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Food Security and Food Production Systems

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This chapter should be cited as:

Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso, 2014: Food security and food production systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

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Executive Summary

The effects of climate change on crop and terrestrial food production are evident in several regions of the world (*high confidence*). Negative impacts of climate trends have been more common than positive ones. {Figures 7-2, 7-7} Positive trends are evident in some high-latitude regions (*high confidence*). Since AR4, there have been several periods of rapid food and cereal price increases following climate extremes in key producing regions, indicating a sensitivity of current markets to climate extremes, among other factors. {Figure 7-3, Table 18-3} Several of these climate extremes were made more likely as the result of anthropogenic emissions (*medium confidence*). {Table 18-3}

Climate trends are affecting the abundance and distribution of harvested aquatic species, both freshwater and marine, and aquaculture production systems in different parts of the world. {7.2.1.2, 7.3.2.4, 7.4.2} These are expected to continue with negative impacts on nutrition and food security for especially vulnerable people, particularly in some tropical developing countries {7.3.3.2}, but with benefits in other regions that become more favorable for aquatic food production (*medium confidence*). {7.5.1.1.2}

Studies have documented a large negative sensitivity of crop yields to extreme daytime temperatures around 30°C. {WGII AR4 Chapter 5, 7.3.2.1} These sensitivities have been identified for several crops and regions and exist throughout the growing season (*high confidence*). Several studies report that temperature trends are important for determining both past and future impacts of climate change on crop yields at sub-continental to global scales (*medium confidence*). {7.3.2, Box 7-1} At scales of individual countries or smaller, precipitation projections remain important but uncertain factors for assessing future impacts (*high confidence*). {7.3.2, Box 7-1}

Evidence since AR4 confirms the stimulatory effects of carbon dioxide (CO₂) in most cases and the damaging effects of elevated tropospheric ozone (O₃) on crop yields (*high confidence*). Experimental and modeling evidence indicates that interactions between CO₂ and O₃, mean temperature and extremes, water, and nitrogen are nonlinear and difficult to predict (*medium confidence*). {7.3.2.1, Figure 7-2}

Changes in climate and CO₂ concentration will enhance the distribution and increase the competitiveness of agronomically important and invasive weeds (*medium confidence*). Rising CO₂ may reduce the effectiveness of some herbicides (*low confidence*). The effects of climate change on disease pressure on food crops are uncertain, with evidence pointing to changed geographical ranges of pests and diseases but less certain changes in disease intensity (*low confidence*). {7.3.2.3}

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). {7.3.3.1, Table 7-1} There remains limited quantitative understanding of how non-production elements of food security will be affected, and of the adaptation possibilities in these domains. Nutritional quality of food and fodder, including protein and micronutrients, is negatively affected by elevated CO₂, but these effects may be counteracted by effects of other aspects of climate change (*medium confidence*). {7.3.2.5}

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation will negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). {7.4, Figure 7-4} Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10% and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. {Figure 7-5} After 2050, the risk of more severe impacts increases. {Figure 7-5} Regional Chapters 22 (Africa), 23 (Europe), 24 (Asia), 27 (Central and South America), and Box 7-1 show crop production to be consistently and negatively affected by climate change in the future in low-latitude countries, while climate change may have positive or negative effects in northern latitudes (*high confidence*). Climate change will increase progressively the inter-annual variability of crop yields in many regions (*medium confidence*). {Figure 7-6}

On average, agronomic adaptation improves yields by the equivalent of ~15-18% of current yields {Figure 7-8, Table 7-2}, but the effectiveness of adaptation is highly variable (*medium confidence*) ranging from potential dis-benefits to negligible to very substantial (*medium confidence*). {7.5.1.1.1} Projected benefits of adaptation are greater for crops in temperate, rather than tropical, regions (*medium confidence*) {7.5.1.1.1, Figures 7-4, 7-7}, with wheat- and rice-based systems more adaptable than those of maize (*low confidence*). {Figure 7-4} Some adaptation options are more effective than others (*medium confidence*). {Table 7-2}

Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). Risks to food security are generally greater in low-latitude areas. {Box 7-1, Table 7-3, Figures 7-4, 7-5, 7-7}

Changes in temperature and precipitation, without considering effects of CO₂, will contribute to increased global food prices by 2050, with estimated increases ranging from 3 to 84% (*medium confidence*). Projections that include the effects of CO₂ changes, but ignore O₃ and pest and disease impacts, indicate that global price increases are about *as likely as not*, with a range of projected impacts from -30% to +45% by 2050. {7.4.4}

Adaptation in fisheries, aquaculture, and livestock production will potentially be strengthened by adoption of multi-level adaptive strategies to minimize negative impacts. Key adaptations for fisheries and aquaculture include policy and management to maintain ecosystems in a state that is resilient to change, enabling occupational flexibility, and development of early warning systems for extreme events (*medium confidence*). {7.5.1.1.2} Adaptations for livestock systems center on adjusting management to the available resources, using breeds better adapted to the prevailing climate and removing barriers to adaptation such as improving credit access (*medium confidence*). {7.5.1.1.3}

A range of potential adaptation options exist across all food system activities, not just in food production, but benefits from potential innovations in food processing, packaging, transport, storage, and trade are insufficiently researched. {7.1, 7.5, 7.6, Figures 7-1, 7-7, 7-8} More observational evidence is needed on the effectiveness of adaptations at all levels of the food system. {7.6}

7.1. Introduction and Context

Many definitions of food security exist, and these have been the subject of much debate. As early as 1992, Maxwell and Smith (1992) reviewed more than 180 items discussing concepts and definitions, and more definitions have been formulated since (DEFRA, 2006). Whereas many earlier definitions centered on food production, more recent definitions highlight access to food, in keeping with the 1996 World Food Summit definition (FAO, 1996) that food security is met when “all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life.” Worldwide attention on food access was given impetus by the food “price spike” in 2007–2008, triggered by a complex set of long- and short-term factors (FAO, 2009b; von Braun and Torero, 2009). FAO concluded, “provisional estimates show that, in 2007, 75 million more people were added to the total number of undernourished relative to 2003–05” (FAO, 2008); this is arguably a low-end estimate (Headey and Fan, 2010). More than enough food is currently produced per capita to feed the global population, yet about 870 million people remained hungry in the period from 2010 to 2012 (FAO et al., 2012). The questions for this chapter are how far climate and its change affect current food production systems and food security and the extent to which they will do so in the future (Figure 7-1).

7.1.1. Food Systems

A food system is all processes and infrastructure involved in satisfying a population’s food security, that is, the gathering/catching, growing, harvesting (production aspects), storing, processing, packaging, transporting, marketing, and consuming of food, and disposing of food waste (non-production aspects). It includes food security outcomes of these activities related to availability and utilization of, and access to, food as well as other socioeconomic and environmental factors (Ericksen, 2008; Ericksen et al., 2010; Ingram, 2011). This chapter synthesizes and evaluates evidence for the impacts of climate on both production and non-production elements and their adaptation to climate change (Figure 7-1).

The impacts of climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by socioeconomic conditions (Vermeulen et al., 2012). Changes in food system drivers give rise to changes in food security outcomes (*medium evidence, high agreement*), but often researchers consider only the impacts on the food production element of food security (Figure 7-1). Efforts to increase food production are nevertheless increasingly important as 60% more food will be needed by 2050 given current food consumption trends and assuming no significant reduction in food waste (FAO et al., 2012).

7.1.2. The Current State of Food Security

Most people on the planet currently have enough food to eat. The vast majority of undernourished people live in developing countries (*medium evidence, medium agreement*), when estimated based on aggregate national calorie availability and assumptions about food distribution and nutritional requirements. More precise estimates are possible with detailed household surveys, which often show a higher incidence of food insecurity than estimated by FAO. Using food energy deficit as the measure of food insecurity, Smith et al. (2006) estimated average rates of food insecurity of 59% for 12 African countries, compared to a 39% estimate from FAO for the same period (Smith et al., 2006). While there is *medium evidence, medium agreement* on absolute numbers, there is *robust evidence, high agreement* that sub-Saharan Africa has the highest proportion of food-insecure people, with an estimated regional average of 26.8% of the population undernourished in 2010–2012, and where rates higher than 50% can be found (FAO et al., 2012). The largest numbers of food-insecure persons are found in South Asia, which has roughly 300 million undernourished (FAO et al., 2012). In addition to common measures of calorie availability, food security can be broadened to include nutritional aspects based on the diversity of diet including not only staple foods but also vegetables, fruits, meat, milk, eggs, and fortified foods (FAO, 2011). There is *robust evidence and high agreement* that lack of essential micronutrients such as zinc and vitamin A affect hundreds of millions of additional people (Lopez et al., 2006; Pinstrup-Andersen, 2009).

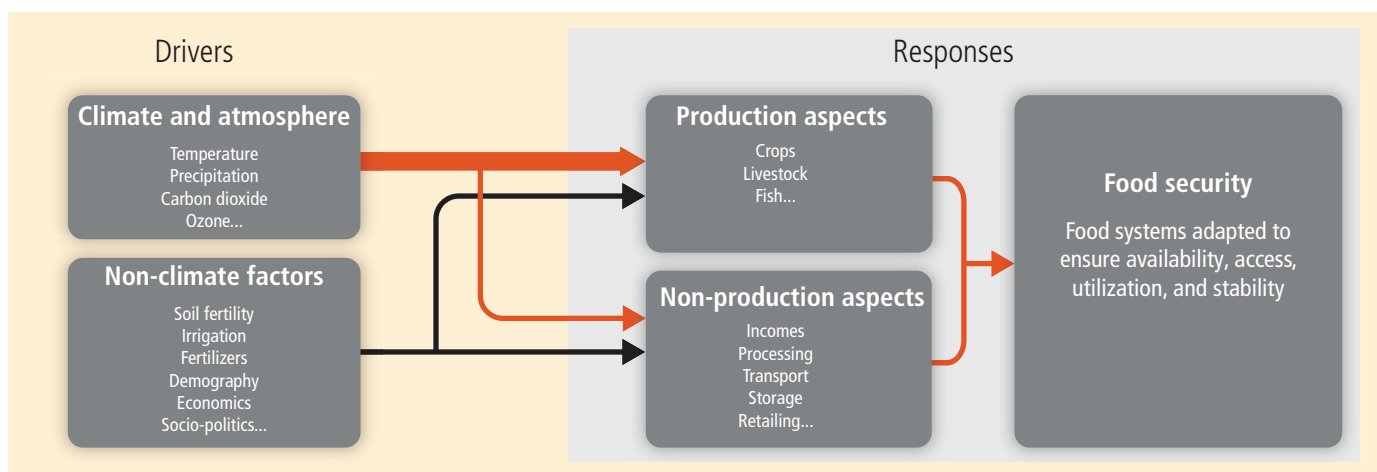


Figure 7-1 | Main issues of the chapter. Drivers are divided into climate and non-climate elements, affecting production and non-production elements of food systems, thereafter combining to provide food security. The thickness of the red lines is indicative of the relative availability of refereed publications on the two elements.

Food insecurity is closely tied to poverty; globally about 25 to 30% of poor people, measured using a US\$1 to US\$2 per day standard, live in urban areas (Ravallion et al., 2007; IFAD, 2010). Most poor countries have a larger fraction of people living in rural areas and poverty rates tend to be higher in rural settings (by slight margins in South Asia and Africa, and by large margins in China). In Latin America, poverty is more skewed to urban areas, with roughly two-thirds of the poor in urban areas, a proportion that has been growing in the past decade (*medium evidence, medium agreement*). Rural areas will continue to have the majority of poor people for at least the next few decades, even as population growth is higher in urban areas (*medium evidence, medium agreement*) (Ravallion et al., 2007; IFAD, 2010).

The effects of price volatility are distinct from the effects of gradual price rises, for two main reasons. First, rapid shifts make it difficult for the poor to adjust their activities to favor producing higher value items. Second, increased volatility leads to greater uncertainty about the future and can dampen willingness to invest scarce resources into productivity enhancing assets, such as fertilizer purchases in the case of farmers or rural infrastructure in the case of governments. Several factors have been found to contribute to increased price volatility: poorly articulated local markets, increased incidence of adverse weather events, and greater reliance on production areas with high exposure to such risks, biofuel mandates, and increased links between energy and agricultural markets (World Bank, 2012). Vulnerability to food price volatility depends on the degree to which households and countries are net food purchasers; the level of integration into global, regional, and local markets; and their relative degree of volatility, which in turn is conditional on their respective governance (*robust evidence, medium agreement*) (HLPE, 2011; World Bank, 2012).

7.1.3. Summary from AR4

Food systems as integrated drivers, activities, and outcomes for food security did not feature strongly in AR4. Summary points from AR4 were that, with *medium confidence*, in mid- to high-latitude regions moderate warming will raise crop and pasture yields. Slight warming will decrease yields in low-latitude regions. Extreme climate and weather events will, with *high confidence*, reduce food production. The benefits of adaptation vary with crops and across regions and temperature changes; however, on average, they provide approximately a 10% yield benefit when compared with yields when no adaptation is used (WGII AR4 Section 5.5.1). Adaptive capacity is projected to be exceeded in low-latitude areas with temperature increases of more than 3°C. Local extinctions of particular fish species are expected at the edges of their ranges (*high confidence*) and have serious negative impacts on fisheries (*medium confidence*).

7.2. Observed Impacts, with Detection and Attribution

7.2.1. Food Production Systems

Formal detection of impacts requires that observed changes be compared to a clearly specified baseline that characterizes behavior in the absence

of climate change (Chapter 18). For food production systems, the number and strength of non-climate drivers, such as cultivar improvement or increased use of irrigation and fertilizers in the case of crops, make defining a clear baseline extremely difficult. Most non-climatic factors are not very well characterized in terms of spatial and temporal distributions, and the relationships between these factors and specific outcomes of interest (e.g., crop or fish production) are often difficult to quantify.

Attribution of any observed changes to climate trends are further complicated by the fact that models linking climate and agriculture must, implicitly or explicitly, make assumptions about farmer behavior. In most cases, models implicitly assume that farming practices or technologies did not adjust in response to climate over the period of interest. This assumption can be defended in some cases based on ancillary data on practices, or based on small differences between using models with and without adaptation (Schlenker and Roberts, 2009). However, in some instances the relationship between climate conditions and crop production has been shown to change over time because of management changes, such as introduction of irrigation or changes in crop varieties (Zhang et al, 2008; Liu et al., 2009; Sakurai et al., 2012).

7.2.1.1. Crop Production

Many studies of cropping systems have estimated impacts of observed climate changes on crop yields over the past half century, although they typically do not attempt to compare observed yields to a counterfactual baseline, and thus are not formal detection and attribution studies. These studies employ both mechanistic and statistical approaches (Section 7.3.1), and estimate impacts by running the models with observed historical climate and then computing trends in modeled outcomes. Based on these studies, there is *medium confidence* that climate trends have negatively affected wheat and maize production for many regions (Figure 7-2) (*medium evidence, high agreement*). Because many of these regional studies are for major producers, and a global study (Lobell et al., 2011a) estimated negative impacts on these crops, there is also *medium confidence* for negative impacts on global aggregate production of wheat and maize. Effects on rice and soybean yields have been small in major production regions and globally (Figure 7-2) (*medium evidence, high agreement*). There is also *high confidence* that warming has benefitted crop production in some high-latitude regions, such as northeast China or the UK (Jaggard et al., 2007; Chen et al., 2010; Supit et al., 2010; Gregory and Marshall, 2012).

More difficult to quantify with models is the impact of very extreme events on cropping systems, as by definition these occur very rarely and models cannot be adequately calibrated and tested. Table 18-3 lists some notable extremes over the past decade, and the impacts on cropping systems. Despite the difficulty of modeling the impacts of these events, they clearly have sizable impacts (Sanchez et al. 2014) that are apparent immediately or soon after the event, and therefore not easily confused with effects of more slowly moving factors. For a subset of these events, climate research has evaluated whether anthropogenic activity has increased or decreased their likelihood (Table 18-3).

A sizable fraction of crop modeling studies were concerned with production for individual sites or provinces, spatial scales below which

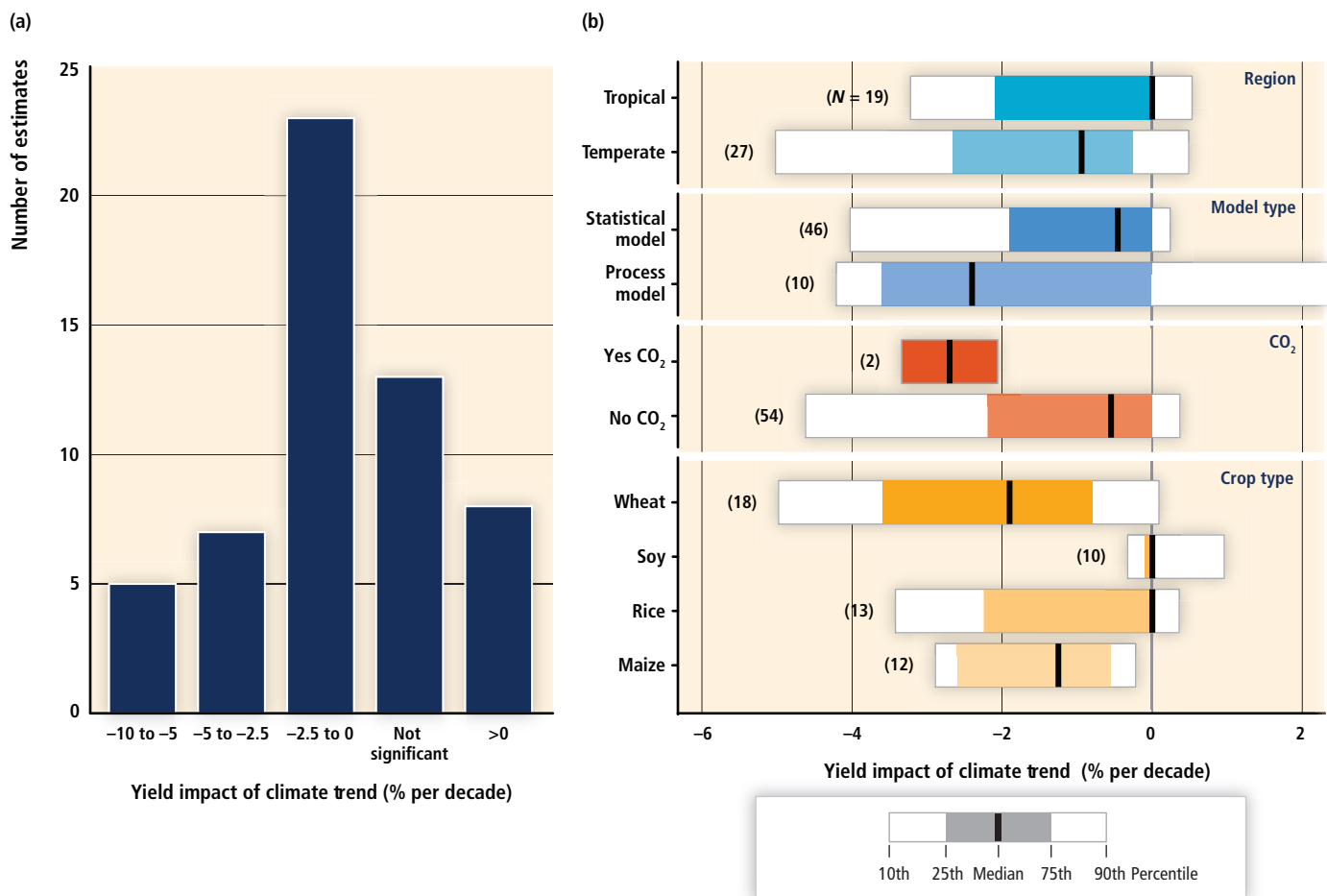


Figure 7-2 | Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive carbon dioxide (CO₂) trends (Section 7.3.2.1.2) but most did not. (a) Number of estimates with different level of impact (% yield per decade). (b) Boxplot of estimates separated by temperate vs. tropical regions, modeling approach (process-based vs. statistical), whether CO₂ effects were included, and crop. Boxplots indicate the median (vertical line), 25th to 75th percentiles (colored box), and 10th to 90th percentiles (white box) for estimated impacts in each category, and numbers in parentheses indicate the number of estimates. Studies were for China (Tao et al., 2006, 2008a, 2012; Wang et al., 2008; You et al., 2009; Chen et al., 2010), India (Pathak et al., 2003; Auffhammer et al., 2012), USA (Kucharik and Serbin, 2008), Mexico (Lobell et al., 2005), France (Brisson et al., 2010; Licker et al., 2013), Scotland (Gregory and Marshall, 2012), Australia (Ludwig et al., 2009), Russia (Licker et al., 2013), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch et al., 2010; Lobell et al., 2011a). Values from all studies were converted to percentage yield change per decade. Each study received equal weighting as insufficient information was available to judge the uncertainties of each estimate.

the changes in climate conditions are attributable to anthropogenic activity (WGI AR5 Chapter 10). Similarly, most crop studies have focused on the past few decades, a time scale shorter than most attribution studies for climate. However, some focused on continental or global scales (Lobell and Field, 2007; You et al., 2009; Lobell et al., 2011a), at which trends in several climatic variables, including average summer temperatures, have been attributed to anthropogenic activity. In particular, global temperature trends over the past few decades are attributable to human activity (WGI AR5 Chapter 10), and the studies discussed above indicate that this warming has had significant impacts on global yield trends of some crops.

