Supplementary Material

Section SM5.1

Table SM5.1 A gendered approach to understanding how climate change affects dimensions of food security across pastoral and agro-pastoral livestock-holders (adapted from McKune et al. (2015); Ongoro and Ogara (2012) and Fratkin et al. (2004). ↑ increased, ↓ decreased

Group	Livelihoods	Health	Nutrition
Pastoral	↑ time demand on *women* and *girls* for water, fuel collection ↑ time demand on *men* to seek out water sources with herd ↑ *men* exposure to attacks from other groups ↑ *men* migration resulting in ↑ *women* workload ↑ productive and reproductive demands on *women* ↓ financial autonomy of *women* due to liquidation of small animal assets ↑ women poverty due to livestock losses of men	↑ disease risk due to proximity of *women'*s work to disease agents ↑ *children* health and growth due to reduced milk consumption ↑ *women* and *girls* exposure to insecurity and dangers when looking for water ↑ *women* and *children* vulnerability to water-borne diseases ↑ vulnerability to *maternal mortality* due to ↑ fertility due to sedentarisation ↓ mental and emotional health due to increased stress/loss of social support for both *men and women* ↑ vulnerability of newly sedentarized households, particularly *women*	↑ undernutrition of *men and women* due to ↓ availability of plant and animal foods ↑ undernutrition of *men and women* due to separation of from milk-producing animals ↑ undernutrition in *men and women* due to unfavorable trade-offs in diet between animal products and grains ↑ risk of food insecurity I *men and women* due to ↓ production of livestock and ↑ prices
Agro-pastoral	↑ time demand on *women* due to migration of men for herding or wage labor ↓ financial autonomy of *women* due to liquidation of small animal assets ↑ constraints on herd management due to shifts in responsibilities ↑ susceptibility to market	Earlier weaning, shortened birth intervals, and risk of *maternal depletion* ↑ incidence of anemia and stunting in *children* ↑ susceptibility to infectious diseases that are sensitive to climate change in both *men and women* ↑ *child* mortality rates	↑ exposure of *men and women* to foods that have become spoiled Less varied and less nutritious diets for *men and women* ↑ malnutrition, including overnutrition, in *men and women*

	fluctuations		

Section SM5.2

Table SM5.2 Impacts of selected climate drivers on food security pillars.

Food security pillar	**Driver of climate change**	**Process**	**Impact**	**Reference**
Availability	Increase in temperature	• Increased water demand • Increased heat and drought stress • Shorter growing period • More frequent heat wave • Terminal heat • Reduced grain filling period • Decreased soil fertility • Land degradation • Higher pre-harvest loss due to disease and pest attack • Negative effects on physiological processes	Decreased crop yield and animal performance	Zhao et al. (2017) Asseng et al. (2015) Myers et al. (2017) Ovalle-Rivera et al. (2015) Rosenzweig et al. (2014) Medina et al. (2017) Paterson and Lima (2011) Schlenker and Roberts (2009)
	CO_2 concentration	• Increased photosynthesis in C3 crops • Increased water use efficiency	Increased crop yield	Franzaring et al. (2013) Mishra and Agrawal (2014) Myers et al. (2014) Ishigooka et al. (2017) Zhu et al. (2018) Loladze (2014) Yu et al. (2014)
	Precipitation (untimely, erratic, decreased)	• Drought and heat stress • Crop failure • Land degradation • Reduced soil fertility	Decreased crop yield and pasture stocking rates and animal performance	Leng and Hall (2019) Zscheischler et al. (2018) Meng et al. (2016) Zimmerman et al. (2017) FAO et al. (2018)

	Extreme events (drought, flood, cyclones etc.)	• Decrease in organic matter • Soil erosion • Crop failure • Disruption of distribution and exchange	Decreased crop yield Increased livestock mortality Decreased distribution and exchange	Leng and Hall (2019) Rivera-Ferre (2014)
Access	Increase in Temperature	• Increase in price • Loss of agricultural income • Disproportionate impact on low-income consumers	Increased food price and reduced purchasing power	Morris et al. (2017) Vermeulen et al. (2012) Abid et al. (2016) Harvey et al. (2014) UNCCD (2017)
	Precipitation (untimely, erratic, decreased)	• Low yield, price increase • Loss of agricultural income due to reduced yield and productivity • Decrease in barley yield • Inability to invest in adaptation and diversification measures to endure price rises	Increased food price and reduced purchasing power	FAO (2016) Kelley et al. (2015) Morris et al. (2017) Vermeulen et al. (2012) Abid et al. (2016) Harvey et al. (2014) UNCCD (2017)
	Extreme Events (drought, flood, cyclones etc.)	• Price increase due to low yield or sporadic crop failure • Loss of agricultural income	Increased food price and reduced purchasing power	Valin et al. (2014) Robinson et al. (2014) Nelson et al. (2013) Schmitz et al. (2014)
Utilization	Increase in Temperature	• Decreased in nutritional content • Increased mycotoxins • Reduced water quantity and	Reduced quality	Tirado and Meerman (2012) Aberman and Tirado (2014) Thompson et al. (2012)

		quality to prepare food • Negative impact on food safety • Higher post-harvest loss both in quantity and quality		
	CO_2 Concentration	• Decreased protein content • Less zinc content • Less iron content • Increased biomass but reduced multiple nutrients • Less radiation interception and less biomass production	Reduced quality	Myers et al. (2014) Smith et al. (2017) Myers et al. (2015) Medek et al. (2017) Bahrami et al. (2017) Rosenzweig and Hillel (2015)
	Extreme Events (drought, flood, cyclones etc.)	• Adverse weather affects food storage and distribution	Reduced quality	Wellesley et al. (2017) Thompson et al. (2012)
Stability	Increase in Temperature	• Disruption of food supply	Fluctuation in production, supply and price	Allen et al. (2017) Tigchelaar et al. (2018)
	Precipitation (untimely, erratic, decreased)	• Disruption of food supply • Yield variability • Fluctuation in yield, supply and price • Crop failure due to extreme drought	Fluctuation in production, supply and price	Schmidhuber and Tubiello (2007) Kelley et al. (2015) Selby et al. (2017) Kelley et al. (2017) Medina-Elizalde and Rohling (2012)

