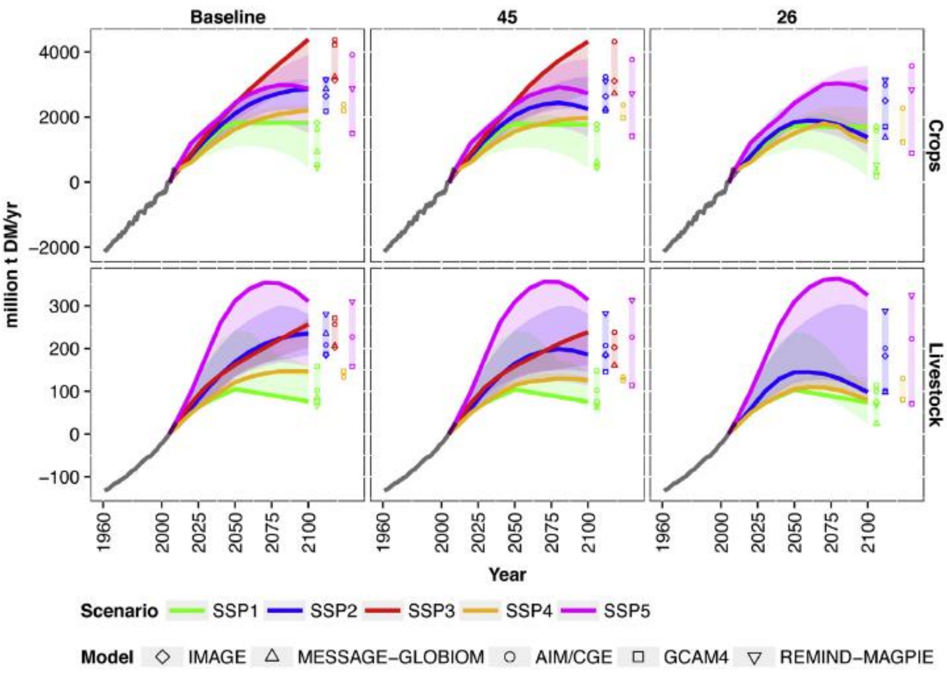


Figure 5.25 Change in global demand for crops and livestock products

Frank et al. (2018) also demonstrated that there are interactions between supply and demand side mitigation. They found that the level of demand-side mitigation needed is partly dependent on the level of effort to achieve supply-side mitigation. They found that at carbon prices up to 100 USD tCO_2e^{-1} by 2050, dietary shifts to realise significantly higher non-CO_2 emission reductions compared to the scenarios with business-as-usual (BAU) diets (7). At 100 USD tCO_2e^{-1}, emissions can be on average reduced by additional 0.4 $GtCO_2e$ yr^{-1} in 2050 across models, which corresponds to a 19% increase in mitigation potentials (+50% at 20 USD tCO_2e^{-1}).

However, with increasing levels of mitigation efforts, the additional emission reductions resulting from the diet shift decline rapidly and effects are almost negligible in scenarios with higher prices, where the mitigation potential increases only by 3%. Still, the diet shift enables to achieve the same amount of mitigation at lower carbon prices. Hence, though effects on total emission reductions may be limited, the diet shift may yield economic and socio-economic i.e. food security, benefits as it reduces the carbon price and hence mitigation costs. Moreover, distribution of animal calorie intake levels is more balanced across developing and developed regions in the diet shift scenarios.

Given the very inelastic demand in high-income countries, under BAU diets even a carbon tax of 2,500 USD tCO_2e^{-1} yields only a 15% decrease in animal product consumption in developed countries compared to baseline levels. In the diet shift scenarios, diets become more homogeneous between regions, as the additional consumption cuts (up to -36%) in overconsuming regions enable developing countries to even slightly improve their animal product consumption. For example, animal calorie intake levels increase by 16% in India and 10% in Sub-Saharan Africa in CP2500_D with diet shift compared to CP2500. Hence, even though a shift towards reduced livestock consumption might not contribute to the mitigation effort under higher levels of mitigation effort for the supply side, preference shifts will still allow achieving the same amount of emission reductions with more favourable outcomes in terms of food security (Figure 5.26).

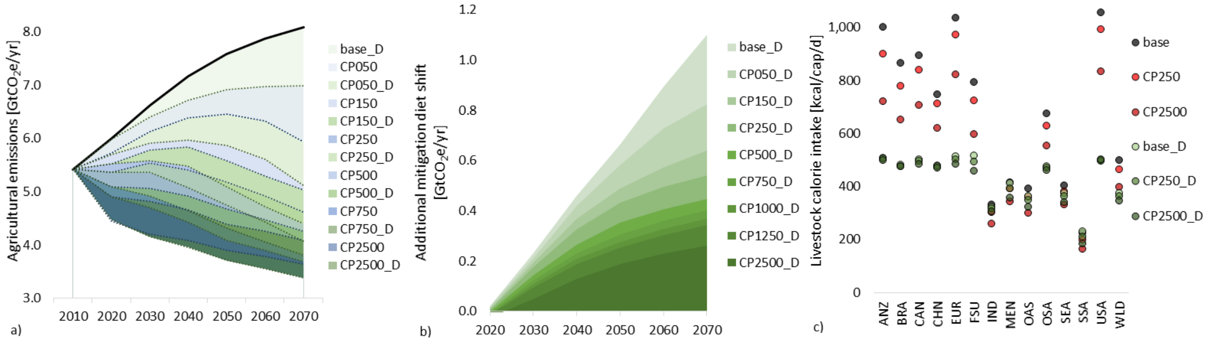


Figure 5.26 Panel a) Development of global agricultural baseline (base) emissions and emission reductions in the carbon price (CP) and diet shift (_D) scenarios until 2070. b) Global emission savings in the diet shift scenarios compared to the corresponding carbon price scenario without diet shift. c) Livestock calorie intake across regions for selected scenarios. Displayed results represent an average across models.

5.8.3 Food and nutrition security

Food prices have been traditionally seen as the result of supply, demand and trade relations. Earlier studies (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 its impacts on food and nutrition security is the level of mitigation necessary to stabilise the global temperature increases. Hasegawa et al. (2017) (Figure 5.27) using an ensemble of seven global economic models across four RCPs and three SSPs, 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.

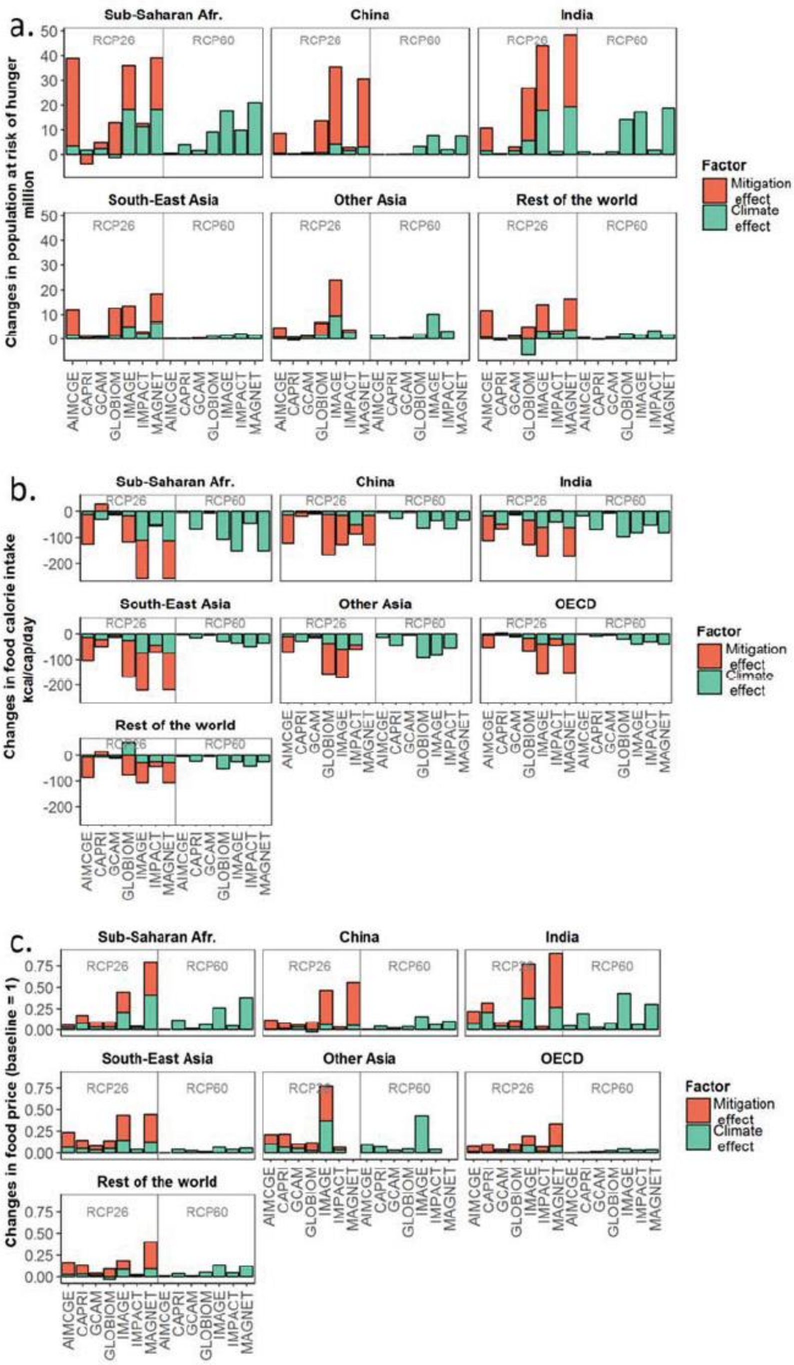


Figure 5.27 Regional impacts of climate change and mitigation on a) undernourishment, b) mean calorie intake and c) food price in 2050 under intermediate socio-economic scenario (SSP2). Values indicate changes from no climate change and no climate change mitigation scenario. MAgPIE is excluded due to inelastic food demand. The value of India includes that of Other Asia in MAGNET (Hasegawa et al. 2017)

5.8.4 Land use

Land use and land use change and agricultural intensification are central to achieving food and nutrition security at lower emissions targets. Popp et al. (2017) synthesised the projections under the SSP x RCP framework and described that the use of cropland for food and feed production increases moderately in SSP2 (plus 231 Mha between 2005 and 2100), due to relatively high demand for food and feed crops, combined with high yield increases (by a factor of 1.6 between 2005 and 2100) (Figure 5.28). Pasture area increases in SSP2 due to increases in demand for livestock products (plus 204 Mha until 2100). Agricultural expansion mainly happens in MAF and LAM as a result of livestock product demand being satisfied mostly through extensive ruminant livestock production systems. These increases in agricultural land happen at the expense of forest areas (LAM) and other natural land (MAF). In SSP1, low demand for food and higher agricultural intensification lead to the lowest agricultural land demand of the SSPs. As a consequence of such agricultural abandonment and regrowth of natural vegetation, other natural land and forests expand strongly in all regions.

The highest increases in pasture and cropland for food and feed production (mainly in MAF and LAM at the cost of forests and other natural land) are observed in SSP3, mostly driven by an increasing global population combined with low agricultural intensification. SSP4 shows primarily, large increases of pastureland (mainly in MAF) at the expense of forests (Figure 5.29). SSP5 shows an increasing use of cropland until 2050 (mainly in ASIA, LAM & MAF) which then decreases towards medium levels in 2100 and a decline in pasture throughout the century. These findings are fairly consistent across baseline marker and non-marker scenarios, with all models showing lower cropland area in SSP1 and higher cropland area in SSP3 than in SSP2. Forest area, in contrast, is largest in SSP1 and smallest in SSP3 in all models (with the exception of IMAGE SSP3). Land cover in SSP4 and SSP5 are more similar to SSP2 in most cases; however, models diverge in some instances.

