Chapter 7. Food Security and Food Production Systems

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Executive Summary

The effects of climate change on food production are already evident in several regions of the world (*medium evidence, high agreement*). Negative impacts of climate trends have been more common than positive ones, although the latter predominate at high latitudes (*high confidence*). Since AR4, there have been several periods of rapid food price increases, demonstrating the partial sensitivity of current markets to climate variability. The role of climate change in these recent price changes is poorly understood, but *likely* small relative to other factors (*medium evidence, high agreement*). Social and economic issues such as energy policy and changes in household income will remain the main drivers of changes in food security in the near-term, regionally and locally. [7.2, Figures 7-2/3/4, Table 7-1]

By mid-century, when the global population will reach about nine billion people, many elements of the food system will be adversely affected by changes in climate (*high confidence*). Thereafter, and with *robust evidence and high agreement,* the human food system at scales from the local to global and particularly in low-latitude lands will be seriously and negatively affected by projected climate change from the mid-21st century onwards. [7.1, 7.2, 7.4] Global arable area is likely to increase from 2007 to 2050 (*medium evidence, high agreement*), with projected increases over this period of between 9% and 25% (*medium evidence, medium agreement*). When the effects of global warming are included, estimates range from a 20% increase in cropping area to a decline of 9% but with large regional differences (*limited evidence, low agreement*). [7.4.1]

Under scenarios of high levels of warming, leading to global mean temperatures of 4-6 ºC or higher above pre-industrial levels, extrapolation from current models suggests that the global risk to food production and security becomes very severe (*medium evidence, high agreement*). Such risks could affect ca. 90% of the global population based on the human population at that time and its demographic distribution (*medium evidence, low agreement*). These effects will be additively compounded by other factors such as the rise in tropospheric ozone

levels (*medium evidence, medium agreement*) and competition for water resources as between agriculture, food systems and other sectors of the economy. [7-4, Figure 7-5]

Long term climate changes are impacting 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, 7.3.2.6, 7.4.2] These are expected to continue with negative impacts on nutrition and food security for especially vulnerable people in some regions but with benefits in other regions which become more favourable for aquatic food production (*medium evidence, high agreement*). [7.5.1.1.3]

There is new understanding since AR4 of the sensitivity of crops to extreme heat, which reinforces the importance of temperature changes for determining impacts of climate change on crop yield at regional scales (*medium evidence, medium agreement*). At scales of individual countries or smaller, differences in precipitation projections continue to be an important source of uncertainty in future impacts (*medium evidence, high agreement*). [7.3]

Extreme heat also a negative effect on food quality in terms of nutrition and processing (*robust evidence, high agreement*). Impacts of increased heat stress and more frequent extreme events will be negative in all regions for livestock (*robust evidence, high agreement*); changes in animal diseases and vectors are less certain (*medium evidence, medium agreement*). Extreme climatic events, defined as extremely high and low temperatures and droughts and floods, are important for all food and fodder production, but particularly for annual determinate crops in which yield is harvested as seeds *(medium evidence, medium agreement)*. [7.3.2]

Evidence since AR4 confirms the positive effects of CO_2 and negative effects of elevated tropospheric ozone on crop yields (*high confidence*). There is emerging experimental and modelling evidence (*medium evidence, high agreement*) that interactions between production factors such as CO_2 and ozone, mean temperature, extremes, water and nitrogen can alter primary food production in complex ways. In concert with experimental results, the chapter results take more account of model and other uncertainties than has been the case previously. The large number of studies on mean crop yield impacts of changes in climate and CO_2 allow more robust statements than previously possible, but less confidence is given to simulated increases in yield variability (*medium evidence, medium agreement*). [7.3, Figures 7-5/7]

Changes in climate and CO_2 levels will enhance the distribution and increase the competiveness of agronomically important and invasive weeds (*robust evidence, high agreement*). Rising CO_2 reduces the effectiveness of herbicides (*medium evidence, high agreement*). The effects of climate change on disease pressure on food crops is uncertain, with evidence pointing to changed geographical ranges of diseases but less certain changes in disease intensity (*medium evidence, low agreement*). [7.3.2.1.2]

Without adaptation, moderate warming of up to 2ºC local temperatures are expected to reduce yields on average for the major cereals (wheat, rice and maize) in temperate regions, although many individual locations may benefit (*medium confidence*). There is confirmation that even modest warming up to 2ºC will decrease yields in low-latitude tropical regions (*robust evidence*, *medium agreement*). Reductions of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. From the 2070s onwards, all of the positive yield changes are in temperate regions, suggesting that yield reduction in the tropics are very likely by this time and substantial, particularly for wheat (*robust evidence, high agreement*). [7-4, Figures 7-5/6/7]

Adaptation possibilities of food systems to climate change show a very wide range in effectiveness, with *medium confidence* that adaptation will increase in effectiveness with increasing local mean temperature up to ca. 3ºC local warming above pre-industrial, after which the net benefits no longer increase (*medium evidence, medium agreement*). Most studies however, have focussed on food production rather than on adapting food systems. Generally (*medium evidence, high agreement,*) adaptation leads to lower reductions in food production than in its absence with an overall crop yield difference in adaptation cases of about 15-20% over non-adaption cases, with more effective adaption at higher latitudes (*limited evidence, medium agreement,*) but with some adaptation options more effective than others. Thus, benefits of adaptation are greater for wheat, rice and maize in temperate rather than tropical regions. Key adaptations for fisheries are for policy and management to maintain ecosystems in a state that is resilient to change, enabling occupational flexibility, and developing early warning systems for extreme events (*medium evidence, high agreement*). [7.5.1.1.3] Livestock systems' adaptations centre around 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 evidence, medium agreement*). A range of potential adaptation options exist across all food system activities, not just in the 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 7-5/9]

In summary, the key messages from the synthesis and evaluation of the current evidence of the impacts of climate change on food security and food production systems and their adaptation are that:

- **The effects of climate change on food production systems and security are starting to be evident. [7.2]**
- **The combination of an extra two billion people who will require upwards of 50% more food by the mid-21st century in combination with predicted decreases in yields of the major cereals for global warming of more than *ca.* 2-3ºC, will put ever increasing pressure on the food system as a whole, even after taking account of calculated uncertainties. [7.1, 7.4]**
- **Adaptation is predicted to be partially effective in ameliorating the negative effects of warming. [7.5]**
- **Extremely high levels of warming (i.e., above 4°C increase in global mean temperature) will place immense pressure on global food security. [7.4]**
- **Climate changes impacts on the abundance and distribution of harvested aquatic species will affect the nutrition and food security for especially vulnerable peoples. [7.3, 7.4]**

7.1. Introduction and Context

Many definitions of food security exist. Maxwell and Slater (2003) noted over 200 as early as 1992 (Spring, 2009) and more have been formulated (Defra, 2006). While many of the earlier definitions centred on food production, the majority of more recent definitions promote the notion of access to food. The 1996 World Food Summit definition (FAO, 1996), which states 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*", is still widely adopted. This definition puts the notion of access to food centre stage, also integrating dimensions of food availability, food utilisation and stability over time. The definition has a focus on the under-consumption of food whereas overconsumption and obesity are also relevant as factors in global public health.

While food security has been on the development agenda for decades, world-wide attention was given considerable impetus by the food 'price spike' in 2007-08, triggered by a complex set of long-term and short-term factors (von Braun and Torero, 2009). According to some estimates, the 'price spike' increased the number of hungry people by some 40 million (FAO, 2008) but other studies report a lower number (Headey and Fan, 2010). This link between food prices and numbers of food insecure people underscores the importance of the affordability of food in relation to food security. There is strong agreement that more than enough food is currently produced *per capita* to adequately feed the global population, yet about 870 million people remained hungry in 2012 (FAO, 2012), and millions more with insufficient nutrient (Pinstrup-Andersen, 2009). The two overriding questions for this chapter are how far climate change adds to current issues in food production systems and food security and the extent that it will do so in the future.

7.1.1. Summary from AR4

Food systems as integrated activities dealing with the impacts of climate change on the supply and demand for food did not feature strongly in AR4, where the strong emphasis was on food, fibre and forest production. Summary points from AR4 were that, with *medium confidence*, in mid- to high-latitude regions moderate warming will raise crop and pasture yields. However, even slight warming will decrease yields in low-latitude regions. Extreme climate and weather events will, with *high confidence*, reduce food production with or without changes in mean conditions. The benefits of adaptation in crops such as changing varieties and/or planting times and other managements enable avoidance of a 10-15% reduction in yield corresponding to 1-2°C local temperature increase. Adaptive capacity will be exceeded in low-latitude areas with temperature increases of more than 3°C. Local extinctions of particular fish species are expected with *high confidence* at the edges of their ranges and any slowing in the meridional overturning circulation will have serious negative impacts on fisheries with a *medium confidence* level.

7.1.2. Food Systems

A food system includes all processes and infrastructure involved in satisfying a population's food security. It relates to the *Activities* of gathering/catching, growing, harvesting, storing, processing, packaging, transporting, marketing, consuming food, and disposing of food waste and food-related items (the 'food chain'). It also includes the food security *Outcomes* of these *Activities* related to availability and utilization of, and access to, food as well as those related to other socioeconomic and environmental factors. Drawing together the extensive (yet relatively distinct) literatures built up by the food chain and food security communities, respectively, a revised 'food systems' model has been formalised (Ericksen, 2008; Ericksen *et al*., 2010; Ingram, 2011). This model recognises that food systems operate within, are influenced by, and feed back to social, political, economic and environmental contexts (Figure 7-1).

[INSERT FIGURE 7-1 HERE
Figure 7-1: Main global environmental change (GEC) and socioeconomic drivers of food systems, the main food system activities, and the outcomes of these activities. The figure also shows the three main components of food security (circles), all of which need to be stable over time: Availability (with elements of production, distribution and trade); Access (affordability, allocation and preference); and Utilisation (nutritional value, cultural value and safety).]

There is good agreement that the impacts of climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by socio-economic conditions (Vermeulen *et al*., 2012). Changes in food system activities give rise to changes in food security outcomes, *(medium evidence, high agreement)* but often researchers only consider the impacts on the food production element of food security. Food security needs consideration of how any intervention (i.e. a change in the food system activities) will also affect all other components of the food security outcomes; in principle, any intervention, even if only targeted at only one component (e.g. availability) will affect all three components due to the dynamic interactions between them, either directly or mediated via the feedback loops in Figure 7-1. Efforts to increase food production are nevertheless increasingly important as 50% more food will be needed by 2030 given current food consumption trends and assuming no significant reduction in food waste (FAO, 2010a).

7.1.3. The Current State of Food Security

There were an estimated 870 million people undernourished during the period 2010-2012, approximately 12.5% of the global population (FAO *et al*., 2012); thus, the vast majority of people currently have sufficient food. The vast majority of the undernourished (852 million) live in developing countries *(medium evidence, medium agreement).* Typically this is 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 higher incidence of food insecurity than estimated by FAO. Smith *et al*., (2006) estimated average food insecurity rates of 59% for 12 African countries, compared to 39% estimate from FAO for the same period.

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 up to 60% of people consuming insufficient calories for an active life. The largest numbers of food insecure 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 (Lopez *et al*., 2006; Pinstrup-Andersen, 2009).

Food insecurity is closely tied to poverty, and more detailed surveys on poverty provide insight into where the food insecure live. Globally, about 25 to 30 percent of poor people – measured using either a $1 or $2 per day standard - live in urban areas (Ravallion *et al*., 2007; IFAD 2010). This is partly because most poor countries have a greater fraction of people living in rural areas, but also because 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 found in urban areas, a number that has been growing in the past decade *(medium evidence, medium agreement)*. The urban share of poverty has also been rising in other regions, although more slowly. It is expected that 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).

For urban poor, who produce relatively small amounts of food, increases in food prices generally reduce food security. Since most rural poor produce some portion of the food they consume, the picture is more complicated. Much of the poor's income is from agricultural activities, which stands to benefit if prices rise. As mentioned, however, the rural poor still tend to be net consumers or marginal net producers. That is, they consume nearly all of what they grow and still need to buy additional food. If prices are rising more quickly for crops they grow, they can sell those and buy cheaper calories, resulting in a net increase in well-being. Rural wage rates may also increase in response to higher prices (for example, if workers are paid with a set amount of grain), with benefits for the many who earn part of their income from working other lands. Thus, the long-term welfare effects of price rises on rural poor are complex, and can vary depending on local factors.