In general, little work in food production or food security research has focused on determining whether climate trends affecting agriculture can be attributed to anthropogenic influence on the climate system. However, as the field of climate detection and attribution proceeds to finer spatial and temporal scales, and as agricultural modeling studies

expand to broader scales, there should be many opportunities to link climate and crop studies in the next few years. Importantly, climate attribution is increasingly documented not only for measures of average conditions over growing seasons, but also for extremes. For instance, Min et al. (2011) attributed changes in rainfall extremes for 1951–1999 to anthropogenic activity, and these are widely acknowledged as important to cropping systems (Rosenzweig et al., 2002). Frost damage is an important constraint on crop growth in many crops, including for various high-value crops, and significant reductions in frost occurrence since 1961 have been observed and attributed to greenhouse gas (GHG) emissions in nearly every region of the world (Zwiers et al., 2011; IPCC, 2012).

Increased frequency of unusually hot nights since 1961 are also attributable to human activity in most regions (WGI AR5 Chapter 10). These events are damaging to most crops, an effect that has been observed most commonly for rice yields (Peng et al., 2004; Wassmann

et al., 2009; Welch et al., 2010) as well as rice quality (Okada et al., 2011). Extremely high daytime temperatures are also damaging and occasionally lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009), and trends at the global scale in annual maximum daytime temperatures since 1961 have been attributed to GHG emissions (Zwiers et al., 2011). At regional and local scales, however, trends in daytime maximum are harder to attribute to GHG emissions because of the prominent role of soil moisture and clouds in driving these trends (Christidis et al., 2005; Zwiers et al., 2011).

In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition on crops. Increase of atmospheric CO₂ by greater than 100 ppm since preindustrial times has *virtually certainly* enhanced water use efficiency and yields, especially for C₃ crops such as wheat and rice, although these benefits played a minor role in driving overall yield trends (Amthor, 2001; McGrath and Lobell, 2011).

Emissions of CO₂ often are accompanied by ozone (O₃) precursors that have driven a rise in tropospheric O₃ that harms crop yields (Morgan et al., 2006; Mills et al., 2007; Section 7.3.2.1.2). Elevated O₃ since preindustrial times has *very likely* suppressed global production of major crops compared to what they would have been without O₃ increases, with estimated losses of roughly 10% for wheat and soybean and 3 to 5% for maize and rice (Van Dingenen et al., 2009). Impacts are most severe over India and China (Van Dingenen et al., 2009; Avnery et al. 2011a,b), but are also evident for soybean and maize in the USA (Fishman et al., 2010).

7.2.1.2. Fisheries Production

The global average consumption of fish and other products from fisheries and aquaculture in 2010 was 18.6 kg per person per year, derived from a total production of 148.5 million tonnes, of which 86% was used for direct human consumption. The total production arose from contributions of 77.4 and 11.2 million tonnes respectively from marine and inland capture fisheries, and 18.1 and 41.7 million tonnes respectively from marine and freshwater aquaculture (FAO, 2012). Fisheries make particular contributions to food security and more than 90% of the people engaged in the sector are employed in small-scale fisheries, many of whom are found in the poorer countries of the world (Cochrane et al., 2011). The detection and attribution of impacts are as confounded in inland and marine fisheries as in terrestrial food production systems. Overfishing, habitat modification, pollution, and interannual to decadal climate variability can all have impacts that are difficult to separate from those directly attributable to climate change.

One of the best studied areas is the Northeast Atlantic, where the temperature has increased rapidly in recent decades, associated with a poleward shift in distribution of fish (Perry et al., 2005; Brander, 2007; Cheung et al., 2010, 2013). There is *high confidence* in observations of increasing abundance of fish species in the northern extent of their ranges while decreases in abundance have occurred in the southern part (Section 30.5.1.1.1). These trends will have mixed implications for fisheries and aquaculture with some commercial species negatively and others positively affected (Cook and Heath, 2005). There is a similar

well-documented example in the oceans off southeast Australia with large warming trends associated with more southward incursion of the Eastern Australian Current, resulting in southward migration of marine species into the oceans around eastern Tasmania (*robust evidence, high agreement*; Last et al., 2011).

As a further example, coral reef ecosystems provide food and other resources to more than 500 million people and with an annual value of US\$5 billion or more (Munday et al., 2008; Hoegh-Guldberg, 2011). More than 60% of coral reefs are considered to be under immediate threat of damage from a range of local threats, of which overfishing is the most serious (Burke et al., 2011; see also Box CC-CR) and the percentage under threat rises to approximately 75% when the effect of rising ocean temperatures is added to these local impacts (Burke et al., 2011). Wilson et al. (2006) demonstrated that declines in coral reef cover typically led to declines in abundance of the majority of fish species associated with coral reefs. There is *high confidence* that the availability of fish and invertebrate species associated with coral reefs that are important in many tropical coastal fisheries is *very likely* to be reduced (Section 30.6.2.1.2). Other examples around the world are described in Section 30.5.1.1.1.

These changes are impacting marine fisheries: a recent study that examined the composition of global fisheries catches according to the inferred temperature preferences of the species caught in fisheries found that there had been changes in the species composition of marine capture fisheries catches and that these were significantly related to changes in ocean temperatures (Cheung et al. 2013; Section 6.4.1.1). These authors noted that the relative contribution to catches by warmer water species had increased at higher latitudes while the contributions of subtropical species had decreased in the tropics. These changes have negative implications for coastal fisheries in tropical developing countries, which tend to be particularly vulnerable to climate change (Cheung et al., 2013; Sections 6.4.3, 7.5.1.1.2).

There is considerably less information available on climate change impacts on fisheries and fishery resources in freshwater systems and aquaculture. Considerable attention has been given to the impacts of climate change in some African lakes but with mixed interpretations (Section 22.3.3.1.4). There is evidence that increasing temperature has reduced the primary productivity of Lake Tanganyika in East Africa and a study by O'Reilly et al. (2003) estimated that this would have led to a decrease of approximately 30% in fish yields. However, Sarvala et al. (2006) disagreed and concluded that observed decreases in the fish catches could be explained by changed fishery practices. There has been a similar difference of opinion for Lake Kariba, where Ndebele-Murisa et al. (2011) argued that a reduction in fisheries productivity had been caused by climate change while Marshall (2012) argued that the declines in fish catches can only have been caused by fishing. There is *medium confidence* that, in India, changes in a number of climate variables including an increase in air temperature, regional monsoon variation, and a regional increase in incidence of severe storms have led to changes in species composition in the River Ganga and to have reduced the availability of fish spawn for aquaculture in the river Ganga while having positive impacts on aquaculture on the plains through bringing forward and extending the breeding period of the majors carps (Vass et al., 2009).

Frequently Asked Questions

FAQ 7.1 | What factors determine food security and does low food production necessarily lead to food insecurity?

Observed data and many studies indicate that a warming climate has a negative effect on crop production and generally reduces yields of staple cereals such as wheat, rice, and maize, which, however, differ between regions and latitudes. Elevated CO₂ could benefit crops yields in the short term by increasing photosynthesis rates; however, there is big uncertainty in the magnitude of the CO₂ effect and the significance of interactions with other factors. Climate change will affect fisheries and aquaculture through gradual warming, ocean acidification, and changes in the frequency, intensity, and location of extreme events. Other aspects of the food chain are also sensitive to climate but such impacts are much less well known. Climate-related disasters are among the main drivers of food insecurity, both in the aftermath of a disaster and in the long run. Drought is a major driver of food insecurity, and contributes to a negative impact on nutrition. Floods and tropical storms also affect food security by destroying livelihood assets. The relationship between climate change and food production depends to a large degree on when and which adaptation actions are taken. Other links in the food chain from production to consumption are sensitive to climate but such impacts are much less well known.

7.2.1.3. Livestock Production

In comparison to crop and fish production, considerably less work has been published on observed impacts for other food production systems, such as livestock or aquaculture, and to our knowledge nothing has been published for hunting or collection of wild foods other than for capture fisheries. The relative lack of evidence reflects a lack of study in this topic, but not necessarily a lack of real-world impacts of observed climate trends. A study of blue-tongue virus, an important ruminant disease, evaluated the effects of past and future climate trends on transmission risk, and concluded that climate changes have facilitated the recent and rapid spread of the virus into Europe (Guis et al., 2012). Ticks that carry zoonotic diseases have also *likely* changed distribution as a consequence of past climate trends (Section 23.4.2).

7.2.2. Food Security and Food Prices

Food production is an important aspect of food security (Section 7.1), and the evidence that climate change has affected food production implies some effect on food security. Yet quantifying this effect is an extremely difficult task, requiring assumptions about the many non-climate factors that interact with climate to determine food security. There is thus limited direct evidence that unambiguously links climate change to impacts on food security.

One important aspect of food security is the prices of internationally traded food commodities (Section 7.1.3). These prices reflect the overall balance of supply and demand, and the accessibility of food for consumers integrated with regional to global markets. Although food prices gradually declined for most of the 20th century (FAO, 2009b) since AR4 there have been several periods of rapid increases in international food prices (Figure 7-3). A major factor in recent price changes has been increased crop demand, notably via increased use in biofuel production related both to energy policy mandates and oil price fluctuations (Roberts and Schlenker, 2010; Mueller et al., 2011; Wright, 2011). Yet

fluctuations and trends in food production are also widely believed to have played a role in recent price changes, with recent price spikes often following climate extremes in major producers (Figure 7-3). Moreover, some of these extreme events have become more likely as a result of climate trends (Table 18-3). Domestic policy reactions can also amplify international price responses to weather events, as was the case with export bans announced by several countries since 2007 (FAO, 2008). In a study of global production responses to climate trends (Lobell et al., 2011a) estimated a price increase of 19% due to the impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of increased CO₂ over the study period were considered. Because the price models were developed for a period ending in 2003, these estimates do not account for the policy responses witnessed in recent years which have amplified the price responses to weather.

7.3. Assessing Impacts, Vulnerabilities, and Risks**7.3.1. Methods and Associated Uncertainties****7.3.1.1. Assessing Impacts**

Methods developed or extended since AR4 have resulted in more robust statements on climate impacts, both in the literature and in Section 7.3.2. Two particular areas, which are explored below, are improved quantification and presentation of uncertainty; and greater use of historical empirical evidence of the relationship between climate and food production.

The methods used for field and controlled environment experiments remain similar to those at the time of AR4. There has been a greater use of remote sensing and geographic information systems for assessing temporal and spatial changes in land use, particularly in agricultural land use for assessment of food security status (Thenkabail et al., 2009;

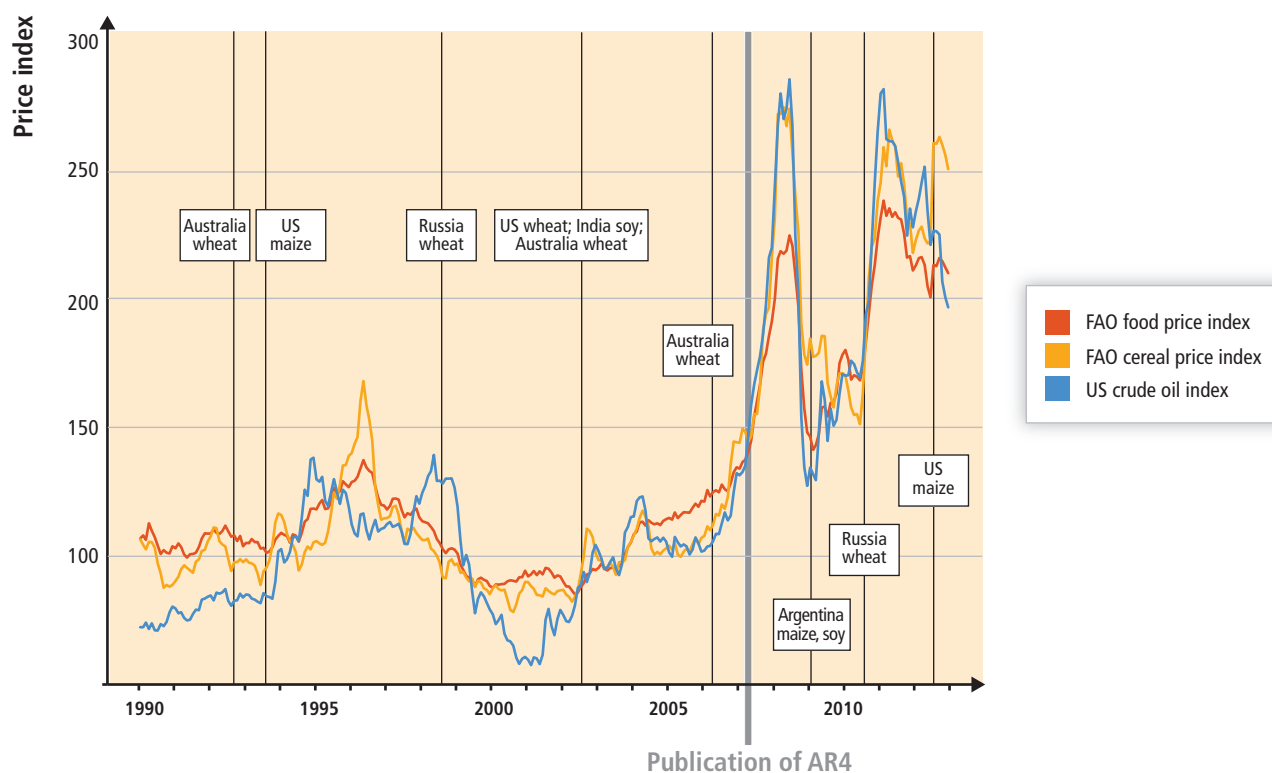


Figure 7-3 | Since the AR4, international food prices have reversed historical downward trend. The plot shows the history of FAO food and cereal price indices (composite measures of food prices), with vertical lines indicating events when a top five producer of a crop had yields 25% below trend line (indicative of a seasonal climate extreme). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years. At the same time, food prices are increasingly associated with the price of crude oil (blue line), making attribution of price changes to climate difficult. Thus, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002–2004 averages. Food price and crop yield data from FAO (<http://www.fao.org/worldfoodsituation/foodpricesindex> and <http://faostat.fao.org/>) and oil price data from <http://www.eia.gov>.

Fishman et al., 2010; Goswami et al., 2012). There has also been an increase in the number of Free Air Concentration Enrichment (FACE) studies that examine O_3 instead of, or in addition to, CO_2 . In agriculture, FACE experiments have been used for assessing impacts of atmospheric CO_2 on grain yield, quality characteristics of important crops (Erbs et al., 2010), elemental composition (Fernando et al., 2012), and diseases (Chakraborty et al., 2011; Eastburn et al., 2011). A number of meta-analyses of experimental studies, in particular FACE studies, have been made since AR4. However, debate continues on the disparities between results from FACE experiments and non-FACE experiments, such as in open-top chambers or greenhouses. As reported in AR4, FACE studies tend to show lower elevated CO_2 responses than non-FACE studies. Although some authors have claimed that the results of the two are statistically indistinct, others have argued that the results are similar only when the FACE experiments are grown under considerably more water stress than non-FACE experiments (Ainsworth et al., 2008; Kimball, 2010). Hence comparisons between different methodologies must take care to control for differences in water availability and microclimate. Another reason for differences between experiments may be differences in the temporal variance of CO_2 , that is, whether concentrations are fluctuating or constant (Bunce, 2012). Unfortunately, the FACE experiments are carried out mostly in the USA and in China, and thus limited to specific environmental conditions, which do not fully reflect tropical or subtropical conditions, where CO_2 and soil nutrient interactions could lead to large differences in photosynthesis rate, water use, and yield.

Also, the number of FACE studies is still quite low, which limits statistical power when evaluating the average yield effects of elevated CO_2 or interactions with temperature and moisture (Section 7.3.2).

Numerical simulation models can be used to investigate a larger number of possible environmental and management conditions than possible via physical experiments. This, in turn, enables a broader range of statements regarding the possible response of food production systems to climate variability and change. Previous assessment reports have documented new knowledge resulting from numerical simulation of the response of food production to climate change. AR4 noted the increasing number of regional studies, which is a trend that has continued to date (Craufurd et al., 2013; Zhu et al., 2013). Since AR4, crop models have been used to examine a large number of management and environmental conditions, such as interactions among various components of food production systems (Lenz-Wiedemann et al., 2010), determination of optimum crop management practices (Soltani and Hoogenboom, 2007), vulnerability and adaptability assessments (Sultana et al., 2009), evaluation of water consumption and water use efficiency (Kang et al., 2009; Mo et al., 2009), and fostering communication among scientists, managers, policymakers, and planners.

The trend toward quantification of uncertainty in both climate and its impacts has continued since AR4. Novel developments include methodologies to assess the impact of climate model error on projected

agricultural output, particularly for crops (Ramirez-Villegas et al., 2013, Watson and Challinor, 2013). Models that integrate crop growth models as part of broader land surface and earth systems models (Bondeau et al., 2007; Osborne et al., 2007) are also increasingly common. Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Bayesian methods to constrain crop model parameters (Tao et al., 2008b, 2009a; Iizumi et al., 2009). It is also increasingly common to assess both biophysical and socioeconomic drivers of crop productivity within the same study (Fraser et al., 2008; Reidsma et al., 2009; Challinor et al., 2010; Tao et al., 2011b). Finally, an important recent development is the systematic comparison of results from different modeling and experimental approaches for providing insights into model uncertainties as well as to develop risk management (Challinor and Wheeler, 2008; Kang et al., 2009; Schlenker and Lobell, 2010; Rosenzweig et al., 2013, 2014).

Increased quantification of uncertainty can lead to clear statements regarding climate impacts. Studies with different methods have been shown to produce convergent results for some crops and locations (Challinor et al., 2009; *medium evidence, medium agreement*). The methods used to describe uncertainty have also improved since AR4. The projected range of global and local temperature changes can be described by quantifying uncertainty in the temporal dimension, rather than that in temperature itself (Joshi et al., 2011), and a similar approach can be used for crop yield (Figure 7-5). Descriptions of uncertainty that present key processes and trade-offs, rather than ranges of outcome variables, have also proved to be useful tools for understanding future impacts (Thornton et al., 2009a; Hawkins et al., 2012; Ruane et al., 2013). Section 7.3.2 reviews the results of such studies.

A considerable body of work since AR4 has used extensive data sets of country-, regional-, and farm-level crop yield together with observed and/or simulated weather time series to assess the sensitivity of food production to weather and climate (Tao et al., 2009a, 2011). Statistical models offer a complement to more process-based model approaches, some of which require many assumptions about soil and management practices. Process-based models, which extrapolate based on measured interactions and mechanisms, can be used to develop a causal understanding of the empirically determined relationships in statistical models (cf. Schlenker and Roberts, 2009; Lobell et al., 2013a). Although statistical models forfeit some of the process knowledge embedded in other approaches, they can often reproduce the behavior of other models (Iglesias et al., 2000; Lobell and Burke, 2010) and can leverage within one study a growing availability of crop and weather data (Welch et al., 2010; Lobell et al., 2011b). However, statistical models usually exclude the direct impact of elevated CO₂, making multi-decadal prediction problematic. In determining future trends, crop models of all types can extrapolate only based on historically determined relationships. Agro-climatic indices provide an alternative to crop models that avoid various assumptions by developing metrics, rather than providing yield predictions per se (Trnka et al., 2011). However, correlations between climate or associated indices and yield are not always statistically significant.

The robustness of crop model results depends on data quality, model skill prediction, and model complexity (Bellocchi et al., 2010). Modeling and experiments are each subject to their own uncertainties. Measurement

uncertainty is a feature of field and controlled environment experiments. For example, interactions among CO₂ fertilization, temperature, soil nutrients, O₃, pests, and weeds are not well understood (Soussana et al., 2010) and therefore most crop models do not include all of these effects, or broader issues of water availability, such as competition for water between industry and households (Piao et al., 2010). There are also uncertainties associated with generalizing the results of field experiments, as each one has been conducted relatively few times under a relatively small range of environmental and management conditions, and for a limited number of genotypes. This limits breadth of applicability both through limited sample size and limited representation of the diversity of genotypic responses to environment (Craufurd et al., 2013). For example, yield increases normalized by increase in CO₂ have been found to vary between zero and more than 30% among crop varieties (Tausz et al., 2011).

Uncertainty in climate simulation is generally larger than, or sometimes comparable to, the uncertainty in crop simulation using a single crop model (Iizumi et al., 2011), although temperature-driven processes in crop models have been shown to dominate the causes of uncertainty (Koehler et al., 2013). There is significant uncertainty in agricultural simulation arising from climate model error. Since AR4 the choice of method for General Circulation Model (GCM) bias correction has been identified as a significant source of uncertainty (Hawkins et al., 2012). There is also a contribution to uncertainty in crop model output from yield measurement error, through the calibration procedure. Yield measurements rarely have associated error bars to give an indication of accuracy. Greater access to accurate regional-scale crop yield data can lead to decreased uncertainty in projected yields (Watson and Challinor, 2013).

The use of multiple crop models in impacts studies is relatively rare. Field-scale historical model intercomparisons have shown variations in the simulation of mean yield and above-ground biomass of more than 60% (Palosuo et al., 2011). Early results from impacts studies with multiple crop models suggest that the crop model uncertainty can be larger than that caused by GCMs, due in particular to high temperature and temperature-by-CO₂ interactions (Asseng et al., 2013). However, in contrast to absolute values, yield changes can be consistent across crop models (Olesen et al., 2007). Given these different strengths and weaknesses, and associated dependencies, it is critical that both experimental and modeling lines of evidence, and their uncertainties, are examined carefully when drawing conclusions regarding impacts, vulnerabilities, and risks. This approach to assessment is applied to each of the topics described in the rest of the chapter.