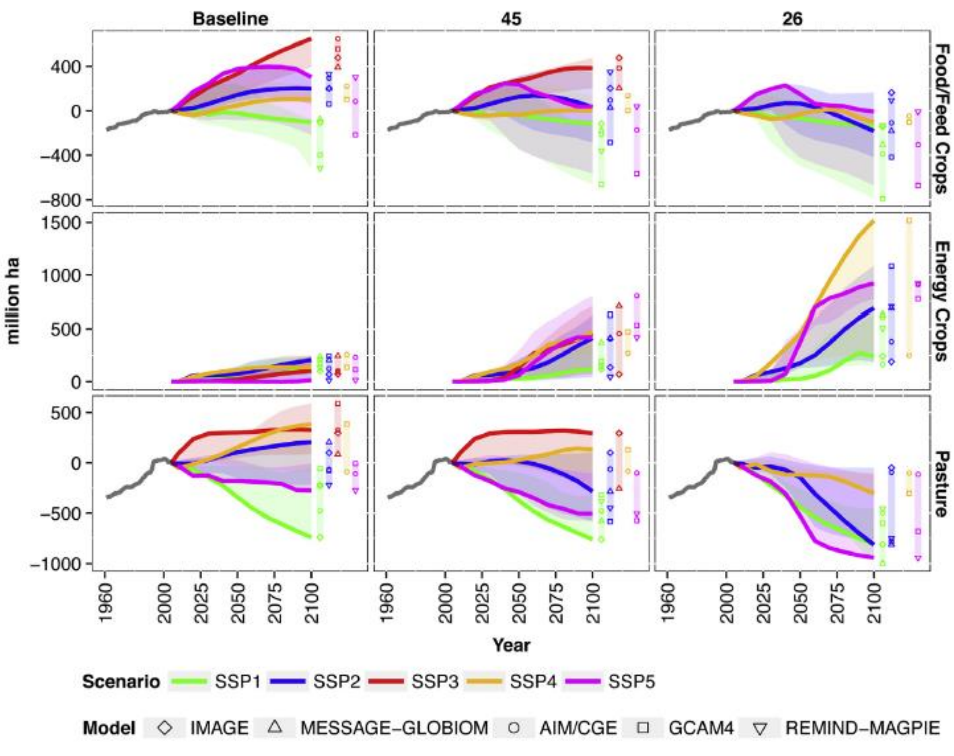


Figure 5.28 Change in global land for food and feed crops, energy crops, and pasture of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP 2.6 (right column) cases. Coloured lines indicate the marker model results for each SSP. Coloured bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Grey line shows historical trends based on FAO data (Popp et al. 2017)

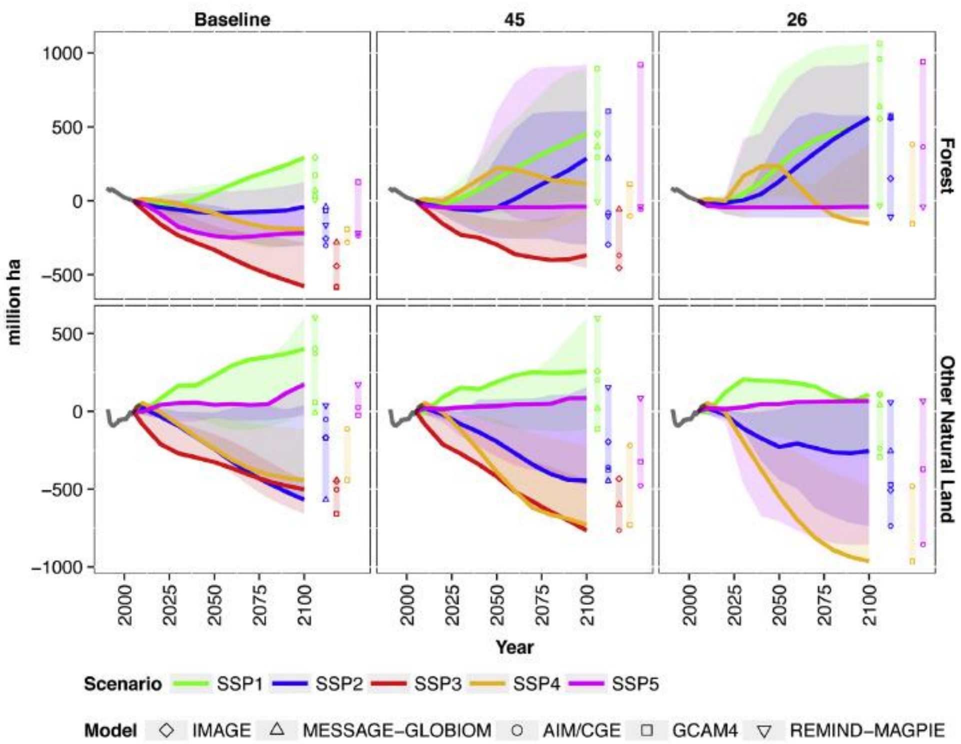


Figure 5.29 Change in global land for forest (upper row) and other natural land (lower row) of the five SSP marker scenarios for the baseline (left column), RCP 4.5 (middle column) and RCP 2.6 (right column) cases. Coloured lines indicate the marker model results for each SSP. Coloured bars indicate the range of data in 2100 across all marker and non-marker proections for each SSP (models are depicted by icon). Grey line shows historical trends based on FAO data (Popp et al. 2017).

A carbon tax on food can drive GHG savings and health benefits (Springmann et al. 2016c), and food price can help meet multiple SDGs (Obersteiner et al. 2016) by changing demand for food. See also (Stevanović et al. 2017) for an analysis that suggests changing food preferences rather than prices may be more effective. Healthy diets can have bigger social savings than environmental ones (Springmann et al. 2016b).

It is possible by reducing waste and over-consumption and changing dietary preferences to significantly reduce GHG from the food system while providing a healthy diet for all. While most of the literature takes a life cycle analysis approach, recommending reduction in ruminant products (beef, lamb, mutton, milk) in favour of poultry, there is an alternate viewpoint that pasture land serves many purposes and would otherwise be abandoned, whereas poultry directly competes with humans for arable-grown food. From a systemic perspective, it is possible to imagine a beef + dairy + plant-based diet that matches the emissions of a chicken + plant based diet, even if different quantities of meat were eaten (Schader et al. 2015). However, what this illustrates is that there is no simple evidence-based “climate-smart diet”, as what is the most appropriate farming system depends on the time and place (Garnett et al. 2017).

5.8.5 Food loss and waste, food and nutrition security, and land use

Food loss and waste impacts food and nutrition security by reducing global and local food availability, limiting food access due to increase in food price and decrease of producers’ income, and effecting future food production due to unstainable use of natural resources (HLPE 2014). The amount of food currently wasted is enough to nourish around 1 to 1.4 billion people (Kummu et al. 2012; Hiç et al. 2016). Changing consumer behaviour to reduce per capita overconsumption offers substantial potential to improve food and nutrition security by avoiding related health burdens (Alexander et al. 2017b; Smith 2013) and reduce emissions associated with the extra food.

Reduction of food loss and waste can contribute to feeding undernourished people, however, this is debatable and needs to be systematically explored (Chaboud and Daviron 2017). Reducing food loss and waste in the EU can reduce food prices in sub-Saharan Africa, which has differential impacts across producers and consumers (FAO and LEI 2015).

Local, national and regional food self-sufficiency can be enhanced by avoiding food waste (Pradhan et al. 2014). Halving the food waste reduces the need for cropland area by around 14% and GHG emissions by 22%-28% (4.5GtCO_{2e} yr^{-1}) in combination with closing yield gaps compared to baseline scenarios with food waste and current yield trends for 2050 (Bajželj et al. 2014). Reduction of food waste can reduce GHG emissions for Sweden but only after technological improvement and dietary changes (Bryngelsson et al. 2016).

Avoiding food loss and waste will also contribute to reduce emissions from the agriculture sector. For example, by 2050, GHG emissions associated with food waste may increase tremendously to 1.9–2.5 GtCO_2eq yr^{-1} which would be about one tenth of overall global GHG emissions from agriculture (Hiç et al. 2016).

5.8.6 Integrated Practices – Competition and co-benefits

5.8.6.1 Food vs. energy – Competition for land

Net CO_2 emissions from land use change result from an interplay between the use of land to produce food and other non-food products, to produce bioenergy, and to store carbon in land. In general, most scenarios project declining CO_2 emissions from land use changes as a result of declining deforestation rates, both with and without mitigation, and many scenarios project a net uptake of CO_2 as a result of reforestation after 2050 (Clarke et al. 2014). Bioenergy with Carbon Capture and Storage (BECCS) is a GHG mitigation technology that produces negative carbon dioxide emissions by combining biomass use with geologic carbon capture and storage. Bioenergy could play a critical role in stabilising climate change, if conversion of high carbon-density ecosystems (forests, grasslands and peatlands) is avoided and best-practice land management is implemented (Smith et al. 2014). Food vs. energy competition necessitates nexus thinking (See section 5.8.6.1) for improved use of large land areas for afforestation or for bioenergy. These changes could increase food prices, and compromise food and nutrition security, if land normally used for food production is converted to bioenergy or forests (Clarke et al. 2014). Solutions include enabling, integration and optimisation of climate change policies with other priorities such as land use planning and protection of water resources (Victor et al. 2014).

Agroforestry can play a role in providing co-benefits of both mitigation and adaptation, but these co-benefits vary depending on which function is analysed (Figure 5.30).

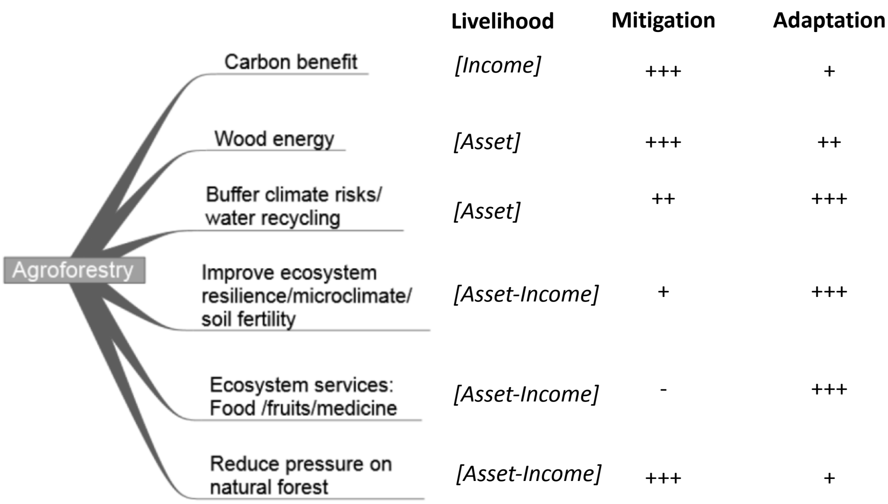


Figure 5.30 Co-benefits between Mitigation and Adaptation. +++: very high positive impact; ++: high positive impact; +: limited positive impact; -: zero positive or potential negative impact (Mbow et al. 2014)

5.8.6.2 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. 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 and nutrition security (Garnett et al. 2013), but also reduces the loss of such production inputs and associated emissions (Sapkota et al. 2017e; Wollenberg et al. 2016). Closing yield gaps is a way to become more efficient in use of land per unit production.

Sustainable Intensification acknowledges that enhanced productivity needs to go hand in hand with the maintenance of other NCPs and enhanced resilience to shocks (Vanlauwe et al. 2014). 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 the pathways to meet food and nutrition security and climate change adaptation and mitigation goals. However, sustainable intensification does not always confer co-benefit in terms of food and nutrition security and climate change adaption/mitigation.

For example, in 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. 2010b) in sub-Saharan Africa, reported that at low population densities and high land availability, food and nutrition 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 and nutrition 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)

5.8.6.3 Climate-smart agriculture

Some have put forward a 'climate smart' approach to tackle current food and nutrition security and climate change challenges (FAO 2011d). This is designed to be a pathway towards development and food and nutrition security built on three pillars: increasing productivity and incomes, enhancing resilience of livelihoods and ecosystems and reducing and removing GHG emissions from the atmosphere. However, the climate-smart approach has been contested.