	Extreme Events (drought, flood, cyclones etc.)	• Impacts on world market export prices that carry through to domestic consumer prices • Widespread crop failure contributing to migration and conflict • Disruption of food supply due to civil disturbance and social tension	Fluctuation in production, supply and price	Kelley et al. (2015) Willenbockel (2012) Hendrix (2018) Selby et al. (2017) Kelley et al. (2017)

Detection and attribution methods

Observed impacts of climate change on food security have been noted as a cause of concern (HLPE 2012) and assessed in AR5 (Porter et al. 2014; Cramer et al. 2014) and SR15 (IPCC 2018). Assessing evidence for detection and attribution of observed climate change impacts on the food system remains a challenge because agriculture is a managed system with practices changing over time. Using AR5 and SR15 findings that observed climate changes attributable to human influence include rising temperatures, increases in the intensity and frequency of hot days and nights, more areas with increases than decreases in the frequency, intensity, and or amount of heavy precipitation, and drying trends in some regions especially in the Mediterranean region (including southern Europe, northern Africa and the Near East), we assess recent studies of observed climate change impacts on the food system that utilise IPCC attribution methods (Hegerl et al. 2010), as well as others that depend on local knowledge from the developing world.

New work has addressed observed climate effects on expanded aspects of the food system, including pastoral systems (Rasul et al. 2019; Abiona et al. 2016), pests, diseases, and pollinators (Bebber et al. 2014; Schweiger et al. 2010), and adaptation (Li et al. 2017) (see Section 5.3). Surveys of farmer perceptions of climate changes and their impacts are being increasingly utilised in developing countries for example (Hussain et al. 2016) (Ifeanyi-obi et al. 2016; Onyeneke 2018).

Improvements in projection methods since AR5

Since AR5, methods for assessment of future climate change impacts on food systems have improved in several areas, providing new insights. These methods include greater number of ensembles of multiple climate, crop, and economic models, with improved characterisation of uncertainty (Wiebe et al. 2015); further comparison of results from process-based crop models and statistical models (Zhao et al. 2017); advances in regional integrated assessments (Rosenzweig and Hillel 2015), and new coordinated global and regional studies (Rosenzweig et al. 2017; Ruane et al. 2018). Temperature response functions in crop models have been improved (Wang et al. 2017).

Expanded meta-analyses of free-air carbon dioxide experiments (FACE) have examined effects of high CO_2 on crop nutrients not just on yield (Smith and Myers 2018; Zhu et al. 2018) (Section 5.2.4.2). Recent reviews have confirmed that higher CO_2 concentrations increase crop growth and yield, especially in crops with C3 photosynthetic pathways, but realisation of these direct CO_2 effects depends on nutrient and water availability (Lombardozzi et al. 2018; Toreti et al.; Uddin et al. 2018) *(high confidence)*. New work has considered future impacts of farming systems, extreme events, fruits and vegetables, rangelands and livestock, and aquaculture, as well as food safety, pests and diseases, and food quality (Section 5.2).

However, several sources of uncertainty exist in projection of climate change crop impacts, partly stemming from differences between the models and methods utilised, sparse observations related to current climate trends, and other agro-ecosystem responses (e.g., to CO_2 effects) (Mistry et al. 2017; Li et al. 2015; Bassu et al. 2014; Asseng et al. 2013). The uncertainty in climate simulations is generally larger than, or sometimes comparable to, the uncertainty in crop simulations using a single model (Iizumi et al. 2011), but is less than crop model uncertainty when multiple crop models are used as in AgMIP (Rosenzweig et al. 2014b) and CO_2 is considered (Hasegawa et al. 2018; Müller et al. 2014; Asseng et al. 2013).

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

Table SM5.3 Observed climate change impacts on crop production, data sources, and detection and attribution methods

Climate observations	Climate data source	Observed impacts	Impact method/source	Time period	Region	Detection &Attribution method	Reference	Continent
Warming temperatures	Chinese Meteorological Administration	If 1980 variety was still grown, maize yield would stagnate or decrease; due to adoption of maize varieties with long growth period yield increased by 7-17% per decade.	China Agricultural Database	1980-2009	Heilongjiang Province, Northeast China	Single step attribution	(Meng et al. 2014)	Asia
Warming temperatures	Chinese Meteorological Administration	Changes in winter wheat phenology; observed dates of sowing, emergence, and beginning of winter dormancy were delayed by 1.2, 1.3, and 1.2 days per decade. Dates of regrowth after dormancy, anthesis, and maturity advanced 2.0, 3.7, and 3.1 days per decade. Growth duration, overwintering period, and vegetation phase shortened by 4.3, 3.1, and 5.0 days per decade.	Local agro-meterological experimental stations maintained by Chinese Meterological Administration	1981-2009	Loess Plateau, Northwest China	Single step attribution	(He 2015)	Asia