The methods used for assessing impacts, vulnerabilities, and risks in fisheries and aquaculture face the constraint that meaningful controlled experiments are usually not practical for fisheries in large rivers, lakes, and marine environments because of the typical open and connected nature of these ecosystems. Experimentation has been used to examine responses to impacts at the scale of individual species, for example, to demonstrate the impacts of high atmospheric CO₂ in reducing coral calcification and growth (Hoegh-Guldberg et al., 2007) and to study the temperature tolerances of different cultured species (Ficke et al., 2007; De Silva and Soto, 2009). The far more common approach, however, is the empirical analysis of data collected in the field. This has been used

to examine the effect of climate-related factors on recruitment to a population, growth, and population production of specific species, for example (Brander, 2010; see also Chapters 6 and 30). Different modeling approaches have also been used to integrate available information and assess the impacts of climate change on ecosystems and fish production at scales from national to global (Cheung et al., 2010; Fulton, 2011; Merino et al., 2012; see also Section 6.5). Efforts to assess the vulnerability of those dependent on fisheries and aquaculture have increased in recent years and range from studies that use available information on exposure, sensitivity, and adaptive capacity to provide an index of vulnerability (Allison et al., 2009; Cinner et al., 2012) to more detailed social and economic studies focused on particular communities or localities (Daw et al., 2009).

7.3.1.2. Treatment of Adaptation in Impacts Studies

Adaptation occurs on a range of time scales and by a range of actors. Incremental adaptation, such as a change in crop management, can occur relatively autonomously within farming systems. It is the type of adaptation most commonly assessed in the impacts literature, and it is the only form of adaptation discussed in Sections 7.3 and 7.4. Systemic and transformational adaptations are discussed in Section 7.5. Methods exist to examine impacts and adaptation together in the context of non-climatic drivers (Mandryk et al., 2012), but conclusions are difficult to generalize.

7.3.2. Sensitivity of Food Production to Weather and Climate

7.3.2.1. Cereals and Oilseeds

7.3.2.1.1. Mean and extremes of temperature and precipitation

Both statistical and process-based models have been used widely since AR4 to assess the response of crop yield to temperature. Model results confirm the importance of known key physiological processes, such as the shortening of the time to maturity of a crop with increasing mean temperature (Iqbal et al., 2009), decline in grain set when high temperatures occur during flowering (Moriondo et al., 2011), and increased water stress at high temperatures throughout the growing cycle (Lobell et al., 2013a). Temperature responses are generally well understood for temperatures up to the optimum temperature for crop development. The impacts of prolonged periods of temperatures beyond the optimum for development are not as well understood (Craufurd and Wheeler, 2009). For example, temperatures above 32–34°C after flowering appear to speed senescence rapidly in wheat (Asseng et al., 2011; Lobell et al., 2012), but many crop models do not represent this process (Sanchez et al., 2014). Crop models can be used to quantify abiotic stresses such as these, although only by hypothesizing that the functional responses to weather derived from experiments are valid at regional scales. Thus, although many fundamental biophysical processes are understood at the plant or field scale, it remains difficult to quantify the extent to which these mechanisms are responsible for the observed regional-scale relationships between crop yield and weather. Despite these particular areas where specific understanding is lacking, the evidence from regional-

scale statistical analyses (Schlenker and Roberts, 2009) and process-based models shows clear negative impacts of temperatures above 30°C to 34°C on crop yields (depending on the crop and region) (*high evidence, high agreement*).

The overall relationship between weather and yields is often crop and region specific, depending on differences in baseline climate, management and soil, and the duration and timing of crop exposure to various conditions. For example, rice yields in China have been found to be positively correlated with temperature in some regions and negatively correlated in others (Zhang et al., 2008, 2010). The trade-offs that occur in determining yield are therefore region-specific. This difference may be due to positive correlation between temperature and solar radiation in the former case, and negative correlation between temperature and water stress in the latter case. Similarly, although studies consistently show spikelet sterility in rice for daytime temperatures exceeding 33°C (Jadadish et al., 2007; Wassmann et al., 2009), some statistical studies find a positive effect of daytime warming on yields because these extremes are not reached frequently enough to affect yields (Welch et al., 2010). Responses to temperature may vary according whether yields are limited by low or high temperatures. However, there is evidence that high temperatures will limit future yields even in cool environments (Semenov et al., 2012; Teixeira et al., 2013).

The relative importance of temperature and water stress for crop productivity can be assessed using models, and can vary according to the criteria used for assessment (Challinor et al., 2010). There are also some cases where the sign of a correlation depends on the direction of the change. For example, Thornton et al. (2009b) found that the response of crop yields to climate change in the drylands of East Africa is insensitive to increases in rainfall, as wetter climates are associated with warmer temperatures that act to reduce yields. Because precipitation exhibits more spatial variability than temperature, temporal variations in the spatial average of precipitation tend to diminish as the spatial domain widens. As a result, precipitation becomes less important as a predictor of crop yields at broad scales (Lobell and Field, 2007; Li et al., 2010). Similarly, projected changes in precipitation from climate models tend to be more spatially variable than temperature, leading to the greater importance of projected temperatures as the spatial scale of analysis grows wider (Lobell and Burke, 2008). There is also evidence that where irrigation increases over time the influence of temperature on yields starts to dominate over that of precipitation (Hawkins et al., 2012). The impact of drought on crop yield is a more common topic of research than the impact of floods.

Analysis of 66 yield impact studies for major cereals, including both pre- and post-AR4 contributions, gives broadly similar results to AR4 (Figure 7-4). Figure 7-4 shows that yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics. Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with warming of 3°C to 5°C. These data confirm AR4 findings that even slight warming will decrease yields in low-latitude regions (*medium evidence, high agreement*). However, although AR4 had few indications of yield reductions at less than 2°C of local warming, the new analysis has, in the absence of incremental adaptation, more yield decreases than increases at all temperatures. Hence, although AR4 concluded with *medium confidence* that in mid- to high-latitude

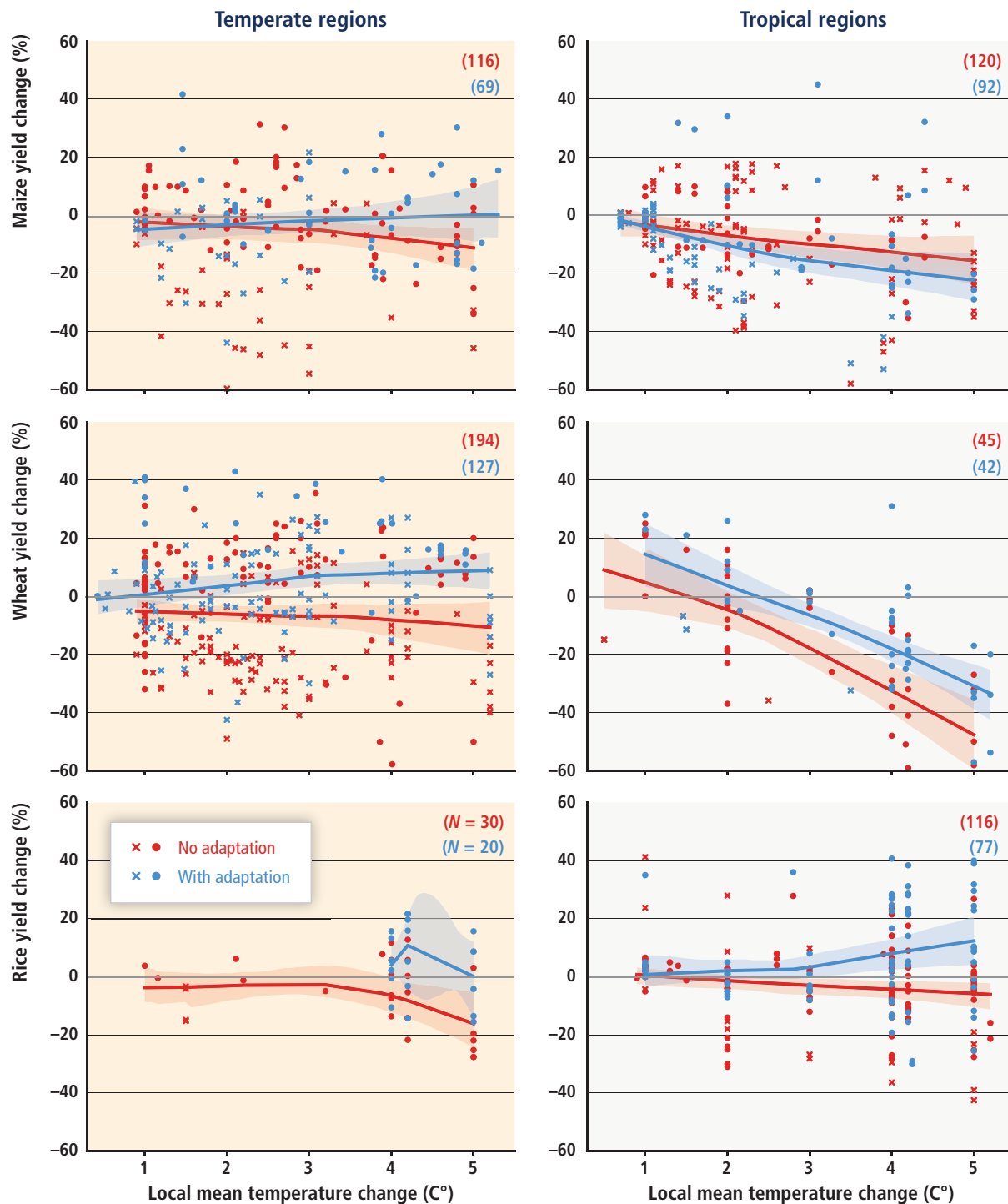


Figure 7-4 | Percentage simulated yield change as a function of local temperature change for the three major crops and for temperate and tropical regions. Dots indicate where a known change in atmospheric CO_2 was used in the study; remaining data are indicated by x. Note that differences in yield value between these symbols do not measure the CO_2 fertilization effect, as changes in other factors such as precipitation may be different between studies. Non-parametric regressions (LOESS, span = 1 and degree = 1) of subsets of these data were made 500 times. These bootstrap samples are indicated by shaded bands at the 95% confidence interval. Regressions are separated according to the presence (blue) or absence (red) of simple agronomic adaptation (Table 7-2). In the case of tropical maize, the central regression for absence of adaptation is slightly higher than that with adaptation. This is due to asymmetry in the data—not all studies compare adapted and non-adapted crops. Figure 7-8 presents a pairwise adaptation comparison. Note that four of the 1048 data points across all six panels are outside the yield change range shown. These were omitted for clarity. Some of the studies have associated temporal baselines, with center points typically between 1970 and 2005. Note that local warming in cropping regions generally exceeds global mean warming (Figure 21-4). Data are taken from a review of literature: Rosenzweig and Parry, 1994; Karim et al., 1996; El-Shaher et al., 1997; Kapetanaki and Rosenzweig, 1997; Lal et al., 1998; Moya et al., 1998; Winters et al., 1998; Yates and Strzepek, 1998; Alexandrov, 1999; Kaiser, 1999; Reyenga et al., 1999; Alexandrov and Hoogenboom, 2000; Southworth et al., 2000; Tubiello et al., 2000; DeJong et al., 2001; Izaurrealde et al., 2001; Aggarwal and Mall, 2002; Abou-Hadid, 2006; Alexandrov et al., 2002; Corobov, 2002; Chipanshi et al., 2003; Easterling et al., 2003; Jones and Thornton, 2003; Luo et al., 2003; Matthews and Wassmann, 2003; Droogers, 2004; Howden and Jones, 2004; Butt et al., 2005; Erda et al., 2005; Ewert et al., 2005; Gbetibouo and Hassan, 2005; Izaurrealde et al., 2005; Porter and Semenov, 2005; Sands and Edmonds, 2005; Thomson et al., 2005; Xiao et al., 2005; Zhang and Liu, 2005; Zhao et al., 2005; Abraha and Savage, 2006; Brassard and Singh, 2007, 2008; Krishnan et al., 2007; Lobell and Ortiz-Monasterio, 2007; Xiong et al., 2007; Tingem et al., 2008; Walker and Schulze, 2008; El Maayar et al., 2009; Schlenker and Roberts, 2009; Thornton et al., 2009a, 2010, 2011; Tingem and Rivington, 2009; Byjesh et al., 2010; Chhetri et al., 2010; Liu et al., 2010; Piao et al., 2010; Tan et al., 2010; Tao and Zhang, 2010, 2011a,b; Arndt et al., 2011; Deryng et al., 2011; Iqbal et al., 2011; Lal, 2011; Li et al., 2011; Rowhanji et al., 2011; Shuang-He et al., 2011; Osborne et al., 2013.

regions moderate warming will raise crop yields, new knowledge suggests that temperate wheat yield decreases are *about as likely as not* for moderate warming. A recent global crop model intercomparison for rice, wheat, and maize shows similar results to those presented here, although with less impacts on temperate rice yields (Rosenzweig et al., 2013, 2014). That study also showed that crop models without explicit nitrogen stress fail to capture the expected response.

Quantitative assessments of yield changes can be found in Section 7.4. Across the globe, regional variability, which has not been summarized in meta-analyses except in contributing to the spread of data (Figure 7-4), will be important in determining how climate change affects particular agricultural systems.

7.3.2.1.2. Impact of carbon dioxide and ozone

There is further observational evidence since AR4 that response to a change in CO₂ depends on plant type: C₃ or C₄ (DaMatta et al., 2010). The effect of increase in CO₂ concentration tends to be higher in C₃ plants (wheat, rice, cotton, soybean, sugar beets, and potatoes) than in C₄ plants (corn, sorghum, sugarcane), because photosynthesis rates in C₄ crops are less responsive to increases in ambient CO₂ (Leakey, 2009). The highest fertilization responses have been observed in tuber crops, which have large capacity to store extra carbohydrates in belowground organs (Fleisher et al., 2008; Högy and Fangmeier, 2009). There is observational evidence, new since AR4, that the response of crops to CO₂ is genotype specific (Ziska et al., 2012). For example, yield enhancement at 200 ppm additional CO₂ ranged from 3 to 36% among rice cultivars (Hasegawa et al., 2013).

FACE studies have shown that the impact of elevated CO₂ varies according to temperature and availability of water and nutrients, although the strong geographical bias of FACE studies toward temperate zones limits the strength of this evidence. FACE studies have shown that yield enhancement by elevated CO₂ is limited under both low (Shimono et al., 2008; Hasegawa et al., 2013) and high temperature. Theory suggests that water-stressed crops will respond more strongly to elevated CO₂ than well-watered crops, because of CO₂-induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from elevated CO₂ than irrigated systems.

Both the Third Assessment Report (TAR) and AR4 cited the expectation that rain-fed systems benefit more from elevated CO₂ than systems under wetter conditions. New evidence based on historical observations supports this notion by demonstrating that the rate of yield gains in rain-fed systems is higher in dry years than in wet years (McGrath and Lobell, 2011). However, this response is not seen consistently across models and FACE meta-analyses, and there is some suggestion that the relationship between water stress and assimilation may vary with spatial scale, with canopy analyses showing a reversal of the expected leaf-level dry versus wet signal (Challinor and Wheeler, 2008).

O₃ in the stratosphere provides protection from lethal short-wave solar ultraviolet radiation, but in the troposphere it is a phytotoxic air pollutant. The global background concentration of O₃ has increased since the preindustrial era due to anthropogenic emission of its precursors

(carbon monoxide, volatile organic compounds, and oxides of nitrogen), by vehicles, power plants, biomass burning, and other sources of combustion. Like CO₂, O₃ is taken up by green leaves through stomata during photosynthesis but, unlike CO₂, its concentration is significantly variable depending on geographic location, elevation, and extent of anthropogenic sources. Being a powerful oxidant, O₃ and its secondary by-products damage vegetation by reducing photosynthesis and other important physiological functions (Mills et al., 2009; Ainsworth and McGrath, 2010). This results in stunted crop plants, inferior crop quality, and decreased yields (Booker et al., 2009; Fuhrer, 2009; Vandermeiren et al., 2009; Pleijel and Uddling, 2012) and poses a growing threat to global food security (*robust evidence, high agreement*).

The literature published since AR4 further corroborates the negative impacts of increasing concentrations of surface O₃ on yield at global (Van Dingenen et al., 2009; Avnery et al., 2011a,b; Teixeira et al., 2011) and regional scales (Northern Hemisphere: Hollaway et al., 2011; USA: Emberson et al., 2009; Fuhrer, 2009; Fishman et al., 2010; India: Roy et al., 2009; Rai et al., 2010; Sarkar and Agrawal, 2010; China: Wang et al., 2007, 2011; Piao et al., 2010; Bangladesh: Akhtar et al., 2010; Europe: Hayes et al., 2007; Fuhrer, 2009; Vandermeiren et al., 2009). Global estimates of yield losses due to increased O₃ in soybean, wheat, and maize in 2000 ranged from 8.5 to 14%, 3.9 to 15%, and 2.2 to 5.5% respectively, amounting to economic losses of US\$11 to 18 billion (Avnery et al., 2011a). O₃ may have a direct effect on reproductive process, leading to reduced seed and fruit development and abortion of developing fruit (*robust evidence, high agreement*; Royal Society, 2008).

The interactive effects of O₃ with other environmental factors such as CO₂, temperature, moisture, and light, are important but not well understood. Generally, the ambient and increasing concentrations of O₃ and CO₂ individually exert counteractive effects on C₃ plants (Tianhong et al., 2005; Ainsworth et al., 2008; Gillespie et al., 2012), but their interactive effect may compensate for each other (Ainsworth et al., 2008; Taub et al., 2008; Gillespie et al., 2012). However, the losses might be greater when elevated O₃ combines with high temperature (Long, 2012) particularly during grain filling of wheat, when elevated O₃ causes premature leaf senescence (Feng et al., 2008b, 2011). Periods of abundant radiation and adequate water supply are favorable for both agricultural production and the formation of surface O₃; thus, the effects of O₃ on crops can be difficult to detect (Long, 2012).

7.3.2.2. Other Crops

Earlier flowering and maturity have been observed (*robust evidence, high agreement*) worldwide in grapes (Duchêne et al., 2010; García-Mozo et al., 2010; Jorquera-Fontena and Orrego-Verdugo, 2010; Sadras and Petrie, 2011; Webb et al., 2011), apples (Fujisawa and Koyabashi, 2010; Grab and Craparo, 2011), and other perennial horticultural crops (Glenn et al., 2013). Cassava (also known as manioc) is an important source of food for many people in Africa and Latin America and recent studies suggest (*medium evidence, medium agreement*) that future climate should benefit its productivity as this crop is characterized by elevated optimum temperature for photosynthesis and growth, and a positive response to CO₂ increases (El-Sharkawy, 2012; Jarvis et al., 2012; Rosenthal and Ort, 2012).

7.3.2.3. Pests, Weeds, Diseases

As a worldwide average, yield loss in major crop species due to animal pests and (non-virus) pathogens, in the absence of any physical, biological, or chemical crop protection, has been estimated at 18% and 16%, respectively (Oerke, 2006), but weeds produce the highest potential loss (34%). Climate change will alter potential losses to many pests and diseases. Changes in temperature can result in geographic shifts through changes in seasonal extremes, and thus, for example, overwintering and summer survival. CO₂ and O₃ can either increase or decrease plant disease, and can exhibit important interactions (Chakraborty and Newton, 2011; Garrett et al., 2011), suggesting the need for system-specific risk assessment (Chakraborty et al., 2008; Eastburn et al., 2011). Interactions with landscape effects may be particularly important in forests and grasslands (Pautasso et al., 2010).

The rarity of long-term studies of plant diseases and pests is a problem for the evaluation of climate change effects, but there are some examples of the potential for such analyses. Ongoing wheat experiments at Rothamsted Research Station UK, maintained for more than 160 years, have revealed shifts in foliar wheat pathogens linked to rainfall, temperature, and sulfur dioxide (SO₂) emissions (Bearchell et al., 2005; Shaw et al., 2008). Wheat rust risk has been observed to respond to El Niño-Southern Oscillation (ENSO; Scherm and Yang, 1995). Over almost 7 decades, earlier and more frequent epidemics of potato late blight, and more frequent pesticide use, were observed in Finland, associated with changing climate conditions and lack of crop rotation (Hannukkala et al., 2007).

Changes in climate are expected to affect the geographic range of specific species of insects and diseases for a given crop growing region. For example, Cannon (1998) has suggested that migratory insects could colonize crops over a larger range in response to temperature increases, with subsequent reductions in yield. Climate change may also be a factor in extending the northward migration of agronomic and invasive weeds in North America (Ziska et al., 2011). Weed species also possess characteristics that are associated with long-distance seed dispersal, and it has been suggested (Hellman et al., 2008) that they may migrate rapidly with increasing surface temperatures. Predator and insect herbivores respond differently to increasing temperature, leading to possible reductions in insect predation and thus greater insect numbers. However, ecosystems are complex and insect and disease occurrence can go down as well as up. Overall, our ability to predict CO₂/climate change impacts on pathogen biology and subsequent changes on yield is limited because, with few exceptions (Savary et al., 2011), experimental data are not available and analyses focus on individual diseases rather than the complete set of important diseases (*medium evidence, medium agreement*).

Elevated CO₂ can reduce yield losses due to weeds for C₃ crops (soybean, wheat, and rice), as many agricultural weeds are C₄ species; and the C₃ pathway, in general, shows a stronger response to rising CO₂ levels. However, both C₃ and C₄ weed species occur in agriculture, and there is a wide range of responses among these species to recent and projected CO₂ levels (Ziska, 2010). For example, in the USA, every crop, on average, competes with an assemblage of 8 to 10 weed species (Bridges, 1992). CO₂ and climate can also affect weed demographics. For example, with

field grown soybean, elevated CO₂ per se appeared to be a factor in increasing the relative proportion of C₃ to C₄ weedy species with subsequent reductions in soybean yields (Ziska and Goins, 2006). For rice and barnyard grass (C₄), increasing CO₂ favored rice, but if both temperature and CO₂ increased simultaneously, the C₄ weed was favored, primarily because higher temperatures resulted in increased seed yield loss for rice. For weeds that share physiological, morphological, or phenological traits with the crop, including those weeds that are wild relatives of the domesticated crop species (often among the “worst” weeds in agronomic situations, e.g., rice and red rice), the decrease in seed yield from weeds may be greater under elevated CO₂ (Ziska, 2010).