Many agricultural practices and technologies already provide proven benefits to farmers' food and nutrition 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. 2017b; Harvey et al. 2014).

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 and nutrition security and climate change mitigation (Sapkota et al. 2017b, 2015). 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. 2014; 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.

5.8.6.4 Conservation agriculture

Conservation agriculture practices include soil management, agroforestry, and crop sward management. Intensive agriculture during the second half of the 21st century led to soil degradation and loss of natural resources and contributed to climate change. Therefore, sustainable soil management practices can address both food and nutrition 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). For example, conservation agriculture (CA), an approach based on the principles of minimum soil disturbance, permanent soil cover combined with appropriate crop rotation, 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). Similarly, replacing mono-cropping systems with more diversified cropping systems and agroforestry can buffer temperatures as well as increase carbon storage (Mbow et al. 2014; Bioversity International 2016), and provide diversified and healthy diet in the face of climate change.

5.8.6.5 Food-Energy-Water Nexus

Emerging interdisciplinary science efforts are providing new understanding of the interdependence of food, energy, and water (FEW) systems and these interdependencies are beginning to be taken into account climate change, food and nutrition security, and AFOLU assessments (Scanlon et al. 2017). These science advances, in turn, provide critical information for coordinated management to improve the affordability, reliability, and environmental sustainability of FEW 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 FEW nexus; ground-based monitoring and modelling at local-to-regional scales; 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 FEW decisions (Scanlon et al. 2017).

There are many important linkages between water use in agriculture and energy consumption to access water and to transform agricultural products. The interface between the three resources with land dynamics as modulator should be seen as a leverage point for sustainability and resource efficiency improvement to address carbon intensity reduction targets (Cremades et al. 2016). The world is at the crossroads to secure food for a growing global food demand with many possible trajectories that imply various use of water, energy and land use and management. The current trends on the various segments of the nexus will not help meet projected food demand sustainably. The project sue of fresh water for agriculture is estimated to 70% in additional withdrawal of the liquid already under severe pressure (Niasse 2017). The surface area of the arable land is not only shrinking in many parts of the world, including in many leading crop-producing countries, but the quality of soils is also declining. Therefore, alternative approaches are called for.

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). By 2050, the demand for water is expected to rise by 55% and demand for food by 60% because of a world's population of 9 billion. Additionally, a bigger world economy could be using up to 80% more energy and the increased resource demand will dictate that we look at the bigger picture that integrate water, food and energy (OECD 2012). This assessment follows a 'business as usual' scenario, i.e., current trends of increasing meat consumption.

5.9 Hotspots

Hotspots are here defined as either climate risks of particular importance to the food systems of many regions (e.g., droughts, heatwaves, inland and coastal flooding), or as characteristics of a food system that contribute to its vulnerability (short and long supply chains), or as particularly challenging in regard to mitigation and adaptation synergies and trade-offs (intense livestock production). A final hotspot is urban areas since climate change and food system interactions on the demand side are especially important there.

5.9.1 Droughts and Heatwaves

Drought and heatwaves are both very detrimental to crop and livestock production and can have adverse effects on supply chain activity as well, especially shipping and storage. They can contribute to food price spikes, effects on regional and global markets and trade, conflicts and migration (Box 5.4). Agricultural drought refers to conditions when soil moisture is insufficient and results in reduced or terminated crop growth and loss of production (Rosenzweig and Hillel 2015). Heatwaves can be particularly damaging to annual crops when they occur at critical growth stages such as anthesis. Livestock such as dairy cattle are affected by heat stress by reduced milk production and low fertility. Drought and heatwaves sometimes occur simultaneously.

Box 5.4 Causes and consequences of Russian drought (2010-2015)

The 2010-2011 food price spike was sparked by Europe's 2010 exceptional heatwave, extending from Europe to the Ukraine and Western Russia (Barriopedro et al. 2011; Watanabe et al. 2013; Hoag 2014). In Russia, the heatwave was extreme in both temperature (over 40°C) and duration (from July to mid-August in 2010), creating a shortfall in yields of about a third (Wegren 2011; Philippe et al. 2016). At the same time, the Indus Valley in Pakistan, received unprecedented rainfall creating flooding that disrupted the lives of 20 million people. These two events were causally linked through the more meandering jet-stream created by Arctic warming (Puma et al. 2015; Mann et al. 2017).

In response to its shortfall in yields, Russia imposed an export ban, which fuelled price rises on the global markets (Welton 2011). Other countries responded in a largely uncoordinated way, each driven by internal politics as well as national self-interests (Jones and Hiller 2017).

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 response contributed to food-related civil unrest in a number of countries in 2010-2011 (Natalini et al. 2017). In Pakistan, where there were food-related riots in 2010, food price rises were made worse by the economic impacts of the floods.

In the UK, the upturn in global commodity prices influenced food prices, with approximately a five-fold increase in food inflation in the latter half of 2010. Analysis of purchases in the five years from 2007 to 2011 in the UK indicated that consumers bought 4.2% less food, but paid 12% more for it. The poorest 10% spent 17% more in 2011 than in 2007 (Defra 2012; Tadasse et al. 2016). People also traded down to save money by buying cheaper alternatives. However, *in extremis*, people simply could not afford food, and the use of emergency food handouts from the Trussell Trust increased by 50% in 2010.

5.9.2 Inland and coastal floods

Many aspects of food systems are vulnerable to inland and coastal flooding, both of which are projected in become more frequent and intense in many agricultural regions (Porter et al. 2014b; Wong et al. 2014).

Inland flooding and food systems. In 2011, the Australian State of Queensland suffered widespread flooding from intense rainfall that destroyed roads and highways, isolated towns, and caused deaths of people and animals. Agricultural land was inundated and many towns experienced food shortages (Smith et al. 2016) Long food supply chains fared worse than short ones. Supermarkets experienced difficulties in supplying food, while more local markets that relied on supplies from growers in peri-urban areas and community-based food initiatives functioned better. Conceptualising food chains in terms of key elements of resilience – scale, diversity, flexibility and cohesion – may be more fruitful than the short-long dichotomy alone (Smith et al. 2016).

Historical data shows that, since 1970, the scale, intensity and duration of floods have increased in Bangladesh and Nepal, causing human suffering, disruptions in normal life and activity, and damages to infrastructure, crops and agricultural land with severe impacts on the economy (Dewan 2015). In Nepal, monsoon floods result in inundation and sand deposition over large areas and thus damage crops and land resulting in long term food insecurity (Dewan 2015).

Inland flooding of rivers can disrupt food distribution, such as in the Mississippi Basin and other major river basins.

Coastal flooding and food systems. There are many situations in which coastal agricultural production makes an important contribution to the local economy or to national agricultural production. This is the case in many small islands and in many countries where agriculture may be concentrated on the coastal plains or in fertile river deltas, as in Bangladesh and Egypt (FAO 1998). According to AR5 WGII, coastal agriculture has experienced negative impacts due mainly to increased frequency of submersion of agricultural land by saltwater inundation (Wong et al. 2014). Climate change is an increasingly important factor for storm-driven and “sunny-day” nuisance floods worldwide (Dawson et al. 2018). Coastal flooding exacerbated by sea level rise will also affect supply chains, such as port and shipping activity.

Combined inland and coastal flooding. The food bowl of the Mekong River Basin in South-East Asia is vulnerable to both inland and coastal flooding. It is a climate change hotspot (de Sherbinin 2014; Lebel et al. 2014) and is critically important to regional food security (Smajgl et al. 2015) (SR1.5, in review). Climate projections indicate increased annual average temperatures and precipitation (Zhang et al. 2016), and increased flooding and related disaster risks (Smith et al. 2013b; Ling et al. 2015; Zhang et al. 2016). Sea level rise and saline intrusion are ongoing risks to agricultural systems as well (Renaud et al. 2015). One of the main climate impacts in the Mekong will be on agricultural productivity and food security (Smajgl et al. 2015) and livelihoods such as fishing and farming (Wu et al. 2013).

5.9.3 Short supply chains – Subsistence food systems

Climate change impacts on local and regional food systems with short supply chains, e.g., smallholder and subsistence farms, will be compounded by environmental and social processes affecting production at the landscape, watershed, or community scales; with indirect effects affecting human health and non-agricultural livelihoods (Morton 2007). Subsistence food systems refer to activities carried out for the use of the individual person or their family with few or no outputs available for sale, and therefore short supply chains. Many subsistence and smallholder livelihood systems suffer from a number of non-climate stressors, but are also characterised by having certain resilience factors (e.g., efficiencies associated with the use of family labour and livelihood diversity to spread risks) (Dasgupta et al. 2014).

5.9.3.1 Role of Neglected and Underutilised Species

Subsistence agriculture can provide more diversified diets associated with better dietary quality and nutrition status (Dewey 1981). Subsistence food systems hold most of the genetic resources of “orphan” crops, which are not commercially grown but often are of higher nutritional quality and more resilient to climate stresses (Cheng et al. 2017a). For example, in Sub-Saharan Africa, pearl millet, amaranth and beans were found to be more drought tolerant than rice, wheat and maize (Chivenge et al. 2015). However, this diversification has been diminished in some regions (Box 5.5).

There are gender-related issues as well that are important when climate change adaptation is planned., because in many regions of the developing world, women often work with subsistence crops, minor crops, and vegetable gardens (World Bank 2009). As a general trend, women produce crops to feed their families (gendered crops) while men produce more cash crops (Carr 2008).

Box 5.5 Climate change and mountain 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 beans, barley, millets 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 barely with its short growing period because of a shorter growing window. Buckwheat is commonly grown in 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 Hindu-Kush Himalayan (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, 2017). 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 Himalayan region, mountains are agro-ecologically suitable for cultivation of traditional food crops, such as barley, millet, sorghum, buckwheat, beans, 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, barely, 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.

5.9.3.2 Climate change and food systems in Africa

When the continent of Africa confronts challenges of climate change, it should be noted at the outset that GHG emissions per capita are very low in most countries (Figure 5.31).

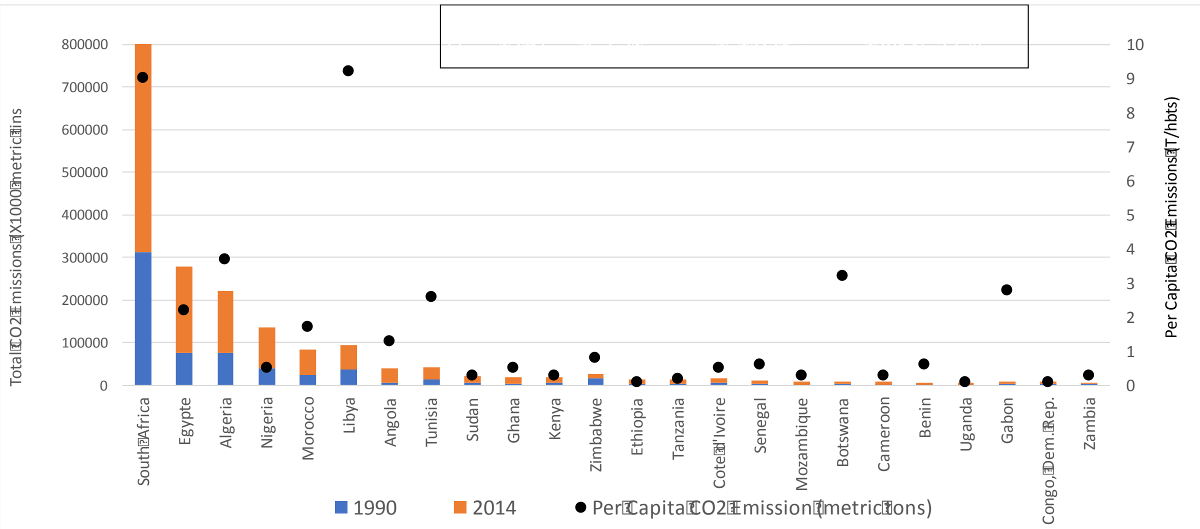


Figure 5.31 Share of CO_2 emissions in Africa

At the same time, **Error! Reference source not found.** shows that Africa has a low calorie intake compared to Europe and North America, although the trend is rising slowly. With approximately 33 million small farms, representing 80%of all farms in the region with the majority of farmers being smallholders (Altieri and Koohafkan 2008), vulnerability, impacts, adaptation, and resilience in relation to its food systems and their provision of food and nutrition security are the main climate change challenges.