Warming temperatures	Central China Meteorological Agency	Advance in sowing and phenological stages advanced by 23-26 days	Agrometeorological experimental station Wulanwusu, China	1981-2010	Northwest China	Statistical relationships for cotton phenologies, seed cotton yields, and climate parameters using Pearson correlation analysis.	(Huang and Ji 2015)	Asia
Warming temperatures	China Meteorological Administration	Changes in temperature, precipitation and solar radiation in past three decades and increased wheat yield in northern China by 0.9-12.9%; reduced wheat yield in southern China by 1.2-10.2 %.	China Meteorological Administration	1981-2009	China	Correlations between annual yields with climate variables. Partial correlations with detrended yields and climate variables.	(Tao et al. 2014)	Asia
Warming temperatures	Pakistan Meteorological Department	Change in phenology of sunflowers. Sowing dates for spring sunflowers 3.4-9.3 days per decade earlier. Sowing dates for autumn sunflower delayed by 2.7-8.4 days per decade.	Punjab Agriculture Department	1980-2016	Punjab, Pakistan	Single step attribution	(Tariq et al. 2018)	Asia

Warming temperatures	Pakistan Meteorological Department	Change in phenology in maize. Sowing dates for spring maize 3.5-5.5 days per decade earlier. Sowing dates for autumn maize 1.5-4.2 days per decade later.	Punjab Agriculture Department	1980-2014	Pujab, Pakistan	Single step attribution	(Abbas et al. 2017)	Asia
Increases in max and min temperatures	India Meteorological Department (IMD)	Reduced wheat yields by 5.2% . 1 degree C increase in maximum temperature lowers yields by 2.3% while same increase in minimum temperature lowers yields by 3.6%.	Indian Harvest Database Centre of Monitoring the Indian Economy (CMIE) and Directorate of Economics, Ministry of Agriculture.	1981-2009	India	Regression analysis between temperature and yield.	(Gupta et al. 2017)	Asia
Reduced rainfall and rising temperatures	Australian Bureau of Meteorology	Stagnated wheat yields. Declines in water-limited yield potential.	Agricultural Commodity Statistics	1965-2015	Australia	Single step attribution	(Hochman et al. 2017)	Australia

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Increases in temperature and drought	Czech Hydrometerological Institute (CHMI), 268 climatological stations, and 774 rain gauge stations	Long-term impacts on fruiting vegetables (+4.9 to 12.2% per degree C) but decreases in stability of tradionally grown root vegetables in warmest areas of country.	Database of 12 field-grown vegetables at district level as reported by Czech Statistical Office.	1961-2014	Czech Republic	Associative pattern attribution	(Potopová et al. 2017)	Europe
Long-term temperature and precipitation trends	Precipitation: 1900-2008 Gridded Monthly Time Series Version 2.01. Available at: http://climate.geog.udel.edu/~climate/.	Wheat and barley yields declined by 2.5% and 3.8%, and maize and sugar beet yields have increased due to temperature and precipitation changes.	EU Farm Accountancy Data Network (FADN)	1989-2009	Europe	Associative pattern attribution	(Moore and Lobell 2015)	Europe

Notes: See Hegerl et al. (2010) for full definitions of attribution methods: Single Step: where a model(s) is run with and without a single variable of interest (i.e., temperature) and results compared to observed changes within a system; Multi-Step: Through processes modelling and/or a statistical link, a change in climate is linked to a variable of interest, and then that variable of interest is linked to an observed change; Associative Pattern: Involves the synthesis of multiple observations – and demonstrates a pattern of strong association between these changes and changes in temperatures due to anthropogenic forcing.