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 favour 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). In some cases, trade interventions intended to reduce domestic food price volatility (e.g. export bans) had adverse effects both in local and global markets (HLPE, 2011; 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 upon their respective governance (HLPE, 2011; World Bank, 2012) with *robust evidence* and *medium agreement*.

7.2. Observed Impacts, with Detection and Attribution

7.2.1. Food Production Systems

Food production systems have changed substantially over the past few decades. These changes were primarily the result of factors other than atmospheric CO_2 or climate, such as cultivar improvement and increased use of synthetic fertilizers, herbicides and irrigation. In many contexts the effects of past changes in weather or CO_2 level are viewed as noise that obscures the effects of agronomic or genetic changes. Yet understanding the effect of past CO_2 and climate shifts are a useful precursor to assessing future impacts and adaptation needs.

The number and strength of non-climate drivers of food systems and food security make formal detection and attribution of impacts extremely difficult. Most of these confounding factors, such as fertilizer use or adoption of modern hybrids in the case of crops, 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 production) are often difficult to quantify. Attribution in other food production sectors is equally difficult. No studies to our knowledge simulate historical trends in food-related outcomes with and without changes in anthropogenic emissions of greenhouse gases. A possible exception (Auffhammer *et al*., 2006) compared rice yield predictions in India using climate model simulations of temperature in the late 20[th] century with yields using observed temperatures for 1930-1960, the latter period used as a surrogate for climate without changes in greenhouse gases after 1960. In their study, they find rice yields would have been significantly higher without greenhouse gas emissions, thus attributing negative impacts to emissions but with *limited evidence*.

Attributions of crop changes are further complicated by the fact that models linking climate and agriculture must, implicitly or explicitly, make assumptions about farmer behaviour. 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 (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 changes in climate over the past few decades. Based on these studies, there is *medium confidence* (*medium evidence, high agreement*) that climate trends have negatively affected wheat and maize production for many regions, as well as *medium confidence* (*medium evidence, high agreement,*) for negative impacts on global aggregate production of these crops (Figure 7-2). There is also medium confidence (*medium evidence, high agreement*) that effects on rice and soybean yields have been small in major production regions and globally (Figure 7-2). There is also *high confidence* (*robust evidence*, *high agreement)* that warming has benefitted crop production in some cold regions, such as Northeast China or the United Kingdom (Jaggard *et al*., 2007; Supit et al., 2010; Chen *et al*., 2011; Gregory and Marshall, 2012).

[INSERT FIGURE 7-2 HERE
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 (e.g., stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO_2 trends (see 7.3.2.1.2) but most did not. (a) shows number of studies with different level of impact (% yield per decade), (b) shows boxplot of studies separated by temperate vs. tropical regions, modelling approach (process-based vs. statistical), whether CO2 effects were included, and crop. Studies were for China (Tao *et al*., 2006; Tao *et al*., 2008; Wang *et al*., 2008; You *et al*., 2009; Chen *et al*., 2010; Tao *et al*., 2012), India (Pathak *et al*., 2003; Auffhammer *et al*., 2012), United States (Kucharik and Serbin, 2008), Mexico (Lobell *et al*., 2005), France (Brisson *et al*., 2010), Scotland (Gregory and Marshall, 2012) Australia (Ludwig *et al*., 2009), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch *et al*., 2010; Lobell *et al*., 2011). Values from all studies were converted to percentage yield change per decade.]

A sizable fraction of crop modelling studies were concerned with production for individual sites or provinces, scales below which the changes in climate conditions are attributable to anthropogenic activity (IPCC 2013, WG1, 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*., 2011), at which trends in several climatic variables, including average summer temperatures, have been attributed to anthropogenic activity (IPCC 2013, WG1, Chapter 10). In particular, global temperature trends over the past few decades are attributable to human activity (IPCC, 2013, WG1, Chapter 10), and the studies discussed above indicate that this warming has had significant impacts on global yield trends of some crops.

Figure 7-3 presents a summary of the detectability of changes in growing season conditions (as measured by total degree-days during summer) and crop yield changes, as well as the ability to attribute changes to climate and CO_2 trends (in the case of yield changes) or anthropogenic emissions (in the case of growing season climate changes). As discussed above, attribution of yield impacts relies on multi-step attribution based on process understanding and observed climate trends. Also illustrated in Figure 7-3 is the fact that not all major cropping regions have experienced significant climate trends in the past few decades, with the United States (in the lower, left-hand corner) the most notable example.

[INSERT FIGURE 7-3 HERE
Figure 7-3: Confidence in detection and attribution of observed impacts on crop yields and growing season degree days. Yield impacts include both direct climate effects and effects of elevated CO_2, but do not consider farmer adaptation. Confidence Levels were derived based on expert judgement of the available literature, following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010). Negative yield impacts: 1= Global maize , 2= Global wheat, 3= South Asia wheat; 4 = China maize and wheat; Positive yield impacts: 5 = UK wheat, sugarbeet, and potato. Increase in growing degree days: 6 = South Asia, main crops; 7 = China, main crops; 8 = Europe, main crops; 9 = Latin America, main crops; 10 = North America, maize and soybean. Yield impact confidence based on studies listed in Figure 7-2. Growing degree day confidence based on detection and attribution of trends in growing season temperatures (IPCC 2013, WG1, Chapter 10).]

In general, little work in food production or food security research has focused on formally attributing observed changes 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 modelling 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) attribute changes in rainfall extremes 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 have been observed and attributed to greenhouse gas emissions in nearly every region of the world (Alexander *et al.*, 2006; Zwiers *et al.*, 2011; IPCC, 2012). Positive trends in the occurrence of unusually hot nights are also attributable to human activity in most regions (Perring *et al.*, 2010, IPCC 2013, WG1, 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 have been attributed to greenhouse gas emissions (Zwiers *et al.*, 2011). At regional and local scales, however, trends in daytime maximum are harder to attribute to greenhouse gas emissions because of the prominent role of soil moisture and clouds in driving these trends (Christidis *et al.*, 2005; Lobell *et al.*, 2007; Zwiers *et al.*, 2011).

In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition on crops. It is *virtually certain* that the increase of atmospheric CO_2 by over 100 ppm since pre-industrial times has enhanced water use efficiency and yields, especially for C_3 crops, although these benefits played a minor role in driving overall yield trends (Amthor, 2001; Long *et al.*, 2006; McGrath and Lobell, 2011). As described earlier, increases in carbon dioxide are expected to have had negative impacts on carbon accretion in coral reefs with potential consequences for associated ecosystems and dependent social and economic activities (Hoegh-Guldberg *et al.*, 2007).

Emissions of CO_2 have also been associated with ozone (O_3) precursors that have driven a rise in tropospheric O_3 that harms crop yields (Morgan *et al.*, 2006; Mills *et al.*, 2007; *Section 7.3.2.1.2*). It is *very likely* that elevated O_3 since pre-industrial times has suppressed global production of major crops compared to what they would have been without O_3 increases, with estimated losses of roughly 10% for wheat and soybean and 3-5% for maize and rice (van Dingenen *et al.*, 2009). Impacts are most severe over India and China, but are also evident for soybean and maize in the United States (Fishman *et al.*, 2010; Boone et al. 2013).

7.2.1.2. Fisheries Production

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 inter-annual 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 North East 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; *robust evidence, high agreement*). In the North Sea, within the NE Atlantic, the average species richness in the region, as indicated by the number of species recorded per year increased by approximately 33% between 1985 and 2006, a period during which North Sea bottom temperatures also rose significantly (Hiddink and Hofstede, 2008); inferring that the increase in richness has been related to the rising water temperature. 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 SE Australia with large warming trends associated with more southwards incursion of the Eastern Australian Current. This has resulted in southward migration of marine species into the oceans around eastern Tasmania with consequent impacts on ecosystem dynamics (Last *et al*., 2011; *robust evidence, high agreement*).

Coral reef ecosystems are important sources of fish for food for local inhabitants. 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 followed by coastal development and pollution. The percentage under threat rises to 75% when the effect of rising ocean temperatures is added to these local impacts (Burke *et al*., 2011). There have been ongoing incidences of coral bleaching from rising sea temperatures since the 1970s which have already caused a global decline in coral reef cover and the trend is expected to continue as temperatures continue to rise (Munday *et al*., 2008; Chapter 30.6.1.1.2). Ocean acidification presents an additional threat by reducing carbon accretion (see Box 5-3 for further information). Wilson et al. (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, with species that depended on live coral for food and shelter most impacted while some species that fed on invertebrates, algae or detritus increased.

There is considerably less information available on climate change impacts on fisheries and fishery resources in freshwater systems. (Xenopoulus *et al*., 2005) investigated the effect of climate change and water withdrawal on freshwater fish extinctions under the assumptions of two scenarios which they reported were consistent with IPCC SRES 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 rivers experiencing reduced discharge, by 2070 up to 75% of the local fish biodiversity would be 'headed toward extinction' because of changes in climate and water consumption. The areas where the highest rates of fish extinctions were forecast tended to be in tropical and subtropical areas. The authors concluded that climate change, through increased evapotranspiration and reduced precipitation, would be the most important cause of this loss under the two SRES scenarios with water consumption making a considerably smaller contribution. Rates of extinction in fish species cannot be directly related to changes in fishery production but their results indicate that there will be changes in riverine fish communities and productivity which will impact on fisheries, with negative impacts more probable in tropical and sub-tropical systems (*limited evidence; low agreement*).

Considerable attention has been given to the impacts of climate change in some African lakes but with mixed interpretations (see also Chapter 22.3.3.1.4.). For inland fisheries, there is evidence that increasing temperature has reduced the primary productivity of Lake Tanganyika in East Africa by increasing the stability of the water column and thereby reducing upwelling of nutrients into surface waters. The 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 (Marshall, 2012) argues that the declines in fish catches experienced there can only have been caused by fishing. The Sahel region in northern Africa has historically demonstrated high variability. It experienced good rainfall in the 1960s, followed by severe drought over the next 7 years and below average precipitation from then until 2007. This dry period resulted in the area of Lake Chad decreasing from 26,000 km^2 in the 1960s to 1,425 km^2 in 2003. The decreasing area was associated with a decline in reported fish catches in Chad from over 100,000t in the late 1960s to under 70,000t in the early 1990s although there is considerable doubt about the accuracy of the reported catch figures, including up to the present (Welcomme, 2011; *medium evidence, low agreement*).

7.2.1.3. Livestock Production

In comparison to crop production, considerably less work has been published on observed impacts for non-crop food production systems, such as livestock and fisheries, and to our knowledge nothing has been published for hunting or collection of wild foods. 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).

7.2.2. Food Security

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 global food prices (Section 7.1.3). Although food prices gradually declined for most of the 20th century, since AR4 there have been several periods of rapid increases in international food prices (Figure 7-4). 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; Wright, 2011; Mueller et al. 2011; Abbot et al. 2011). Yet fluctuations and trends in food production are also widely believed to have played a role in he recent price changes, as illustrated in Figure 7-4. Spikes in prices do not always follow weather induced shortfalls in supply, as illustrated by the lack of response to several events in the 1990's. However, price effects are especially likely in years with low stocks, which can result from sustained periods of low supply growth relative to demand. 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*., 2011) 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 CO_2 over the study period were considered. Since 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.

[INSERT FIGURE 7-4 HERE
Figure 7-4: Since the AR4 report, food prices have reversed historical downward trend. Plot shows history of FAO food and cereal price index, along with events when a top 5 producer of a crop had yields 25% below trend line (indicative of a big weather effect). 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, perhaps reflecting the importance of interactions with global storage levels and rapid growth in crop demand. At the same time, because of increased biofuel demand, food prices are also increasingly linked to the price of crude oil, shown in the blue line (data available at http://www.eia.gov). Therefore, 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.]

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 through:

- Improved quantification and presentation of uncertainty. Descriptions of processes and trade-offs, and expression of uncertainty in the temporal dimension, are two methods that have been shown to be more effective that presentation of uncertainty in the outcome variable (e.g. yield).