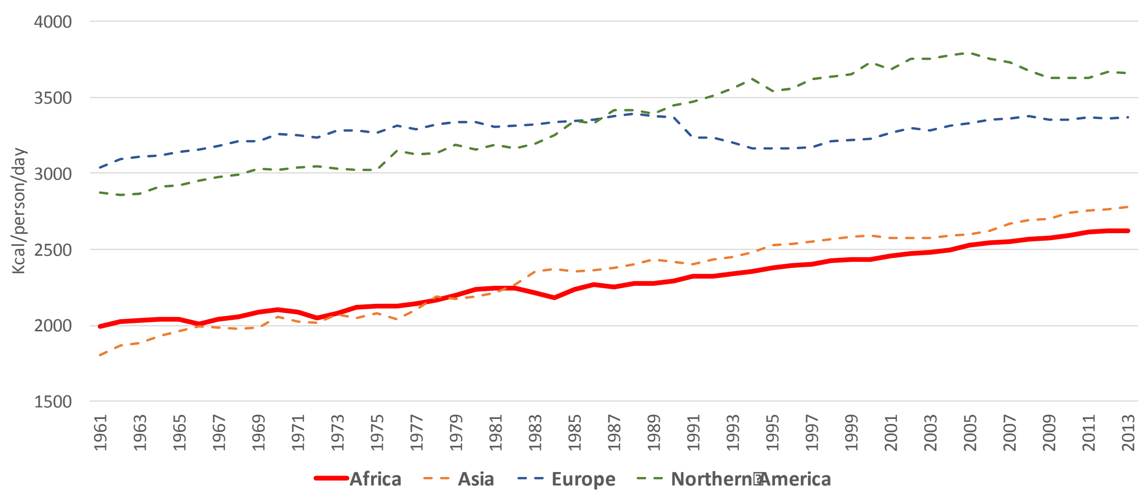


Figure 5.32 Daily supply of calories per person

Climate change projections. A large majority of GCMs place the median temperature increase in Africa at around 3-4°C warming by the end of the century relative to the period 1980 to 1999 for June–July. Spatial variation of rainfall is less certain than the temperature change as there is no model consensus for changes. The lack of agreement in projected rainfall between GCMs is related to their coarse resolution and the complex bio-physical factors that determine precipitation in e.g., West Africa. Extreme events such as droughts and prolonged periods of high temperatures are more likely and their prediction more robust than changes in mean precipitation.

Projected impacts on food systems. It is difficult to generalise climate change impact on both smallholder and commercial food systems in sub-Saharan Africa (SSA) due to the widely differing conditions themselves as well as the different assumptions and methods regarding GCMs, emission scenarios, downscaling, crop models, locations, scales, cropping systems and timeframes considered. Crop modelling studies predict mean temperature increases, elevated CO_2, and increased frequency of high temperatures, droughts and floods to be key drivers of future impacts. Many crops are already near their optimum temperature of growth and are henceforth sensitive to projected rise in temperature (Hatfield and Prueger 2015). Webber et al (2014) argue that current low yields and cropping systems already reflect high variability in precipitation and the larger change expected in crop yield will be driven by temperature change.

Yield losses are projected to be larger for the Sudano-Sahalian zone than for coastal areas in the Guinean zone as warming is buffered by the ocean effect. When CO_2 fertilisation effects are included there is again divergence on expected outcomes, with (Müller et al. 2014) predicting yield increases by 8% for Africa by 2046–2055 relative to 1996–2005 and (Parry et al. 2004) finding no significant impact until 2080. The differences highlight the uncertainty concerning crop response to increased atmospheric CO_2 at field and larger scales, and its representation in crop models, particularly in combination with water stress (Ainsworth and Long 2005; Tubiello et al. 2007). This poses a challenge to adaptation planning, but which can be overcome with multi-model ensembles such as the AgMIP Regional Integrated Assessment (RIA) approach (Rosenzweig and Hillel 2015).

Market structure. As an importer of grains, Africa relies on a fragile market structure with lower grain prices that is not necessarily improving food security for the majority of food buyers. Since the food crisis of 2008, there is a growing awareness that climate change is expected to contribute to higher world market prices for cereals, which would affect food accessibility (Wheeler and Braun 2013). The business model according to which cash crops can generate enough resources to secure food for smallholder famers does not seem to be viable. Because farmers have expenditure requirements, many smallholder farmers purchase grain during the hunger season at a higher price and are obliged to sell at harvest when prices are lowest. Globally higher food prices related to negative climate impacts, are predicted to result in a 1.3% decrease in food availability across SSA by the middle of the century.

Farmers who grow cash crops (e.g., cocoa, coffee, groundnuts, cotton) are not paid enough to secure their food and nutrition security and are unable to create savings to buffer repeated extreme events like droughts or heat waves. These reduce poor people's ability to cope with crop failures or maintain the human capital to maintain the production systems in place.

However, there is likely to be great variability in Africa in how this decline in access will be distributed across regions and groups . In a study to identify vulnerable hot spots of food insecurity in SSA in 2030, Liu et al. (2008) found that the impacts of climate change are expected to be worse for food security than for food availability or crop productivity alone.

At the same time, Africa is a net grain importer despite its 600 million ha of uncultivated arable land (McKinsey Global Institute 2010). This constitutes approximately 60% of all the world arable lands. Inversely, an Africa-wide survey of land degradation by the Montpellier Panel (Montpellier Panel 2014) reported that about 65% of the currently cultivated lands in Africa are infertile due to soil erosion and high human pressure reducing crop yields.

Feasible options for a sustainable food system. There is potential to close yield gaps and increase food production by restoring degraded soils, accessing new arable lands, and transforming technologies and agricultural products (Box 5.6). The slow increase in food production together with factors such as high population growth, policy distortions, weak institutions, poor infrastructure, extreme weather events, and political instability could explain why African countries are still dependent on food imports (WEF 2015). Food production also suffers from poor harvesting and storage facilities leading to large food loss and wastage, and weak value chains embedded in economic systems that favour external markets. Most of these limitations are strongly amplified by climate change driving dominant rain-fed production systems.

Africa has tried to adopt the 'Green Revolution' approach through development/adoption of hybrid seeds and high-tech approaches. This approach is founded on ecosystem simplification, hence mono-cropping with high-yield varieties, irrigation, increased use of fertilisers and pesticides, and intensive tillage (WEF 2015). The export crops such as cotton, cocoa, coffee, tea and palm oil are examples of developing crop commodity for international market. Except for cotton and coffee, the production and market value of these crops have increased during the last 10 years (Figure 5.33). In the continent, such approaches have been shown to result in massive short-term production but they will need to be tailored and more carefully contextualised to Africa's specific agricultural conditions to avoid enormous impacts on land health, quality of food, and ecosystems.

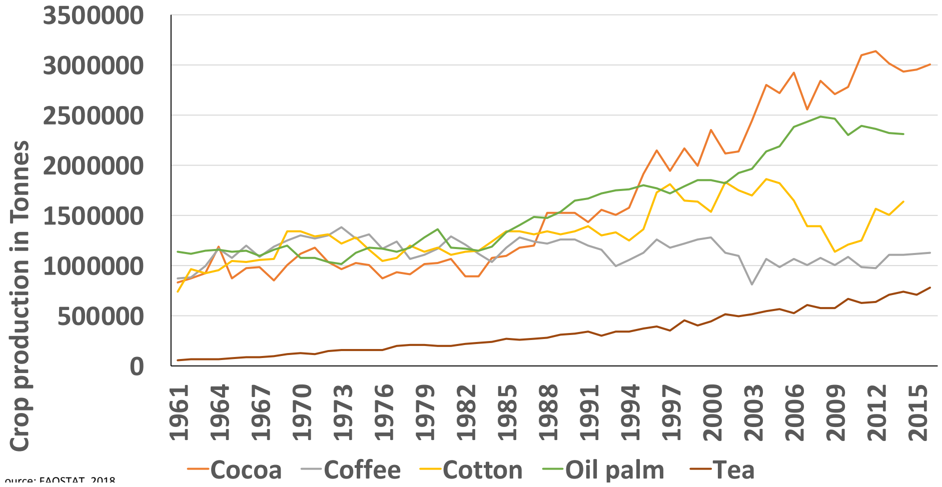


Figure 5.33 Production of export crops in Africa from 1961 to 2015 (FAO 2018)

In practice, many smallholder farmers in Africa lack the minimum asset endowments such as built, human, political and financial capital (IFAD 2016) to enable them to efficiently adopt all aspects of modern farming systems. This is due to their relative cost but mostly to their unsuitability for livelihood diversification needs. Smallholder farmers usually spread their source of living on a range of NCPs and mixed cropping systems, including agroforestry and maintenance of biodiversity. Application of intense chemical fertilisers is therefore not sufficient to deliver long-term yield performance since soil analysis has not been taken into account to determine the appropriate fertilisers. The heterogeneity of African soils requires the use of targeted fertiliser applications (WEF 2015).

Improvement of agricultural productivity through closing of yield gaps is essential. By turning attention to modernised agriculture, animal husbandry, and investments in agro-chemical and allied industries, initiatives aimed at boosting production could include nature without diverting from market-based financing, savings, and business investments. Agriculture in Africa is a unique opportunity for merging adaptation and mitigation through climate-friendly approaches (CCAFS 2012; FAO 2012). Agroforestry, the combination of agriculture with trees, is an important system that can contribute to climate change resilience (Mbow et al. 2014).

Policies. In most of the regional policy programs — the Comprehensive African Agricultural Development Program (CAADP) consolidated by the Maputo (2003) and Malabo (2013) declarations, the AU 2063/Aspiration Number 1 (African Union Commission 2015), and recently the African Development Bank (African Development Bank Group 2016) — investments in input and technology-based expansion of food production was a key means of achieving food security in Africa. These policy instruments are aimed at crop intensification that are both market and technology driven (Byerlee et al. 2014) to bridge the yield gap and secure food for all for a rising population.

Food security in Africa will require a combination of targeted technologies and policies such as zero-carbon energy, smart irrigation systems and climate-resilient agriculture; forward-looking infrastructure plans at local, national, and regional levels; and the evolution of market-based change. Agricultural landscapes have many contributions beyond market-oriented commodity production because of their diversity and multi-functionality supporting NCPs such as the delivery of water, management of disease, and delivery of energy, fibre, and building materials. Additionally, safe and healthy environments are also essential to maintaining and sustaining productivity levels in the long term, while being able to withstand climate change disturbances and shocks related to heat, rainfall events, and pest invasions that can damage crops no matter what their production promises are.

Box 5.6 Sustainable solutions for food systems and climate change in Africa

African countries face momentous choices and challenges to achieve resilient food systems and food and nutrition security under changing climate conditions (Figure 5.34). These are challenges that they are often poorly equipped to handle with current paradigms, analytical resources, and decision-making processes. Choices involve following current trajectories that pose growing threats, or following a new direction that finally combines economic progress with social justice and environmental sustainability.