With respect to control, a number of studies have, to date, indicated a decline in herbicide efficacy in response to elevated CO₂ and/or temperature for some weed species, both C₃ and C₄ (Archambault, 2007; Manea et al., 2011). Some of the mechanisms for this are understood, for example, for the invasive plant species Canada thistle (*Cirsium arvense*), elevated CO₂ results in a greater root biomass, thus diluting the active ingredient of the herbicide used and reducing chemical control (Ziska, 2010). To date, studies on physical, cultural, or biological weed control are lacking.

7.3.2.4. Fisheries and Aquaculture

The natural and human processes in fisheries and aquaculture differ from mainstream agriculture and are particularly vulnerable to impacts and interactions related to climate change. Capture fisheries in particular, comprising the largest remaining example of harvesting natural, wild resources, are strongly influenced by global ecosystem processes. The social, economic, and nutritional requirements of the growing human population are already driving heavy exploitation of capture fisheries and rapid development of aquaculture (Section 6.4.1.1). This trend will continue over the next 20 to 30 years at least: Merino et al. (2012) forecast that in addition to a predicted small increase in marine fisheries production, between 71 and 117 million tonnes of fish will need to be produced by aquaculture to maintain current average per capita consumption of fish. The impacts of climate change add to and compound these threats to the sustainability of capture fisheries and aquaculture development (FAO, 2009a). Expected changes in the intensity, frequency, and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification, and changes in precipitation with associated changes in groundwater and river flows are expected to result in significant changes across a wide range of aquatic ecosystem types and regions with consequences for fisheries and aquaculture in many places (FAO, 2009a; see also Section 30.5.1.1). Ocean acidification will also have negative impacts on the culture of calcifying organisms (Section 30.6.2.1.4), including mollusc species of which 14.2 million tonnes were produced by aquaculture in 2010, equivalent to 23.6% of global aquaculture production (FAO, 2012). There are also concerns that climate change could lead to the spread of pathogens with impacts on wild and cultured aquatic resources (De Silva and Soto, 2009).

Given the proximity of fishing and aquaculture sites to oceans, seas, and riparian environments, extreme events can be expected to have impacts on fisheries and aquaculture with those located in low-lying

areas at particular risk. The consequences of sea level rise and the expected increased frequency and intensity of storms include increased risks of loss of homes and infrastructure, increased safety risks while fishing, and the loss of days at sea because of bad weather (Daw et al., 2009). In areas that experience water stress and competition for water resources, aquaculture operations and inland fisheries production will be at risk.

Food production from fisheries and aquaculture will be affected by the sensitivity of the caught and cultured species to climate change and both positive and negative outcomes can be expected. Changes in marine and freshwater mean temperatures, ocean acidification, hypoxia, and other climate-related changes will influence the distribution and productivity of fished and farmed aquatic species (Sections 6.4.3, 7.2.1.2, 30.6.2). Changes in temperature extremes are also likely to have impacts. Many aquatic species are routinely subjected to large daily and seasonal fluctuations in temperature and are able to cope with them: for example, temperatures in shallow coastal habitats in the tropical Pacific can vary by more than 14°C diurnally (Pratchett et al., 2011). Nevertheless, distribution and productivity of aquatic species and communities are sensitive to changes in temperature extremes. A study on salmon populations in Washington State, USA (Mantua et al., 2010), demonstrated important impacts of seasonal variations and extremes. The study concluded that warming in winter and spring would have some positive impacts while increased summertime stream temperatures, seasonal low flows, and changes in the peak and base flows would have negative impacts on the populations. Coral reefs are particularly susceptible to extremes in temperature: temperatures 1°C or 2°C in excess of normal maximums for 3 to 4 weeks are sufficient to disrupt the essential relationship between endosymbiotic dinoflagellates and their coral hosts, leading to coral bleaching. Large-scale bleaching of coral reefs has increased in recent decades both in intensity and frequency (Hoegh-Guldberg et al., 2007).

The impacts of climate change on the fisheries and aquaculture sector will have implications for the four dimensions of food security, that is, availability of aquatic foods, stability of supply, access to aquatic foods, and utilization of aquatic products (FAO, 2009a). Where climate-driven ecological changes are significant, countries and communities will need to adapt through, for example, changes in fishing and aquaculture practices and operations (Section 7.5.1.1.2).

7.3.2.5. Food and Fodder Quality and Human Health

Food quality is any characteristic other than yield that is valuable to the producer or consumer. Examples include wheat protein and starch concentrations, which affect dough quality; amylose content in rice, which affects taste; and mineral concentrations, which affects nutrient intake of consumers. Climate change will have some adverse impacts on food quality through both biotic and abiotic stresses (Ceccarelli et al., 2010). These changes may affect crop quality by altering carbon and nutrient uptake and biochemical processes that produce secondary compounds or redistribute and store compounds during grain development and maturation. This in turn could impact human and livestock health by altering nutritional intake and/or affect economic value by altering traits valuable to processors or the consumers.

Change in nitrogen concentration, a proxy for protein concentration, is the most examined quality trait and since AR4 studies have been extended to almost all the major food crops. Cereals grown in elevated CO₂ show a decrease in protein (Pikki et al., 2007; Högy et al., 2009; Erbs et al., 2010; Ainsworth and McGrath, 2010; DaMatta et al., 2010; Fernando et al., 2012). Meta-analysis of 228 experimental observations finds decreases between 10 and 14% in edible portions of wheat, rice, barley, and potato, but only 1.5% in soybeans, a nitrogen-fixing legume, when grown in elevated CO₂ (Taub et al., 2008).

Mineral concentration of edible plant tissues are affected by growth in elevated CO₂ in a similar manner to nitrogen. Although there are numerous studies measuring mineral concentration, there are relatively few measurements for any given mineral relevant to human health. Although there were several studies published before the release of AR4, this topic was not covered in any depth in AR4. Meta-analysis of studies prior to 2002 finds that phosphorus, calcium, sulfur, magnesium, iron, zinc, manganese, and copper decline by 2.5 to 20% in wheat grain and leaves of numerous species in elevated CO₂, but potassium increases insignificantly in wheat grain (Loladze, 2002; Högy et al., 2009; Fernando et al., 2012). Since 2002, studies generally find decreases in zinc, sulfur, phosphorus, magnesium, and iron in wheat and barley grain; increase in copper, molybdenum, and lead (from a limited number of studies); and mixed results for calcium and potassium (Högy et al., 2009; Erbs et al., 2010; Fernando et al., 2012). Changes in mineral concentration due to elevated CO₂ are determined by several factors including crop species, soil type, tissue (tubers, leaves, or grain) and water status.

Elevated CO₂ can lower the nutritional quality of flour produced from grain cereals (Högy et al., 2009; Erbs et al., 2010) and of cassava (Gleadow et al., 2009). When coupled with increased crop and pathogen biomass, elevated CO₂ can result in increased severity of the *Fusarium pseudograminearum* pathogen, leading to shriveled grains with low market value (Melloy et al., 2010).

Extreme temperatures and elevated CO₂ concentrations reduce milling quality of rice by increasing chalkiness, but can improve taste, through, for example, reduced amylase concentration (Yang et al., 2007). Cultivars vary in their susceptibility to these processes (Ambardekar et al., 2011; Lanning et al., 2011). Overall, there is *robust evidence* and *high agreement* that elevated CO₂ on its own likely results in decreased nitrogen concentrations. Combining knowledge of nitrogen and mineral studies, there is *medium evidence* and *medium agreement* that mineral concentrations will decline. The majority of these data are from wheat, with comparatively little information from key crops such as maize, rice, potato, and cassava; thus magnitudes are uncertain for these species.

Elevated O₃ concentrations appear to have the opposite effect as elevated CO₂. Meta-analysis of about 50 wheat experiments found that elevated O₃ increased grain protein concentration by decreasing yield (Pleijel and Uddling, 2012). For other species, studies find both increases and decreases of N and several minerals (Taub et al., 2008), and as such no firm conclusions can be drawn, but they mostly respond similarly. Likewise, experiments examining the effect of drought on mineral concentrations find both decreases and increases (Ghorbanian et al., 2011; Sun et al., 2011).

Confidence in the impact of climate, CO₂, and O₃ on food quality does not imply confidence in changes regarding human health for several reasons. Processing of food affects nutrient concentrations, when the nutrient-rich outer layers of rice are removed, leaving the starch dense endosperm. Also, elevated CO₂ can increase crop yield, thus increasing the overall yield of minerals (Duval et al., 2011) and permitting greater mineral consumption. Furthermore, since calorie intake is the primary concern in many food-insecure populations, even if intake of minerals is decreased, those negative effects could be outweighed by increased calorie intake. In assessing impacts on health, current diets must be considered. Decreased mineral intake will matter for those who currently do not meet, or just barely meet, requirements, but will not affect those who already exceed requirements. Little is known about combined effects of climate change factors on food quality or the economic and behavioral changes that will occur. Thus, there is little confidence regarding effects of climate change on human health through changes in nutrient composition.

7.3.2.6. Pastures and Livestock

Pastures response to climate change is complex because, in addition to the direct major atmospheric and climatic drivers (CO₂ concentration, temperature, and precipitation), there are important indirect interactions such as plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions. Projected increases in temperature and the lengthening of the growing season should extend forage production into late fall and early spring, thereby decreasing the need for accumulation of forage reserves during the winter season in USA (Izaurre et al., 2011). In addition, water availability may play a major role in the response of pasturelands to climate change although there are differences in species response (Izaurre et al., 2011). There is general consensus that increases in CO₂ will benefit C₃ species; however, warmer temperatures and drier conditions will tend to favor C₄ species (Hatfield et al., 2011; Izaurre et al., 2011; Chapter 4). While elevated atmospheric CO₂ concentrations reduce sensitivity to lower precipitation in grassland ecosystems and can reduce mortality and increase recovery during severe water stress events, it is still unclear how general this result is (Soussana et al., 2010).

Temperature is an important limiting factor for livestock. As productivity increases, be it increasing milk yield in dairy cattle or higher growth rates and leanness in pigs or poultry, so metabolic heat production increases and the capacity to tolerate elevated temperatures decreases (Zumbach et al., 2008; Dikmen and Hansen, 2009). Over the long term, single-trait selection for productivity will tend to result in animals with lower heat tolerance (Hoffmann, 2010). Recent work adds to previous understanding (WGII AR4 Chapter 5) and indicates that heat stress (*medium evidence, high agreement*) in dairy cows can be responsible for the increase in mortality and economic losses (Vitali et al., 2009); it affects a wide range of parameters in broilers (Feng et al., 2008a); it impairs embryonic development and reproductive efficiency in pigs (Barati et al., 2008); and affects ovarian follicle development and ovulation in horses (Mortensen et al., 2009). Water stress also limits livestock systems. Climate change will affect the water resources available for livestock via impacts on runoff and groundwater (Chapter 3). Populated river basins may experience changes in river discharge, and large human and

livestock populations may experience water stress such that proactive or reactive management interventions will almost certainly be required (Palmer et al., 2008). Problems of water supply for increasing livestock populations will be exacerbated by climate change in many places in sub-Saharan Africa and South Asia.

7.3.3. Sensitivity of Food Security to Weather and Climate

7.3.3.1. Non-Production Food Security Elements

As indicated in the discussion in Section 7.1.1 and Figure 7-1, food security is dependent on access and consumption patterns, food utilization and nutrition, and overall stability of the system as much as food production and availability. The overall impact of climate change on food security is considerably more complex and potentially greater than projected impacts on agricultural productivity alone. Figure 7-1 indicates the main components of food security and their key elements. All of these will be affected by climate change to some extent. For example, climate change effects on water, sanitation, and energy availability have major implications for food access and utilization as well as availability. Likewise, changes in the frequency and severity of climate extremes can affect stability of food availability and prices, with consequent impacts on access to food.

7.3.3.2. Accessibility, Utilization, and Stability

7.3.3.2.1. Climate change impacts on access

As noted in the discussion in Section 7.1.3, change in the levels and volatility of food prices is a key determinant of food access. Given the hypothesis that climate change will be a contributing factor to food price increases, and hence its affordability, the vulnerability of households to reduced food access depends on their channel of food access (*medium evidence, medium agreement*). Table 7-1 divides households into five main categories of food access, indicating their relative impacts of food price increases.

Concern about the impact of increased food prices on poverty and food security arises due to the high share of income that poor consumers spend on food, thus generating a disproportionately negative effect of price increases on this group (FAO, 2011). A study by the World Bank estimated a net increase of 44 million people in extreme poverty in low- and middle-income countries as a result of food price increases since June 2010 (Ivanic et al., 2011).

The distribution of net food buyers and net food sellers varies considerably across countries and can be expected to change with the process of economic development (Zezza et al., 2008; Aksoy et al., 2010; FAO, 2011). Changing consumption patterns associated with dietary transitions that accompany income growth, urbanization, market development, and trade liberalization determine the rate and nature of food demand growth and nutritional levels, and thus is a key determinant of global and local food security (Kearney, 2010). However, the evidence base on potential climate change impacts on consumption patterns, or on other non-production elements of food security is thin, particularly when

Table 7-1 | Households divided into five categories of food access, indicating the impacts of food price increases.

Food access category	Characteristics	Impacts of food price increase on food access
Primarily subsistence (autarkic)	Subsistence farmers, herders, fishers, and forest-dependent populations; generally low share of population (Karfakis et al., 2011)	Limited impact
Food producers: net sellers	Generally lower share of population compared with net buyers (Aksoy and Sid-Dimelik, 2008; Zezza et al., 2008; FAO, 2011)	Positive impact through increased income effect. Major beneficiaries are those with greatest surplus (e.g., larger, more commercialized farms) (FAO, 2011)
Food producers: net buyers	Majority of poor rural households (IFAD, 2010; FAO, 2011)	Ambiguous: depends on relative size of income and price effects, but generally expected to be negative due to high share of income spent on food (Ivanic and Martin, 2008; FAO, 2011; Ivanic et al., 2011)
Rural non-farming households	Rural landless: characterized by high rates of food insecurity; average share of population for 15 low-income countries was 22% (Aksoy et al., 2010)	Negative impact due to high share of income spent on food; however, some limited evidence that wage increases may accompany price increases, in which case overall effects are ambiguous (Aksoy and Sid-Dikmelik, 2008; FAO, 2011)
Urban consumers	Growing share of population in most countries (IFAD, 2010)	Negative impact by reducing food affordability. Especially vulnerable to changes in global food prices, as they are more likely to consume staple foods derived from tradable commodities (FAO, 2008; Ivanic et al., 2011)

compared with the literature on climate change impacts on food production and availability.

Current and future variation in the distribution and vulnerability to loss of food access across household types makes impacts assessment complex and difficult. Nonetheless, there are reasons for concern about food access due to the current high rates of food insecurity in many low income countries. Agricultural producers who are net food buyers are particularly vulnerable. Similarly, low-income agricultural dependent economies that are net food importers, which are those that already have high rates of food insecurity, could experience significant losses in food access through a double negative effect on reduced domestic agricultural production and increased food prices on global markets.

7.3.3.2.2. Climate change impacts on stability

There is increasing evidence of and confidence in the effect of climate change on increasing the incidence and frequency of some types of climate extreme events (IPCC, 2012), and this will have significant impacts on food security (*medium evidence, medium agreement*). Recent experience of global climate patterns affecting food security indicates the potential nature and magnitude of increased variability. An impact assessment of the 2010 Pakistan floods surveyed 1800 households 6 months after the floods and found that 88% of the households reported income losses of up to 50%, with significantly higher rates in rural than urban areas (Kirsch et al., 2012). The same study indicated that loss of key services such as electricity, sanitation, and clean water resulted in lower standards of living even in the wake of significant relief attempts, again with significantly heavier effects on rural populations (Kirsch et al., 2012). The Russian heat wave of 2010 and subsequent export ban contributed to the more than doubling of global wheat prices by the end of the year. The degree to which these price increases affected domestic consumers and poverty depended on national responses in importing countries, although a significant net negative effect on poverty was found (Ivanic et al., 2011).

Increased incidence of climate extremes reduces incentives to invest in agricultural production, potentially offsetting positive impacts from increasing food price trends. This is particularly true for poor smallholders with limited or no access to credit and insurance. Greater exposure to climate risk, in the absence of well-functioning insurance markets, leads

to (1) greater emphasis on low-return but low-risk subsistence crops (Roe and Graham-Tomasi, 1986; Fafchamps, 1992; Heltberg and Tarp, 2002), (2) a lower likelihood of applying purchased inputs such as fertilizer (Kassie et al., 2008; Dercon and Christiansen, 2011), (3) a lower likelihood of adopting new technologies (Feder et al., 1985; Antle and Crissman., 1990), and (4) lower investments (Skees et al., 1999). All of these responses generally lead to both lower current and future farm profits (*robust evidence, high agreement*) (Rosenzweig and Binswanger, 1993; Hurley, 2010).

It is also well documented that in many rural areas, smallholders in particular do not have the capacity to smooth consumption in the face of climate shocks, particularly generalized shocks that affect a majority of households in the same location (Dercon, 2004; Skoufias and Quisumbing, 2005; Dercon, 2006; Fafchamps, 2009; Prakash, 2011). Any increases in climate extremes will exacerbate the vulnerability of all food-insecure people, including smallholders (*robust evidence, high agreement*). Currently, smallholders rely to a large extent on increasing labor off-farm where possible (Fafchamps, 1999; Kazianga and Udry, 2006), but also by decreasing both food consumption and non-food expenditures, such as those on education and health care (*medium evidence, high agreement*; Skoufias and Quisumbing, 2005). Furthermore, some evidence also suggests that poorer households are more likely to reduce consumption, while wealthier households liquidate assets to cover current deficits (*limited evidence, medium agreement*; Kazianga and Udry, 2006; Carter and Lybbert, 2012). Reductions in food consumption, sales of productive assets, education, and health care can lead to long-term losses in terms of income generation and thus to future food security (*limited evidence, medium agreement*; Skoufias and Quisumbing, 2005; Hoddinot et al., 2008). Increased uncertainty of future climate conditions and increases in climate extremes will increase food insecurity unless these significant barriers to consumption and asset smoothing can be addressed (*medium evidence, medium agreement*).

7.3.3.2.3. Climate change impacts on utilization

Climate change impacts on utilization may come about through changes in consumption patterns in response to shocks, as well as changes in nutrient content of food as well as food safety (*medium evidence, medium agreement*). Rationing consumption to prioritize calorie-rich but nutrient-poor foods is another common response (Bloem et al.,

2010). The effects are a decrease in dietary quality as well as quantity, which are magnified by pre-existing vulnerabilities—and lead to long-term loss of health, productivity capacity, and low incomes (*medium evidence, medium agreement*) (Alderman, 2010; Bloem et al., 2010; Brinkman et al., 2010; Campbell et al., 2010; Sari et al., 2010). The biological effects of climate change on nutrient content of foods are one of the main pathways for effects on utilization. A summary of recent literature on the impacts of climate change on the composition of nutrients in food items is given in HLPE (2012). Research on grains generally shows lowering of protein content with elevated temperature and CO₂ levels (Erda et al., 2005; Ainsworth and McGrath, 2010; Hatfield et al., 2011). There is good agreement that for plant-derived foods, mycotoxins are considered the key issue for food safety under climate change (Miraglia et al., 2009). The impacts of climate change on mycotoxins in the longer term are complex and region-specific; temperatures may increase sufficiently to eliminate certain mycotoxin-producing species from parts of the tropics but, in colder tropical regions and temperate zones, infections may increase (Cotty and Jaime-Garcia, 2007).

7.3.4. Sensitivity of Land Use to Weather and Climate

As noted in the AR4, changes in land use, for example, adjusting the location of crop production, are a potential adaptation response to climate change. Studies since the AR4 have confirmed that high-latitude locations will, in general, become more suitable for crops (Iqbal et al., 2009). Trnka et al. (2011), for example, examined projections of eleven agro-climatic indices across Europe, and found that declines in frost occurrence will lead to longer growing seasons, although temperature and moisture

stress will often lead to greater interannual variability in crop suitability. The potential influence of pests and diseases is commonly beyond the scope of such studies (Gregory et al., 2009).

For tropical systems where moisture availability or extreme heat rather than frost limits the length of the growing season, there is a likelihood that the length of the growing season and overall suitability for crops will decline (*medium evidence, medium agreement*; Jones and Thornton, 2009; Zhang and Cai, 2011). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat stressed by the 2050s, while temperate wheat environments will expand northwards as climate changes (Ortiz et al., 2008). Similarly, by 2050, the majority of African countries will experience climates over at least half of their current crop area that lie outside the range currently experienced within the country (Burke et al., 2009). The majority of these novel climates have analogs in other African countries. In mountainous regions, where temperature varies significantly across topography, changes in crop suitability can be inferred from the variation of temperature across topography. The resulting vertical zones of increasing, decreasing, and unchanging suitability can be relatively robust in the face of uncertainty in future climate (Schroth et al., 2009).