- 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 interest in the use of Remote Sensing (RS)/Geographic information System (GIS) techniques for assessing temporal and spatial changes in land use particularly in agricultural land use for assessment of food security status (Fishman *et al*., 2010). There has also been an increase in the number of Free Air Concentration Enrichment (FACE) studies that examine ozone instead of, or in addition to, carbon dioxide. 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 only similar when the FACE experiments are grown under considerably more water stress than non-FACE experiments (Ainsworth *et al*., 2008). Hence comparisons between different methodologies must take care to control for differences in water levels. Another reason for differences between experiments may be differences in the temporal variance of CO_2 – i.e. whether concentrations are fluctuating or constant (Bunce, 2012). Unfortunately, the number of FACE studies are 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 physical experiments. This, in turn, enables a broader range of statements regarding the 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 (Challinor *et al*., 2009). 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 (Humaira *et al*., 2009), evaluation of water consumption and water use efficiency (Mo *et al*., 2009; Kang *et al*., 2009), estimation of changes and uncertainties (Bellocchi *et al*., 2010) and fostering communication between scientists, managers, policymakers and planners (*robust evidence; medium agreement*).

Novel developments since AR4 in the methodologies used for modelling since include more work that quantifies uncertainty in both climate and its impacts, particularly for crops, and models that include crop growth as part of broader land surface and earth systems models (e.g. (Bondeau *et al*., 2007; Osborne *et al*., 2007). Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Baysian methods to constrain crop model parameters (Iizumi *et al*., 2009; Tao *et al*., 2009a). It is also increasingly common to assess both bio-physical and socio-economic drivers of crop productivity within the same study (Fraser *et al*., 2008; Reidsma *et al*., 2009; Tao *et al*., 2009b; Challinor *et al*., 2010). Finally, an important recent development is the systematic comparison of results from different modelling 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 David, 2010; Rosenzweig *et al*., 2013).

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*., 2009; Hawkins *et al*., 2012; Ruane *et al*., 2013).

A considerable body of work since AR4 has used extensive datasets of country- , regional- and farm- level crop yield together with observed and/or simulated weather time series in order to assess the sensitivity of food production to weather and climate. These statistical models offer a complement to more process-based model approaches, some of which require many assumptions about soil and management practices. The regional-scale statistical models that have been developed in recent years can thus produce more widely applicable results than field and controlled environment experiments, whilst avoiding the need for assumptions regarding management and planting dates. 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.*, 2011). Statistical models usually exclude the direct impact of elevated CO_2, making multi-decadal prediction problematic. Similarly, technological progress and its interaction with climatic variability are not simulated by statistical models. Regional-scale process-based models tend to include at least some of these processes. In determining future trends, crop models of all types can only extrapolate based on historically-determined relationships. Process-based models extrapolate based on measured interactions and mechanisms, whilst statistical models extrapolate based on empirically determined relationships. Agro-climatic indices provide another alternative to process-based crop models that avoid various assumptions by focusing on farmer-relevant 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). Modelling and experiments are each subject to their own uncertainties. Measurement uncertainty is a feature of field and controlled environment experiments. For example, interactions between CO_2 fertilisation, temperature, soil nutrients, ozone, pests and weeds is not well understood (Soussana *et al.*, 2010) and therefore most crop models do not include all these effects, nor 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, since 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 normalised by increase in CO_2 have been found to vary between zero and over 30% among crop varieties (Tausz *et al.*, 2011).

Models have the advantage of exploring a larger number of situations, but with less certainty in the determination of the response variable than in field studies. The uncertainty in climate simulation is generally larger than, or sometimes comparable to, the uncertainty in crop simulation using a single model (Iizumi *et al.*, 2011).There is significant uncertainty in agricultural simulation arising from climate model error, and since AR4 the choice of method for GCM bias correction has been identified as a source of uncertainty, even in the absence of downscaling, which is comparable in some cases to that from scenarios and choice of GCM (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

The use of multiple crop models in impacts studies is relatively rare. Field-scale historical model intercomparisons have shown variations in yield and biomass of more than 100% (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-CO_2 interactions (Asseng *et al.*, 2013). 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.

7.3.1.2. Treatment of Adaptation in Impacts Studies

Adaptation occurs on a range of timescales 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.

7.3.2. *Sensitivity of Food Production to Weather and Climate*

Since AR4, understanding of the impacts of a range of biophysical processes and associated outcomes has been improved:

- Heat stress effects have been better quantified at regional and local scales. There is no evidence that the response is uniform across spatial scale.
- AR4 states that water stressed crops may benefit more than well-watered crops from elevated CO2. Work since then suggests this may not consistently be the case.
- Evidence shows the greater importance of temperature over precipitation in determining regional-scale crop yields in some regions
- Impacts on crop yield as a function of local temperature change: AR4 confirmation that even slight warming will decrease yields in low-latitude regions (*medium confidence*) and that temperate wheat yield decreases are *about as likely as not* for moderate warming.

The majority of research into the sensitivity of food production to weather and climate remains focussed on crops. The majority of that work is focussed on impacts on the major annual crops such as maize, wheat and rice, a focus that is commensurate with the area harvested of these crops (White *et al*., 2011). Whilst there are many other crops of importance to food systems, the crops discussed here reflect both the availability of research and the global remit of this chapter.

7.3.2.1. Cereals, Oilseeds, and Legumes

7.3.2.1.1. Mean and extremes of temperature and precipitation

Both statistical and process-based models have widely been used since AR4 to assess the response of crop yield to temperature. Model results confirm the importance of known 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*., 2013b). Temperatures responses are generally well-understood for temperatures up to the optimum temperature for 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 34 °C after flowering appear to rapidly speed senescence in wheat (Lobell *et al*., 2013b; Asseng *et al*., 2013), but many crop models do not represent this process.

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*., 2010). 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 cooler environments (Semenov et al., 2012; Teixeira *et al*., 2013).

In cool season legumes, the threshold for heat stress during the reproductive phase is above 25ºC (daily maximum temperature) and experimental results with field-pea in North India show that temperatures higher than 25ºC at the onset of the reproductive phase led to reductions in pod setting (30%), seeds per pod (41%) and seed weight (36%) and consequently total productivity decreased by 48% (Ali and Gupta, 2012). Also in North India chickpea yields during the last years decreased between 0.53 and 3 q. ha^{-1} per 1ºC increase in seasonal temperature (Kalra *et al*., 2008).Even if chickpea is more heat tolerant than other cool season legumes, high temperatures (above 30ºC) during the reproductive phase can affect seed yield (Devasirvatham *et al*., 2012). Simulation results for short duration pigeon pea in Kenya projected decreases in yields between 7% and 28.7% with 1ºC and 5ºC increase in temperature respectively (Cooper *et al*., 2009).

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*., 2009) found that the response crop yields to climate change in the drylands of East Africa is insensitive to rainfall, since wetter climates are associated with warmer temperatures that act to reduce yields. Variation in crop-climate relationships can also result from the analytical methods used and/or the spatial scale of the analysis e.g. (Challinor and Wheeler, 2008). For example, increases in daily maximum temperature have been found to increase the yield of rice at a number of sites across Asia (Welch *et al*., 2010), whilst negative responses due to spikelet sterility are a well-known phenomenon in controlled environment experiments. Crop models can be used to quantify abiotic stresses such as these (Challinor *et al*., 2009), although only by hypothesizing that the functional responses to weather derived from experiments are valid at regional scales. Thus, whilst many fundamental bio-physical 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.

Since 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)

A meta-analysis of yield impact studies for major cereals (Challinor *et al*., 2013), including both pre- and post- AR4 contributions, gave broadly similar results to AR4 and to a more recent meta-analysis using multiple impacts models (Frieler *et al*., 2013). Challinor *et al*. (2013) reported tropical and temperate regions separately: yields of maize, wheat and rice begin to decline with 1-2ºC of local warming in the tropics, with temperate maize yields being less clearly affected at these temperatures and moderately affected for greater warming (Figure 7-5). The new analysis confirms AR4 findings that even slight warming will decrease yields in low-latitude regions (*medium evidence, high agreement*). However, whilst AR4 had few indications of yield reductions at less than 2ºC of local warming, the new analysis has, in the absence of incremental adaptation, more yield decreases than increases at all temperatures. Hence, whilst AR4 concluded with *medium confidence* that in mid- to high-latitude regions moderate warming will raise crop yields, new knowledge suggests that temperate wheat yield decreases are *about as likely as not* for moderate warming. Quantitative assessments of yield changes can be found in section 7.4. Within both tropical and temperate regions regional variability, which cannot be summarised in meta-analyses, will be important in determining how climate change affects particular agricultural systems.

[INSERT FIGURE 7-5 HERE
Figure 7-5: Percentage simulated yield change as a function of local temperature change temperature for the three major crops and for temperate and tropical regions. Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, which are separated according to the presence (blue) or absence (red) of adaptation. Note that 10 of the 1125 datapoints across all six panels are outside the yield change range shown. These were omitted for clarity.]

7.3.2.1.2. Impact of carbon dioxide and ozone

There is further observational evidence since AR4 that response to a change in CO_2 depends on plant type; C_3 or C_4 (DaMatta *et al*., 2010). The effect of increase in CO_2 concentration tends to be higher in C_3 plants (e.g. wheat, rice, cotton, soybean, sugar beets, and potatoes) than in C_4 plants (e.g. corn, sorghum, sugarcane), because photosynthesis rates in C_4 crops are less responsive to increases in ambient CO_2 (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).

FACE studies have shown that the impact of elevated CO_2 varies according to temperature and availability of water and nutrients; yet there is a strong geographical bias of FACE studies towards temperate zone (Leakey et al., 2013). Water-stressed crops are expected to respond more strongly to elevated CO_2 than well-watered crops, because of CO_2 induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from elevated CO_2 than irrigated systems, and that rain-fed systems in drier regions or years will benefit more than in wetter conditions. This expectation has been cited in TAR and AR4, and new evidence based on historical observations supports this notion by demonstrating that the rate of yield gains in rain-fed systems is higher for dry years than for 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 vs wet signal (Challinor and Wheeler, 2008).

Ozone in the stratosphere provides protection from lethal short-wave solar ultraviolet radiation, but in the troposphere it is a phytotoxic air pollutant. Global background concentration of ozone has increased since pre-industrial era due to anthropogenic emission of its precursor, by vehicles, power plants, biomass burning and other sources of combustion. Like $CO_{2,}$ O_3 is taken up by green leaves through stomata during photosynthesis but unlike CO_2, its concentration is significantly variable depending on geographic location, elevation and extent of anthropogenic sources. Being a powerful oxidant, ozone 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 posing 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 ozone on yield losses on global (Van Dingenen *et al.*, 2009; Teixeira *et al.*, 2011; Avnery *et al.*, 2011a; Avnery *et al.*, 2011b) and regional level (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; Piao *et al.*, 2010); Bangladesh: (Akhtar *et al.*, 2010); Europe: (Hayes *et al.*, 2007; Vandermeiren *et al.*, 2009; Fuhrer, 2009). The global yield losses of soybean, wheat and maize in 2000 ranged from 8-15% amounting to production losses of $11-18 billion (Avnery *et al.*, 2011a). The projected yield losses for the near future (year 2030) would be substantial but less severe under IPCC B2 scenario than A2; yield reduction under A2 would be 9-25% with production losses of $17-35 billion and under B1 scenario 9-17% with production losses of $12-21 billion (Avnery *et al.*, 2011b). In separate meta-analyses, some researchers reported even higher losses in wheat yield (Feng *et al.*, 2008) and high losses in rice yield (Ainsworth, 2008) at elevated ozone concentrations. These studies also pointed out the regional hotspots of East and South-east Asia and Eastern US, strong seasonality of O_3 formation (with peaks in pre- and post-monsoon months in India) depending on precursor emission and climate factors and role of crop management practices, such as cropping system, crop species (Teixeira *et al.*, 2013) and crop genotype (Feng *et al.*, 2011), (Biswas *et al.*, 2008; Zhu *et al.*, 2011). The sensitivity of crops to O_3 damage was in the order: soybean ≥ wheat > rice > maize. The irrigated crops suffered highest production losses. Ozone may have direct effect on reproductive process, leading to reduced seed and fruit development and abortion of developing fruit (Royal Society, 2008; *robust evidence, high agreement*).