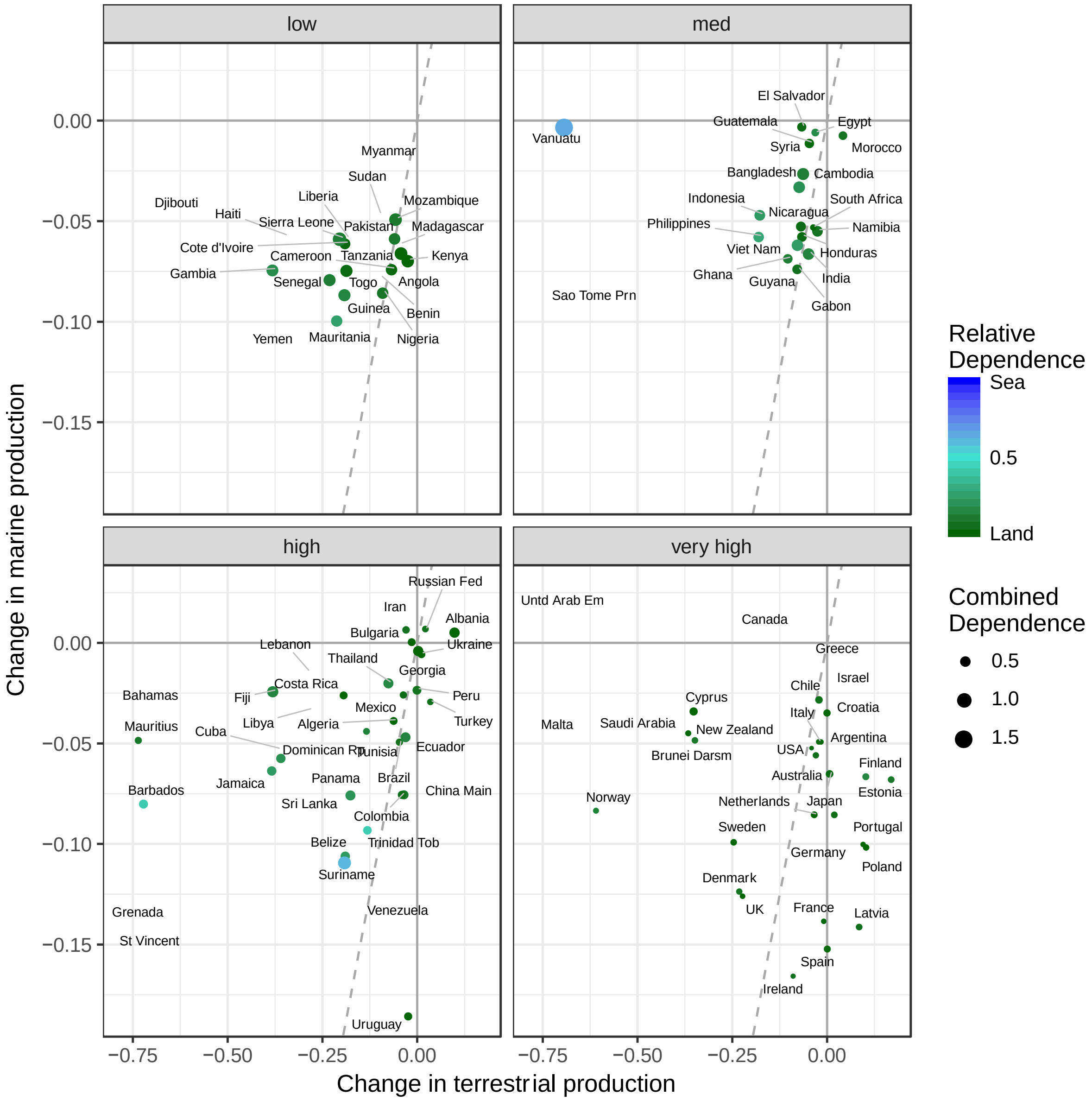

Figure SM5.1 Climate change impacts and adaptive capacity by continent across land and sea. Vulnerability of societies to climate change impacts in fisheries and agriculture under RCP6.0. Changes in marine fisheries (Tittensor 2017) and terrestrial crop production (Rosenzweig et al. 2014b) **are expressed 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 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. Modified from: Blanchard et al. 2017.**

Table SM5.4 Models included in Hasegawa et al. (2018)

Model	Reference
AIM/CGE	(Fujimori et al. 2012)
CAPRI	(Britz and Witzke 2014)
GCAM	(Kyle et al. 2011; Wise and Calvin 2011)
GLOBIOM	(Havlik et al. 2014)
IMAGE 3.0	(Stehfest et al. 2014)
IMPACT 3	(Robinson et al. 2015)
MAGNET	(Woltjer et al. 2014)
MAgPIE	(Lotze-Campen et al. 2008; Popp et al. 2014)

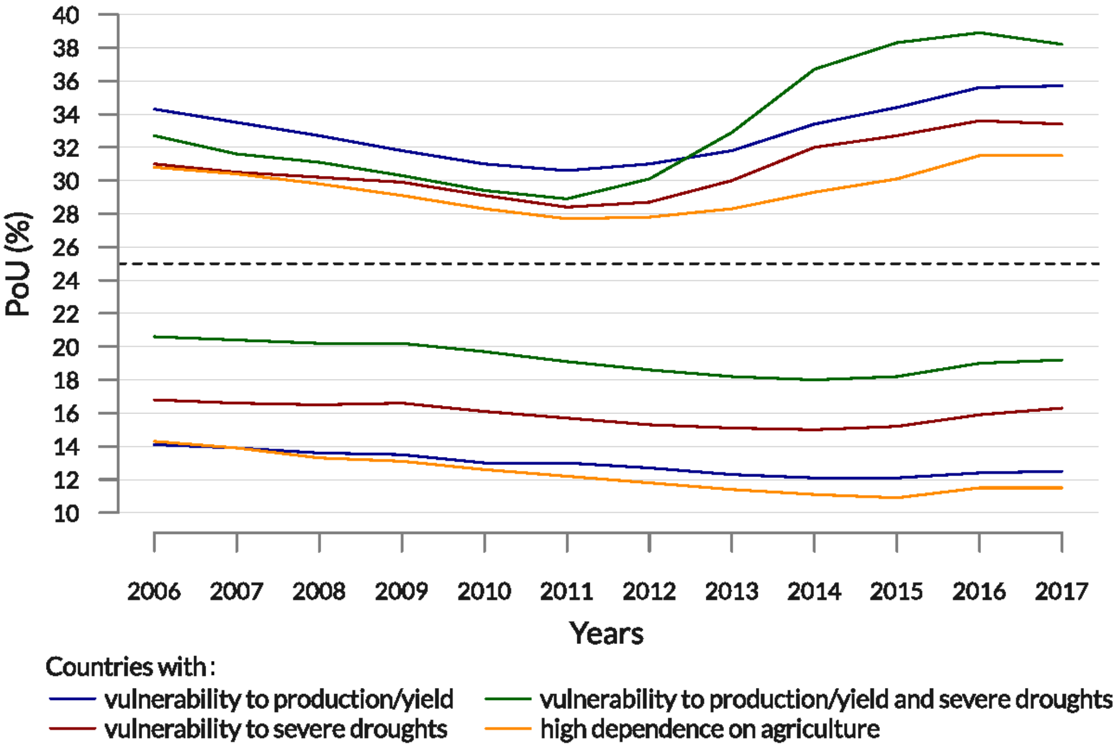

Figure SM5.2 Undernourishment is higher when exposure to climate extremes is compounded by high levels of vulnerability in agriculture (FAO et al. 2018).

Section SM5.5

Livestock mitigation strategies

Intensification of animal diets. It is well established that appropriate diet regimes may contribute to reduce the amount of GHG produced per unit of animal product (Gerber et al. 2013b), which, within the appropriate implementation including governance, may lead to mitigation of absolute emissions. This increased efficiency can be achieved through improved supplementation practices or through land use management with practices like improved pasture management, including grazing rotation, fertiliser applications, soil pH modification, development of fodder banks, improved pasture species, use of legumes and other high protein feeds, the use of improved crop by-products and novel feeds (i.e., black soldier fly meal, industrially produced microbial protein (Pikaar et al. 2018).