The interaction between water resources and agriculture is expected to become increasingly important as climate changes. For example, whilst projected changes in crop productivity in China are uncertain, even within a single emissions scenario, irrigation has significant adaptation potential (Piao et al., 2010). However, limitations to availability of water will affect this potential. Changes in water use, including increased water diversion and development to meet increasing water demand,

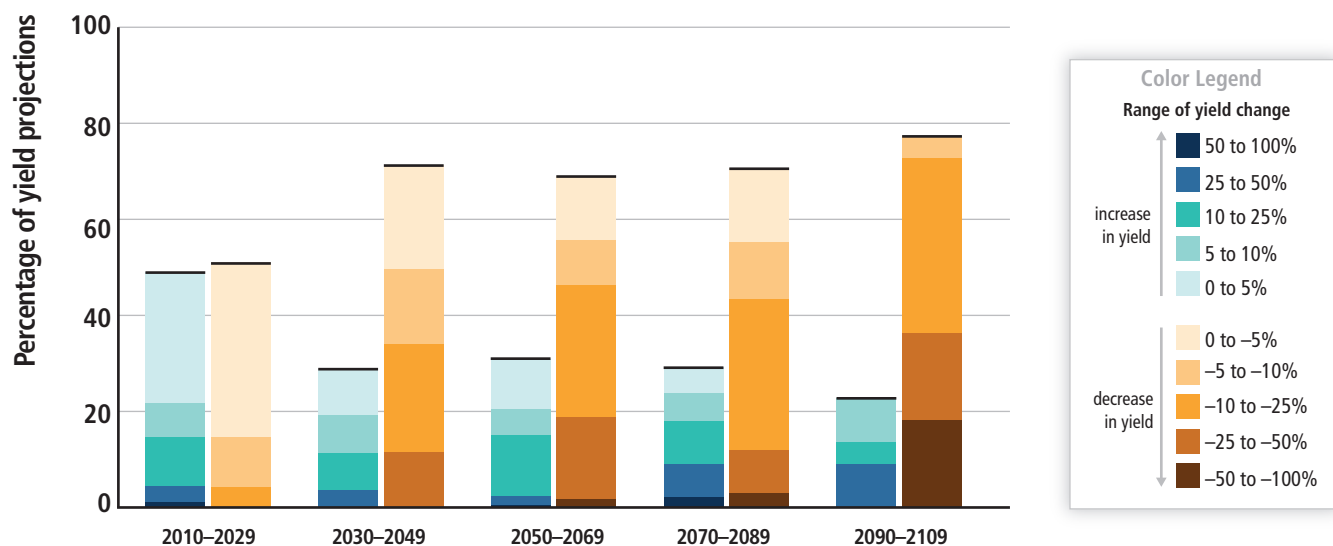


Figure 7-5 | Summary of projected changes in crop yields, due to climate change over the 21st century. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near-term and long-term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%. Projections taken from Abraha and Savage, 2006; Alexandrov and Hoogenboom, 2000; Arndt et al., 2011; Berg et al., 2013; Brassard and Singh, 2008; Brassard and Singh, 2007; Butt et al., 2005; Calzadilla et al., 2009; Chhetri et al., 2010; Ciscar et al., 2011; Deryng et al., 2011; Giannakopoulos et al., 2009; Hermans et al., 2010; Iqbal et al., 2011; Izaurrealde et al., 2005; Kim et al., 2010; Lal, 2011; Li et al., 2011; Lobell et al., 2008; Moriondo et al., 2010; Müller et al., 2010; Osborne et al., 2013; Peltonen-Sainio et al., 2011; Piao et al., 2010; Ringler et al., 2010; Rowhanji et al., 2011; Schlenker and Roberts, 2009; Shuang-He et al., 2011; Southworth et al., 2000; Tan et al., 2010; Tao & Zhang, 2010; Tao and Zhang, 2011; Tao et al., 2009; Thornton et al., 2009; Thornton et al., 2010; Thornton et al., 2011; Tingem and Rivington, 2009; Tingem et al., 2008; Walker and Schulze, 2008; Wang et al., 2011; Xiong et al., 2007; Xiong et al., 2009.

and increased dam building will also have implications for inland fisheries and aquaculture, and therefore for the people dependent on them (Ficke et al., 2007; FAO, 2009a). In the case of the Mekong River basin, a large proportion of the 60 million inhabitants are dependent in some way on fisheries and aquaculture that will be seriously impacted by human population growth, flood mitigation, increased offtake of water, changes in land use, and overfishing, as well as by climate change (Brander, 2007). Ficke et al. (2007) reported that at that time there were 46 large dams planned or already under construction in the Yangtze River basin, the completion of which would have detrimental effects on those dependent on fish for subsistence and recreation.

The models used in projections of land suitability and cropland expansion discussed above rely on assumptions about non-climatic constraints on crop productivity, such as soil quality and access to markets. These assumptions are increasingly amenable to testing as the climate system shifts, by comparing observed changes in cropland area with model predictions. The location of the margin between cropping land and extensive grazing in southern Australia has varied with decadal climate conditions and is projected to shift toward the coast with hotter and drier conditions, notwithstanding the positive impacts of elevated CO₂ (Nidumolu et al., 2012). Recent trends in climate have seen reductions in cropping activity consistent with these projections (Nidumolu et al., 2012).

7.4. Projected Integrated Climate Change Impacts

7.4.1. Projected Impacts on Cropping Systems

Crop yields remain the most well studied aspect of food security impacts from climate change, with many projections published since AR4. These newer studies confirm many of the patterns identified in AR4, such as negative yield impacts for all crops past 3°C of local warming without adaptation, even with benefits of higher CO₂ and rainfall (Figure 7-4).

Figure 7-5 shows projected impacts on mean crop yield in 20-year bins, including cases with no adaptation and a range of incremental adaptations. The data indicate that negative impacts on average yields become *likely* from the 2030s. Negative impacts of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. Some important differences by emission scenario and region are masked in Figure 7-5. From the 2080s onwards, negative yield impacts in the tropics are *very likely*, regardless of adaptation or emission scenario. This is consistent with the meta-analysis of Knox et al. (2012), and a recent model intercomparison of global gridded crop models (Rosenzweig et al., 2013, 2014).

A few studies have explicitly compared projections for different regions or crops to identify areas at most risk. Lobell et al. (2008) used a statistical crop model with 20 GCMs and identified South Asia and southern Africa as two regions that, in the absence of adaptation, would suffer the most negative impacts on several important crops. Yields changes have also been assessed by regional meta-analyses: Knox et al. (2012) synthesized projections from 52 studies and estimated an expected 8% negative yield impact in both regions by 2050 averaged over crops, with wheat,

maize, sorghum, and millets more affected than rice, cassava, and sugarcane.

Changes in the interannual variability of yields could potentially affect stability of food availability and access. Figure 7-6 shows projected changes in the coefficient of variation (CV) of yield from some of the few studies that publish this information. The data shown are consistent with reports of CV elsewhere: Müller et al. (2014) conducted gridded simulations across the globe and reported an increase of more than 5% in CV in 64% of grid cells, and a decrease of more than 5% in 29% of cases. Increases in CV can be due to reductions in mean yields and/or increases in standard deviation of yields, and often simulated changes are a combination of the two. Overall, climate change will increase crop yield variability in many regions (*medium evidence, medium agreement*).

Estimated impacts of both historical and future climate changes on mean yields are summarized along with projected impacts on yield variability in Figure 7-7, with all impacts expressed as the average percentage impact per decade. This comparison illustrates that future impacts are expected to be consistent with the trajectory of past impacts, with the majority of locations experiencing negative impacts while some locations benefit. Each additional decade of climate change is expected to reduce mean yields by roughly 1%, which is a small but nontrivial fraction of the anticipated roughly 14% increase in productivity per decade needed to keep pace with demand. For future projections, enough studies are available to assess differences by region and adaptation scenario, with significant adaptation effects apparent mainly in temperate systems (Section 7.5).

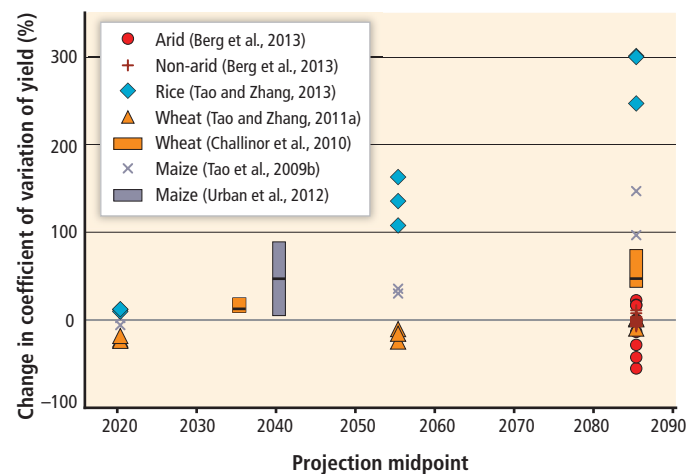
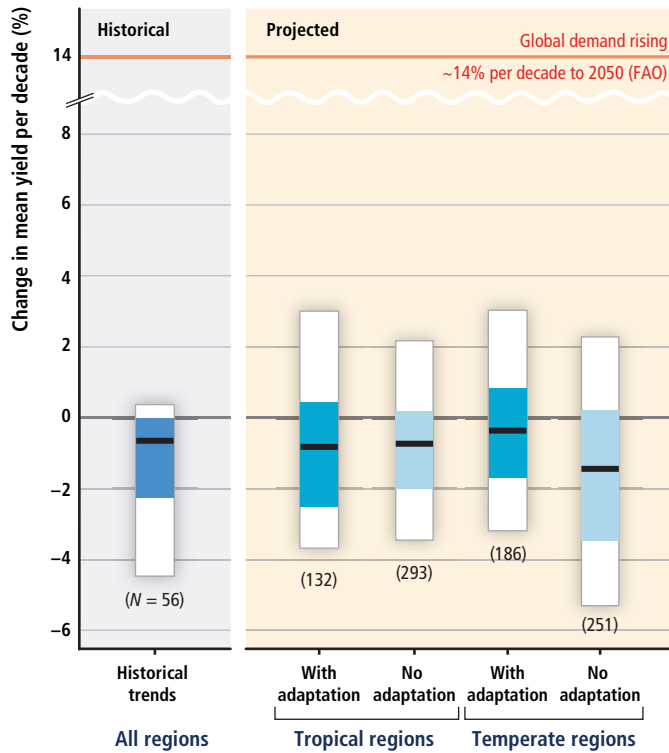


Figure 7-6 | Projected percentage change in coefficient of variation (CV) of yield for wheat (Tao and Zhang, 2011a; Challinor et al., 2010), maize (Tao et al., 2009b; Urban et al., 2012), rice (Tao and Zhang, 2013), and C₄ crops (arid and non-arid, Berg et al., 2013). The data from Urban et al. (2012) show the range (mean plus and minus one standard deviation) of percentage changes in CV. For the Challinor et al. (2010) data, paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. All other studies plot individual data points. A total of 81 data points are plotted in the figure, although the underlying data consist of many thousands of crop model simulations. The studies used a range of scenarios (Special Report on Emissions Scenarios (SRES) A1B, A2, A1F1, and B1). Berg et al. (2013) is a global study of the tropics, Urban et al. (2012) is for US maize, and the remaining data points are for China.

(a) Impact of climate trend on mean crop yield



(b) Impact on year-to-year crop yield variability

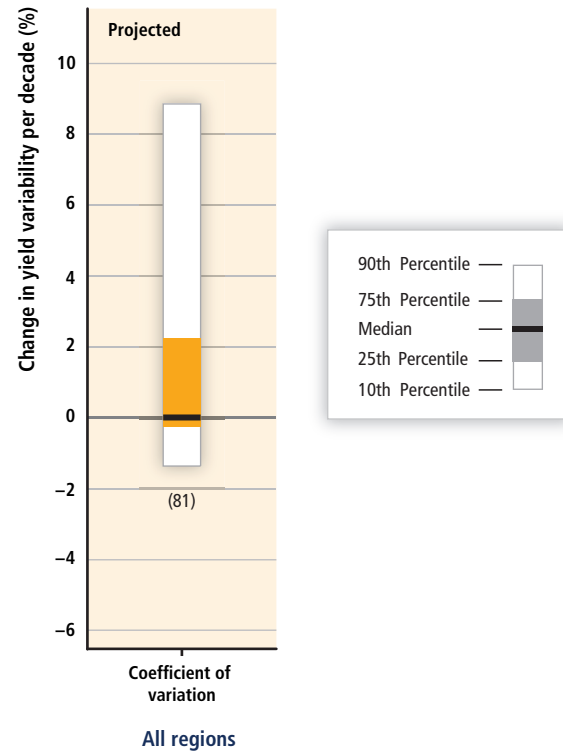


Figure 7-7 | Boxplot summary of studies that quantify impact of climate and CO₂ changes on crop yields, including historical and projected impacts, mean and variability of yields, and for all available crops in temperate and tropical regions. All impacts are expressed as average impact per decade (a 10% total impact from a 50-year period of climate change would be represented as 2% per decade). References for historical impacts are given in Figure 7-2, for projected mean yields in Figure 7-5, and for yield variability in Figure 7-6. *N* indicates the number of estimates, with some studies providing multiple estimates. In general, decreases in mean yields and increases in yield variability are considered negative outcomes for food security. Also indicated in the figure is the expected increase in crop demand of 14% per decade (Alexandratos and Bruinsma, 2012), which represents a target for productivity improvements to keep pace with demand.

Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. An analysis for sub-Saharan Africa predicted overall decreases of 19% for maize yields, 68% decrease for bean yields, and a small increase for fodder grass (*Brachiaria decumbens*) given 5°C global average warming (Thornton et al., 2011). Rötter et al. (2011) conclude that positive effects of modest warming and increased CO₂ levels on crop yields in Finland will be reversed at global temperatures increases of 4°C, leading to negative yield impacts in excess of 20% in relation to current conditions.

For perennial crops, winter chill accumulation that is important to many fruit and nut trees is projected to continue its decline, with, for instance, a 40 chill-hours per decade reduction projected for California for the period up to 2100 (Baldocchi and Wong, 2008). Averaging over three GCMs, annual winter chill loss by 2050 compared to 1970 would amount 17.7% to 22.6% in Egypt (Farg et al., 2010). Several studies have projected negative yield impacts of climate trends for perennial trees, including apples in eastern Washington (Stöckle et al., 2010) and cherries in California (Lobell and Field, 2011), although CO₂ increases may offset some or all of these losses. Reductions in suitability for grapevine are expected in most of the wine-producing regions (Hall and Jones, 2009; White et al., 2009; Jones et al., 2010). Wine grape production and quality will be affected in Europe, USA, Australia (Jones et al., 2005; Wolfe et al., 2008; Cozzolino et al., 2010; Chapter 25), although it could be a benefit in Portugal (Santos et al., 2011) and British Columbia in

Canada (Rayne et al., 2009). Important crops in Brazil such as sugarcane and coffee are expected to migrate toward more favorable zones in the South (Pinto, 2007; Pinto et al., 2008; Chapter 27). Sugarcane fresh stalk mass is generally expected to gain from both warming and elevated CO₂ in Brazil (Marin et al., 2013). The suitability for coffee crops in Costa Rica, Nicaragua, and El Salvador will be reduced by more than 40% (Glenn et al., 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops toward higher altitudes by mid-century (Ramirez-Villegas et al., 2012). In the same way, increases in temperature will affect tea production, in particular at low altitudes (Wijeratne et al., 2007).

Consideration of pest, weed, and disease impacts are omitted from most yield projections, yet other studies have focused on projecting impacts of these biotic stressors. For pests and diseases, range expansion has been predicted for the destructive *Phytophthora cinnamomi* in Europe (Bergot et al., 2004) and for phoma stem canker on oilseed rape in the UK (Evans et al., 2008). Increased generations under climate change for the coffee nematode have been predicted for Brazil (Ghini et al., 2008). Walnut pests in California are predicted to experience increased numbers of generations under climate change scenarios (Luedeling et al., 2011). Luck et al. (2011) summarized the mixed results for the qualitative effects of climate change on pathogens that cause disease of four major food crops—wheat, rice, soybean, and potato—where some diseases increased in risk while others decreased under climate change scenarios. In syntheses, there is a tendency for risk of insect

damage to plants to increase (Paulson et al., 2009). Typical scenario analyses are limited by simplistic assumptions, and work remains to evaluate how conclusions will change as more complete scenarios, such as those including migration and invasion patterns and other types of global change, are considered (Savary et al., 2005; Garrett et al., 2011). Effects on soil communities represent an area that needs more attention (Pritchard, 2011). Mycotoxins and pesticide residues in food are an important concern for food safety in many parts of the world, and identified as an important issue for climate change effects in Europe (Miraglia et al., 2009).

Weed populations and demographics are expected to change (*medium confidence*), with an overall poleward migration in response to warming (Ziska et al., 2011). An overview of crop and weed competitive studies indicate that weeds could limit crop yields to a greater extent with rising levels of CO₂ per se (Ziska, 2010). This may be related to the greater degree of phenotypic and genotypic plasticity associated with weedy species relative to the uniformity inherent in large cropping systems (Section 4.2.4.6). Chemical control of weeds, which is the preferred management method for large-scale farms, may become less effective (*limited evidence, medium agreement*), with increasing economic and environmental costs (Section 7.3.2.3).

Climate change effects on productivity will alter land use patterns, both in terms of total area sown to crops and the geographic distribution of that area. For example, the suitability for potato crops is expected to increase in very high latitudes and high tropical altitudes toward 2100 (Schaeffleitner et al., 2011). Given expected trends in population, incomes, bioenergy demand, and agricultural technology, global arable area is projected to increase from 2007 to 2050, with projected increases over this period of +9% (Bruinsma, 2009), +8% (Fischer et al., 2009), +10 to 20% (Smith et al., 2010), and +18 to 23% (Lobell et al., 2013b) (*medium evidence, medium agreement*). Not all such studies included the effects of global warming. Where this is the case, estimates range from a 20% increase in cropping area to a decline of 9% (Zhang and Cai, 2011), but with large regional differences (*limited evidence, low agreement*). Countries at northern latitudes and under the current constraint of low temperature may increase cultivated area (*limited evidence, low agreement*). The generally lower nutrient quality of soils and the lack of necessary infrastructure required to convert virgin land

into productive arable land make estimates of cropping area increases highly uncertain.

7.4.2. Projected Impacts on Fisheries and Aquaculture

Many studies have projected impacts of climate change on capture fisheries (Chapters 6 and 30) and only a subset of the more indicative studies at different ecological and geographical scales is included here. Overall, there is *high confidence* that climate change will impact on fisheries production with significant negative impacts particularly for developing countries in tropical areas, while more northerly, developed countries may experience benefits (Section 6.4.3).

Simulation studies on skipjack and bigeye tuna in the Pacific under both the Special Report on Emissions Scenarios (SRES) B1 and A2 scenarios indicate that catches of skipjack in the region as a whole are likely to increase by approximately 19% in 2035 compared to recent catch levels while catches of bigeye are projected to increase only marginally. By 2100, under the B1 scenario, catches of skipjack are projected to be 12.4% higher than recent levels but 7.5% lower under the A2 scenario, while catches of bigeye will be 8.8% and 26.7% lower under the B1 and A2 scenarios, respectively. The models indicate important regional differences, with a general trend that catches of tuna will decrease in the Western Pacific and increase in the Eastern Pacific (Lehodey et al., 2011; see also Sections 6.5.3, 30.6.2.1.1). These changes have important implications for the future of national fishing fleets and canneries in the Western Pacific (Bell et al., 2009). Climate change is expected to impact directly on the productivity of coastal fisheries in the Pacific island countries and territories through increased sea surface temperature and ocean acidification and indirectly through climate-driven damage to coral reefs, mangroves, seagrasses, and intertidal flats (Pratchett et al., 2011). Extreme events such as increased severity of tropical cyclones could also impact on some species. Under both B1 and A2 emissions scenarios, the vulnerability of coastal fisheries as a whole in 2035, as estimated through the framework described in Bell et al. (2009), is considered to be low. Extended to 2100, the projected impacts under the A2 emissions scenario are more severe, with reductions in coastal fisheries production by 20 to 35% in the west and 10 to 30% in the east (Pratchett et al., 2011).

Frequently Asked Questions

FAQ 7.2 | How could climate change interact with change in fish stocks and ocean acidification?

Millions of people rely on fish and aquatic invertebrates for their food security and as an important source of protein and some micronutrients. However, climate change will affect fish stocks and other aquatic species. For example, increasing temperatures will lead to increased production of important fishery resources in some areas but decreased production in others while increases in acidification will have negative impacts on important invertebrate species, including species responsible for building coral reefs that provide essential habitat for many fished species in these areas. The poorest fishers and others dependent on fisheries and subsistence aquaculture will be the most vulnerable to these changes, including those in Small Island Developing States, central and western African countries, Peru and Colombia in South America, and some tropical Asian countries.

Brown et al. (2010) project that, under the A2 emissions scenario, primary production in the ocean around Australia will increase over the 50-year period from 2000 to 2050 as a result of small increases in nutrient availability from changes in ocean stratification and temperature, although the authors acknowledge considerable model uncertainty. This increase is forecast, in general, to benefit fisheries catch and value. In a complementary study, Fulton (2011) used available end-to-end models to forecast the impacts of climate change under the A2 scenario across approximately two-thirds of Australia's exclusive economic zone. The results indicated that by 2060, the large-scale commercial fisheries, aided by their adaptive flexibility, would experience an overall increase of more than 90% in the value of their operations, although differing across sectors. The change in returns for the small-scale sector varied regionally from a decrease of 30 to 51% to a potential increase of 9 to 14%.

At the global scale, projections based on a dynamic bioclimatological envelope model under the SRES A1B scenario suggested that climate change could lead to an average 30 to 70% increase in fisheries yield from high-latitude regions (>50°N in the Northern Hemisphere), but a decrease of up to 40% in the tropics by 2055 compared to yields obtained in 2005 (Cheung et al., 2010). Another study using a suite of models linking physical, ecological, fisheries, and bioeconomic processes projected that, under the A1B scenario, the global yield from "large" fish could increase by 6% and that of the "small fish" used in fishmeal production by approximately 3.6%, assuming that marine fisheries and fish resources would be managed sustainably (Merino et al., 2012).