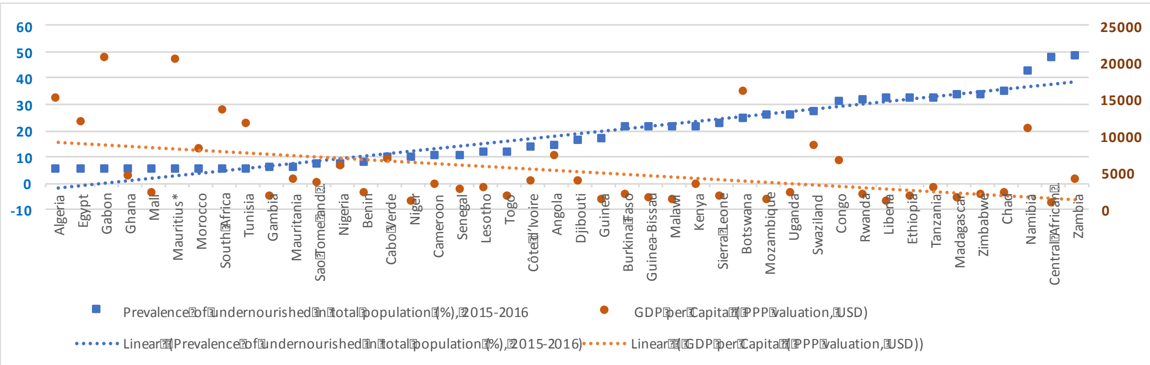


Figure 5.34 Prevalence of undernourished population in Africa.

Strategies to effectively link productivity and resilience tend to be disconnected and, in many cases, work against each other. Given the trend towards sustainable development and the need to minimise ecological footprints of economic activities, linking productivity and resilience should be the basis for an alternative approach to targeting agricultural investments with more realistic, long term expectations that meet societal demands—that is, no significant erosion of ecological functioning and preservation of natural capital.

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

- Closing yield gaps through intensification technologies that combine production and preservation of ecosystems essential functions.
- Identifying appropriate agroecological practices/strategies, in favour of biodiversity conservation trade-offs or even synergies and support NCPs.
- Paying attention to the food-water nexus, especially water use and re-utilisation efficiency but also management of rain water.
- 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.
- Building on local knowledge, culture and traditions while seeking innovations for food waste reduction and transformation of agricultural products.
- Improving access of agricultural credits and making land reforms to give farmers security of tenure.

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 and communities to be able to adapt to, respond to and recover from environmental, economic and social shocks which can affect their livelihoods.

The challenge for improving Africa's food and nutrition 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 and nutrition 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.

5.9.4 Long supply chains – Large-scale commercial food systems

Food systems with long supply chains are often characterised by a reliance on imports, unhealthy diets and prevalence of over-weight and obesity forms of malnutrition, and increasing levels of food loss and waste. This section focuses on Europe as an example of large-scale commercial food systems with long supply chains. The main food and nutrition 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, development of a circular bioeconomy, reduction in waste, and reduction of obesogenic diets. 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.

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 very variable climate (Francis and Vavrus 2015; Mann et al. 2017), with its impact on domestic productivity. There is a need for greater resilience in farming. There is growing vulnerability of imports from geopolitical and climate risk, and there is a need to build resilience and transparency in trade networks and relationships (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.

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.

5.9.5 Low-carbon climate-resilient livestock systems

Land use change has been the primary driving force of human impact on terrestrial ecosystems (Weindl et al. 2017). In particular, agriculture and cattle ranching are key drivers of deforestation and greenhouse gas (GHG) emissions (Bogaerts et al. 2017). Foley et al. (2011) found that there is an urgent need to develop integrated systems that reduce the impact of food production on the climate (Lal 2004) and to improve the resilience of food production to future environmental changes (Smith 2013), while ensuring food security.

Many countries, such as Brazil, are developing integrated low-carbon climate-resilient systems that integrated crops, livestock, and forest systems to address these challenges (Box 5.7). These systems, based on intercropping, succession, and/or rotation, can optimise the biological cycling of nutrients among soil, plants and animals, improving production efficiency and maintaining long-term soil fertility. Economic benefits from such systems can include lower costs compared to conventional systems, greater profitability, and higher product quality. Social benefits can accrue from jobs created directly and indirectly, as well as the potential for retention of rural populations.

Box 5.7 Integrated crop-livestock-forest systems in Brazil

South America has undergone profound landscape transformation between the 1970s and the 2000s due to expansion of livestock and crop areas. The increase in beef and grain growing enabled a great expansion of food production in the region, much of which is exported to Europe and the US. However, this process also contributed to increased deforestation rates during that period, since agriculture and cattle ranching are key drivers of deforestation and greenhouse gas (GHG) emissions (Bogaerts et al. 2017; Fearnside 2015; Beuchle et al. 2015; Grecchi et al. 2014; Celentano et al. 2017; Soares-Filho et al. 2014).

The Amazon region provides crucial NCPs, including biodiversity; hydrological processes through evapotranspiration, cloud formation, and precipitation; and geochemical cycles including carbon, but it is also among the most undeveloped areas in the region. Economic development is often pursued through forest conversion to cattle ranching and agriculture, mediated by logging (Köberle et al. 2017). Nonetheless, deforestation in Brazil has not led to inclusive socioeconomic development, but rather has exacerbated social inequality and more challenging living conditions for the poor (Celentano et al. 2017; Köberle et al. 2017)

Expansion of agricultural land also threatens other ecologically important biomes, including the Brazilian savannah (*Cerrado* and *Catinga*) (Beuchle et al. 2015; Ribeiro et al. 2016). Over the last decades, these Brazilian biomes experienced significant net loss of natural vegetation. Between 1985 and 2005, the area lost in the *Cerrado* was approximately 42% of its natural vegetation, and erosion risks increased significantly (Grecchi et al. 2014). The land use changes of both native tropical forest and savannah biomes due to the expansion of agriculture and livestock in South America has resulted in significant environmental losses and land degradation. However, new financial incentives and policies are creating opportunities for a more sustainable development trajectory, which is based on better use of natural resources, including ecosystems services.

In Brazil, agriculture is playing a large role in reaching the nation’s voluntary commitments to reduce GHG emissions under UNFCCC. The Low Carbon Agriculture Plan is a set of production technologies with objectives to increase yield, mitigate GHG emissions, adapt to climate change, and reduce deforestation, while improving social and environmental conditions.

In order to reduce agricultural and livestock emissions, the main actions of the Low Carbon Agriculture Plan include restoration of degraded pastures, agroforestry integrated systems, and no-till agricultural techniques. Land degradation may be avoided by the proper management of pastures, namely by maintaining a sustainable stocking rate that is compatible with carrying capacity, periodic resting periods, and adequate fertilisation (Macedo et al. 2014). The implementation of Integrated Systems (IS) in areas of degraded land combines crop, livestock and/or forests in the same area, thereby increasing soil fertility and organic matter content (Gil et al. 2015; Bungenstab 2012). This not only increases carbon sequestration potential of the soil, but also allows for a higher stocking ratio, which can lead to reduced area requirements (Strassburg et al. 2014), and a shorter time to slaughter, which reduces lifetime enteric fermentation emissions (IPCC 2014).

For example, an integrated system that includes tropical forage grasses can improve soil organic matter, recycle nutrients from deeper layers, and contribute to enhancement of soil biodiversity and microbial activity due to their extensive root systems. In a study conducted in the Brazilian Amazon region, (Conceição et al. 2017) showed the great potential of soil carbon sequestration by an integrated crop-livestock-forest system. After only three years' establishment, the integrated crop-livestock-forest system reached values similar of those measured in the native forest. Nogueira et al. (2016) showed a reduction of 75% in GHG emissions in the integrated crop-livestock-forest system compared to the no-tillage crop production system.

Economic benefits include lower implementation and maintenance costs, compared to conventional systems, with greater profitability and product quality. Social benefits are due to the jobs created directly and indirectly from the use of such systems, as well as decreased migration out of rural areas.

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. 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 (Köberle et al. 2017).

In summary, integrated crop-livestock-forest systems are able to mitigate GHG emissions, recover degraded areas at relatively low costs, producing more volume of grain, meat, fibre and wood, without need to open up new areas, optimising land use while providing social benefits. In addition, multi-dimensional agricultural systems improve the resilience of the agro-economic systems, therefore contributing to adaptation efforts to a changing climate.

5.9.6 Urban areas

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; Infante Amate and González 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; Pérez 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 ecological footprints (Goldstein et al. 2017).

5.9.6.1 Urban food and nutrition security

With increasing urbanisation, a growing challenge is to ensure urban food and nutrition 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 and nutrition 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 and nutrition security depends on social and physical infrastructure beyond income, calling for better urban planning. Few cases also show improvement on food and nutrition security for people living in informal settlements in the recent years, e.g., Johannesburg, South Africa (Naicker et al. 2015).

5.9.6.2 Urban and peri-urban agriculture

Urban and peri-urban agriculture can contribute to enhanced urban food and nutrition security, reduced greenhouse gas emissions, and to adapt to impacts of climate change (*Medium agreement and robust evidence*). Around 15 % of the world’s food is grown in urban areas (Gerster-Bentaya 2013). Urban and peri-urban agriculture (defined as production occurring 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, e.g., backyard, roof-top, balcony, community gardening, urban-fringe agriculture, and livestock grazing in open spaces (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, e.g., 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 poor (Frayne et al. 2014) because it is not possible to produce all the required food for all communities in urban and peri-urban areas. Hence urban inhabitants may still need to rely on supermarkets 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).

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). These multiple functions and associated social missions (e.g., connecting producers and consumers) are the reasons for the recent growth of urban and peri-urban agriculture despite the limited quantity of food production (Dimitri et al. 2016). Furthermore, this can also be considered as a response to growing concerns about conventional food systems and its effects on public health, ecological integrity, and social justice (Morgan 2015). The social mission of reconnection of urban inhabitants to the cycles of nature is also a way to increase awareness about climate change to urban inhabitants.

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 and nutrition 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 urban 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).

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).

Climate resilient urban governance assessment framework should include (1) decentralisation and autonomy, (2) accountability and transparency, (3) responsiveness and flexibility, (4) participation and inclusion and (5) experience and support (Tanner et al. 2009; Rosenzweig et al. 2018).

5.10 Enabling conditions and knowledge gaps

5.10.1 Pathways to low-carbon, climate-resilient food systems

Both supply-side and demand-side mitigation options can provide pathways to climate change solutions.

Supply-side mitigation mechanisms are available to contribute to climate change solutions *(robust evidence, high agreement)*. There are many opportunities to improve the efficiency of crop and livestock systems. For livestock, improving efficiency is an important first step, although reductions in total emissions would require a reduction in global herd size coupled with reduction in pasture area. The options differ between regions and systems, but tend to reduce GHG emissions intensity (emissions per unit product), although not necessarily total emissions due to spill over and rebound effects *(medium evidence, medium agreement)*. These mechanisms can help countries move toward increased land sparing and sharing, and may contribute under appropriate policy interventions to reduce total emissions.

Demand management for food can help to achieve the global GHG mitigation and human health targets *(robust evidence, high agreement)*. In the past decades, diet shifts have occurred across the world towards an increase in the consumption of animal products, vegetable oils, and sugar/sweeteners, which result in excess intake, unhealthy outcomes, and, in the case of meat consumption, a larger carbon footprint. Low-carbon footprint diets tend to be healthier and have a smaller land footprint *(robust evidence, high agreement)*. Cost savings due to healthy diets can be greater than costs of agriculture mitigation *(limited evidence; medium agreement)*.

Practices that create synergies between mitigation and adaptation can lead to low-carbon and climate-resilient pathways for food and nutrition security *(medium evidence, medium agreement)*.

There are many opportunities to improve the productivity/efficiency of livestock systems around the world, which are the biggest source of agricultural emissions. The options differ between regions and systems, but they all share the common feature that they tend to increase total production and total emissions (but the latter by less than total production), and as a result of the two, the emissions intensity (emissions per unit product) is reduced as a result of such productivity interventions (Gerber et al. 2013; GRA 2018). While systems changes can increase productivity and reduce emissions intensity (Havlik et al. 2014), there is also large potential for increasing efficiency of existing systems.