The interactive effects of ozone with other environmental factors such as CO_2, temperature, moisture, light, are important but not well understood. Generally, the ambient and increasing concentrations of O_3 and CO_2 individually exert counteractive effects on C_3 plants (Tianhong *et al.*, 2005; Ainsworth, 2008; Gillespie *et al.*, 2012); but their interactive effect may compensate for each other (Ainsworth, 2008; Taub *et al.*, 2008; Gillespie *et al.*, 2012). In some studies, crops grown in both elevated CO_2 and O_3 concentrations showed yield losses which were less than with O_3 alone (Taub *et al.*, 2008; Fuhrer, 2009). The losses might also be greater when elevated O_3 combines with high temperature (Long, 2012) particularly during grain filling of wheat, when elevated ozone causes premature leaf senescence (Feng *et al.*, 2008; Feng *et al.*, 2011). Such interactions may be important for understanding ozone tolerance in C_3 food crops and for exploiting rising CO_2 concentrations for yield enhancement (Ainsworth *et al.*, 2008; Mittler and Blumwald, 2010; Ziska *et al.*, 2012). Periods of abundant radiation, high temperature and adequate water supply most favourable for agricultural production are also favourable for the formation of surface ozone; thus the effects of ozone on crops are often not visible in contrast to other yield reducing factors such as insect pests and diseases (Long, 2012).

7.3.2.2. Other Crops

Increases in temperature are already affecting phenology in perennial crops since the accumulation of winter chill hours is decreasing. Observed trends in winter chill range between -50 and -260 chill hours per decade in California and predicted rates of reduced winter chill, for the period between 1950 and 2100, are on the order of -40 h per decade (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 (Farag *et al.*, 2010). The analysis made by (Wolfe *et al.*, 2008) using HadCM3 projections under A1F1 and B1 scenarios indicate that some 400 h could be assured along the century, benefiting species with low chill requirement in the north-eastern USA.

Earlier flowering and maturity have been observed *(robust evidence, high agreement*) worldwide in grapes (García-Mozo *et al.*, 2010; Duchêne *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 (Sugiura *et al.*, 2012; Glenn *et al.*, 2013). Assessing climate change impacts on fruit production in California towards 2050, (Lobell and Field, 2011) found a slightly positive yield trend (*ca.* 5%) for almonds and negative trends for table grapes (5%), berries (10%) and cherries (20%) as compared to 2000. Also in eastern Washington in US under A1F1 and B1 scenarios without the effect of elevated CO2, future climate change is projected to decrease apple production by 1%, 3%, and 4% for 2020, 2040, and 2080 respectively, but when the effect of CO_2 is added, yields are projected to increase by 6% (2020s), 9% (2040s), and 16% (2080s) (Stöckle *et al.*, 2010). 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). Grapes/wine production and quality will be affected in Europe, US, Australia
(Jones *et al.*, 2005; Wolfe *et al.*, 2008; Cozzolino *et al.*, 2010), Chapter 25 WG2), 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 like sugarcane and coffee are expected to migrate towards more favorable zones in the South (Pinto, 2007; Marin *et al.*, 2009; Pinto et al., 2008; Chapter 27 WG2). 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 40% (Glenn *et al.*, 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops towards 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).

Cassava is an important source of food for many people in Africa and Latin America and recent studies suggest that future climate could not significantly affect its productivity as this crop is characterized by elevated optimum temperature for photosynthesis and growth, and a positive response to CO_2 increases (Jarvis *et al.*, 2012; Rosenthal and Ort, 2012; El-Sharkawy, 2012).

The suitability for potato crops is expected to increase in very high latitudes and high tropical altitudes towards 2100 (Schaefleitner *et al.*, 2011). Projections for Europe indicate that by 2030 and 2050 the impacts on potato yields will be mostly positive but towards the end of the century negative impacts are expected in the overall continent except in some northern countries (Supit *et al.*, 2012). In Eastern China yields are expected to increase in the North and to decrease in the South by 2100 (Chavas *et al.*, 2009), also in the Peruvian Altiplano negative impacts are expected under A2 and B2 scenarios by 2100 (Sanabria and Lhomme, 2012) while in eastern Washington in US, potato yields could slightly decrease (-2/-3%) under A1F1 and B1 scenarios (Stöckle *et al.*, 2010).

7.3.2.3. Pests, Weeds, Diseases

7.3.2.3.1. Sensitivity of pests, weeds, and diseases to weather and climate

As a world-wide average, current 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, is estimated at 18% and 16%, respectively (Oerke, 2006). Although physical changes associated with climate uncertainty are recognized and assessed, (e.g. drought, water, temperature) in the context of agricultural productivity, less attention has focused on biological interactions and climate, even though it is universally recognized that weeds, insects and diseases have limited crop yield potential. A fair question then is to ask whether such limitations will increase or decrease in response to future changes in CO_2/climate?

The effects of weather on important diseases and pests, including optimal temperature and moisture conditions, have been studied in detail for decades (De Wolf and Isard, 2007). This research forms a base for understanding that climate change will change potential losses to many pests and diseases. Changes in temperature can support range expansions through changes in winter and summer extremes, and thus the potential for overwintering or summer survival. CO2 and ozone can either increase or decrease plant disease, and can exhibit important interactions in effects, suggesting incorporation of these risk factors in analyses may need to be system specific (Chakraborty *et al.*, 2008; Eastburn *et al.*, 2011). It is challenging to estimate the extent to which observed changes in effects may be due to climate change because of the many factors that interact to result in pest and disease risk and management decisions (Chakraborty and Newton, 2011; Garrett *et al.*, 2011). Interactions with landscape effects may be particularly important in such perennial agricultural systems as 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 available. Studies of a wheat experiment at Rothamsted Research Station UK, maintained for over 160 years, have revealed shifts in foliar wheat pathogens linked to rainfall, temperature, and SO_2 emissions (Bearchell *et al.*, 2005; Shaw *et al.*, 2008). Wheat rust risk has been observed to respond to ENSO (Scherm and Yang, 1995). Over almost seven 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). Up to a point, adaptation to climate change will be similar to adaptation to other new scenarios as agricultural systems have moved around the world (Coakley *et al.*, 1999; Juroszek and von Tiedemann, 2011). As an example of the effect of climate on management efficacy, higher diversity potato systems designed for management of potato late blight had lower utility in climatic zones where potato growing seasons were longer and presumably there were higher regional pathogen loads (Garrett et al., 2009).

Changes in climate are expected to affect the 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. Guitierrez (2000) has suggested that predator and insect herbivores are will respond differently to increasing temperature, with possible reductions in insect predation (i.e. greater insect numbers). While plant-pathogen interactions are recognised as a factor affecting crop yields, our ability to predict CO_2/climate change impacts on pathogen biology and subsequent changes on yield of rice, soybean, wheat inter alia is tenuous at best, 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*).

Ostensibly, since many agricultural weeds are C_4, and soybean, wheat and rice, C_3, increasing CO_2 should reduce crop losses due to weedy competition since the C_3 pathway, in general, shows a stronger response to rising carbon dioxide levels. However, the argument that rising CO_2 will reduce weedy competition because the C_4 photosynthetic pathway is over-represented among weed species (Holm, 1977) does not consider the range of available C_3 and C_4 weed species present within the agronomic seed bank. For example, in the United States, every crop, on average, competes with an assemblage of 8-10 weed species (Bridges, 1992). In addition, CO_2, and/or climate, can also affect weed demographics. For example, with field grown soybean, elevated CO_2 per se appeared to be a factor in increasing the relative proportion of C_3 to C_4 weedy species with subsequent reductions in soybean yields (Ziska and

Goins, 2006). For rice and barnyard grass (C_4), increasing CO_2 favored rice, but if both temperature and CO_2 increased simultaneously, the C_4 weed was favored, primarily because higher temperatures resulted in increased seed yield loss for rice (Alberto et al, 1996). Overall, rising atmospheric CO_2 can increase the extent of crop losses due to a greater response of the weed relative to the crop (Ziska, 2000; Ziska, 2003). If weeds are not managed such losses may exceed any observed stimulation in crop yield associated with elevated CO_2 (Ziska, 2000; Ziska, 2003). 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, in fact, be greater in response to increasing atmospheric CO_2 (Ziska, 2010). Climate change may be a factor in extending the northward migration of agronomic and invasive weeds (e.g. (Ziska *et al*., 2011). The projected warming may be exceeding maximum rates of plant migration observed in post-glacial time periods (Malcolm *et al*., 2002), resulting in preferential selection for the most mobile plant species. A number of characteristics associated with long-distance dispersal are commonly found among weeds (Rejmánek, 1996) suggesting that they will be among the fastest to migrate with increasing temperatures (Dukes and Mooney, 1999). In addition, climate (e.g. precipitation) and/or temperature may change the demographics of C_3 and C_4 weed species in crop production (e.g. (Ziska and Goins, 2006; McDonald *et al*., 2009).

Initial studies indicate a potential decline in herbicide efficacy with rising CO_2 and/or temperature for some weeds (Ziska and Goins, 2006; Archambault, 2007; Manea *et al*., 2011). For Canada thistle, increasing CO_2 appears to have induced greater below-ground growth of roots, diluting the active ingredient of the herbicide and making chemical control less effective (Ziska *et al*., 2004). To date, studies on physical, cultural or biological weed control are lacking.

7.3.2.3.2. Effects of climate change on pests, weeds, and diseases

Climate change scenario analyses are available for some pests and diseases. For example, 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 the coffee nematode in 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). Potato late blight risk increases in some areas of the world, and decreases in others, under climate change scenarios (Sparks *et al*., 2013). Luck (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 (Deutsch *et al*., 2008; 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).

7.3.2.4. Pastures and Livestock

Pastures response to climate change is complex because, in addition to the major climatic drivers (CO_2 concentration, temperature, and precipitation), other plant and management factors affect this response (e.g., 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. In addition, water availability may play a major role in the response of pasturelands to climate change although there are differences in species response (Izaurralde *et al*., 2011). There is general consensus that increases in CO_2 will benefit C_3 species; however, warmer temperatures and drier conditions will tend to favour C_4 species (Izaurralde *et al*., 2011; Hatfield *et al*., 2011, WG2 Chapter 4).

Projected scenarios for Europe indicate that increased temperatures and CO_2 concentrations have the potential to increase herbage growth and to favour legumes more than grasses, but changes in seasonal precipitation would reduce these benefits particularly in areas with low summer rainfall (Hopkins and Del Prado, 2007). Similarly, legume content of grasslands in most of southern Australia is projected to increase to the 2070s, with larger increases in wetter locations (Moore and Ghahramani, 2013). Further implications for grasslands may arise from increased frequency of droughts, storms and other extreme events (Hopkins and Del Prado, 2007).

Impacts of climate change on feed crops and grazing systems include changes in herbage growth brought about by changes in atmospheric CO_2 concentrations and rainfall and temperature regimes, and changes in the composition of pastures and in herbage quality. The interactions among climate, plants, livestock grazing and land management practices are complex, and evaluating the impacts of climate change on these elements is difficult (Craine *et al*., 2010). In North American cattle production systems, future increases in precipitation will probably not compensate for the declines in forage quality that accompany projected temperature increases, and cattle will experience greater nutritional stress in the future (Craine *et al*., 2010) Also in French grasslands (Graux *et al*., 2013) and in sown pastures in Tasmania (Perring *et al*., 2010), results from simulations indicate that forage quality will decrease in the future.

Pastureland species in the USA may experience accelerated metabolism and advanced development with rising temperature, often resulting in changes in length of the growing season, although soil resources will often constrain temperature effects (Izaurralde *et al*., 2011). Similar effects are projected for European grasslands, many of which may be mediated via management - sometimes with impacts on mitigation too: ruminants fed tropical legumes produced 20% less methane than those fed C_4 grasses (Archimède *et al*., 2011).

While elevated atmospheric CO_2 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). Evaluating the differential responses of plant species to elevated CO_2 will require models to include mechanisms of resource capture and use among plant functional types (Lazzarotto *et al*., 2009; Soussana *et al*., 2010). Studies on climate change impacts on pastureland that include assessment of the mediating effects of management as well as changes in water, carbon, and nutrient cycling have been undertaken (e.g. (Rütting *et al*., 2010; Moore and Ghahramani, 2013), but more comprehensive studies are needed (McKeon *et al*., 2009; Izaurralde *et al*., 2011).

Moreover, IPCC emission scenarios for many cropland regions project elevated ozone concentrations in the atmosphere to the 2050s and beyond. At the same time, crop sensitivity may decline in areas where warming is accompanied by drying, such as in central Europe (Soussana *et al*., 2010). Parameters in models for ozone risk assessment are uncertain and model improvements will be needed to identify regions most at risk from ozone in future climates (Fuhrer, 2009). At this stage, more experiments using free-air ozone enrichment will be needed across different habitats, climates and productivity levels before generalisations about the sensitivity of pastures to ozone can be made (Fuhrer, 2009).