When done through increased feeding of grains, transition to improved diets shifts the contributions of different GHG gases to the total emissions. This is due to the fact that the proportion of methane to total emissions is reduced (due to lower roughage intake), while the proportion of emissions associated with feed manufacture (energy and land use change) increases. Therefore, CO_2 emissions from land use change increase while methane emissions per unit of output decrease (Gill et al. 2010). As a consequence, the quantified benefits of a given strategy wil also depend on the assumed GWP of methane.

Of the available livestock GHG mitigation options, improved feeding systems are relatively easy to implement at the farm level. A prerequisite for these options to work is that the livestock systems need to be geared towards market-oriented production, as otherwise there is little incentive to improve feeding systems. This in turn implies that costs and benefits to farmers are appropriate to incentivise specific management changes and also assess the impact that market-orientation may have in some societies, such as pastoralists (López-i-Gelats et al. 2016). Examples of where this option could be applicable are smallholder dairy-crop mixed systems in Africa and Asia, dual-purpose and dairy production in Latin America and beef cattle operations, where significant mitigation opportunities exist. Other mitigation options include manipulation of rumen microflora, breeding for lower methane production, and the use of feed additives (Hristov et al. 2013).

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

Control of animal numbers, shifts in breeds, and improved management. Increases in animal numbers are one of the biggest factors contributing directly to GHG emissions (Tubiello, 2019). Regions with intensive animal production, such as concentrated animal feeding operations (CAFOs), can control animal numbers, conduct breeding programs for efficient animals, and improve feeding management. In the developing world, many low-producing animals could be replaced by fewer but better-fed cross-bred animals of a higher potential, with improved grazing management (i.e., attention to feed, herbage availability, and allowances) playing an important role. In both developed and developing countries these practices are able to reduce total emissions while maintaining or increasing the supply of livestock products.

However, attention must be paid to synergies and trade-offs between livelihoods and specific mitigation strategies, such as controlling animal numbers, recognising the multiple objectives that livestock raising may contribute to within specific settings, especially in low-input systems. Improvements in animal health can also significantly reduce emissions intensity by improved yields and fertility per animal and reductions in mortality (ADAS 2015).

Changes in livestock species. Switching species to better suit particular environments is a strategy that could yield higher productivity per animal for the resources available. At the same time, structural changes in the livestock sector from beef to sheeps and goats, or mainly from ruminants to monogastrics (e.g., from beef to pig or poultry production) could lead to reduced methane emissions and higher efficiency gains. Assessment done using integrated assessment models (IAMs) have shown that 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. In currently adopted feeding systems, large amounts of nutrients and carbon are lost in connection with manure storage (e.g., Herrero et al. 2013). In many places 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, for instance, 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.

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 intensive systems, emissions of ammonia and nitrous oxide can be managed by spatially shifting livestock pens or the facilities where they overnight. Other options in more-intensive grazing systems may include nitrification inhibitors, stand-off pads, delayed manure spreading collected in milking sheds, although the fate of the full applied N and its partitioning between direct and indirect emissions as a result of the specific option chosen must be evaluated (e.g., Lam et al., 2017)

Uncertainties in demand-side technical mitigation potential

There are several unresolved issues regarding modelling and quantification of marginal emissions identified in the literature. Diet shift studies often focus on beef production emission intensities, although the cattle industry in many locations includes both meat and dairy production; these activities may be integrated in different types of farming systems (Flysjö et al. 2012) with significantly lower emission intensities (Gerber et al. 2013a; Flysjö et al. 2012). Links between ruminant meat production, the dairy sector (primarily cows and goats), and wool production in sheep are often overlooked in diet shift studies. FAOStat 2017 data indicate there are 278 million dairy cows worldwide, which make significant contributions to meat production (304 million head slaughtered per year) by providing calves (lactating cows must calve to produce milk) and dairy cows (replacements by younger females).

Attributional LCA values are often applied to diet shifts studies, overlooking the feedback loop (rebound effect) of demand on production system emission intensities. There are a few examples of consequential analysis of diet shifts (Tukker et al. 2011) (de Oliveira Silva et al. 2016) (Zech and Schneider 2019), reporting modest potential for mitigation (i.e., from 0-8%) but each of them emphasise only one particular aspect of diet shifts. Further, the application of those models to different regions of the world may require further development.

Current attributional LCA studies present inconsistencies related to the definition of system boundaries, allocation of co-products (including dairy), method of attribution of land use change, and pasture productivity effects on soil carbon stocks (Lynch 2019) (Yan et al. 2011; Dudley et al. 2014). Major differences in the results are due to how land use change affects emissions and soil carbon stocks,, particularly when addressing developing countries where deforestation and intensification can both take place at the same time. Deforestation-related emissions have been attributed to first land use (Bustamante et al. 2012), the activities under a given amortization time (Persson et al. 2014), change in total land covered by the activity (Gerber et al. 2013a), or the missed potential carbon sink, i.e., the opportunity for natural vegetation recovery (Schmidinger and Stehfest 2012) (Schmidt et al. 2015).

Also, variation in soil carbon stocks is not considered in most studies, while a few account for variations up to 0.3 m soil depth, and very rarely consider 1.0 m soil depth for estimating soil carbon variation. Overlooking soil carbon at deeper soil layers largely contributes to underestimating the environmental benefits of transition to more productive systems. Time considerations in soil carbon stocks dynamics also vary among studies, with some applying a standard 20-year equilibrium time instantaneously and others using dynamic (discrete or continuous) models.

The type of food replacement is another major source of uncertainty in calculating the impact of dietary changes (Smetana et al. 2015). Nutritional replacement with animal-based protein candidates such as chicken, eggs, pork, fish, and insects is likely to vary widely in different geographical contexts. While chicken and soybean are currently dominating international trade of protein sources (FAOStat), legumes, pulses, seaweed, and yeast-derived foods are being tested as ingredients by the food industry.