There is limited information available on projected impacts on food production in inland fisheries. Xenopoulos et al. (2005) investigated the effect of climate change and water withdrawal on freshwater fish extinctions under the assumptions of two scenarios consistent with scenarios A2 and B2. They forecast that discharge would increase in between 65 and 70% of river basins in the world but it would decrease by as much as 80% in 133 rivers for which fish species data were available. In the latter group, by 2070, up to 75% (quartile range, 4-22%) of the local fish biodiversity would be "headed toward extinction" because of changes in climate and water consumption, with the highest rates of extinction forecast mainly in tropical and subtropical areas. These results are not directly translatable into changes in fishery production but do give cause for concern for the likely affected areas (*limited evidence, low agreement*).

Information on future impacts on aquaculture is equally limited. Huppert et al. (2009) considered the impacts on the coast of Washington State, USA. They concluded that inundation of low-lying coastal areas from sea level rise, flooding from major storm events, and increased ocean temperatures and acidification would create significant challenges for the important shellfish aquaculture industry in the state. Inundation of existing shellfish habitats from sea level rise and increased incidence of harmful algal blooms were also contributory factors. Using a structured vulnerability framework and considering the B1 and A2 emission scenarios to project impacts on aquaculture in the tropical Pacific to 2035 and 2100, Pickering et al. (2011) concluded that production of freshwater species such as tilapia, carp, and milkfish will probably benefit from the expected climate changes, while coastal enterprises are expected to encounter problems in the same time horizons, varying according to species. Aquaculture production of calcifying organisms

such as molluscs will experience loss of suitable habitats through ocean acidification. This will be particularly pronounced at and in the vicinity of eastern boundary upwelling systems (Section 30.6.2.1.4).

The food security consequences of the different impacts on capture fisheries and aquaculture are more difficult to estimate than the biological and ecological consequences. A preliminary study by Allison et al. (2009) examined the vulnerability of the economies of 132 countries to climate change impacts on fisheries in 2050 under the A1FI and B2 scenarios. Vulnerability was considered as a composite of three components: exposure to the physical effects of climate change, the sensitivity of the country to impacts on fisheries, and adaptive capacity within the country. This analysis suggested that under both scenarios several of the least developed countries were also among the most vulnerable to climate change impacts on their fisheries. They included countries in central and western Africa, Peru and Colombia in South America, and four tropical Asian countries.

7.4.3. Projected Impacts on Livestock

Climate change impacts on livestock will include effects on forage and feed, direct impacts of changes in temperature and water availability on animals, and indirect effects via livestock diseases. Many of the relevant processes and projected impacts for rangelands are discussed in Section 4.3.3.2, as well as in chapters for regions with prominent livestock sectors (Sections 22.3.4.2, 23.4.2, 25.7.2.1). In North American cattle systems, warming is expected to lengthen forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurralde et al., 2011). Simulations for French grasslands (Graux et al., 2013) and sown pastures in Tasmania (Perring et al., 2010) also project negative impacts on forage quality. Similarly, legume content of grasslands in most of southern Australia is projected to increase to the 2070s for SRES A2, with larger increases in wetter locations (Moore and Ghahramani, 2013).

There is *high confidence* that high temperatures tend to reduce animal feeding and growth rates (André et al., 2011; Renaudeau et al., 2011). The impacts of a changing UK climate on dairy cow production were analyzed by Wall et al. (2010), who showed that, in some regions, milk yields will be reduced and mortality increased because of heat stress throughout the current century, with annual production and mortality losses amounting to some £40 million by the 2080s under a medium-high GHG emission scenario.

Existing challenges of supplying water for an increasing livestock population will be exacerbated by climate change in many places (*limited evidence, high agreement*). For example, Masike and Urich (2008) project that warming under SRES A1 emission scenario will cause an annual increase of more than 20% in cattle water demand by 2050 for Kgatleng District, Botswana. At the same time, there is ample scope to improve livestock water productivity considerably (Molden et al., 2010); for example, in mixed crop-livestock systems of sub-Saharan Africa via feed, water, and animal management (Descheemaeker et al., 2010).

Host and pathogen systems in livestock will change their ranges because of climate change (*high confidence*). Species diversity of some

Box 7-1 | Projected Impacts for Crops and Livestock in Global Regions and Sub-Regions under Future Scenarios

Projected impacts for crops and livestock in global regions and sub-regions under future scenarios. Crop yield impacts in parentheses correspond to parentheses in the scenario column. $-CO_2$ = without CO_2 effects; $+CO_2$ = with CO_2 effects; (I) = irrigated; (R) = rainfed. ARPEGE = Action de Recherche Petite Echelle Grande Echelle; CSIRO = Commonwealth Scientific and Industrial Research Organisation; ECHAM4 = European Centre for Medium Range Weather Forecasts Hamburg 4; GFDL-CM2.0/2 = Geophysical Fluid Dynamics Laboratory-Climate Model 2.0/2; HadCM3 = Met Office Hadley Centre Climate Prediction Model 3; HIRHAM = High-Resolution Hamburg Climate Model; MIROC = Model for Interdisciplinary Research On Climate; MPI-OM = Max Planck Institute; MRI-CGCM2.3.2 = Meteorological Research Institute of Japan Meteorological Agency-Coupled General Circulation Model 2.3.2; PRECIS = Providing Regional Climates for Impact Studies; RCA3 = Rossby Centre Regional Atmospheric Model 3.

Regional impacts on crops

Region	Sub-region	Yield impacts (%)	Scenario	Reference
World		<ul style="list-style-type: none"> • (I) Maize: -4, -7 • (R) Maize: -2, -12 • (I) Rice: -9.5, -12 • (R) Rice: -1, +0.07 • (I) Wheat: -10, -13 • (R) Wheat: -4, -10 	A1B CSIRO, MIROC 2050	Nelson et al. (2010)
East Asia	China	(I) Maize: <ul style="list-style-type: none"> • -10.9 to -1.4 (-7.8 to -1.6), • -21.7 to -9.8 (-16.4 to -10.2), • -32.1 to -4.3 (-26.6 to -3.9) (R) Maize: <ul style="list-style-type: none"> • -22.2 to -1.0 (-10.8 to +0.7), • -27.6 to -7.9 (-18.1 to -5.6), • -33.7 to -4.6 (-25.9 to -1.6) (I) Rice: <ul style="list-style-type: none"> • -18.6 to -6.1 (-10.1 to +3.3), • -31.9 to -13.5 (-16.1 to +2.5), • -40.2 to -23.6 (-19.3 to +0.18) 	+1°C, +2°C, +3°C $-CO_2$ (+ CO_2)	Tao et al. (2011)
	Eastern China	Rice: <ul style="list-style-type: none"> • -10 to +3 (+7.5 to +17.5), • -26.7 to +2 (0 to +25), • -39 to -6 (-10 to +25) 	2030, 2050, 2080 $-CO_2$ (+ CO_2)	Tao and Zhang (2013)
	Huang-Huai-Hai Plain, China	Wheat-maize: +4.5 ± 14.8, -5.8 ± 25.8	+2°C, +5°C	Liu et al. (2010)
	North China Plain	<ul style="list-style-type: none"> • (I) Wheat: -0.9 (+23) • (R) Wheat: -1.9 (+28) 	A1B 2085-2100 $-CO_2$ (+ CO_2) MIROC	Yang et al. (2013)
	Yangtze River, China	<ul style="list-style-type: none"> • (I) Rice: -14.8 (-3.3) • (R) Rice: -15.2 (-4.1) 	B2 2021-2050 $-CO_2$ (+ CO_2)	Shen et al. (2011)
South Asia	South Asia	<ul style="list-style-type: none"> • Maize: -16 • Sorghum: -11 	2050	Knox et al. (2012)
	South Asia	Net cereal production -4 to -10	+3°C	Lal (2011)
	India	Winter sorghum: up to -7, -11, -32	A2 2020, 2050, 2080	Srivastava et al. (2010)
		<ul style="list-style-type: none"> • (I) Rice: -4, -7, -10 • (R) Rice: -6, -2.5, -2.5 	A1B; A2; B1; B2 2020, 2050, 2080 $+CO_2$ MIROC; PRECIS/HadCM3	Kumar et al. (2013)
		<ul style="list-style-type: none"> • Monsoon maize: -21 to 0, -35 to 0, -35 to 0 • Winter maize: -13 to +5, -50 to +5, -60 to -21 	A2 2020, 2050, 2080 HadCM3	Byjesh et al. (2010)
	Northeast India	<ul style="list-style-type: none"> • (I) Rice: -10 to +5 • (R) Rice: -35 to +5 • Maize: up to -40 • Wheat: up to -20 	A1B 2030 $+CO_2$ PRECIS/HadCM3	Kumar et al. (2011)
	Coastal India	<ul style="list-style-type: none"> • (I) Rice: -10 to +5 • (R) Rice: -20 to +15 • (I) Maize: -50 to -15 • (R) Maize: -35 to +10 		
	Western Ghats, India	<ul style="list-style-type: none"> • (I) Rice: -11 to +5 • (R) Rice: -35 to +35 • Maize: up to -50 • Sorghum: up to -50 		
	Pakistan	Wheat: -7, -24 (Swat); +14, +23 (Chitral)	+1.5°C, +3°C	Section 24.4.4.3
<ul style="list-style-type: none"> • Wheat: -6, -8 • Rice: -16, -19 		B2, A2 2080	Iqbal et al. (2009)	

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Box 7-1 (continued)

Region	Sub-region	Yield impacts (%)	Scenario	Reference
West Asia	Yarmouk Basin, Jordan	<ul style="list-style-type: none"> Barley: -8, +5 Wheat: -20, +18 	-20%, +20% precipitation	Al-Bakri et al. (2010)
Africa	All regions	<ul style="list-style-type: none"> Wheat: -17 Maize: -5 Sorghum: -15 Millet: -10 	2050	Knox et al. (2012)
	All regions	Maize: -24 ± 19	2090 +5°C	Thornton et al. (2011)
	East Africa	<ul style="list-style-type: none"> Maize: -3.1 to +15.0, -8.6 to +17.8 Beans: -1.5 to +21.8, -18.1 to +23.7 	A1FI; B1 2030, 2050 HadCM3; ECHam4	Thornton et al. (2010)
	Sahel	Millet: -20, -40	+2°C, +3°C	Ben Mohamed (2011)
Central & South America	Northeastern Brazil	<ul style="list-style-type: none"> Maize: 0 to -10 Wheat: -1 to -14 Rice: -1 to -10 	2030	Table 27-5; Lobell et al. (2008)
	Southern Brazil	<ul style="list-style-type: none"> Maize: -15 Bean: up to +45 	A2 2080 +CO ₂ HadCM3	Table 27-5; Costa et al. (2009)
	Paraguay	<ul style="list-style-type: none"> Wheat: +4, -9, -13 (-1, +1, -5) Maize: +3, +3, +8 (+3, +1, +6) Soybean: 0, -10, -15 (0, -15, -2) 	A2 (B2) 2020, 2050, 2080 PRECIS	Table 27-5; ECLAC (2010)
	Central America	<ul style="list-style-type: none"> Wheat: -1 to -9 Rice: 0 to -10 	2030	Table 27-5; Lobell et al. (2008)
		<ul style="list-style-type: none"> Maize: 0, 0, -10, -30 Bean: -4, -19, -29, -87 Rice: +3, -3, -14, -63 	A2 2030, 2050, 2070, 2100	Table 27-5; ECLAC (2010)
	Panama	Maize: -0.5, +2.4, +4.5 (-0.1, -0.8, +1.5)	A2 (B1) 2020, 2050, 2080 +CO ₂	Table 27-5; Ruane et al. (2013)
	Andean region	<ul style="list-style-type: none"> Wheat: -14 to +2 Barley: 0 to -13 Potato: 0 to -5 Maize: 0 to -5 	2030	Table 27-5; Lobell et al. (2008)
	Chile	<ul style="list-style-type: none"> Maize: -5% to -10% Wheat: -10% to -20% 	A1FI 2050 +CO ₂ HadCM3	Table 27-5; Meza and Silva (2009)
Argentina	<ul style="list-style-type: none"> Wheat: -16, -11 (+3, +3) Maize: -24, -15 (+1, 0) Soybean: -25, -14 (+14, +19) 	A2, B2 2080 -CO ₂ (+CO ₂) PRECIS	Table 27-5; ECLAC (2010)	
North America	Midwestern United States	<ul style="list-style-type: none"> Maize: -2.5 (-1.5) Soy: +1.7 (+9.1) 	+0.8°C -CO ₂ (+CO ₂)	Hatfield et al. (2011)
	Southeastern United States	<ul style="list-style-type: none"> Maize: -2.5 (-1.5) Soy: -2.4 (+5.0) 		
	United States Great Plains	Wheat: -4.4 (+2.4)		
	Northwestern United States	<ul style="list-style-type: none"> Winter wheat: +19.5, +29.5 Spring wheat: -2.2, -5.6 	A1B 2040, 2080 +CO ₂	Stöckle et al. (2010)
	Canadian prairies	<ul style="list-style-type: none"> Small grains: -48 to +18 Oilseeds: -50 to +25 	+1°C, +2°C, +20% precipitation, -20% precipitation	Kulshreshtha (2011)
Europe	Boreal	Wheat, maize, soybean: +34 to +54	A2, B2 2080 HadCM3/HIRHAM, ECHAM4/RCA3	Iglesias et al. (2012)
	Alpine	Wheat, maize, soybean: +20 to +23		
	Atlantic North	Wheat, maize, soybean: -5 to +22		
	Atlantic Central	Wheat, maize, soybean: +5 to +19		
	Atlantic South	Wheat, maize, soybean: -26 to -7		
	Continental North	Wheat, maize, soybean: -8 to +4		
	Continental South	Wheat, maize, soybean: +11 to +33		
	Mediterranean North	Wheat, maize, soybean: -22 to 0		
	Mediterranean South	Wheat, maize, soybean: -27 to +5		

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Box 7-1 (continued)

Region	Sub-region	Yield impacts (%)	Scenario	Reference
Australia	South	Wheat: -15, -12	A2; Low, high plant available water capacity 2080 +CO ₂ CCA-M	Luo et al. (2009)
	Southeast	Wheat: -29 (-25)	B2, A2, A1F1 2080 -CO ₂ (+CO ₂) CCA-M	Anwar et al. (2007)

Regional impacts on livestock

Region	Sub-region	Climate change impacts	Scenarios	Reference
Africa	Botswana	Cost of supplying water from boreholes could increase by 23% due to increased hours of pumping, under drier and warmer conditions.	A2, B2 2050	Section 22.3.4.2
	Lowlands of Africa	Reduced stocking of dairy cows, a shift from cattle to sheep and goats, due to high temperature.		
	Highlands of East Africa	Livestock keeping could benefit from increased temperature.		
	East Africa	Maize stover availability per head of cattle may decrease due to water scarcity.		
	South Africa	Dairy yields decrease by 10–25%.	A2 2046–2065/2080–2100 ECHAM5/MPI-OM, GFDL-CM2.0/2, MRI-CGCM2.3.2	Nesamvuni et al. (2012)
Europe	Netherlands	Dairy production affected at daily mean temperatures above 18°C		Section 23.4.2
	Italy	Mortality risk to dairy cattle increased by 60% by exposure to high air temperature and high air humidity during breeding.		
	French Uplands	Annual grassland production system significantly reduced by 4-year exposure to climatic conditions.	A2 2070	Cantarel et al. (2013)
	France	No impact on dairy yields.	A2 1970–1999, 2020–2049, 2070–2099 ARPEGE	Graux et al. (2011)
	Ireland, France	Grassland dairy system increases potential of dairy production, with increased risk of summer–autumn forage failure in France.	A1B By the end of century	Graux et al. (2011)
	Overall Europe	Spread of bluetongue virus (BTV) in sheep and ticks in cattle due to climate warming. No increase in risk of incursion of Crimean–Congo hemorrhagic fever virus in livestock.	2080	
Australia	Northern Australia	3°C increase in temperature will result in 21% reduction in forage production for CO ₂ at 350 ppm level and no change at 650 ppm level. Changes of ±10% in rainfall were exacerbated to ±15% change in forage production at 350 ppm CO ₂ .	A1B 2030	McKeon et al. (2009)
	Australia (other than Tasmania)	Dairy output will decline under 1°C increase in temperature.	A1B 2030	Section 25.7.2.1
	25 sites in southern Australia	Profitability of fodder supply production declined at most sites due to shorter growing season.	A2 2050	
	Southern Australia	Decline in NPP of grassland from historical climate will be 9% in 2030, 7% in 2050, and 14% in 2070. Declines in ANPP were larger at lower rainfall locations. Operating profit (at constant prices) fell by an average of 27% in 2030, 32% in 2050, and 48% in 2070.	A2 2030, 2050, 2070	Moore and Ghahramani (2013)
	Tasmania	Dairy yields increase 0.5–6.2%	A1B, ECHAM5/MPI-OM 2050	Hanslow et al. (2014)
	Victoria	Dairy yields decrease 1.3–6.7%		
	New South Wales	Dairy yields decrease 1.4–6.6%		
	Southern Australia	Dairy yields decrease 2.2–8.1%		
	New Zealand	Change in agricultural production: • Dairy: -2.8%, -4.3% • Sheep and beef: -6.1%, -8.8%	2030 Global temperature change 25%, 75% of the way between lower and upper bounds of scenarios in IPCC 2001 Third Assessment Report.	Wratt et al. (2008)

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Box 7-1 (continued)

Region	Sub-region	Climate change impacts	Scenarios	Reference
Central and South America	Andean Mountain countries	Beef and dairy cattle, pigs, and chickens could decrease between 0.9 and 3.2% while sheep could increase by 7%.	2060 Hot and dry scenario	Section 27.3.4.1
	Colombia, Venezuela, and Ecuador	Beef cattle choice declined.	2060 Milder and wet scenario	
	Argentina and Chile	Beef cattle choice increased.	Future climate change	
	Pernambuco, Brazil	Milk production and feed intake in cattle strongly affected.	Future climate change	Silva et al. (2009)
North America	Central United States	Dairy yields decrease 16–30%.	Baseline CO ₂ , 2× CO ₂ , 3× CO ₂ CGCM/Hadley	Mader et al. (2009)

pathogens may decrease in lowland tropical areas as temperatures increase (Mills et al., 2010). The temperate regions may become more suitable for tropical vector-borne diseases such as Rift Valley fever and malaria, which are highly sensitive to climatic conditions (Rocque et al., 2008). Vector-borne diseases of livestock such as African horse sickness and bluetongue may expand their range northward to the Northern Hemisphere because rising temperatures increase the development rate and winter survival of vectors and pathogens (Lancelot et al., 2008). Diseases such as West Nile virus and schistosomiasis are projected to expand into new areas (Rosenthal, 2009). The distribution, composition, and migration of wild bird populations that harbor the genetic pool of avian influenza viruses will all be affected by climate change, although in ways that are somewhat unpredictable (Gilbert et al., 2008). The changing frequency of extreme weather events, particularly flooding, will affect diseases too. For example, outbreaks of Rift Valley fever in East Africa are associated with increased rainfall and flooding due to ENSO events (Gummow, 2010; Pfeiffer and Dobler, 2010). In general, the impacts of climate change on livestock diseases remain difficult to predict and highly uncertain (Mills et al., 2010; Tabachnick, 2010).

Box 7-1 summarizes impacts on a regional basis for crops and livestock. Developing countries rely heavily on climate-dependent agriculture and especially in conjunction with poverty and rapid increase in population they are vulnerable to climate change. While food insecurity is concentrated mostly in developing countries situated in the tropics (St. Clair and Lynch, 2010; Ericksen et al., 2011; Berg et al., 2013) global food supply may also be affected by heat stress in both temperate and subtropical regions (Teixeira et al., 2013). Chapter 22 identifies Africa as one of the regions most vulnerable to food insecurity. Climate change will also affect crop yields, food security, and local economies in Central America, northeast Brazil, and parts of the Andean region (Chapter 27) as well as in South Asia (Iqbal et al., 2009; see also Chapter 24). As shown in Box 7-1, in spite of uncertainties in responses at regional/national and subnational level, there is *high confidence* that most developing countries will be negatively affected by climate change in the future, although climate change may have positive effects in some regions. In high latitudes (such as Russia, northern Europe, Canada, South America) global warming may increase yields and expand the growing season and acreage of agricultural crops, although yields may be low due to poor soil fertility and water shortages in some regions (Kiselev et al., 2013; see also Chapters 23, 24, 26, 27). Although there is slim evidence, some studies do indicate a significant increase in crops

yields in some parts of China, Africa, and India. Like crops, livestock are also negatively affected by climate change in almost all the continents, as evidenced by the regional chapters of Working Group II. The dairy, meat, and wool systems primarily rely on fodders, grasslands, and rangelands. Climate change can impact the amount and quality of produce, profitability, and reliability of production (Chapters 23, 25). Higher temperature would lead to decline in dairy production, reduced animal weight gain, stress on reproduction, increased cost of production, and lower food conversion efficiency in warm regions. Disease incidence among livestock is expected to be exacerbated by climate change as most of the diseases are transmitted by vectors such as ticks and flies (Chapter 23), whose proliferation depends on climatic parameters of temperature and humidity.

7.4.4. Projected Impacts on Food Prices and Food Security

AR4 presented a summary of food price projections based on five studies that used projected yield impacts as inputs to general or partial equilibrium models of commodity trade. Many additional projections of this type have been made since AR4, expanding the number of trade models used, the diversity of yield projections considered, and the disaggregation of prices by commodity (Hertel et al., 2010; Calzadilla et al., 2013; Lobell et al., 2013b; Nelson et al., 2013). Many of the studies did not include CO₂ effects, which is sometimes justified on the grounds that studies are concerned with “worst-case” scenarios, or that the bias from omitting positive CO₂ effects balances the known bias from omitting negative effects of elevated O₃ and increased weed and pest damage. Studies also typically ignore potential changes in yield variability (Figure 7-6) and policy responses such as export bans which have important international price effects (Section 7.2.2).