As livestock 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 declines (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 (AR4 Chapter 5) and indicates that heat stress 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, 2008); 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). The impacts of a changing UK climate on dairy cow production were analysed 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, under a medium-high greenhouse gas emissions scenario, annual production and mortality losses amounting to some £40 million by the 2080s. Given that there is a genotype-by-environment interaction on the impacts of heat stress (Bohmanova *et al*., 2008), breeding goals that focus on production traits tend to reduce heat tolerance. Breeding goals that aim to reduce greenhouse gas emissions need to take possible future climatic conditions into account (Hoffmann, 2010). Tools to do this in developed country situations are becoming available (e.g. (Hayes *et al*., 2009). Developing countries may be more reliant on local breeds, most of which are not well characterized, although such breeds may be not only heat tolerant but also tolerant of poor seasonal nutrition and parasites and diseases (Hoffmann, 2010).

Host and pathogen systems will change their ranges because of climate change. Species diversity of some 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). An overall increase in suitable conditions for pathogens and vectors is expected, rather than just a shift in distribution, because minimum temperatures are increasing more than maximum temperatures (Ostfeld, 2009). Vector-borne diseases of livestock such as African horse sickness and bluetongue may expand their range northwards because rising temperatures increase the development rate and winter survival of vectors and pathogens (Cutler *et al*., 2010). 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 harbour 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 El Niño-Southern Oscillation events (Gummow, 2010; Pfeffer 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).

Current trends in consumption, production and environmental patterns will lead to water crises in many parts of the world (de Fraiture *et al*., 2010). Every populated river basin in the world will experience changes in river discharge, and large human and livestock populations will experience water stress such that proactive or reactive management interventions will almost certainly be required (Palmer *et al*., 2008). Climate change will affect the water resources available for livestock production and keeping via impacts on runoff and groundwater. In Kgatleng District, Botswana, climate change could lead to an annual increase of more than 20% in cattle water demand by 2050 because of increased temperatures under A1 SRES emission scenarios. At the same time, a decline is to be expected in the contribution of surface pan water to cattle water supply, leading to substantial increases in the abstraction of groundwater for cattle (Masike and Urich, 2008). Such problems of water supply for increasing livestock populations will be exacerbated by climate change in many places in sub-Saharan Africa and South Asia. Nevertheless, there are sufficient water resources available to satisfy global food demands during the next 50 years, but only if water is managed more effectively (de Fraiture and Wichelns, 2010). 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).

7.3.2.5. Food and Fodder Quality and Human Health

Climate change is will have some adverse impacts 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 which in turn could impact human and livestock health by altering nutritional intake. They also affect economic value by altering traits valuable to processers or the consumers. Food quality is any characteristic other than yield that is valuable to the producer or consumer, and includes properties such as protein and starch concentrations, which affect dough quality, dough strength, and loaf volume of wheat flour; chalkiness, amylose content and gelatinization temperature in rice, which affect taste; and mineral concentrations, which affect nutrient intake of consumers.

Change in N 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. Meta-analysis of 228 experimental observations finds decreases between 10 to 14 % in edible portions of wheat, rice, barley and potato, but only 1.5 % in soybeans, a nitrogen-fixing legume, when grown in elevated (540 - 958 ppm CO_2) compared to current (315 - 400 ppm CO_2) concentrations (Taub et al, 2008). The decrease in protein content of cereals grown in elevated CO_2 concentrations was reported by many other workers (Piikki *et al*., 2007; Hogy *et al*., 2009; Erbs *et al*., 2010; Ainsworth and McGrath, 2010; DaMatta *et al*., 2010; Erda et al., 2010; Fernando *et al*., 2012).

Mineral concentration of edible plant tissues are affected by growth in elevated CO_2 in a similar manner as N. Although there are numerous studies measuring mineral concentration, there are many minerals relevant to human health. Therefore, there are relatively few measurements for any given mineral. 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 P, Ca, S, Mg, Fe, Zn, Mn and Cu decline by 2.5 - 20 % in wheat grain and leaves of numerous species in elevated CO_2, but K increases insignificantly in wheat grain (Loladze, 2002; Hogy *et al*., 2009; Fernando *et al*., 2012). Since 2002, studies generally find decreases in Zn, S, P, Mg and Fe in wheat and barley grain, but results are mixed for Ca and K, whereas limited evidence shows an increase in Cu, Mo and Pb (Hogy *et al*., 2009; Erbs *et al*., 2010; Fernando *et al*., 2012). The magnitude of such decreases is likely to be affected by several factors including crop species, soil type, tissue (e.g. tuber, leaves or grain) and water status. In addition to effects of climate on plants directly, climate change-mediated soil degradation may affect nutrient composition by altering mineral availability (Lal, 2009).

The primary reason for the decline in protein concentration, and by extension mineral concentrations, is that enhanced production of carbohydrates in elevated CO_2 decreases the concentrations of all non-carbonaceous compounds because the increase in canopy carbon uptake increases without a concomitant increase in nutrient uptake. Thus, the increased amount of carbon dilutes the concentrations of other nutrients (Poorter *et al*., 1997). The declines in nitrogen concentration are usually larger than expected from carbon dilution alone though (Taub *et al*., 2008; Pleijel and Uddling, 2012) which indicates that nutrient uptake per unit biomass is lower under elevated CO_2 concentration. The reasons for this are unclear but altered root architecture, reduced root uptake activity and reduced flow of nutrients to the roots (Taub and Wang, 2008). Understanding the basis for these declines is imperative as it would allow for prediction of nutrient decline in various environments, and give some insight into nutrient change in relation to change in other environmental factors in the future climate.

Elevated O_3 concentrations appear to have the opposite effect as elevated CO_2. Meta-analysis of about 50 wheat experiments found that elevated O_3 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 likely response similarly. Similarly, experiments examining the effect of drought on mineral concentrations find both decreases and increases in mineral concentrations (Ghorbanian *et al*., 2011; Sun *et al*., 2011).

Elevated CO_2 can lower the nutritional quality of flour produced from grain cereals (Hogy *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). High and low temperature even for a short time during reproductive growth can cause pollen sterility and shriveling of grain in wheat with consequent reduction in yield and market value. Extreme temperatures and elevated CO_2 concentrations reduce milling quality of rice by increasing chalkiness, which causes breakage during milling, leading to reduced head yield (the percentage of unbroken kernels) but increased consumer -valued traits, such as reduced amylase concentration , increased mass viscosity and increased breakdown, all of which correlate with taste, are increased (Yang *et al*., 2007) . The cultivars, however, vary in their susceptibility (Ambardekar *et al*., 2011; Lanning *et al*., 2011). Rice is sensitive to daytime extreme temperature and humidity during flowering and also to high night-time temperature causing a decrease in rice eating quality and assimilates accumulation, and yield (Okada *et al*., 2009; Wassmann *et al*., 2009).

There is robust evidence and high agreement that elevated CO_2 on its own likely results in decreased N concentrations. Combining knowledge of N 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 the species. Increases in CO_2 concentration are global and uniform, thus this effect will have global impacts, but confidence in this effect does not imply confidence in changes regarding human health for several reasons. First, elevated CO_2 can increase yield of minerals (g mineral per m^2 land area) even though concentrations are decreased (Duval *et al*., 2011). Therefore, for any group for which increased crop yields allows for greater consumption (e.g., because they produce and consume the food directly, or through effects of prices) intake of calories and minerals could increases, despite lower mineral concentrations. 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. Second, altered temperature, precipitation and ozone concentrations affect nutrient concentrations and their effects are globally variable. Third, changes in mineral concentrations do not directly relate to changes in consumption since many foods are processed in ways that affect nutrient concentrations, e.g., the nutrient-rich outer layers of rice are removed, leaving the starch dense endosperm. Lastly, impacts on health must take into account current diets. Decreased mineral intake will matter for those who currently do not meet, or just barley 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 to no confidence regarding effects of climate change on human health through changes in nutrient composition. Hence, a complete understanding of how climate-induced changes in food quality will impact human health in different environments and how this information will be used to make predictions about impacts on health is needed.

7.3.2.6. Fisheries and Aquaculture

The fisheries and aquaculture sector differs from mainstream agriculture and is characterized by distinct interactions and needs in relation 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. This demand will increase 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 MT of fish will need to be produced by aquaculture to maintain current average *per capita* consumption of fish. Climate change is an additional threat to the sustainability of capture fisheries and aquaculture development, adding to the threats of over-fishing and other environmental impacts (FAO, 2009). 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. There is no conclusive evidence at this stage, but the potential risks of climate change enabling the spread of pathogenic species has been raised and there are some concerns that, for example, poleward increases in temperature could lead to the spread of pathogens with impacts on wild and cultured aquatic resources (De Silva and Soto, 2009).

7.3.2.6.1. Mean and extremes of temperature and precipitation

There is widespread agreement that, under most emission scenarios, increasing mean temperatures will lead to changes in the distribution of marine fish and invertebrate species. In general, the distribution of species will shift towards the poles as has already been observed in, for example, the North Sea (Brander, 2007)) and Australia (Hobday, 2010) JP: I have highlighted the following in red for you to decide if it needs to be deleted,Chapter 6 of this volume). These shifts will result in positive and negative impacts on fisheries production with the direction of change varying from locality to locality and species to species. Overall, increased temperatures are expected to reduce ecosystem productivity in most tropical and subtropical oceans, seas and lakes and to increase productivity in high latitudes. Projections based on a dynamic bioclimate envelope model under the SRES A1B scenario suggested that climate change could lead to an average 30–70% 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). A recent 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 3.5%. This forecast was predicated on the assumption that marine fisheries and fish resources would be managed sustainably (Merino *et al.*, 2012). A study on the effects of climate warming on marine fish along the Portuguese coast forecast, under the A2 and B2 emission scenarios, that fish species richness would increase, potentially creating opportunities for the development of new commercial fisheries (Vinagre *et al*., 2011). 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 EEZ. The results indicated that by 2060 the large-scale commercial fisheries in all of the regions that were covered by the models would experience an overall increase of 90% in their economic returns, although differing across sectors. The change in returns for the small-scale sector varied between the regions from a decrease of 30-51% in some regions to an increase of 9-14% in another. The difference between the sectors was because the large-scale fisheries had greater flexibility to adapt to changes in distribution, composition and abundance of their target species (Fulton, 2011). These and other available forecasts demonstrate substantial differences in the direction and magnitude of impacts of climate change on fisheries production around the world, driven by different physical and biological attributes and the ability of fisheries operations and management to adapt to the changes that do occur.

The changes in marine yields projected by (Cheung *et al*., 2010) result from changes in distribution of important fish stocks. In the case of freshwater fisheries, natural boundaries will frequently restrict the ability of species to change distribution. Endemic species, those in fragmented habitats and those in aquatic systems with a predominantly east–west orientation will be particularly restricted (Ficke *et al*., 2007), as will food production systems dependent on them.

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, changes in temperature extremes are expected to have impacts in some cases. For example, a study on salmon populations in Washington State, USA by (Mantua *et al*., 2010) demonstrated the important impacts of seasonal variations and extremes, as opposed to means, on population responses to climate change. 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. Coral reefs are particularly susceptible to extremes in temperature: temperatures 1 or 2°C in excess of normal maximums for 3 to 4 weeks are sufficient to disrupt the essential relationship between endosymbiotic dino-flagellates 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); Box 5-3).

Reliable fine scale projections are not available at present because of the ecological complexity of the responses as well as the potential role of human adaptation in minimising risks and taking advantage of new opportunities.

7.3.2.6.2. Impact of ocean acidification

The impact of increasing CO2 concentrations on coral reefs as a result of higher concentrations of carbonic acid in the ocean reducing the availability of carbonate to the reef building organisms is addressed in the Cross-chapter ocean acidification box (IPCC 2014, WG2). It is reported there, citing the original references, that the annual economic cost of ocean-acidification-induced coral reef loss by 2100 has been estimated to be 870 and 500 billion USD respectively for A1 and B2 SRES emission scenarios and that the global cost of loss of production of molluscs could be over 100 billion USD by 2100.

7.3.2.6.3. Combined impacts on fish and seafood production

Climate change is modifying the distribution of marine and freshwater species with a general displacement towards the poles and is leading to changes in the size and productivity of suitable aquatic habitats. This will have a mixture of negative and potentially positive impacts which will vary from locality to locality. The ability to take advantage of new opportunities brought about by these changes will depend on the adaptive capacity of countries and local communities.