Gerber et al. (2013) found that there is potential to reduce total emissions by as much as 30% in some regions. However, that work rested on the assumption that total production remains the same while productivity increases, and thus the reduced emissions intensity therefore resulted in reduced absolute emissions. Evidence from studies show that land sparing does not actually occur where systems become more efficient, and hence additional policies would be needed if an approach that focuses on increasing efficiency and productivity is to serve an overall goal of reducing absolute emissions. Indeed, most evidence suggests that where increases in efficiency occur, the lower cost of production can in ‘rebound’ effects, where total production and/or consumption increases as a direct consequence of this reduced cost (Niles et al. 2018; Borenstein 2014).

Complementary policies are needed to ensure that the reduction in emissions intensity can in turn lead to reductions of absolute emissions. If demand were fixed, then reducing emissions intensity would necessarily reduce absolute emissions, but if demand is flexible and total production/consumption increases, then this may not be the case. In a world with a growing population demanding more protein-rich food, emissions can still be reduced below the future baseline (i.e., continuation of current trends).

Key questions in regard to the potential of and limitations to this approach are to what extent can increases in productivity/efficiency of systems help reduce emissions below baseline; what policies can be implemented from the onset to ensure increased land sparing/sharing arising from more productive systems; and to what extent does an increase in productivity serve to increase demand itself.

Most development interventions that increase farm productivity will affect (and generally reduce) emissions intensity. This is clearly relevant from a food security perspective, but questions remain about how far can such interventions succeed, what is needed to turn the reductions in emissions intensity into reductions of absolute emissions, and what contribution can this make to the overall reductions that are necessary and possible from agriculture.

Policies that place an absolute cap on output (or altering consumption patterns that result in a limited demand) will result in an absolute emissions reduction in the context of increasing production efficiency. This will occur due to the fact that increasing production efficiency results in increased output of meat/milk per animal and less animals are required to produce a given output. However, where output is capped, this can also reduce some of the impetus to improve efficiencies. If a cap is placed on the *total animal population*, however, the impetus to achieving higher output per animal remains. An absolute emissions reduction will still be achieved, although it will be a lower level of reduction since GHG per animal can still increase. In the case of crop production, placing a cap on total cropland area will have the same effect.

Programs such as the Global Research Alliance on Agricultural Greenhouse Gases have as a key objective the reduction of greenhouse gas emissions intensity while supporting food security. A focus on emissions intensity can serve as a useful springboard to progress towards reductions in absolute emissions once countries have gathered some experience and have improved their monitoring, reporting, and verification (MRV) systems. See e.g. (GRA 2018)

5.10.2 Policy -- Agriculture, food, environment, health

Recent agricultural policies together with advancement in agricultural sector have promoted the intensification of agriculture, coupled with globalised trading systems. These have become focused on relatively few commodity crops (just eight supply 75% of the world's consumed calories (Cassidy et al. 2013), which underpin the homogenisation of global diets (Khoury et al. 2014a), over-consumption of calories and associated non-communicable diseases increasingly affecting every country (even sometimes, those where undernutrition is also endemic) (Collaboration, 2016). At the same time, the global intensification of agriculture affects soil, water, air quality and biodiversity in major and negative ways (Paulot and Jacob 2014; Amundson et al. 2015; García-Ruiz et al. 2015; Newbold et al. 2015; Tamea et al. 2016; Dalin et al. 2017).

These challenges require action throughout the food systems which enhance synergy and co-benefits and minimise trade-offs among the multiple objectives of food and nutrition security, adaptation and mitigation (Sapkota et al. 2017c; Palm et al. 2010a; Jat et al. 2016; Sapkota et al. 2015). In short, this requires greater policy alignment and coherence between traditionally separate policy domains to recognise the systemic nature of the problem. 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.

One of the important policy implications for enhanced food and nutrition 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). In addition, Wittman et al., (2017) described the conflict between biodiversity conservation and food and nutrition security as the latter is widely recognised as a driver of biodiversity decline; the study suggested a harmonisation of food and nutrition security and biodiversity conservation. However, food production does not necessarily reduce biodiversity; it depends on the system and its management.

5.10.3 Markets, trade, finance, and insurance

Global trade remains essential in achieving food and nutrition security under climate change, mostly in cases of extreme events; 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. 2017). Food preference can foster or slow food and nutrition 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 and nutrition security in Kenya in the future (Alemu et al., 2017). More recently, attention has turned to the mediating role of trade in a study of global trade reform and climate change using Global Trade (Philippe et al. 2016).

The main purpose of agricultural production in past, and also at present to some extent, is to supply localised food demand. Recently, agriculture has more commercialised because of better production environment in certain parts of the world than others. A study estimates that some 66 countries are currently incapable of being self-sufficient in food (Fader et al. 2013). This is because many countries lack the capacity to produce sufficient quantities of their own food due to climatic conditions, soil quality, water constraints, and availability of farmland (FAO 2015b). City states such as Singapore, as well as many small island economies, for example, do not have adequate farmland to support their populations, while a number of sub-Saharan African countries are projected to be negatively impacted by climate change, and will likely find it difficult to produce all of their own food supplies (Agarwal et al. 2002). Encouraging domestic production where possible and sourcing food from nearby markets rather than long-distance transport can help minimise GHG emissions associated with marketing and trade (Michalský and Hooda 2015).

One study estimates that already some 16% of the world's population relies on international trade to meet their food needs, and projects that the number of people who will need to rely on imported food could rise to 51% of the world's population by 2050 (Fader et al. 2013). Another study calculates that around 1.6 billion people globally depend on international trade, including 1 billion people from Asia and Africa on cross-continental agricultural trade, in 2000 and estimates that the number of trade dependant people will vary between 1.5 and 6 billion by 2050 depending dietary shifts, climate change, and closing yield gaps (Pradhan et al. 2014). Supply chains of agricultural commodities involve processing, transportation and storage, which requires large amounts of energy leading to higher environmental footprints.

Transformation of the food system towards delivering healthier, less wasteful diets, more sustainably and equitably, can arise from a range of changes affecting the dynamics of the market, including exogenous events (such as climate shocks Challinor *et al.*, (2018)). Some areas include:

Capital markets. Two areas are often discussed. First, investment in disruptive technologies that might stimulate climate-smart food systems (WEF/McKinsey & Company 2018; Bailey and Wellesley 2017), including alternative proteins, such as laboratory or "clean meat", which has significant ability to impact on land use requirements (Alexander et al. 2017b). Second, widespread adoption of (and perhaps underpinned by regulation for) natural capital accounting as well as financial accounting, so that investors can see the risk exposure of institutions, which undermine sustainability through externalising costs onto the environment. The prime example of this in the realm of climate change is the Carbon Disclosure Project, with around 2500 companies voluntarily disclosing their carbon footprint, representing nearly 60% of the world's market capital (CDP 2018).

Insurance and re-insurance markets to incentivise actors' behaviour towards greater climate mitigation or adaptation, including building resilience. For example, Lloyd's of London (2015) published a paper on implications of extreme weather for the insurance market, and conclude from it: "The insurance industry is in a position to make an important contribution to improving the resilience and sustainability of the global food system, by encouraging businesses to think about their exposure to risks throughout the food supply chain, and by providing innovative risk transfer products to enhance global resilience to systemic food system shocks." (Lloyd 2015).

Public investment and policy. The public sector can change the way the market operates in many ways. This includes investment in research and innovation to drive incremental change and disruptive technologies. It can change regimes of subsidies to incentivise change. For example, the emergence of renewable energy as a strong market sector was partly achieved by re-profiling subsidies for energy, away from fossil fuel. In 2016, the International Energy Agency estimates that fossil fuels received USD 260 billion vs the renewable energy sector receiving 140 billion USD on a global basis (OECD/IEA 2017). Other levers of change from the public sector include education and awareness raising (via schools and campaigns), changing food environments (e.g. using planning policy to change the distribution of food stores, using public procurement to change diets in schools, prisons, civil service canteens etc.), and promoting different diets through a range of incentive schemes (including through health insurance premiums). In addition, of course, there is the potential to shift diets through changing the broader regulator and tax policy around trade and food (e.g. tariffs on imported food, carbon or "sin taxes" on unhealthy diets).

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

5.10.4 Governance and institutions

Governance refers to the system of rules, authority and institutions that coordinate or manage a society, as well as the relationships involved in the process of governing (Pierre and Peters, 2000). A food system governance to address climate change should therefore reflect the policies, rules and norms needed to tackle both mitigation and adaptation of food systems to climate change, while ensuring food and nutrition security. To assess which governance options exist and how they can address food systems under climate change, we assess both food systems and climate change governance literature in order to find interlinkages and connections among them.

In the governance arrangements of climate change, several differences exist between mitigation and adaptation options, which need to be considered when developing governance alternatives for food systems under climate change. Huitema et al. (2016) summarised these: First, it is generally accepted that mitigation needs global agreements and national policies while adaptation needs local and regional considerations; second, 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); third, mitigation action is constituted mainly by government measures, mostly concentrated on the distinction between regulation and market-based and information approaches (such as labelling, emissions trading, carbon taxation). Adaptation actions however have mostly emphasised self-organisation and adaptation by social actors. Coordinated adaptation is also more likely to incorporate issues of fairness in process and to promote the interests and voice of vulnerable populations and more just outcomes.

Governance of food systems is a major challenge given the fact that it is only recently that a food system approach has been embraced by policy makers. Apart from the processes which are specific to climate change, food systems also 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.

By applying this framework to selected South African governance arrangements which deliberately exposed a holistic perspective, (Termeer et al. 2018) found several barriers to achieving the food system approach: reversion to a technical one-dimensional problem framing during the implementation; dominance of single departments; limited attention to monitoring and flexible responses; and exclusion of those most affected by food insecurity. Climate change governance and food system governance encompass multiple scales and involve the local, national and international institutions capable of addressing the multiple social and ecological dimensions of climate change and food systems.

Ostrom (2009, 2010) proposed polycentric systems for coping with climate change, to address both mitigation and adaptation. Food systems, where both mitigation and adaptation need to be addressed, will also need polycentric approaches to address the multiple dimensions associated to them, as well as the different types of food systems currently coexisting. Mitigation options for food systems will require international arrangements to address global trade of food, labelling and taxes to food system activities and actions that increase GHG emissions. Yet, these measures are intended to change individual behaviour, which means we need closer structurer to monitor achievements and develop learning capacities. Adaptation options will require local and regional governance structures capable to deal with the specific cultural, social, economic and ecological dimension of food systems, but they will also need global agreements where big infrastructures may be needed to facilitate adaptation options to poor communities and countries where e.g. investments to roads for food selling and storage structures to keep food in prevention of food-shortages can help to adapt, but they will not have the required assets to do it.

Polycentric approaches not only help to address the multiple dimensions associated to food systems, but also the different types of food systems. Polycentric systems are characterised by multiple governing authorities at differing scales. Each of them exercises considerable independence to make norms and rules within a specific domain (from local to global). Participants in a polycentric system have the advantage of using local knowledge, required in local food systems, as well as learning from others. As larger units get involved, problems associated with non-contributors, or equity can be addressed. At higher levels, major investments can be made where required. Polycentric systems tend to enhance innovation, learning, adaptation, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales (Ostrom 2009). All of this is required in developing governance structures capable to address the challenges of food systems under climate change.

5.10.5 Knowledge, capacity building, technology and innovation

Developing and using knowledge for food security and land sustainability under climate change are based on 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 (CCAFs), Rural Resource Centers (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.

To address the challenges of integrating small producers and agents from various stakeholders' groups in dealing with modern value chains, many innovative approaches and strategies are being piloted for promoting competitive business models in the agriculture sector. The language used when talking about developing countries' agriculture and food systems has been shifting in recent years with a strong orientation towards scaling-up innovation and adoption by local farmers.

Capacity building is therefore diverse and objectives variable. Countries with higher rates of labour force schooling witnessed more rapid adoption of new agricultural technologies. The challenges for smallholder farmers are numerous and extremely difficult to master individually. These range from the provision of services to development of business skills to deal with the new circumstances. In developing countries, the more educated workers are more likely to migrate to non-farm or urban jobs. Nonetheless, changes in average schooling levels, like literacy rates, reflect the importance countries give to general education, particularly since most labour in SSA is employed in agriculture.