In regard to food quality, reducing meat consumption may lower the iron and zinc nutritional status of certain vulnerable groups. For example, in Europe 22% of preschool children, 25% of pregnant women, and 19% of nonpregnant women already have anemia (WHO, 2008). Reductions in red meat consumption also may have food safety implications. Substituting meat with poultry or seafood might increase foodborne illnesses, whereas replacement with pulses and vegetables would reduce them (Lake et al., 2012).

GHG emissions associated with food preparation and food waste are usually unaccounted for in diet shift studies with rare exceptions (Corrado et al. 2019). Dietary supplements (vitamin, minerals and amino acids) are highly recommended for low-meat diets, but they are not considered in GHG mitigation studies of diet shifts, mostly because of lack of LCA data for supplements (Corrado et al. 2019).

The varying proportions of CO_2, CH_4, and N_2O contributions to ruminant-related emissions, with a high proportion of the short-lived methane, make interpretation sensitive to the global warming metrics adopted (Reisinger and Clark 2018) (Lynch 2019). As more intensive systems or other diet alternatives would alter the relative contributions to food of these gases, the choice of metric often changes the ranking of mitigation options (Lynch and Pierrehumbert 2019)(Garnett, 2011). Most projections related to diet shifts do not account for the potential of methane inhibitors, non-symbiotic nitrogen fixation, advances in livestock and forage genetics, and other emerging technologies in the livestock sector, some of which are close to market launch (Jayanegara et al. 2018).

In a systems view, dairy and wool production can be affected if reductions in ruminant meat demand take place. While beef production sytems are often characterised by low energy and protein efficiency, milk production is as efficient energetically as egg production and second after eggs in protein conversion efficiency among animal-based proteins (Eshel et al. 2016).

In summary, systems level analyses revealed wide variation in mitigation estimates of diet shifts, in part due to differing accounting for the main interactions. There is *robust evidence* that diet shifts can mitigate GHG emissions but *low agreement* on how much could be achieved and what would be the effectiveness of interventions to promote diet shifts. In high-income industrialised countries, there is scope for reducing consumption of livestock produce with tangible environmental benefits; in developing countries, high meat-based diets are less prevalent and scope for reductions may be more limited, but there are options for encouraging nutritition transitions towards healthy diets.

Section SM5.6

Global meat consumption

The issue of global meat consumption as a driver of GHG emission, can be weighed against the requirements of healthy diet. Healthy and sustainable diets are high in coarse grains, pulses, fruits and vegetables, and nuts and seeds; low in energy-intensive animal-sourced and discretionary foods (such as sugary beverages and fats); and have a carbohydrate threshold. Based on the potential impact of suboptimal diets on non-communicable diseases (NCD) mortality and morbidity, the World Health Organization (WHO) and the EAT-LANCET report (Willett et al. 2019) highlighted the need for improving diets across nations and made recommendations on how to balance nutrition to prevent malnutrition. The source of protein is not limited to meat; it is found in fish, vegetable and insects. The range of options in balancing protein sources runs primarily into cultural resistance, food habits, economic conditions and the social and economic factors influencing how the food system affects climate and land.

Most recent analyses, like the EAT-LANCET (Willett et al. 2019) work, show that reductions in consumption, especially of red meat, apply to over-consumers, while scope remains for growth in consumption in Low- and Middle-Income Countries (LMICs).

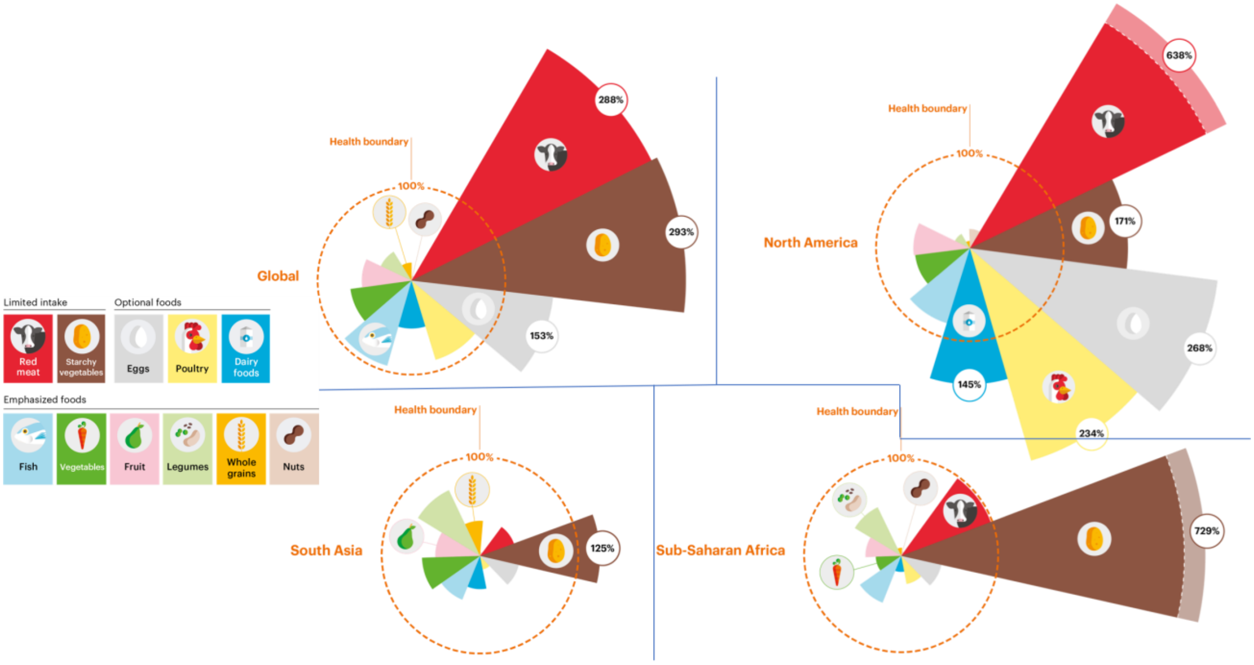

Figure SM5.3 The "diet gap" between current dietary patterns and intakes of food in the planetary health diet (Willett et al. 2019).