Where these ecological changes are significant, countries and communities will need to adapt through, for example, changes in fishing and aquaculture practices and operations. Given the proximity of fishing and aquaculture sites to oceans, seas and riparian environments, extreme events can be expected to have impacts on the associated infrastructure and to affect safety at sea and for communities, with those living in low-lying areas at particular risk. In areas that experience water stress and competition for water resources, aquaculture operations and inland fisheries production will be at risk. The impacts of climate change on the fisheries and aquaculture sector will have implications for the four dimensions of food security i.e. availability of aquatic foods, stability of supply, access to aquatic foods, and utilization of aquatic products (FAO, 2009).

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 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

7.3.2.2.1. 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.

[INSERT TABLE 7-1 HERE
Table 7-1: Households divided into five categories of food access, indicating the impacts for them 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 recent 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).

Recent studies have indicated that 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 determines 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 (*limited evidence, low agreement*), particularly when compared with the literature on climate change impacts on food production and availability.

The variation in the distribution and vulnerability to loss of food access across household types indicates the complexity of assessing the potential effects of climate change on food access at future time periods where these factors may be expected to change. Nonetheless, there are reasons for concern about climate change impacts on food access due to the high rates of food insecurity and significant share of population in many low income countries of one of the most vulnerable groups to loss of access: e.g. agricultural producers who are net food buyers. 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.

7.3.2.2.2. Climate change impacts on stability

There is increasing evidence 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 with global climate pattern impacts on food security indicate the potential nature and magnitude of increased climate extremes. 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 increases uncertainty, which mitigates 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 et al., 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; McPeak, 2004; Kazianga and Udry, 2006), but also by decreasing both food consumption and non-food expenditures, such as those on education and healthcare (Frankenberg, 1999; Skoufias and Quisumbing, 2005) (*medium evidence, high agreement*). 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 healthcare can lead to long-term losses in terms of income-generation and thus to future food security (*limited evidence, medium agreement*) (Hoddinot and Maluccio, 2002; Skoufias and Quisumbing, 2005). 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*).

7.3.2.2.3. 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) (Bloem *et al*., 2010; Alderman, 2010; Brinkman *et al*., 2010; Campbell *et al*., 2010; Sari *et al*., 2010). The biological effects of climate change on nutrient content of foods is one of 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 CO_2 levels (Ainsworth and McGrath, 2010; Erda et al., 2005; 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. Land Use Change and Autonomous Adaptation

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 are likely to become more suitable as the total time regions (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 likely lead to greater inter-annual 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, whilst temperate wheat environments are likely to 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 analogues 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 likely to be 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 (Frieler *et al*., 2013). Changes in water use, including increased water diversion and development to meet increasing water demand, 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, 2009). 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 which 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 towards the coast with hotter and drier conditions, notwithstanding the positive impacts of elevated CO_2 (Nidumolu et al., 2011). Recent trends in climate have seen reductions in cropping activity consistent with these projections (Nidumolu et al., 2011).

The application of first-generation biofuel conversion technologies have expanded the uses for traditional commodities such as maize, oil seeds, and sugarcane, enabling farmers to market their crops beyond the traditional food, feed or industrial food-processing uses. Such changes in land use have potentially adverse consequences for food security. There are a number of developing countries that are relatively food secure, and have a higher demand for fossil-based fuels – Brazil, Malaysia, Peru, Argentina, and Thailand–. A number of these countries which are export-oriented and have relatively large areas of land available are currently expanding biofuel production in order to meet both domestic and international demand (Ewing and Msangi, 2009). However, the expansion of biofuel production has created new linkages, trade-offs, and competition between the agricultural and energy sectors. It has also introduced new food-security risks and new challenges for the poor, particularly when natural-resource constraints have led to trade-offs between food and biofuel production and also to rising food prices (FAO, 2008; von Braun and Torero, 2009; Chum et al., 2011). The current food crop based biofuels are of concern as their development will also exacerbate food insecurity particularly in many of developing countries. Biofuels targets imply that an additional 140 and 150 million people may be at risk of hunger by 2020. Africa and South Asia will account for over two-thirds of those people most affected (Fischer *et al*., 2009).

7.4. Projected Integrated Climate Change Impacts

7.4.1. Projected Impacts on Cropping Systems

Crop productivity remains 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, namely that tropical areas fare worse than temperate areas for small amounts of warming, and all areas are projected to have negative yield impacts past 3°C of local warming without adaptation, even with benefits of higher CO_2 and rainfall (Challinor *et al*., 2013). One exception is that more recent studies often show negative impacts for temperate wheat for 1-3 °C local warming, whereas AR4 showed primarily positive responses at these temperatures.

Figure 7-6 shows the changes in mean crop yield in twenty-year bins, from a meta-analysis of over 1800 projections (Challinor *et al*., 2013), including cases with no adaptation and a range of incremental adaptations. Taking the data as an indication of risk of crop yield reduction shows that reductions in mean yield become *more likely than not* from the 2030s. Reductions of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. Some important regional differences are masked in the figure. From the 2070s onwards, all of the positive yield changes are in temperate regions, suggesting that yield reduction in the tropics are *very likely* by this time. This is consistent with the analysis of Knox *et al*. (2012). A recent model intercomparison of global gridded crop models (Rosenzweig *et al*., 2013) presents a similar pattern for projections from site-based crop models.

[INSERT FIGURE 7-6 HERE
Figure 7-6: Projected changes in crop yield as a function of time. The y-axis indicates degree of consensus and the colours denote percentage change in crop yield. Data are plotted according to the 20-year period in which the centre point of the projection period falls. Taken from (Challinor *et al*., 2013).]

Fewer 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 likely suffer negative impacts on several important crops. Yields changes have also been assessed by regional meta-analyses: Knox *et al*. (2012) found yield reductions of up to 50% in the second half of the century for Sub-Saharan Africa and South Asia, with wheat, maize, sorghum, and millets more affected than rice, cassava, and sugarcane.

Changes in the interannual variability of yields are likely to be important in determining future stability of food availability and access. Figure 7-7 shows projected changes in the coefficient of variation 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*. (2013) conducted gridded simulations across the globe and reported an increase of more than 5% in CV in 64% 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. However, many studies reported increases in standard deviation, for example (Challinor *et al*., 2010) projected increasing occurrence of extremely low crop yields due to heat and water stress. Teixeira *et al*. (2013) report that under SRES A1B for 2070-2100 high temperature stress is likely to affect many parts of the globe, including temperate regions. Semenov and Shewry (2011) also find evidence from models that temperate heat stress will be an important determinant of yield from the 2050s. Thus temperature extremes due to changes in the distribution of climate are likely to increase yield variability. Overall, there is *medium confidence* that climate change will increase variability in crop yield in many regions (*medium evidence, medium agreement*).

[INSERT FIGURE 7-7 HERE
Figure 7-7: Projected percentage change in coefficient of variation (CV) for wheat (gold), maize (green), rice (blue) and C4 crops (red) taken from C2010 (Challinor *et al*., 2010), B2012 (Berg et al., 2012), T2009 (Tao et al., 2009), TZ2013 (Tao and Zhang, 2010), TZ2012 (Tao and Zhang, 2011) and U2012 (Urban et al., 2012). U2012 and C2012 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in CV. For C2012 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. The studies used a range of scenarios (SRES A1B, A2, A1F1 and B1). B2012 is a global study, U2012 is for the US, and the remaining studies are for China.]

Given an increasing likelihood that mean global warming will be in excess of 2ºC (New et al. 2011) and perhaps up to 4ºC by 2100, studies have examined the effects of such warming on two very different regions; sub-Saharan Africa and northern Europe (Finland). With *medium evidence* and *high agreement*, the studies (Rötter et al., 2011; Thornton et al, 2011) conclude that positive effects of modest warming and increased CO_2 levels on crop yields are likely to be reversed at minimum temperatures increases of 4ºC, leading to grain yield decreases in excess of 20% in relation to current conditions (Rötter et al. 2011). 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 descumbens*) given 5ºC global average warming (Thornton *et al*., 2011).

Weed populations and demographics are expected to change, 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 carbon dioxide 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 (Treharne, 1989); such plasticity, in turn, would be advantageous in a rapidly changing climate. Finally, chemical control of weeds, which is the preferred management method for large-scale farms, may become less effective (*medium evidence, medium agreement*), with increasing economic and environmental costs.

Climate change effects on productivity of food systems will alter land use patterns, both in terms of total area sown to crops and the geographic distribution of that area. Given expected trends in population, incomes, bioenergy demand, and agricultural technology, global arable area is likely to increase from 2007 to 2050 (medium evidence, high agreement), with projected increases over this period of +9% (Bruinsma, 2009), +8% (Fischer *et al*., 2009), +10-20% (Smith *et al*., 2010), and +5-25% (Schmitz *et al*., 2013) (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 (Schmitz *et al*., 2013) 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 available and necessary infrastructure required to convert virgin land into productive arable land, make estimates of any actual increase in harvested cropping areas highly uncertain, with this uncertainty increasing even more after 2050.

7.4.2. Projected Impacts on Fisheries and Aquaculture

7.4.2.1. Capture Fisheries

There have been a number of studies on the probable impacts of climate change on capture fisheries (see also Chapters 6 and 30). These take the form of studies on single-species (e.g. tuna species: (Loukos *et al*., 2003; Lehodey *et al*., 2010); and cod: (Drinkwater, 2005), ecologically significant taxonomic groups (e.g. coral reefs: (Hoegh-Guldberg *et al*., 2007; Munday *et al*., 2008), geographical regions (e.g. Australia: (Brown *et al*., 2010) North Sea: (Cook and Heath, 2005; Hiddink and Hofstede, 2008); and the Pacific island countries and territories: (Bell *et al*., 2011) and global (e.g. (Brander, 2007; Cheung *et al*., 2010). All of them make considerable effort to minimise uncertainties but inevitably rely on underlying assumptions and retain considerable residual uncertainty.

Simulation studies on skipjack and bigeye tuna in the Pacific under the B1 and A2 scenarios suggest that the vulnerability of skipjack tuna to climate impacts in 2035 is low under both scenarios but moderate under B1 and high under A2 by 2100. Projections under the A2 scenario suggest a 32% decrease in biomass of skipjack in the western and 50% increase in the eastern Pacific Ocean by 2100 compared to biomasses in 2000, but the authors express lower confidence (evaluated by them at 5-33% confidence) in these results than for the B1 scenario where confidence is evaluated at 33-66% confidence (Lehodey, 2011). For bigeye tuna, the results are broadly similar. These shifts in distribution would tend to favour some of the smaller Pacific Island Countries and Territories (PICTs) in the central Pacific which are particularly dependent on revenues from sale of tuna fishing rights (Bell *et al*., 2011). Tropical tuna fisheries are also discussed in Chapter 30.6.1.1.1.

Coastal fisheries make significant contributions to food security and livelihoods of rural and urban populations in the PICTs where, for the majority of them, average fish consumption is more than 50 $kg.person^{-1}.year^{-1}$. The food requirements of the human population of this area are predicted to increase by between 20 and 60% over the next 20 years (Bell *et al*., 2011). Climate change is expected to impact directly on the productivity of coastal fisheries in the PICTs through increased sea surface temperature and ocean acidification and indirectly through climate-driven damage to coral reefs, mangroves, sea-grasses 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 in 2035 (as estimated through the framework described in Bell et al. (2011b) of coastal fisheries as a whole is considered to be low. Under the B1 emissions scenario, the overall vulnerability of coastal fisheries is considered to be moderate in the PICTs in the west of the region and low for those in the East. The high emissions A2 scenario is expected to lead to major changes in the tropical Pacific, for example through deterioration of coral reef habitats and weakening of the South Equatorial Current and Counter Current. The net result is forecast to be a reduction in coastal fisheries production by 2100, under the A2 scenario, of by 20-35% in the west and 10-30% in the east, leading to an estimated vulnerability of moderate to high in the west and moderate in the east (Pratchett *et al*., 2011).

In a broad-based modelling study (Brown *et al*., 2010) forecast that, under the A2 emissions scenario, primary production in the ocean around Australia will increase over the 50-year period from 2000-2050 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. As another example, described in Section 2.1, impacts on fish and fisheries in the North Sea are widely expected to vary from area to area and species to species.

7.4.2.2. Aquaculture

Complementing the study by Mantua et al. (2010) on the impacts of climate change on salmon populations in Washington State, USA, (Huppert *et al*., 2009) considered the impacts on the coast of that state. They concluded that there would be a number of physical and chemical consequences including inundation of low-lying coastal areas from sea level rise, coastal flooding from major storm events and increased ocean temperatures and acidification. These physical and chemical drivers are forecast to create a number of problems for the important shellfish aquaculture industry in the state arising from reduced growth and reproductive rates as a result of increased temperatures, inundation of existing shellfish habitats from sea level rise, increased incidence of harmful algal blooms and higher rates of mortality as a result of greater acidity of sea water and resulting decreased calcification rates in skelton and shell formation. The authors report that the socio-economic impacts cannot be quantified at this stage but are considered to be substantial.