Based on the studies cited above, it is *very likely* that changes in temperature and precipitation, without considering effects of CO₂, will lead to increased food prices by 2050, with estimated increases ranging from 3 to 84%. The combined effect of climate and CO₂ change (but ignoring O₃ and pest and disease impacts) appears *about as likely as not* to increase prices, with a range of projected impacts from –30% to +45% by 2050. One lesson from recent model intercomparison experiments (Nelson et al., 2014) is that the choice of economic model matters at least as much as the climate or crop model for determining

price response to climate change, indicating the critical role of economic uncertainties for projecting the magnitude of price impacts.

The AR4 concluded that climate changes are expected to result in higher real prices for food past 2050. This conclusion remains intact with *medium confidence*, albeit with a relative lack of new studies exploring price changes to 2100 or beyond. Of course, international prices are only one indicator of global food security, with the pathways by which price changes can affect food security outlined in Section 7.3.3. A limited number of studies have estimated the effects of price changes on food security and related health outcomes. Nelson et al. (2009) project that, without accelerated investment in planned adaptations, climate change by 2050 would increase the number of undernourished children under the age of 5 by 20 to 25 million (or 17 to 22%), with the range including projections with and without CO₂ fertilization. Lloyd et al. (2011) used the projected changes in undernourishment from Nelson et al. (2009) to project the impact of climate change on human nutrition, estimating a relative increase in moderate stunting of 1 to 29% in 2050 compared with a future without climate change. Severe stunting was projected to increase by 23% (central Africa) to 62% (South Asia).

In summary, if global yields are negatively impacted by climate change, an increase in both international food prices and the global headcount of food-insecure people is expected (*limited evidence, high agreement*). However, it is only *about as likely as not* that the net effect of climate and CO₂ changes on global yields will be negative by 2050, but *likely* that such changes will occur later in the 21st century. At the same time, it is *likely* that socioeconomic and technological trends, including changes in institutions and policies, will remain a relatively stronger driver of food security over the next few decades than climate change (Goklany, 2007; Parry et al., 2009). Importantly, all of the studies that project price impacts assume some level of on-farm agronomic adaptation, often by optimizing agronomic practices within the model. Most, but not all, also prescribe income growth rates as exogenous factors, despite the fact that incomes are heavily dependent on agriculture in many poor countries. One study that accounted for income effects found that, in countries such as Indonesia that had both a large share of poverty in agriculturally dependent households and yield impacts that were small relative to other regions, poverty was reduced by the effects of climate change (Hertel et al., 2010). However, in most countries the positive income effects of higher prices could not outweigh the costs of reduced productivity and higher food prices.

Recent work has also highlighted that productivity in many sectors besides agriculture are significantly influenced by warming, with generally negative effects of warming on economic output in tropical countries (Hsiang, 2010; Dell et al., 2012). Given the importance of incomes to food access, incorporating these effects into future estimates of food security impacts will be important. Conflict is also known to be an important factor in food security (FAO, 2010), and evidence of climate variability effects on conflict risk (Hsiang et al., 2011) indicates a need to also consider this dimension in future work (Chapter 12).

Since the impacts of climate change on food production and food security depends on multiple interacting drivers, the timing of extreme events, which are expected to become more frequent (IPCC, 2012), is critical. Extremes contribute to variability in productivity (Figure 7-6)

and can form part of compound events that are driven by common external forcing (e.g., El Niño), climate system feedbacks, or causally unrelated events (IPCC, 2012). Such compound events, where extremes have simultaneous impacts in different regions, may have negative impacts on food security, particularly against the backdrop of increased food price volatility (Figure 7-3). There are very few projections of compound extreme events, and interactions between multiple drivers are difficult to predict. Effective monitoring and prediction, and building resilience into food systems, are likely to be two key tools in avoiding the negative impacts resulting from these interactions (Misselhorn et al., 2010).

7.5. Adaptation and Managing Risks in Agriculture and Other Food System Activities

7.5.1. Adaptation Needs and Gaps Based on Assessed Impacts and Vulnerabilities

7.5.1.1. Methods of Treating Impacts in Adaptation Studies—Incremental to Transformational

The pervasiveness of climate impacts on food security and production (Section 7.2), the commitment to future climate change from past GHG emissions (WGI AR5 SPM), and the very high likelihood of additional and likely greater climate changes from future GHG emissions (WGI AR5 SPM) mean that some level of adaptation of food systems to climate change will be necessary. Here we take adaptation to mean reductions in risk and vulnerability through the actions of adjusting practices, processes, and capital in response to the actuality or threat of climate change. This often involves changes in the decision environment, such as social and institutional structures, and altered technical options that can affect the potential or capacity for these actions to be realized. Adaptation can also enhance opportunities from climate change (WGII AR4 Chapter 5; Section 17.2.3). These adaptations will need to be taken in the context of a range of other pressures on food security such as increasing demand as a result of population growth and increasing per capita consumption (Section 7.1).

Following the AR4, the literature on adaptation and food production has increased substantially, although there has been less focus on adaptations to food systems and on value chains: the linked sets of activities that progressively add value as inputs are converted into products the market demands. Many adaptation frameworks or approaches have been published, informing the approach in the AR4 that addressed both autonomous and planned adaptations. Autonomous adaptations are incremental changes in the existing system including through the ongoing implementation of extant knowledge and technology in response to the changes in climate experienced. They include coping responses and are reactive in nature. Planned adaptations are proactive and can either adjust the broader system or transform it (Howden et al., 2010). Adaptations can occur at a range of scales from field to policy. There is an increasing recognition in the literature that while many adaptation actions are local and build on past climate risk management experience, effective adaptation will often require changes in institutional arrangements and policies to strengthen the conditions favorable for effective adaptation

including investment in new technologies, infrastructure, information, and engagement processes (Sections 14.3-4, 15.2.4). Building adaptive capacity by decision makers at all scales (Nelson et al., 2008) is an increasingly important part of the adaptation discourse which has also further addressed costs, benefits, barriers, and limits of adaptation (Adger et al., 2009). The sector-specific nature of many adaptations means that sectors are initially addressed separately below.

7.5.1.1.1. Cropping

Effective adaptation of cropping could be critical in enhancing food security and sustainable livelihoods, especially in developing countries (WGII AR4 Chapter 5; Section 9.4.3.1). There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times, crop cultivars and species, and marketing arrangements (Fujisawa and Koyabashi, 2010; Olesen et al., 2011; see also Section 9.4.3.1), although this response is not ubiquitous (Bryan et al., 2009). There are a large number of potential adaptations for cropping systems and for the food systems of which they are part, many of them enhancements of existing climate risk management and all of which need to be embedded in the wider farm systems and community contexts.

The possibility of extended growing seasons due to higher temperatures increasing growth in cooler months means that changing planting dates is a frequently identified option for cereals and oilseeds provided there is not an increase in drought at the end of the growing season (Krishnan et al., 2007; Deressa et al., 2009; Magrin et al., 2009; Mary and Majule, 2009; Meza and Silva, 2009; Tingem and Rivington, 2009; Travasso et al., 2009; Laux et al., 2010; Shimono et al., 2010; Stöckle et al., 2010; Tao and Zhang, 2010; Van de Geisen et al., 2010; Olesen et al., 2011; Cho et al., 2012). Aggregated across studies, changing planting dates may increase yields by a median of 3 to 17% but with substantial variation (Table 7-2). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura and Angus, 2010), seedling transplanting, and seed priming and these

adaptations can be integrated with varieties with greater thermal time requirements so as to maximize production benefits and to avoid late spring frosts (Tingem and Rivington, 2009; Cho et al., 2012). There can, however, be practical constraints to early sowing such as seedbed condition (van Oort et al., 2012). In some situations early sowing may allow double cropping or intercropping where currently only a single crop is feasible. For example, this could occur for irrigated maize in central Chile (Meza et al., 2008) and the double crop wheat/soybean in the southern pampas of Argentina (Monzon et al., 2007), increasing productivity per unit land although increasing nitrogen and water demand at the same time. However, in Mediterranean climates, early sowing of cereals is dependent on adequate planting rains in autumn and climate projections indicate that this may decrease in many regions (WGI AR5 SPM), limiting the effectiveness of this adaptation and possibly resulting in later sowings than are currently practiced. In such circumstances, use of short duration cultivars could be desirable so as to reduce exposure to end-of-season droughts and high-temperature events (Orlandini et al., 2008; Walter et al., 2010). There is *medium confidence* that optimization of crop varieties and planting schedules appears to be effective adaptations, increasing yields by up to 23% compared with current management when aggregated across studies (*medium evidence, high agreement*; Table 7-2). This flexibility in planting dates and varieties according to seasonal conditions could be increasingly important with ongoing climate change (Meza et al., 2008; Deressa et al., 2009) and especially in dealing with projections of increased climate variability (Figure 7-6). Approaches that integrate climate forecasts at a range of scales in some cases are able to better inform crop risk management (Cooper et al., 2009; Baethgen, 2010; Li et al., 2010; Sultana et al., 2010) although such forecasts are not always useable or useful (Lemos and Rood, 2010; Dilling and Lemos, 2011; see also Section 9.4.4).

Warmer conditions may also allow range expansion of cropping activities polewards in regions where low temperature has been a past limitation (*limited evidence, medium agreement*) provided varieties with suitable daylength response are available and soil and other conditions suitable. This may particularly occur in Russia, Canada, and the Scandinavian nations although the potential may be less than earlier analyses indicated

Frequently Asked Questions

FAQ 7.3 | How could adaptation actions enhance food security and nutrition?

More than 70% of agriculture is rain fed. This suggests that agriculture, food security, and nutrition are all highly sensitive to changes in rainfall associated with climate change. Adaptation outcomes focusing on ensuring food security under a changing climate could have the most direct benefits on livelihoods, which have multiple benefits for food security, including enhancing food production, access to markets and resources, and reduced disaster risk. Effective adaptation of cropping can help ensure food production and thereby contribute to food security and sustainable livelihoods in developing countries, by enhancing current climate risk management. There is increasing evidence that farmers in some regions are already adapting to observed climate changes, in particular altering cultivation and sowing times and crop cultivars and species. Adaptive responses to climate change in fisheries could include management approaches and policies that maximize resilience of the exploited ecosystems, ensuring fishing and aquaculture communities have the opportunity and capacity to respond to new opportunities brought about by climate change, and the use of multi-sector adaptive strategies to reduce the consequence of negative impacts in any particular sector. However, these adaptations will not necessarily reduce all of the negative impacts of climate change, and the effectiveness of adaptations could diminish at the higher end of warming projections.

Table 7-2 | The simulated median benefit (difference between the yield change from baseline for the adapted and non-adapted cases) for different crop management adaptations: cultivar adjustment; planting date adjustment; adjusting planting date in combination with cultivar adjustment; adjusting planting date in combination with other adaptations; irrigation optimization; fertilizer optimization; other management adaptations. N represents the number of estimates used for each adaptation. The numbers in parentheses are the 25th and 75th percentiles. Data points where assessed benefits of management changes are negative are not included as farmers are unlikely to adopt these intentionally. Only studies with both a “no adaptation” and an “adaptation” assessment are used. Data taken from Rosenzweig et al. (1994); Karim et al. (1996); El-Shaher et al. (1997); Lal et al. (1998); Moya et al. (1998); Yates and Strzepek (1998); Alexandrov (1999); Kaiser (1999); Reyenga et al. (1999); Southworth et al. (2000); Tubiello et al. (2000); DeJong et al. (2001); Aggarwal and Mall (2002); Alexandrov et al. (2002); Corobov (2002); Easterling et al. (2003); Matthews and Wasmann (2003); Droogers (2004); Howden and Jones (2004); Butt et al. (2005); Erda et al. (2005); Ewert et al. (2005); Gbetibouo and Hassan (2005); Xiao et al. (2005); Zhang and Liu (2005); Abraha and Savage (2006); Challinor et al. (2009); Tingem and Rivington (2009); Thornton et al. (2010); Deryng et al. (2011); Lal (2011); Tao and Zhang (2011b).

Management option	Cultivar adjustment (N = 56)	Planting date adjustment (N = 19)	Planting date and cultivar adjustment (N = 152)	Irrigation optimization (N = 17)	Fertilizer optimization (N = 10)	Other (N = 9)
Benefit (%) from using adaptation	23 (6.8, 35.9)	3 (2.1, 8.3)	17 (9.9, 26.1)	3.2 (2, 8.2)	1 (0.25, 4.8)	6.45 (3.2, 12.8)

owing to increased climate extremes, water limitations, and various institutional barriers (Alcamo et al., 2007; Bindi and Olesen, 2011; Dronin and Kirilenko, 2011; Kulshreshtha, 2011; Kvalvik et al., 2011; Tchebakova et al., 2011). In many of these cases, the northerly range expansion may only offset the reduction in southerly cropping areas and yields due to lower rainfall, water shortages, and high temperatures (*limited evidence, high agreement*).

Improving cultivar tolerance to high temperature is a frequently identified adaptation for almost all crops and environments worldwide as high temperatures are known to reduce both yield and quality (Krishnan et al., 2007; Challinor et al., 2009; Luo et al., 2009; Wassmann et al., 2009; Shimono et al., 2010; Stöckle et al., 2010), noting that a new cultivar usually takes between 8 and 20 years to deliver and so it is important to be selecting cultivars for expected future climate and atmospheric conditions (Ziska et al., 2012). Improving gene conservation and access to extensive gene banks could facilitate the development of cultivars with appropriate thermal time and thermal tolerance characteristics (Mercer et al., 2008; Wassmann et al., 2009) as well as to take advantage of increasing atmospheric CO₂ concentrations (Ziska et al., 2012) and respond to changing pest, disease, and weed threats with these developments needing to be integrated with *in situ* conservation of local varieties (IAASTD, 2009).

Similarly, the prospect of increasing drought conditions in many cropping regions of the world (Olesen et al., 2011) raises the need for breeding additional drought-tolerant crop varieties (Naylor et al., 2007; Mutekwa, 2009; Tao and Zhang, 2011a), for enhanced storage and access to irrigation water, more efficient water delivery systems, improved irrigation technologies such as deficit irrigation, more effective water harvesting, agronomy that increases soil water retention through practices such as minimum tillage and canopy management, agroforestry, increase in soil carbon, and more effective decision support (Verchot et al., 2007; Lioubimtseva and Henebry, 2009; Luo et al., 2009; Falloon and Betts, 2010; Piao et al., 2010; Olesen et al., 2011), among many other possible adaptations (Sections 22.4.2, 22.4.3). There is *medium confidence (limited evidence, high agreement)* that crop adaptations can lead to moderate yield benefits (mean of 10 to 20%) under persistently drier conditions (Deryng et al., 2011) and that irrigation optimization for changed climate can increase yields by a median of 3.2% (Table 7-2) as well as having a range of other beneficial effects (Section 3.7).

Diversification of activities is another climate adaptation option for cropping systems (Lioubimtseva and Henebry, 2009; Thornton et al., 2010). For example, Reidsma and Ewert (2008) found that regional farm diversity reduces the risk that is currently associated with unfavorable climate conditions in Europe. Diversification of activities often incorporates higher value activities or those that increase efficiency of a limited resource such as through increased water use efficiency (Thomas, 2008) or to reduce risk (Seo and Mendelsohn, 2008; Seo, 2010; Seo et al., 2010). In some cases, increased diversification outside of agriculture may be favored (Coulthard, 2008; Mary and Majule, 2009; Mertz et al., 2009a,b).

The above adaptations, either singly or in combination, could significantly reduce negative impacts of climate change and increase the benefit of positive changes as found in WGII AR4 Chapter 5 (*medium evidence, high agreement*). To quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been undertaken for wheat, rice, and maize (see Figure 7-4). This meta-analysis adds more recent studies to that undertaken in the WGII AR4 Chapter 5. It indicates that the average benefit (the yield difference between the adapted and non-adapted cases) of adapting crop management is equivalent to about 15 to 18% of current yields (Figure 7-8). This response is, however, extremely variable, ranging from negligible benefit from adaptation (even potential dis-benefit) to very substantial. The responses are dissimilar between wheat, maize, and rice (Figure 7-4) with temperate wheat and tropical rice showing greater benefits of adaptation. The responses also differ markedly between adaptation management options (Table 7-2). For example, when aggregated over studies, cultivar adaptation (23%) and altering planting date in combination with other adaptations (3 to 17%) provide on average more benefit than optimizing irrigation (3.2%) or fertilization (1%) to the new climatic conditions. These limits to yield improvements from agronomic adaptation and the increasingly overall negative crop yield impact with ongoing climate change (Figures 7-4, 7-5) mean a substantial challenge in ensuring increases in crop production of 14% per decade given a population of 9 billion people in 2050. This could be especially so for tropical wheat and maize, where impacts from increases in temperature of more than 3°C may more than offset benefits from agronomic adaptations (*limited evidence, medium agreement*).

Potential increased variability of crop production means that other climate-affected aspects of food systems such as food reserve, storage, and distribution policies and systems may need to be enhanced (IAASTD,

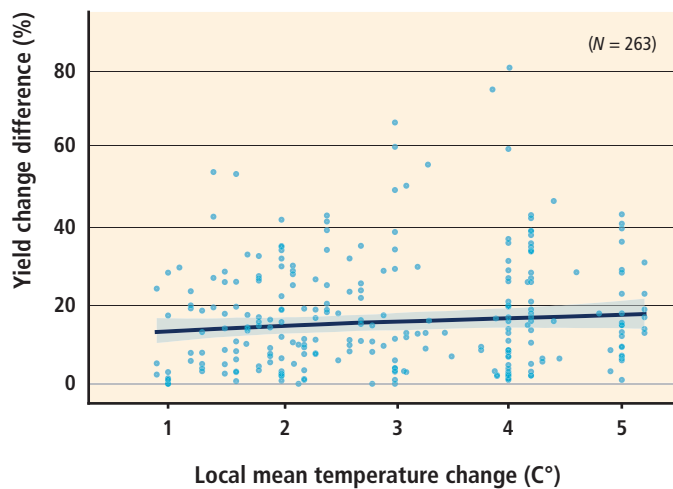


Figure 7-8 | Simulated yield benefit from adaptation calculated as the difference between the yield change from baseline (%) for paired non-adapted and adapted cases as affected by temperature and aggregated across all crops. The shaded bands at the 95% confidence interval are calculated as for Figure 7-4. Data points ($N = 31$) where assessed benefit of management changes are negative are not included as farmers are unlikely to intentionally adopt these. Data sources are the same as for Table 7-2 and only studies that examine both a “no adaptation” and an “adaptation” scenario are used so as to avoid the issues arising from unpaired studies documented in Figure 7-4 for tropical maize.

2009; Stathers et al., 2013) (*medium evidence, high agreement*) along with a range of broader, value-chain issues such as provision of effective insurance markets, clarity in property rights, building adaptive capacity, and developing effective participatory research cultures (Chapter 9; WGII AR4 Chapter 5).

It is notable that most of the above adaptations raised above and used in this analysis are essentially either incremental changes to existing agricultural systems or are systemic changes that integrate new aspects into current systems. Few could be considered to be transformative changes. Consequently, the potential adaptation benefits could be understated (*limited evidence, medium agreement*; Rickards and Howden, 2012).

7.5.1.1.2. Fisheries

Many of the resources for capture fisheries are already fully or overexploited, with an estimated 30% of stocks overexploited in 2009 and 57% fully exploited (FAO, 2012). Comparable global statistics are not available for inland fisheries but the status of those stocks may not be any better. Overfishing is widely regarded as the primary pressure on marine fishery resources but other human activities including coastal and offshore mining, oil and gas extraction, coastal zone development, land-based pollution, and other activities are also negatively impacting stock status and production (Rosenberg and Macleod, 2005; Cochrane et al., 2009). In inland fisheries, overfishing is also widespread, coupled with many other impacts from other human activities (Allan et al., 2005). Climate change adds another compounding influence in both cases.

Adaptive responses to reduce the vulnerability of fisheries and fishing communities could include management approaches and policies that

strengthen the livelihood asset base; improved understanding of the existing response mechanisms to climate variability to assist in adaptation planning; recognizing and responding to new opportunities brought about by climate change; monitoring biophysical, social, and economic indicators linked to management and policy responses; and adoption of multi-sector adaptive strategies to minimize negative impacts (Allison et al., 2009; Badjeck et al., 2010; MacNeil et al., 2010). Complementary adaptive responses include occupational flexibility, changing target species and fishing operations, protecting key functional groups, and the establishment of insurance schemes (Coulthard, 2008; Daw et al., 2009; FAO, 2009a; MacNeil et al., 2010; Koehn et al., 2011). Fishers and fish farmers will be vulnerable to extreme events such as flooding and storm surges that will require a range of adaptations including developing early warning systems for extreme events, provision of hard defenses against flooding and surges, ensuring infrastructure such as ports and landing sites are protected, effective disaster response mechanisms, and others (Daw et al., 2009).

Governance and management of fisheries will need to follow an ecosystem approach to maximize resilience of the ecosystem, and to be adaptive and flexible to allow for rapid responses to climate-induced change (Daw et al., 2009; FAO, 2009a; see also Section 6.4.2). Within an ecosystem approach, habitat restoration will frequently be a desirable adaptation option, particularly in freshwater and coastal environments (Koehn et al., 2011). A wide range of management tools and strategies have been developed to manage fisheries. These are all necessary but not sufficient for adaptation to climate change in fisheries (Grafton, 2010). Grafton argued that the standard tools for fisheries management were developed to control fishing mortality and to maintain adequate levels of recruitment to fishery stocks but without necessarily addressing the needs for resilience to change or to be able to function under changing climates. He therefore proposed that these conventional management tools must be used within processes that (1) have a core objective to encourage ecosystems that are resilient to change and (2) explicitly take into account uncertainties about future conditions and the effect of adaptation, and make use of models to explore the implications of these (Grafton, 2010). There are also opportunities for fisheries to contribute to mitigation efforts (FAO, 2009a; Grafton, 2010).