Farmers need access to efficient market chains that they can rely on to dispose of their products at competitive and stable prices. Small farms face major disadvantages in accessing modern market chains. These include low volumes of produce to sell, variable quality, seasonality and limited storage, high transaction costs, poor market information and contacts, and limited ability to meet the high acceptable requirements of some high value outlets. Although many local market outlets still exist, the best business opportunities often lie with farmers who can organise for urban and export markets. Promising alternatives include contract farming arrangements with large farms or marketing/processing agents, voluntary producer groups, marketing cooperatives and fair trade. Another key issue is how to make staple food markets work better for small farms, particularly in countries where the private sector has not adequately filled the gap left by the demise of state marketing organisations. This implies that commercially oriented smallholder farmers have to organise themselves into strong farmer organisations.

5.10.5.1 Capacity-building

Capacity building is a cross-cutting issue which covers over all the aspects of adaptation and mitigation, as well as all the relevant aspects, however, risk mapping is widely recognised as a first step to clarify the priority issues for adaptation (*very high confidence*). Quite a lot of risk analysis has been done on food production, some of the work has been done for world food trade and pricing, while less work has been done on the risks of food accessibility, utilisation, transportation, and processing (*high confidence*). There is an imbalanced capacity of early-warning systems over the developed countries 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 (*medium confidence*). A lot of ecological restoration practices have been carried out to increase the agricultural resilience, while a systematic summarising on the methodology and guidelines is limited (*medium confidence*). Planning capacity is obviously increased as the public awareness is improved, while monitoring and evaluation capacity for the adaptation to climate change is still very weak (*low confidence*) (Table 5.5).

Table 5.5 Areas of capacity building for climate change and food systems

Key capacity building	Innovation	Transformation	Capacity needed
Outcomes setting	Increased productivity and production	Value-addition and loss reduction	Facilitate achievement and sustenance of high level of productivity; Facilitate an optimal distributional outcome for shared prosperity
Inputs/services	Yield enhancing inputs (seeds, fertiliser, animal breeds, feed, machinery, etc.) Plant and animal health services	Agricultural products (crops, livestock, fisheries, forestry, etc.) – generates demand for agric products Technology and trained/skilled human resources	Ensure delivery of key inputs, resources and services
Supply	Farmers, herders, fisher-folks, foresters, etc.	Agro-processors; agro-dealers, agropreneurs, industrialists	Facilitate and streamline the 'rules of the game' for predictable and optimal outcomes
Policies	Agriculture, land tenure, credit, science, technology and innovation, etc.	Land, industry, trade, health, energy, infrastructure, innovation, finance	Facilitate formulation and implementation of policies
Institutions	R&D, extension services providers, inputs/agro dealers, etc., Financial service providers (micro-finance), Producers' organisations (farmers, herders, fisher-folks	Markets, energy and infrastructure service providers, quality assurance and regulatory agencies, etc., Financial service providers (e.g., banks, insurance companies) Private sector enterprises/companies	Complex and varied roles, empowering rural communities, safeguarding and promoting ownership, responsibility and accountability

5.10.6 Knowledge Gaps

Knowledge gaps are one of the barriers hindering mitigation and adaptation to climate change in the food system and its capacity to deliver food and nutrition security. 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.

On the mitigation side, knowledge gaps include food consumption-based emissions at national scales; and GHG emissions from land-based aquaculture. On the adaptation side, knowledge gaps include impacts of climate shocks as opposed to impacts of slow-onset climate change and how climate-related harvest failures in one continent may influence food and nutrition security outcomes in others and impacts of climate change on fruits and vegetables, and their nutrient contents.

5.11 Supplementary Material

Food and nutrition security

In addressing food and nutrition security the dual aspects of malnutrition – under-nutrition and micro-nutrient deficiency, as well as over-consumption, overweight, and obesity – need to be considered.

The UN agencies' *State of Food and nutrition security and Nutrition* 2017 report (FAO et al. 2017) and the Global Nutrition Report 2017 (Hawkes et al. 2017) focus on the developing-world hunger challenge and highlighted the increase of the global undernourished population from 777 million to 815 million between 2015 and 2016. However, these numbers have been declining on average for the last three decades, though with two periods of upturns (2005-2007, and 2015-2016). These figures may underestimate the trends and the number of undernourished worldwide (Hickel 2016), and at the same time they may significantly under-represent the prevalence of undernourishment in the developed world. For example, a 2003 study in the UK (Schenker 2003b) estimated that 40% of adults, and 15% of children, admitted to hospitals were undernourished, and that undernourishment was significantly under-reported within the UK. This highlights the importance of considering the impact of inequality on food and nutrition security and the way its chronic nature can be obscured by a focus on broader patterns and trends.

Furthermore, interpretation of the state of food and nutrition security depends on how encompassing is its definition. 815 million people are hungry, as many as two billion have some form of nutrient deficiency, and there are more obese adults than underweight. In total, more than half the world's population are underweight or overweight, 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.

Under-nutrition and micro-nutrient deficiency

Globally, the prevalence of hunger has declined, from 15% according to figures for 2000 to 2002, to 11% according to figures for 2014 to 2016 (UNSG 2017). However, more than 800 million people worldwide still lack regular access to adequate amounts of dietary energy according to (FAO et al., 2017). One in eight people in the world remained chronically undernourished in 2014 (Keating et al. 2014). If current trends continue, the zero hunger target will be largely missed by 2030.

The number of undernourished people has recently increased mainly in the regions with conflicts, often induced by extreme climate events (FAO et al. 2017), resulting in protracted crises, with increased vulnerability and food insecurity affecting large parts of the population. Depending on the methodology, the global share of undernourished population ranged from 10.6% (FAO et al. 2017) to 13.0% (von Grebmer et al. 2017). Estimation based on household survey data shows that 9.3% of the global population are affected by severe food undernutrition (FAO et al. 2017). Africa consists of the largest share of food in-secured population (30%) while the largest number of undernourished people still live in Asia (520 million people) (FAO et al. 2017). The persistence of hunger is not simply a matter of food availability (Sen 1987). More and better data on access to food can enable the tracking of progress and guide interventions to fight undernourishment (UNSG 2017).

Prevalence of micro-nutrient deficiencies, also known as hidden hunger, afflicts one in three people globally (FAO 2013c; 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). On a gender basis, (Tulchinsky 2010). Rates of stunting and wasting among children has decreased in the last decades (FAO et al. 2017; von Grebmer et al. 2017). However, the stunting rates are still higher in most parts of Africa while the wasting rates remain high in some regions, mainly South Asia (FAO et al. 2017).

Over-consumption, overweight, obesity, and related non-communicable diseases

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 2017b). 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).

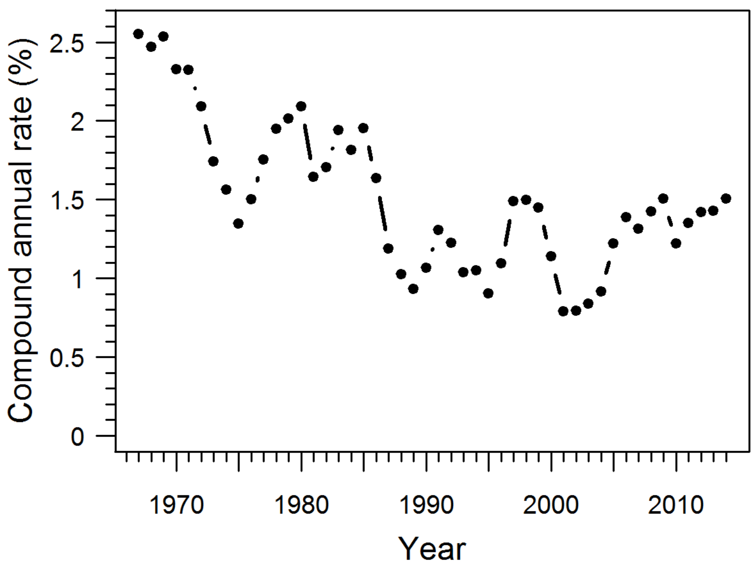
On a gender basis, a larger share of females have suffered from overweight and obesity compared to the males in regions with lower and middle incomes (Doak and Popkin 2017). Similarly, the prevalence of overweight and obesity is higher in girls (under the age of 10) than in boys in Europe (Ahrens et al. 2014) and globally. The prevalence of overweight and obesity is larger in urban than in rural areas in lower and middle-income regions (Doak and Popkin 2017). In Europe, children of low-income and/or lower-education level population groups show the highest prevalence of overweight and obesity (Ahrens et al. 2014).

Overweight and obesity has become a major global health challenge because of associated health risks (Ng et al. 2014; Flegal et al. 2013; Kramer et al. 2013). Currently, more people are killed due to overweight and obesity than due to underweight resulting from undernourishment (FAO et al. 2017; WHO 2017b). Prevalence of overweight and obesity is a major risk factor for non-communicable diseases (NCDs), including cardiovascular disease, diabetes, kidney disease, many cancers, and musculoskeletal disorders (Jiang et al. 2012; Dehghan et al. 2017; Singh et al. 2013; Yatsuya et al. 2014; Lauby-Secretan et al. 2016; Afshin et al. 2017; HLPE 2017). In 2017, the World Obesity Federation published a consensus statement that obesity was itself a disease (Lobstein et al. 2017).

Food production

Widespread adoption of Green Revolution (GR) technologies together with an increased area under cultivation through land clearing led to a substantial increase in crop production between 1960 and 2000. Over this period, total food supply has increased almost threefold in the face of twofold increase in population and very significant shifts in diet related to economic development.

Cereals, which include wheat, rice, barley, maize, millet and oats, are and continue to be the most important food source for human consumption. Globally, livestock production make use of 30% of terrestrial land area for grazing, one-third of global cropland area is devoted to producing animal feed and 32% of freshwater is used to provide direct livelihood and economic benefits to at least 1.3 billion producers and retailers (Herrero et al. 2016a). Recently, rising incomes, urbanisation and the expansion of global markets and facilitating policies are causing a shift in diet towards animal-based products such as meat, milk and dairy. Similarly, fish is an important component in people's diets, providing about 3.1 billion people with almost 20% of their average intake animal protein. Numerous authors have suggested that increasing yields, rather than clearing more land for food production, is the most sustainable path for expanding food availability (Ray et al. 2013; Pingali 2012; Pradhan et al. 2015).This has been contested by other authors considering all environmental and social effects. Moreover, crop yield growth has been shown as an effective tool in reducing global poverty and undernourishment, as farmers themselves constitute the vast majority of the poor and undernourished (Pingali 2012). However, world cereal yield growth rate was in a downward trajectory from 1965 to 2000 and appears to be stabilising since then (Hunter et al. 2017) (Supplementary Supplementary Figure 11).



Supplementary Figure 1 The cereal yield growth rate has decreased in the last 50 years with periodic increase in the growth rate due to technological process and technology transfer. The growth rate needs to be maintained at 2% or more to double the cereal production between 2015 and 2050. Following the method from (Hunter et al. 2017), each point represents the compound annual growth rate of the global cereal yields over the five previous years. The data on cereal yields is obtained from FAOSTAT (FAO 2017). The growth rates were calculated using five-year moving average to smooth intern annual variation.

Feed production

On a global scale, about 36% to 40% of the global crop calories are used as livestock feed and about 4 kcal of crop products are used to generate 1 kcal of animal products (Pradhan et al. 2013b; Cassidy et al. 2013). In terms of mass, livestock consumes six billion tonnes of feed (dry matter) that includes one third of global cereal production (Mottet et al. 2017). In 1961, 1300 trillion kcal of crop were used as feed which had increased by around two times to 3700 kcal in 2000. The ratio of crop calories used as feed and consumed directly by humans remained between 0.7 and 0.8 from 1961 to 2000 (Pradhan et al. 2013a). On average, 2.8 kg and 3.2 kg of human-edible feed is used to produce 1 kg of boneless meat in ruminant and monogastric systems, respectively (Mottet et al. 2017).