Aquaculture is considered to be under-developed in the island states and territories of the tropical Pacific. At present just over 20 000 people are estimated to be employed in aquaculture enterprises throughout the region, including the culture of black pearls in French Caledonia. Starting from this low base, pond aquaculture is seen as an important contributor to meeting the shortage of fish required for food security in the region. Using a structured vulnerability framework which uses the B1 and A2 emission scenarios to make forecasts to 2035 and 2100 (Bell *et al.*, 2011b), it was 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. The drivers of these trends include changes to temperature, rainfall and sea-level rise (Pickering *et al.*, 2011).

7.4.2.3. National and Regional Vulnerability

The consequences of the many and diverse impacts on capture fisheries and aquaculture, both positive and negative, on food security are more difficult to estimate than the biological and ecological consequences. A preliminary but informative study by (Allison *et al.*, 2009) attempted to estimate the vulnerability of the economies of 132 countries to climate change impacts on fisheries in 2050 under the A1FI and B2 scenarios (also discussed in Chapter 6.4.1.1.2). They estimated vulnerability as a composite of three components: exposure to the physical effects of climate change, the sensitivity of the country to impacts on fisheries (measured by total fisheries production, contribution of fisheries to national employment, export income and dietary protein) and adaptive capacity within the country (a composite index derived from life expectancy, indicators of education levels, various indicators of governance effectiveness and size of economy). This analysis suggested that under both scenarios several of the least developed countries were also amongst the most vulnerable. They included countries in central and western Africa, Peru and Columbia in South America and four tropical Asian countries. Food security will be a major consideration in these vulnerable countries.

7.4.3. 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; Baldos and Hertel, 2013; Lobell *et al.*, 2013; Nelson *et al.*, 2013). Many of the studies did not include CO_2 effects, which is sometimes justified on the grounds that studies are concerned with “worst-case” scenarios, or that the bias from omitting positive CO_2 effects balances the known bias from omitting negative effects of elevated O_3 and increased weed and pest damage.

Based on these studies, it is *very likely* that changes in temperature and precipitation, without considering effects of CO_2, will lead to increased food prices by 2050, with estimated increases ranging from 3-84%. The combined effect of climate and CO_2 change (but ignoring O_3 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.*, 2013) 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 change was likely 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. The pathways by which price changes can affect food security are outlined in section 7.3. 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 20-25 million (or 17-22%), with the range including projections with and without CO_2 fertilization. Lloyd et al. (2011) used the projected changes in undernourishment from Nelson (2009) to project the impact of climate change on human nutrition, estimating a relative increase in moderate stunting of 1–29% in 2050 compared with a future without climate change. Severe stunting was projected to increase by 23% (central SSA) to 62% (South Asia). Baldos and Hertel (2013) estimate that climate change results in an increase in global malnourished population by 49 million (11%) in 2050, but that the combined effects of climate change and CO_2, which results in yield increases in their study, reduces the number by 66 million (15%).

In summary, there is *medium confidence* (*limited evidence, high agreement*) that if global yields are negatively impacted by climate change, there would be a resulting increase in both food prices and the global headcount of food insecure people. However, it is only *about as likely as not* that such global yield effects will be experienced by 2050 as the net effect of climate and CO_2 changes, but *likely* that such changes will occur later in the 21st century. At the same time, it is *likely* that overall growth and development will remain a relatively stronger driver of food security over the next few decades, particularly when accompanied by changes in institutions and policies (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, 2010a), and evidence of climate variability effects on conflict risk (Hsiang *et al*., 2011) indicates a need to also consider this dimension in future work.

The impacts of climate change on food production and food security will depend on interactions between the multiple drivers outlined above. The timing of extreme events, which are expected to become more frequent (IPCC, 2012), is one such driver. Extremes contribute to variability in productivity (Figure 7-7) 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 high food price volatility (Figure 7-4). There are very few projections of compound extreme events (IPCC, 2012), and interactions between multiple drivers are difficult to predict. Thus nonlinear interactions in food systems may mean that thresholds are reached through non-predicted mechanisms. 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).

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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 greenhouse gas emissions (cross reference to WGI) and the very high likelihood of additional climate changes from future greenhouse gas emissions (cross reference to WGI) means 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 (IPCC AR4 Chapters 5 and 17). 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).

In the period since 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 which 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 (Glossary). 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 whilst 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 favourable for effective adaptation including investment in new technologies and infrastructure. Building adaptive capacity by decision-makers at all scales (e.g. 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 (e.g. Adger et al. 2009).

The sector-specific nature of many adaptations means that sectors will initially be 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 (Chapter 5 AR4). 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 (e.g. Olesen et al. (2011) and marketing arrangements (WG II Box 9-4, Fujisawa and Koyabashi 2011) 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 because of higher temperatures increasing growth in cooler months means that changing planting dates is a frequently identified option for cereals and oilseeds (Krishnan et al, 2007; Magrin et al., 2009; Travasso et al., 2009; Laux et al., 2010; Stockle et al., 2010; Shimono et al., 2010, Deressa et al. 2009. Van de Giesen et al. 2008, Mary and Majule 2009, Meza and Silva 2009, Olesen et al. 2011, Tao and Zhang 2010, Tingem and Rivington 2010, Cho et al. 2012). Aggregated across studies, changing planting dates may increase yields by a mean of 13% but with substantial variation (Figure 7-8). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura 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 season frosts (e.g. Tingem and Rivington 2010, Crimp et al. 2012, Cho et al. 2012). In some situations early sowing may allow double cropping 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 (WG 1 cross-reference), limiting the effectiveness of this adaptation (Figure 7-8) 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* (*high agreement, medium evidence*) that optimisation of crop varieties appears to be an effective adaptation, increasing yields by around 50% compared with the use of current varieties and planting schedules when aggregated across studies (Figure 7-8). Flexibility in planting dates and varieties according to seasonal conditions could be increasingly important with ongoing climate change (Meza and Silva 2009, Deressa et al. 2009). Approaches that integrate climate forecasts at a range of scales in some cases are able to better inform crop risk (e.g. Cooper et al. 2008; Challinor *et al*., 2009; Baethgen 2010, Li et al. 2010) although care is needed to ensure that the provision of forecasts does not increase existing inequities in farming or fishing communities.

[INSERT FIGURE 7-8 HERE
Figure 7-8: The benefit (% difference from baseline) for different crop management adaptations (CA – cultivar adjustment; IO – irrigation optimisation; PDA – planting date adjustment; PDA early – adjusting planting date earlier; yes – other treatments). The bars indicate ± SE.]

Warmer conditions may also allow range expansion of cropping activities polewards in regions where low temperature has been a past limitation (*low confidence*: *medium agreement, limited evidence*) provided varieties with suitable daylength response are available. This may particularly occur in Russia, Canada and the Scandinavian nations although the potential may be less than earlier analyses indicated due to increased climate extremes, water limitations and various institutional barriers (Alcamo *et al*., 2007; Dronin and Kirilenko, 2011; Kulshreshtha, 2011; Kvalvik *et al*., 2011; Tchebakova *et al*., 2011; Bindi and Olesen 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 (*medium confidence: high agreement, limited evidence*).

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 grain number, fill and quality (Challinor *et al*., 2009; Wassmann *et al*., 2009; Krishnan et al. 2007; Luo et al. 2009; Shimono et al. 2010; Stockle et al. 2010; Wassman et al. 2008) noting that a new cultivar usually takes between 8 and 20 years to deliver. Improving gene conservation and access to gene banks could facilitate the development of cultivars with appropriate thermal time and thermal tolerance characteristics (e.g. Mercer et al. 2008, Wassman et al. 2008) as well as to take advantage of increasing atmospheric CO_2 concentrations (Ziska *et al*., 2012) and respond to changing pest, disease and weed threats with these developments needing **t**o 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 (e.g. Olesen et al. 2011) raises the need for breeding additional drought-tolerant crop varieties (Tao and Zhang, 2011; Mutekwa 2009, Naylor et al. 2007), for enhanced storage and access to irrigation water, more efficient 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, increase in soil carbon and more effective decision support (Olesen et al 2011, Thomas, 2008, Falloon and Betts 2010, Luo et al. 2009, Lioubimtseva et al. 2009; Piao *et al*., 2010) amongst many other possible adaptations (e.g. WG II 22.4.3.7.1). Increasing soil organic carbon levels plays an important role for improved water retention and absorption capacity of soils (El-Hage et al. 2010; Smith and Olesen 2010). Several agricultural practices support increased soil carbon levels, such as use of organic fertilizers (compost, farm yard manure), crop rotations with deep rooting forage legumes or mulching of crop residues (e.g. Diacono and Montemurro 2010; Smith and Olesen 2010). Increasing soil carbon levels can also contribute to climate change mitigation (AR5 WG III). There is *medium confidence* (*high agreement, limited* *evidence*) that crop adaptations can lead to moderate yield benefits under persistently drier conditions (about 10% from aggregation of studies (Challinor et al. 2013) and that irrigation optimisation for changed climate can increase yields by about 4% (Figure 7-8).

Diversification of activities is another climate adaptation option for cropping systems (Thornton *et al*., 2010; Lioubimtseva et al 2009). For example, Reidsma and Ewert (2009) found that regional farm diversity reduces the risk that is currently associated with unfavourable climate conditions in Europe. Diversification of activities often seeks to incorporate higher value activities or those that increase efficiency of a limited resource such as through increased water use efficiency (Thomas, 2008). For future conditions, Seo (2010) assessed that under climate predictions for 2060, integrated crop-livestock farms could increase in number in Africa at the expense of specialized crop or livestock systems. The analysis indicated that the net revenue of the specialized farms could decrease by up to 75% compared with only 10% for the mixed farm but the nature and degree of change will in part depend on the specific climate changes. In some cases, increased diversification outside of agriculture may be favoured (e.g. Coulthard 2008, Mary and Majule 2009; Mertz *et al*., 2009a).

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 AR4 (*high confidence: high agreement, medium evidence*). To quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been undertaken for wheat, rice and maize (see Section 7.5.2). This meta-analysis adds more recent studies to that undertaken in the AR4 (Chapter 5). It indicates that the average benefit (the yield difference between the adapted and non-adapted cases) of adapting crop management increases approximately linearly with increasing temperature change being equivalent to about 15% of current yields for a temperature increase of 5ºC (Figure 7-9). 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 7-5) and differ markedly between adaptation management options (Figure 7-8). For example, cultivar adaptation is assessed by several studies as providing substantially more benefit (mean of over 50%) than changing planting dates (13%) or optimizing irrigation to the new climatic conditions (4%).

[INSERT FIGURE 7-9 HERE
Figure 7-9: Yield change (% difference from baseline) as affected by temperature aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a ‘no adaptation’ and an ‘adaptation’ scenario are used.]

Potential increased variability of crop production means there is *high confidence* (*high agreement, medium evidence*) that other aspects of food systems such as food reserve, storage and distribution policies and systems may need to be enhanced (IAASTD 2009) along with a range of broader issues such as provision of effective insurance markets, clarity in property rights, building adaptive capacity and developing effective participatory research cultures that apply to more than just farming systems (Chapter 9, 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 which integrate new aspects into current systems. Few could be considered to be transformative changes. Consequently, the potential adaptation benefits could be understated and a considerable opportunity cost may emerge (*low confidence: medium agreement, limited evidence*) (Challinor et al. 2013).

7.5.1.1.2. 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 (*high agreement, medium evidence*). These adaptations include matching stocking rates with pasture production, adjusting herd and water 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 (e.g. 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 favour 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, Seo 2010, Thornton et al. 2010). As with other food systems there is a range of barriers to adaptation which 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 2009, Mertz et al. 2009).

Heat stress is an existing issue for livestock in some regions (*high confidence: high agreement, robust evidence*), especially in higher productivity systems (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 (Seo et al. 2008). Breeding livestock with increased heat stress resistance is an adaptation often identified but there are usually trade-offs with productivity (Nardone et al. 2010) and so this option needs careful evaluation. Increased shade provision through trees or cost-effective structures can substantially reduce the incidence of high heat stress days (Nidumolu et al. 2011). In cooler climates, with warming there might be lesser need for winter housing and feed stocks.