From the climate and land perspectives, there is a difference between red meat production and other meat production (Willett et al. 2019). The impacts of meat production will depend on resource use intensity to produce meat calories, the land and climate footprints of the processing and supply chains, and the scale of the production systems (i.e., livestock on crop by-products vs. pasture vs. intensive grain-fed) (Willett et al. 2019). Hence, the question is not about eating less meat for everyone, but to adopt sustainable supply and consumption practices across a broad range of food systems.

The biggest challenge to achieve changes in meat consumption is on how to start a transition that has increasing diversity of food sources with lower land and water requirements and GHG emissions. This could be a gradual transition that recognises the need for just transitions for people whose livelihoods depend on (red) meat production. In this regard, all parts of the food system, including production, trade, and consumption, play important roles.

Section SM5.7

Governance

Governance of climate change and governance of food systems have been developed independently of each other. This section highlights the main characteristics of food and climate governance and assesses what options may exist for establishing arrangements that link the two. See Chapter 7 for important characteristics of governance and institutions; here we describe those relevant for enhancing the interactions between climate change and food systems.

In the governance of climate change, Huitema et al. (2016) highlighted differences between mitigation and adaptation. Mitigation often requires global agreements and national policies while adaptation requires local and regional considerations. However, in the case of food systems this difference does not apply, because mitigation measures also require local actions (e.g., at the farm level), while adaptation actions may also require measures at global and national levels (such as emergency food aid for climate disasters and food safety nets).

Governance of food systems holds particular challenges because it is only recently that a systems approach has been embraced by policy-makers. (Rivera-Ferre et al. 2013) proposed principles for food systems management considering them as complex socioecological systems (SES) including: learning, flexibility, adaptation, participation, diversity enhancement, and precaution. These principles are part of the framework of adaptive governance (see Chapter 7). Termeer et al. (2018) developed a diagnostic framework with five principles to assess governance options appropriate to food systems: 1) system-based problem framing; 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 conditions to foster structural change.

Both the food and climate systems require integrated governance and institutions (*high confidence*). These need to span government levels and actors across a wide range of sectors including agriculture, environment, economic development, health, education, and welfare (Misselhorn et al. 2012). For climate and food system management, the creation of government entities or ministerial units responsible for coordinating among these ministries (horizontal coordination) and for cutting across different administrative levels (vertical coordination) have been proposed (Orr et al. 2017).

However, integration is not easy. Termeer et al. (2018) analysed three South African governance arrangements that explicitly aim for a holistic system-based approach. They found that they were not delivering the expected outcomes due to reversion to technical one-dimensional problem framing. Issues included dominance of single departments, limited attention to monitoring and flexible responses, and exclusion of those most affected by food insecurity. Newell et al. (2018) analysed the governance process of climate smart agriculture (CSA) from global to local scales for Kenya and found a triple disconnect between global, national, and local scales. Different levels of authority and actors imposed their own framing of CSA, and how to implement it.. As a result of the competition among different actors, siloed policy practices were reproduced.

Food systems governance must also include governance of the resources needed to produce food, which vary from land tenure (see chapter 7) and seed sovereignty (see Chapter 6), to other resources such as soil fertility. Montanarella and Vargas (2012) proposed a supranational structure to guarantee soil conservation on all continents, such as the Global Soil Partnership. This can also apply for the governance of food and climate systems.

Polycentric and multiscalar governance structures have been proposed for coping with climate change to address both mitigation and adaptation (Ostrom 2010), and were suggested by Rivera-Ferre et al.

(2013) for food systems. A polycentric approach provides more opportunities for experimentation and learning across levels (Cole 2015), entails many policy experiments from which policymakers at various levels of governance can learn (Ostrom 2010), and contributes to building trust among stakeholders (e.g., nation states, public and private sectors, civil society). Polycentric approaches have been suggested for the Sustainable Development Goals (SDGs) (Monkelbaan 2019).

Another governance option suggested for the SDGs (Monkelbaan 2019) are already implemented in global atmospheric and marine agreements (e.g., the Montreal protocol (De Búrca et al. 2014; Armeni 2015) is global experimentalist governance). Global experimentalist governance is an institutionalised process of participatory and multilevel collective problem-solving, in which the problems (and the means of addressing them) are framed in an open-ended way, and subjected to periodic revision by peer review in the light of locally generated knowledge (De Búrca et al. 2014), This favours learning, participation and cooperation (Armeni 2015). This form of governance can establish processes that enable unimagined alternatives.

Institutions

As Candel (2014) highlighted, based on a systematic review of food security governance focused on hunger, global governance of food security is lacking because there is no institution with a mandate to address concerns across sectors and levels. No international organisation deals with food security in a holistic and inclusive manner. This results in overlapping (often conflicting) norms, rules and negotiations that generate a “regime complex” (Margulis 2013), particularly in regard to agriculture and food, international trade and human rights (e.g. UN Committee of World Food Security (CFS), WTO, G8, G20). In climate change governance there are also multiple overlapping institutions with often-conflicting rules and actors (Keohane and Victor 2011).