Meat exporting countries have developed cattle ranching at large scales that have become a key driver of deforestation to create pastures and land for grain production for animals.

Animals vary greatly in their consumption of grain between 6-20 kg of grain per kg of beef produced (Eshel et al., 2014, Elliott, 2012; Godfray et al., 2010; Garnett, 2009). Higher grain consumption occurs in feedlot beef production, which accounts for 7% of global beef output according to Gerber et al. (2015) and FAO (2009), and 13% according to (Mottet et al. 2017). Feed derived from human edible food (i.e., cereal grains, soybeans, pulses, banana and cassava) or not human-edible (roughages such as grass, crop residues and fodder beets, cotton and rape seeds), have differing implications on land and climate footprints (Mottet et al. 2017). This study used the Economic Fraction Allocation (EFA) to identify which feed co-product is the main driver of land use. If only part of the product is used as feed and that portion is less than 66%, then the feed material is considered as a main driver of land use and therefore in competition with food production. This is the case in soybean cakes (72% EFA) meaning that soybean is an important land use driver of livestock systems. Soyatech (2003) estimated that about 85% of the world's soybeans are processed annually into soybean cake and oil, of which approximately 97% is further processed into animal feed.

Improvements in feed use efficiency and shifts in allocation of crops to animal feed can increase food availability, contributing to enhancing food and nutrition security and to reducing agricultural expansion (Cassidy et al. 2013; Mottet et al. 2017; Pradhan et al. 2013a).

Food loss and waste

Reducing food loss and waste will engender an equivalent GHG abatement along the food system value chain and will improve food supply without agriculture expansion (*High agreement, Medium evidence*). Since 2011, considerable effort around the world has been made to improve estimates of food loss and waste, and, so far, while countries and food systems vary, the figure of 20%-30% loss and waste is taken as a reasonable consensus. FAO (2011b) estimated that one-third of the produced food, about 1.3 billion ton per year, was either lost or wasted in 2007 globally, while Kummu et al. (2012) found around one quarter of the produced food supply (614 kcal $cap^{-1} day^{-1}$) is lost within the food supply chain. The amount of food loss and waste grew threefold from 540 million ton per year in 1961 to 1.6 billion ton per year in 2011 (Porter et al. 2016). The growth in food waste over 50 years shows that food waste has been increasing faster than crop yields (Porter et al. 2016).

The food waste and loss results in 4.4 Gt CO_{2e} yr^{-1} emissions throughout the life cycle of the lost and wasted food, considering various phases of the food supply chain (FAO 2015a, 2013a). 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 production-phase N_2O emissions (more than 200 Gg N_2O-N yr^{-1}) (Reay et al. 2012). When complete avoidance of food loss and wastage is considered, the reduction potential of the N_2O emissions exceed 1 Tg N_2O-N yr^{-1} (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).

Food loss is considered as the reduction of edible food during primary production, postharvest, processing, and distribution. Discarded food at the consumer and household level is referred to as food waste. 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). In absolute terms, a larger amount of per capita food loss and waste occurs in developed countries compared to developing ones (FAO 2011a). Due to variations in definitions and applied methodologies, estimates of food loss and waste differ across studies. The third target of SDG 12 (responsible consumption and production) aims to halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses.

Food loss

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.

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 2011a). In the European Union, 80 kg year^{-1} of food was lost per person in 2013 (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 Europe, 23.6 Mt of fresh fruit and vegetables were lost, resulting in production phase emissions of 5.1 Mt CO2e 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. 2018).

Food waste and overconsumption

In the last 50 years, the difference between required and available food per person grew from 300 kcal /day to 500 kcal/day on the global level, and the associated GHG emissions for producing wasted food increased from 130 Mt CO_2eq yr^{-1} to 530 Mt CO_2eq 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 2011a). Seven percent of food is wasted at the consumer level in China (Liu et al. 2013b). In the European Union, 90 kg year^{-1} of food is wasted per person, resulting in total household waste of around 47 million tons (Stenmarck et al. 2016). For Europe (EU 27), livestock products contribute to 27% and 14% of the total food waste in the retail and household sectors, respectively (see Supplementary Placeholder Table: This will be remade with climate change interactions included.

Supplementary Table 5.1) (Bellarby et al. 2013). Emissions associated with production of livestock products in Europe (EU27) which is wasted both in Europe and outside Europe is up to 56–115 Mt CO_{2e} yr^{-1} (Bellarby et al. 2013).

Placeholder Table: This will be remade with climate change interactions included.

Supplementary Table 5.1 Animal and plant waste (Mt per year) (Bellarby et al. 2013)

Table 5 Animal and vegetal waste in Mt per year (WRAP, 2009; EC, 2010)

	Agriculture, hunting and forestry (Mt)	Manufacture of food products; beverages and tobacco (Mt)	Households (Mt)	Other sectors (Mt)	Total (Mt)
EU27* (EC, 2010)	32.6	37.3	23.4	16.8	110.1
UK* (EC, 2010)	0.02	5.1	3.2	3.5	11.9
UK† (WRAP, 2009)		3	8.3		11.3

*2006;
†2008 (The two UK studies have different methodologies, which explains some of the variation in magnitude between the two sources and years).

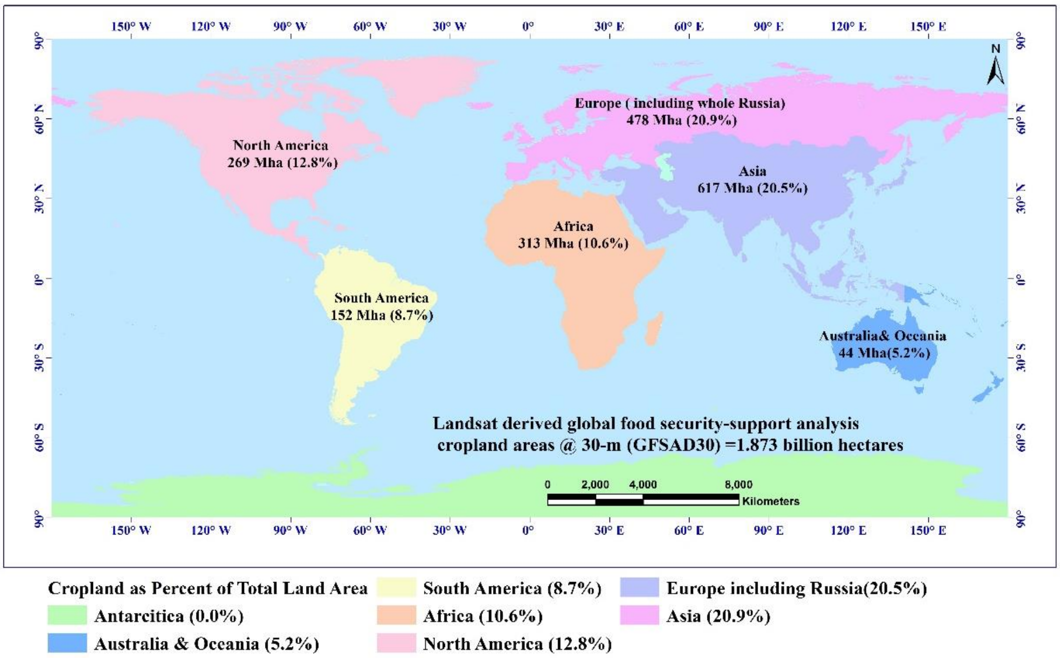
Consumption above nutritional needs can be seen as a form of food waste (Alexander et al. 2017a), and at a global level is as significant as household-related food waste. For example, overconsumption in Australia accounts for about 33% GHG associated with food (Hadjikakou 2017). If human overconsumption, 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. 2017a). Similarly, the food loss associated with consuming resource-intensive animal-based products instead of plant-based alternatives that are nutritionally comparable 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 United States (Shepon et al. 2018).

Sources of productivity growth

Increasing crop productivity can contribute to improving food and nutrition security and reducing GHG emissions, but care must be taken not to increase total emissions overall. Production can be increased by increasing yield, increasing cropping intensities (i.e., by increasing multiple cropping and/or shortening of fallow periods) or expansion of cultivable land and through combinations of these.

Genetic improvement. Genetic improvement provides a prospect of raising crop and livestock yield ceilings to levels not previously possible for a given production environment. Such genetic advances may offer significant technological breakthroughs in the future, and significantly modify our understanding of how to increase global food production (Godfray and Garnett 2014).

Expansion of agricultural land. Notwithstanding the predominance of yield increased in the growth of agricultural production, land expansion will continue to be a significant factor in those developing countries and regions where the potential for expansion exists. Globally, 4900 billion ha land was under agricultural production in 2015 (FAOSTAT 2015). Although there was a marginal increase in total agricultural land over the period between 1961 to 2000 (much of the world food demand for the period was met by increasing productivity), some of the future food demand to 2050 could be met by bringing additional land into cultivation. According to one estimate, up to 1.4 billion ha additional land could be brought under cultivation if needed (Alexandratos and Bruinsma 2012), although Lambin *et al.* (2013) suggest much smaller areas when all constraints are considered.



Supplementary Figure 5.2 Cropland as % of total land area (Teluguntla et al. 2014)

Expanding land-based aquaculture. About 15% of animal-source protein globally comes from fish products. Two-thirds of the global fish supply comes from capture fisheries and one-third from aquaculture. While capture fisheries have stabilised or even declined, future fish products will likely come from specialised aquaculture, particularly of non-carnivorous species, and integrated crop-livestock-fish farming systems (Keating et al. 2014). Integrating aquaculture with mixed crop-livestock-fish farming system can improve nutrient cycling and increase farmers' income. Aquaculture can also make use of land and water not suitable for crop production provided that sustainable feeding systems can be established.

Closing yield gaps. Yield gaps are the difference between yield achieved through best management and average yields achieved by farmers. Yield gaps vary from as low as 10%-20% in developed countries up to 60%-80% in some developing regions, such as Sub-Saharan Africa (Tittonell and Giller 2013; Godfray and Garnett 2014; Keating et al. 2014; Pradhan et al. 2015). Closing yield gaps through investing in technologies that increase input use-efficiency may be one of the important options to improve future productivity. Closing yield gaps requires location-specific agricultural management strategies and inputs that include fertilisers, pesticides, advanced soil management, land improvement, management strategies coping with weather-induced yield variability, and improving market accessibility (Pradhan et al. 2015). One input needed to increase yield is labour. Some management techniques in agroecology, such as polycultures and crop rotations, require more labour to produce more food. It has been estimated that Africa and Asia could achieve food self-sufficiency by closing yield gaps (Pradhan et al. 2014), if accompanied by appropriate policies.

Sustainable intensification. Investments in input and technology-based expansion of food production is based often on radical transformation of agriculture through intensification, development of hybrid seeds, and high technology approaches. This approach is characterised by ecosystem simplification and hence mono-cropping, high dependency on synthetic inputs such as fertilisers and pesticides, and intensive tillage. Such approaches have direct implications on climate and agro-biodiversity. Sustainable intensification can also include agro-ecological practices, such as intercropping.

There is growing interest in strengthening global efforts in sustainable intensification of agriculture (Garnett et al. 2013). Sustainable intensification aims to increase food production from existing farmland in ways that place far less pressure on the environment and that do not undermine capacity to continue producing food in future. This involves an increase in crop yields while also improving fertiliser, pesticide and irrigation use-efficiency. The existence of yield gaps suggests that the scope of sustainable intensification is large. Precision management of land, water, nutrient and other production inputs through application of available technologies and knowledge would be crucial steps towards increasing food production in future. Some 80% of the projected growth in crop production in developing countries comes from intensification in the form of yield increases (73%) and higher cropping intensities (6%) (Pretty et al. 2011).

Increasing crop yield is not achieved only through genetic improvement. Changes in management can have more impact on yields than genetic improvements. One study found that productivity of staple crops in the US and EU over time increased more from improved management than from improved genetics (Heinemann et al. 2014)**.**

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