Aquaculture is the fastest-growing animal-food-producing sector with per capita consumption of products increasing at an average rate of 7.1% per year between 1980 and 2010 (FAO, 2012). Adaptive responses in aquaculture include use of improved feeds and selective breeding for higher temperature tolerance strains to cope with increasing temperatures (De Silva and Soto, 2009) and shifting to more tolerant strains of molluscs to cope with increased acidification (Huppert et al., 2009). Better planning and improved site selection to adapt to expected changes in water availability and quality; integrated water use planning that takes into account the water requirements and human benefits of fisheries and aquaculture in addition to other sectors; and improving the efficiency of water use in aquaculture operations are some of the other adaptation options (De Silva and Soto, 2009).

Integrated water use planning will require making trade-offs between different land and water uses in the watershed (Mantua et al., 2010). Insurance schemes accessible to small-scale producers would help to increase their resilience (De Silva and Soto, 2009). In some near-shore

locations there may be a need to shift property lines as the mean high water mark is displaced landwards by rising sea level (Huppert et al., 2009).

There are no simple, generic recipes for fisheries adaptation with Bell et al. (2011) suggesting a list of 25 separate but inter-related actions, together with supporting policies to adapt fisheries and aquaculture in the tropical Pacific to climate change (see also Section 30.6.2.1.1). These actions fall into three categories according to the primary objective: economic development and government revenue; maintaining the contribution of fish to food security; and maximizing sustainable livelihoods. Actions and policies for adaptation in fisheries and aquaculture must complement those for other sectors. Similar case-by-case, integrated planning will be required in all other regions and at scales from community to regional to achieve clearly defined adaptation goals.

7.5.1.1.3. Livestock

Extensive livestock systems occur over a huge range of biophysical and socio-ecological systems, with a consequent large range of potential adaptations. In many cases, these livestock systems are highly adapted to past climate risk, and there is *high confidence* that this provides a sound starting point for climate change adaptation (*medium evidence, high agreement*; Thornton et al., 2009a). These adaptations include matching stocking rates with pasture production; adjusting herd and watering point management to altered seasonal and spatial patterns of forage production; managing diet quality (using diet supplements, legumes, choice of introduced pasture species and pasture fertility management); more effective use of silage, pasture spelling, and rotation; fire management to control woody thickening; using more suitable livestock breeds or species; migratory pastoralist activities; and a wide range of biosecurity activities to monitor and manage the spread of pests, weeds, and diseases (Fitzgerald et al., 2008; Howden et al., 2008; Nardone et al., 2010; Ghahramani and Moore, 2013; Moore and Ghahramani, 2013). Combining adaptations can result in substantial increases in benefits in terms of production and profit when compared with single adaptations (Ghahramani and Moore, 2013; Moore and Ghahramani, 2013). In some regions, these activities can in part be informed by climate forecasts at differing time scales to enhance opportunities and reduce risks including soil degradation (McKeon et al., 2009). Many livestock systems are integrated with or compete for land with cropping systems and one climate adaptation may be to change these relationships. For example, with increased precipitation, farmers in Africa may need to reduce their livestock holdings in favor of crops, but with rising temperatures, they may need to substitute small ruminants in place of cattle with small temperature increases or reduce stocking rates with larger temperature rises (Kabubo-Mariara, 2009; Thornton et al., 2010). As with other food systems there is a range of barriers to adaptation that could be addressed on-farm and off-farm by changes in infrastructure, establishment of functioning markets, improved access to credit, improved access to water and water management technologies, enhanced animal health services, and enhanced knowledge adoption and information systems (Howden et al., 2008; Kabubo-Mariara, 2008; Mertz et al., 2009b; Silvestri et al., 2012).

Heat stress is an existing issue for livestock in some regions (*robust evidence, high agreement*), especially in higher productivity systems

(Section 7.3.2.6). For example, some graziers in Africa are already making changes to stock holdings in response to shorter term variations in temperatures (Thornton et al., 2009a; see also 9.4.3.1). Breeding livestock with increased heat stress resistance is an adaptation often identified but there are usually trade-offs with productivity as well as benefits including animal welfare and so this option needs careful evaluation (Nardone et al., 2010). Increased shade provision through trees or cost-effective structures can substantially reduce the incidence of high heat stress days, reduce animal stress, and increase productivity, with spraying a less effective option (Gaughan et al., 2010; Nidumolu et al., 2013). In cooler climates, warming may be advantageous because of lesser need for winter housing and feed stocks.

7.5.1.1.4. Indigenous knowledge

Indigenous knowledge (IK) has developed to cope with climate hazards contributing to food security in many parts of the world. Examples in the Americas include Alaska, where the Inuit knowledge of climate variability ensured the source of food to hunters and reduced various risks (Alessa et al., 2008; Ford, 2009; Weatherhead et al., 2010) down to the southern Andes, where the Inca traditions of crop diversification, genetic diversity, raised bed cultivation, agroforestry, weather forecasting, and water harvesting are still used in agriculture (Goodman-Elgar, 2008; Renard et al., 2011; McDowell and Hess, 2012; see also Sections 9.4.3.1, 27.3.4.2). In Africa, weather forecasting, diversity of crops and agropastoralism strategies have been useful in the Sahel (Nyong et al., 2007). Rainwater harvesting has been a common practice in sub-Saharan Africa (Biazin et al., 2012) to cope with dry spells and improve crop productivity, while strategies from agropastoralists in Kenya are related to drought forecasting based on the fauna, flora, moon, winds, and other factors (Speranza et al., 2010). In South Africa, farmers' early warning indicators of wet or dry periods in Namibia based on animals, plants, and climate observations contributed to deal with climatic variability (Newsham and Thomas, 2011). In the same way, in Asia and Australia IK plays an important role to ensure food security of certain groups (Salick and Ross, 2009; Green et al., 2010; Marin, 2010; Speranza et al., 2010; Kalanda-Joshua et al., 2011; Pareek and Trivedi, 2011; Biazin et al., 2012), although IK and the opportunities to implement it can differ according to gender and age in some communities (Rengalakshmi, 2007; Turner and Clifton, 2009; Kalanda-Joshua et al., 2011; see also Section 9.3.5), leading to distinct adaptive capacities and options.

In addition to changes already occurring in climate (seasonal changes, changes in extreme events; IPCC 2012) projected changes beyond historical conditions could reduce the reliance on indigenous knowledge (Speranza et al., 2010; Kalanda-Joshua et al., 2011; McDowell and Hess, 2012) affecting the adaptive capacity of a number of peoples globally (*medium evidence, medium agreement*).

Moreover, there is *medium confidence* that some policies and regulations leading to limit the access to territories, promoting sedentarization, the substitution of traditional livelihoods, reduced genetic diversity and harvesting opportunities, as well as loss of transmission of indigenous knowledge, may contribute to limit the adaptation to climate change in many regions (*medium evidence, medium agreement*; Nakashina et al., 2012).

7.5.1.2. Practical Regional Experiences of Adaptation, Including Lessons Learned

Given the early stages of climate change, there are relatively few unequivocal examples of adaptation (Section 7.5.2) additional to existing climate risk management. Where there have been management changes these have often been in response to several driving variables of which climate is only one (Smit and Wandel, 2006; Mertz et al., 2009a; Chen et al., 2011; Odgaard et al., 2011; see also Section 9.4.3.1). The preparedness to consider adaptation even within an industry varies regionally (Battaglini et al., 2009) and in some regions there already appears to be adaptation to climate change occurring (Fujisawa and Koyabashi, 2010; Olesen et al., 2011; Bohensky et al., 2012; Section 9.4.3.1). Activities to build adaptive capacity to better manage climate change are more widespread (Twomlow et al., 2008) but there remain questions as to how this capacity will evolve and be maintained (Nelson et al., 2009). Crucial in this will be devolution of the decision-making process so as to integrate local, contextual information into adaptation decision making (Nelson et al., 2008).

7.5.1.3. Observed and Expected Barriers and Limits to Adaptation

Adaptation is strongly influenced by factors including institutional, technological, informational, and economic and there can be barriers (restrictions that can be addressed) and limits in all these factors (*robust evidence, high agreement*; Chapters 14, 15, 16). Several barriers to adaptation of food systems have been raised including inadequate information on the climate and climate impacts and on the risks and benefits of the adaptation options, lack of adaptive capacity, inadequate extension, institutional inertia, cultural acceptability, financial constraints including access to credit, insufficient fertile land, infrastructure, lack of functioning markets, and insurance systems (Bryan et al., 2009; Deressa et al., 2009; Kabubo-Mariara, 2009; De Bruin and Dellink, 2011, Silvestri et al., 2012; see also Chapter 16). Limits to adaptation can occur for example where crop yields drop below the level required to sustain critical infrastructure such as sugar or rice mills (Park et al., 2012). In some cases, these can be effectively irreversible. Some studies have shown that access to climate information is not the principal limitation to improving decision making and it can result in perverse outcomes, increasing inequities and widening gender gaps (Coles and Scott, 2009). Incomplete adoption of adaptations may also occur. Lack of technical options can also be a barrier to adaptation. New varieties of crops or breeds of livestock provide possible core adaptations of production systems (*medium evidence, high agreement*; Mercer et al., 2008; Tingem and Rivington, 2009); however, there is substantial investment needed to develop these along with delays before they are available, both of which can act as adaptation barriers. This may be addressed in part by investments to improve local crop varieties or livestock breeds that are easily adopted (IAASTD, 2009). There also can be physiological limits to performance such as upper temperature limits for heat tolerance (WGII AR4 Chapter 5).

7.5.1.4. Facilitating Adaptation and Avoiding Maladaptation

Adaptation actions would usually be expected to provide benefits to farmers, the food industry along the value chain, or perhaps to a broader

community. However, there are possible maladaptations that arise from adapting too early or too late, by changing the incorrect elements of the food system or changing them by the incorrect amount (Section 14.7). A key maladaptation would be one which increased emissions of GHGs, this making the underlying problem worse (*robust evidence, high agreement*; Smith and Olesen, 2010; WGIII AR4 Chapter 11). A recent review of agricultural climate change adaptation options found they tend to reduce GHG emissions (Smith and Olesen, 2010; Falloon and Betts, 2010) (*medium evidence, medium agreement*). These adaptations include measures that reduce soil erosion and loss of nutrients such as nitrogen and phosphorus and for increasing soil carbon, conserving soil moisture, and reducing temperature extremes by increasing vegetative cover. There is a strong focus on incremental adaptation of existing food systems in the literature since AR4, however, and this may result in large opportunity costs that could arise from not considering more systemic adaptation or more transformative change (*limited evidence, medium agreement*; Howden et al., 2010; Kates et al., 2012). For example, in the USA, changes in farming systems (i.e., the combination of crops) have been assessed as providing significant adaptation benefit in terms of net farm income (Prato et al., 2010) although in other regions this might be minor (Mandryk et al., 2012). There is a need to also engage farmers, policymakers, and other stakeholders in evaluating transformative, pro-active, planned adaptations such as structural changes (Mäder et al., 2006; McCrum et al., 2009; Olesen et al., 2011). This could involve changes in land allocation and farming systems, breeding of functionally different crop varieties, new land management techniques, and new classes of service from lands such as ecosystem services (Rickards and Howden, 2012). In Australia, industries including the wine, rice, and peanut sectors are already attempting transformative changes such as change in location so as to be early adopters of what are perceived as opportunities arising from change (Park et al., 2012). There is substantial commonality in adaptation actions within different agricultural systems. For example, changing varieties and planting times are incremental adaptations found in studies of many different cropping systems as evidenced by the sample size in the meta-analysis in this chapter. Collating information on the array of adaptation options available for farmers, their relative cost and benefit, and their broad applicability could be a way of initiating engagement with decision makers. In the climate mitigation domain, this has been attempted using marginal abatement cost curves that identify mitigation options, their relative cost, and the potential size of emission reductions (WGIII AR4 Chapter 11). These curves can be used in setting investment priorities and informing policy discussions. The local nature of many adaptation decisions, their interactions with other highly contextual driving factors, and the time and climate change-sensitive nature of adaptation decisions mean, however, that global, time-independent curves are not feasible. The studies aggregated in Table 7-2 indicate that some options may be more relevant and useful to consider than others. These results illustrate the potential scope and benefit of developing effective adaptation options if implemented in an adaptive management approach.

7.5.2. Food System Case Studies of Adaptation—Examples of Successful and Unsuccessful Adaptation

Incremental, systemic, and transformational adaptation to climate change is beginning to be documented, though the peer-reviewed

literature largely covers vulnerability assessments and intentions to act, not adaptation actions (Berrang-Ford et al., 2010).

Case 1: Incremental Adaptation in the Sahel

Much of the literature covers incremental, reactive adaptation, but given actors are constantly adapting to changing social and economic conditions, incremental adaptation to climate change is difficult to distinguish from other actions (Berrang-Ford et al., 2010; Speranza et al., 2010), and in fact is usually a response to a complex of factors. This case, of the zaï soil management practice in the Sahel region, is an example of a complex of factors driving local actions, and factors such as growing land scarcity and new market opportunities, rather than climate, may be the primary factors (Barbier et al., 2009; Mertz, 2009b). Inherent poor soil quality and human activities have resulted in soil degradation—crusting, sealing, erosion by water and wind, and hardpan formation (Fatondji et al., 2009; Zougmore et al., 2010). Zaï, a traditional integrated soil and water management practice, can combat land degradation and improve yield and decrease yield variability by concentrating runoff water and organic matter in small pits (20 to 40 cm in diameter and 10 to 15 cm deep) dug manually during the dry season and combined with contour stone bunds to slow runoff. A handful of animal manure or compost is placed in each pit. By breaking the soil crust, the pits facilitate greater water infiltration, while the applied organic matter improves soil nutrient status and attracts termites, which have a positive effect on soil structure. The zaï technique is very labor intensive, requiring some 60 days of labor per hectare. Innovations to the system, involving animal-drawn implements, can reduce labor substantially.

Case 2: Mixed Farming Systems in Tanzania

In Morogoro, Tanzania, farming households have adapted in many ways to climatic and other stresses (Paavola, 2008). They have extended cultivation through forest clearance or reducing the length of the fallow period. Intensification is under way, through change in crop choices, increased fertilizer use and irrigation, and especially greater labor inputs. Livelihood diversification has been the main adaptation strategy—this has involved more non-farm income-generating activities, tapping into natural resources for subsistence and cash income (e.g., charcoal production), and has included artisanal gold and gemstone mining. Households have also altered their cropping systems, for example, by changing planting times. Migration is another frequently used strategy—with farmers moving to gain land, access to markets, or employment.

Parents also send children to cities to work for upkeep and cash income to reduce the household numbers that need to be supported by uncertain agricultural income. While many of these strategies help in terms of the short-term needs, in the longer term they may be reducing the capacity of households to cope. For instance, land cover change interacting with climate changes has negative impacts on current and future water supplies for irrigation (Natkhin et al., 2013), and deforestation and forest degradation means faltering forest-based income sources. This will be particularly problematic to the more vulnerable groups in the community, including women and children.

7.5.3. Key Findings from Adaptations—Confidence Limits, Agreement, and Level of Evidence

There have been many studies of crop adaptation since the AR4. In aggregate these show that adaptations to changed temperature and precipitation will bring substantial benefit (*robust evidence, high agreement*), with some adaptations (e.g., cultivar adaptation and planting date adjustment) assessed as on average being more effective than others (e.g., irrigation optimization; Section 7.5.1.1.1). Most studies have assessed key farm-level adaptations such as changing planting dates and associated decisions to match evolving growing seasons and improving cultivar tolerance to high temperature, drought conditions, and elevated CO₂ levels. Limits to adaptation will increasingly emerge for such incremental adaptations as the climate further changes, raising the need for more systemic or transformational changes (*limited evidence, medium agreement*; Section 7.5.1.1). An example of transformational change is latitudinal expansion of cold-climate cropping zones polewards, but this may be largely offset by reductions in cropping production in the mid-latitudes as a result of rainfall reduction and temperature increase (*medium confidence, limited evidence*; Section 7.5.1.1.1). Adaptations to food systems additional to the production phase have been identified and sometimes implemented but the benefits of these have largely not been quantified.

Livestock and fisheries systems also have available a large range of possible adaptations often tailored to local conditions but there is not adequate information to aggregate the possible value of these adaptations although there is *high confidence (medium evidence, high agreement)* that they will bring substantial benefit, particularly if implemented in

Table 7-3 | Schematic key risks for food security and the potentials for adaptation in the near and long term for high and low levels of warming.

Climate-related drivers of impacts						Level of risk & potential for adaptation																				
Warming trend	Extreme temperature	Drying trend	Extreme precipitation	Carbon dioxide fertilization	Ocean acidification																					
Key risk	Adaptation issues & prospects			Climatic drivers	Timeframe	Risk & potential for adaptation																				
Reductions in mean crop yields because of climate change and increases in yield variability. (<i>high confidence</i>) [7.2, 7.3, 7.4, 7.5, Box 7-1]	With or without adaptation, negative impacts on average yields become <i>likely</i> from the 2030s with median yield impacts of 0 to -2% per decade projected for the rest of the century, and after 2050 the risk of more severe impacts increases.				<table border="1"> <thead> <tr> <th></th> <th>Very low</th> <th>Medium</th> <th>Very high</th> </tr> </thead> <tbody> <tr> <td>Present</td> <td colspan="3">[Bar chart showing low risk]</td> </tr> <tr> <td>Near term (2030–2040)</td> <td colspan="3">[Bar chart showing increasing risk]</td> </tr> <tr> <td rowspan="2">Long term (2080–2100)</td> <td colspan="3">[Bar chart showing high risk at 2°C]</td> </tr> <tr> <td colspan="3">[Bar chart showing very high risk at 4°C]</td> </tr> </tbody> </table>		Very low	Medium	Very high	Present	[Bar chart showing low risk]			Near term (2030–2040)	[Bar chart showing increasing risk]			Long term (2080–2100)	[Bar chart showing high risk at 2°C]			[Bar chart showing very high risk at 4°C]			Very low Medium Very high	
	Very low	Medium	Very high																							
Present	[Bar chart showing low risk]																									
Near term (2030–2040)	[Bar chart showing increasing risk]																									
Long term (2080–2100)	[Bar chart showing high risk at 2°C]																									
	[Bar chart showing very high risk at 4°C]																									



combination (Sections 7.5.1.1.2-3). Key livestock adaptations include matching stocking rates with pasture availability; water management; monitoring and managing the spread of pests, weeds, and diseases; livestock breeding; and adjusting to changed frequencies of heat stress and cold conditions (Section 7.5.1.1.3). Fishery adaptations include management approaches and policies that strengthen the livelihood asset base, take a risk-based ecosystem approach to managing the resource, and adopt multi-sector adaptive strategies to minimize negative impacts. Importantly, there is an emerging recognition that existing fishery management tools and strategies are necessary but not sufficient for adaptation to climate (Section 7.5.1.1.2).

Indigenous knowledge is an important resource in climate risk management and is important for food security in many parts of the world. Climate changes may be reducing reliance on indigenous knowledge in some locations but also some policies and regulation may be limiting the contribution that indigenous knowledge can make to effective climate adaptation (*medium evidence, medium agreement*; Section 7.5.1.1.4).

The focus on incremental adaptations and few studies on more systemic and transformational adaptation or adaptation across the food system mean that there may be underestimation of adaptation opportunities and benefits (*limited evidence, medium agreement*; Section 7.5.1.1). In addition to this, there is a range of limits and barriers to adaptation and many of these could be addressed by devolution of the decision-making process so as to integrate local, contextual information into adaptation decision making. A schematic summary of these issues is given in Table 7-3.

7.6. Research and Data Gaps—Food Security as a Cross-Sectoral Activity

Research and data gaps reflect that most work since AR4 has continued to concentrate on food production and has not included other aspects of the food system that connect climate change to food security. Features such as food processing, distribution, access, and consumption have recently become areas of research interest in their own right but only tangentially attached to climate change.

Many studies either do not examine yield variability or do not report it. Closer attention should be paid to yield variability in the quantity and quality of food production, especially given observed price fluctuations associated with climate events. We expect environmental thresholds and tipping points, such as high temperatures, droughts, and floods, to become more important in the future. Specific recommendations are for food production experiments in which changes in variability reflect predicted changes for given warming scenarios. Including thresholds in impact models, for especially high levels of global warming (i.e., 4 to 6°C above preindustrial), are highly likely to result in lower projections of yield, given changes in climate variability and increasing mean temperatures. Important gaps in knowledge continue to be studies of weeds, pests, and diseases, including animal diseases, in response to climate change and how related adaptation activities can be robustly incorporated into food security assessments. Yield and other agronomic data, at a range of spatial scales, are crucial to the development,

evaluation, and improvement of models. Model development is currently limited by lack of data.

Adaptation studies for cropping systems typically assess relatively minor agronomic management changes under future climate conditions only. Forthcoming studies should examine the impact of proposed adaptations when employed in the current climate. In this way management changes that are beneficial in a range of environments can be separated from management changes that are specifically targeted at climate change. Further, studies should be inclusive of the broader range of systemic and transformational adaptation options open to agriculture.

Current forecasts of changes in distribution and productivity of marine fish species and communities are typically at a global or regional scale and include adaptations to only a limited extent. Increasing the resolution to forecast impacts and changes at the national and local ecosystem scale would provide valuable information to governments and stakeholders and enable them to prepare more effectively for expected impacts on food production and security offered by fisheries.

Possibilities for agronomic and breeding adaptations of food production to global warming are possible up to high levels of climate change. However, food security studies are urgently required to estimate the actual range of adaptations open to farmers and other actors in the food system and the implementation paths for these, especially when possible changes in climate variability are included.

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