New multi-stakeholder governance arrangements are emerging, such as the Global Agenda for Sustainable Livestock (Breeman et al. 2015) and the CFS (Duncan 2015). Also relevant in food systems and climate change governance is that food security governance is spread across domains, sectors and spatial scales (global, regional, national, local, community, household, or individual) with a lack of coherency and coordination across multiple scales (*high confidence*). Thus, a major challenge is to coordinate all these domains, sectors and scales.

It is important to consider the variety of actors involved in food security governance at all levels (international bodies, civil society organisations (CSOs), nation states, public sector groups, and private sector entities), with different agendas and values. But new in this regard is the participation of CSOs that can provide the policy-making process with bottom-up knowledge to identify food insecurity issues and locally relevant responses. CSOs can also contribute to multi-sector and multi-scalar approaches by bridging government agencies and levels (Candel 2014). Thus, to facilitate coordination and coherence, new adaptive governance enables interactions across multiple levels and scales (Pereira and Ruysenaar 2012) and the use of “boundary organisations” (Candel 2014). To address different narratives regarding food security (Rivera-Ferre 2012; Lang and Barling 2012), a first step is to agree on basic principles and values (Margulis 2013).

In this regard, an opportunity to address food systems governance challenges arises within the UN Committee on World Food Security (CFS), where diverse actors, voices and narratives are integrated in the global food security governance. As a point of departure, the CFS could provide the platform to develop global experimentalist governance in food sytems (Duncan 2015; Duncan and Barling 2012) providing a combination of bottom-up and top-down initiatives (Lambek 2019). However, the existence of overlapping structures with different focuses on food security and power may hinder the potential of this institution. (Margulis and Duncan 2016).

Mainstreaming of collaborative and more inclusive modes of governance, such as those displayed at the CFS, are needed to effectively address thehe impacts of a changing planet on food systems (Barling and Duncan 2015) and improve the balance of sustainable production and food consumption. Despite improvements in global food security, food systems and climate governance, the main focus is still on food security as undernutrition. New challenges will arise from the increasing evidence of the burden of obesity, for which other institutions, focused on nutrition, will be needed. The new Global Strategy Framework for Food Security and Nutrition (Committee on World Food Security 2017) of the CFS provides a new overarching framework for food security and nutrition strategies, policies and actions that includes environmental concerns within a food system approach and a broad vision of food and nutrition security. This framework fits within the "governance through goals" provided by the SDGs (Biermann et al. 2017).

Both in climate change and food systems, the sub-national governance at the level of cities and communities is also becoming relevant in terms of responses (*high evidence, high agreement*). From a climate change perspective (see Chapter 7 for more examples) transnational municipal networks, particularly transnational municipal climate networks, have played a key role in climate change mitigation and have potential to facilitate adaptation (Fünfgeld 2015; Busch et al. 2018; Rosenzweig et al. 2018). Efficient food systems require subnational governments to include food policy councils (Feenstra 2002; Schiff 2008) and cities networks to address food systems challenges (e.g., Sustainable Food Cities in the UK or Agroecological Cities in Spain). Transition Towns are engaged in common principles towards sustainable development, including food systems transformation for food security (Sage 2014), health and well-being (Richardson et al. 2012), and climate change (Taylor Aiken 2015).

Scope for expanded policies

The interaction of production-based support through agricultural policy, coupled with agricultural research investment and the development of frameworks to liberalise trade has led to a range of consequences for global and local food systems. Together, these policies have shaped the food system and incentivised global intensification of agriculture, and significant gains in global production. However, jointly they have also incentivised a concentration on a small number of energy-dense commodity crops grown at large scales (*high confidence*) (just eight crops supply 75% of the world's consumed calories (West et al. 2014)). The production of these commodity crops underpin global dietary transitions, leading to dietary homogenisation (based primarily on starchy grains/tubers, vegetable oil, sugar and livestock produce) (Khoury et al. 2014).

Global intensification of agriculture, as well as increasing the supply of affordable calories, has impacted soil, water, air quality and biodiversity in major and negative ways (Dalin et al. 2017; Tamea et al. 2016; Newbold et al. 2015; García-Ruiz et al. 2015; Amundson et al. 2015; Paulot and Jacob 2014). Importantly in the context of this report, a narrow focus on productivity has led to a food system that emits a large proportion of GHGs (Section 5.4), is fragile in the face of climate shocks (Section 5.3) and from which food is used inefficiently (through waste and over-consumption, Section 5.5.2.5). Mitigation of climate change, as well as adaptation, can then arise from a transformation of the food system to one that provides nutrition and health (Willett et al. 2019; Springmann et al. 2018b,a; Godfray et al. 2018; Ramankutty et al. 2018; Chaudhary et al. 2018). There is therefore *medium confidence*, that continued focus on the past drivers of the food system will be detrimental for climate change and food security.

Addressing this challenge requires action across the food system to enhance synergies and co-benefits and minimise trade-offs among multiple objectives of food security, adaptation and mitigation (Sapkota et al. 2017; Palm et al. 2010; Jat et al. 2016; Sapkota et al. 2015) (Section 5.6), as well as broader environmental goods exemplified by the SDG framework such as water, air-quality, soil health and biodiversity (Obersteiner et al. 2016; Pradhan et al. 2017). In short, this requires greater policy alignment and coherence between traditionally separate policy domains to recognise the systemic nature of the problem. For example, aligning the policy goals of sustainable land management for the purposes of managing both food security and biodiversity (Meyfroidt 2017; Wittman et al. 2017), or public health and agricultural policies (Thow et al. 2018) that can drive mitigation, as well as the enabling conditions of land rights, tenure and ownership. Significant co-benefits can arise from integrated food systems policies, as well as integrated approaches to generating evidence to underpin coherent policy, exemplified, for example, by the EU's integrated research and innovation strategy "Food2030" that aligns agriculture, environment, nutrition and research policy (European Commission 2018).

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