7.5.1.1.3. Fisheries

The resources for capture fisheries are largely already fully or overexploited with an estimated 32 percent of stocks being overexploited and 53% being fully exploited (FAO 2010). 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 status and production (WG II 30.6.7, Rosenberg and MacLeod 2005, Cochrane et al. 2009). For inland fisheries, overfishing is also widespread but the majority of impacts on the integrity of freshwater ecosystems and their resources originate from outside the sector (Welcomme et al. 2010). Climate change adds another compounding influence in both cases.

The vulnerability of fisheries and fishing communities to climate change will depend on their exposure to its physical and ecological effects, their dependence on the fishery and their sensitivity to physical effects, and their adaptive capacity (Allison et al. 2009). Adaptive responses to climate change in fisheries 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 planning adaptation, recognising 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 minimise negative impacts (WG II 6.4.2.1, Allison et al. 2009, Badjeck et al. 2010, MacNeil et al. 2010). A wide range of management tools and strategies have been developed to manage fisheries. However, Grafton (2010) points out that this array of tools is necessary but not sufficient for adaptation to climate change in fisheries. He argues 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 proposes that these conventional management tools must be used within processes that i) have a core objective to encourage ecosystems that are resilient to change and ii) that 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

(Grafton 2010). Complementary adaptive responses include occupational flexibility, changing target species and fishing operations, protecting key functional groups, developing early warning systems for extreme events and the establishment of insurance schemes (Coulthard 2008, FAO 2009a, Daw et al. 2009, MacNeil et al. 2010, Koehn et al., 2011). Governance and management of fisheries will need to follow an ecosystem approach to maximise resilience of the ecosystem, and to be adaptive and flexible to allow for rapid responses to climate induced change (FAO 2009a, Daw et al. 2009). Some adaptation options for tropical industrial tuna fisheries and coral reef fisheries are presented in Chapter 30, Section 30.6.1.1.

In contrast to capture fisheries, aquaculture is estimated to be the fastest-growing animal-food-producing sector and is outpacing human population growth. Per capita supply from aquaculture increased at an average annual growth rate of 6.6 percent from 1970 to 2008 (FAO, 2010). 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 take into account expected changes in water availability and quality; integrated water use planning that recognises and takes into account the water requirements and social and economic importance of fisheries and aquaculture in addition to other sectors; and improving the efficiency of water use in aquaculture operations are 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 (e.g. Mantua et al. 2010). De Silva and Soto (2009) also describe the need for insurance schemes accessible to small-scale producers so as to increase their resilience. 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. Bell et al. (2011) suggest a list of 24 separate, but inter-related, actions that could be taken to adapt fisheries and aquaculture in the tropical Pacific to climate change. They break these management steps into three categories according to the primary objective: economic development and government revenue; maintaining the contribution of fish to food security; and maximising sustainable livelihoods. These authors also point out that actions and policies for adaptation in fisheries and aquaculture must complement those for other sectors. They suggest that the greater the number of different production systems to which communities have access, the greater the chance that some systems available to them will not be negatively impacted and that some may even benefit from climate change. 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.

7.5.1.1.4. 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 assured the source of food to hunters and reduced various risks (Ford 2009, Alessa 2008, 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). 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. 2011) 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, farmer's early warming 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 assure food security of certain groups (Marin, 2010, Speranza et al. 2010; Biazin et al. 2012, Salick and Ross 2009, Kalanda et al. 2011; Green et al. 2010; Pareek and Trivedi 2011), although IK and the opportunities to implement it can differ according to gender and age in some communities (WG II 9.3.5.2.9, Rengalakshmi 2007; Turner and Clifton 2009, Kalanda et al. 2011) leading to distinct adaptive capacities and options.

However, because of changes already occurring in climate (seasonal changes, changes in extreme events: IPCC Extremes SR IPCC 2012) there is medium confidence that the reliance on IK could be reduced (Kalanda et al. 2011;

Speranza et al. 2009, McDowell & Hess 2012) affecting the adaptive capacity of a number of peoples globally (*medium agreement, medium evidence*). 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 IK, may contribute to limit the adaptation to climate change in many regions (Nakashima et al. 2012) (*medium agreement, medium evidence*).

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 (see 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. 2009, Chen et al. 2011, Odgaard et al. 2011). More farmers express an intention to change rather than having implemented adaptive actions (Battaglini et al. 2009) although in some regions there appears to be adaptation to climate change that is happening now (Olesen et al. 2011, Fujisawa and Kobayashi 2010, Bohensky et al. 2012). 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).

7.5.1.2.1. Observed and expected barriers and limits to adaptation

Adaptation is strongly influenced by factors including institutional, technological, informational and economic (WG II 14, WG II 15) and there can be barriers (restrictions that can be addressed) and limits in all these factors (WG II 16: *very high confidence: high agreement, robust evidence*). Several barriers to adaptation of food systems have been raised including inadequate information on the climate, 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 (WG II 16, Bryan et al. 2009, de Bruin and de Link 2011, Deressa et al. 2009, Kabubo-Mariara 2009). 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 are assessed with *high confidence* as providing possible core adaptations of production systems (*high agreement, medium evidence*) (Mercer et al. 2008, Tingem and Rivington 2010) 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 (AR4 WGII 5.2.1).

7.5.1.2.2. 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. A key maladaptation would be one which increased emissions of greenhouse gases, this making the underlying problem worse (Smith and Olesen 2010; AR5 WGIII Chapter 11, *high agreement, robust evidence*). A recent review of agricultural adaptations however, has found that most categories of climate change adaptation options tend to reduce greenhouse gas emissions (Smith and Olesen 2010, Falloon and Betts 2010) (*medium confidence: medium* *agreement, medium evidence*). These adaptations include measures that reduce soil erosion or reduce leaching of nitrogen and phosphorus, for increasing soil carbon, measures for 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 (see above) however, and there is *medium confidence* that this may result in large opportunity costs that could arise from not considering more systemic adaptation or more transformative change (Kates et al. 2012; Howden et al. 2010) (*high agreement, limited evidence*). 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). There is a need to also engage farmers, policymakers and other stakeholders in evaluating transformative, pro-active, planned adaptations such as structural changes (Mäder, 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 (Howden et al. 2010). In Australia, industries including the wine, rice and peanut industries are already adopting 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. 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 which identify mitigation options, their relative cost and the potential size of emission-reductions (IPCC WG3). 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 means however, that global, time-independent curves are not feasible. The studies in Figure 7-8 indicate that there some options which may be more relevant and useful to consider than others. These results however, illustrate the potential scope and benefit of developing effective crop adaptation options if implemented in an adaptive management approach.

7.5.2. Food System Case Studies – 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 (Berang-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 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 where a complex of factors drives 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 et al. 2010). Inherent poor soil quality and human activities have resulted in soil degradation – crusting, sealing, erosion by water and wind, and hardpan formation (Zougmoré et al. 2010, Fatondji et al. 2009). 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 (20-40 cm in diameter and 10-15 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 labour intensive requiring some 60 days of labour per hectare. Innovations to the system, involving animal-drawn implements, can reduce labour 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 fertiliser use and irrigation, and especially greater labour 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 markets or get 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 has negative impacts on future water supplies for irrigation, 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.

Case 3: Planning for adaptation in a CARE project

Anticipatory and planned adaptation has been initiated in many places, but it has been poorly documented in the peer-reviewed literature. In many cases these adaptation actions are the basis of externally-funded projects. For example, the humanitarian organization CARE is piloting an approach to increase the capacity of vulnerable communities to adapt to adverse climate change (Patt et al. 2009). In their project in Bangladesh they work directly with households to implement practical strategies to support adaptation to climate risk, as well as with local organisations to build their capacity to support communities to adapt. The initial stage in their work involves participatory assessments of vulnerability and adaptive capacity and perceived climate risk. In Bangladesh flooding, salinity, waterlogging and cyclones were the key challenges to be addressed. Given that vulnerability and adaptive capacity is gendered, the assessments were undertaken separately with men's and women's groups. The results of the assessments were then used to identify strategies to increase capacity to cope with the challenges, both present and those predicted under climate change. At the household level an example of an adaptation strategy that was taken up by households was the shift from raising chickens to raising ducks in light of increased flood risks. The work highlighted the difference in family responsibilities between men and women and differing vulnerability, and how this translates to differing priorities when planning for adaptation. Lack of mobility of women means that women have less access to information regarding potential hazards and possible adaptation strategies.

Case 4 Transformational change in the primary industries of Australia

Many of the cases identified in chapter 7 are examples of incremental adaptation; in many circumstances climate change may call for transformational changes in the agricultural sector, as incremental change will be insufficient (Howden et al. 2010). The primary industries in Australia are highly sensitive to the impacts of climate change and transformational adaptation is being considered and planned for (Park et al. 2012; Rickards and Howden 2012). Examples of transformational adaptations being implemented now include 1) relocation of parts of the rice and peanut industries to regions where future rainfall and irrigation water availability are anticipated to be more favourable causing major change in transport chains, inputs and management and, 2) the relocation of parts of the wine industry to cooler regions to offset risks of warming and forcing changes in supply chains through changes in grower contracts to increase the proportion of grape supplies from cooler regions with lower risk from high temperatures (Park et al. 2012). Researchers are working with those transforming to understand the processes needed so as to generalize and communicate them.

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,(*high confidence: high agreement, robust evidence*) with some adaptations (e.g. cultivar adaptation) being more effective than others (e.g. irrigation optimisation) (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 CO_2 levels. There is *medium confidence* (*medium agreement, limited evidence*) that limits to adaptation will increasing emerge for such incremental adaptations beyond temperature changes of around 2ºC raising the need for more systemic or transformational changes (7.5.1, 7.5.1.2.2), 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 due to rainfall reduction and temperature increase (*medium confidence: high agreement, limited evidence) (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* (*high agreement, medium evidence*) that they will bring substantial benefit, particularly if implemented in combination (7.5.1.1.2, 7.5.1.1.3). 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 (7.5.1.1.2). Fishery adaptations include management approaches and policies that strengthen the livelihood asset base, take an ecosystem approach to managing the resource and adoption of multi-sector adaptive strategies to minimise negative impacts. Importantly, there is an emerging recognition that existing fishery management tools and strategies are necessary but not sufficient for adaptation to climate (7.5.1.1.3).

Indigenous knowledge is an important resource in climate risk management and is important for food security in many parts of the world. There is *medium confidence* (*medium agreement, medium evidence*) that climate changes are reducing reliance on indigenous knowledge in some locations but also that some policies and regulation are limiting the contribution that indigenous knowledge can make to effective climate adaptation (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 is *medium confidence* (*high agreement, limited evidence*) that there may be underestimation of adaptation opportunities and benefits (7.5.1.2.2). 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 (7.5.1.2.2).

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

Research and data gaps are seen mainly in the fact that most work since AR4 has concentrated on food production and not included other aspects of the food system that connects 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.

Other areas of neglect include food quality and nutritional aspects of climate change, the need to update and revise food production impact models, the need to create reliable, integrated food systems models at the regional and global scales geared to including climate change effects on the global food system.

In terms of crop production, important research questions are the extent to which CO_2 acts as a stimulant to crop growth, particularly in combination with other trace gases such as ozone. More attention needs to be given to the interaction between crop physiological thresholds in terms of high and low temperatures and drought and flooding. To date crop-climate models have not adequately included such thresholds and need to include them and examine their effects on crop yields and their quality under low and high levels of global warming. Excluding such features from models means that currently they may underestimate the impacts of global warming.

One of our conclusions from attempts to synthesise information on yield variation is that many studies either do not examine yield variability or do not report it. We recommend that closer attention is paid to yield variability, both for quantity and quality of food production, especially given observed price fluctuations associated with climate events. Within the context of yield variability, we expect environmental thresholds and tipping points, such as high temperatures, droughts and floods, to become more important in the future. Specific recommendations are food production experiments in which changes in variability reflect predicted changes for given warming scenarios. Including such thresholds in models for high levels of global warming (i.e. 4-5 °C above pre-industrial) will very likely lead to reduced predictions of yield given changes in climate variability and increasing mean temperature. Research has also demonstrated that accurate crop productivity data would significantly improve future projections of yield. 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.

Current forecasts of changes in distribution and productivity of marine fish species and communities are typically at a global or regional scale only and include adaptations to 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.

The real contribution of inland fisheries and small-scale aquaculture to food security and nutrition is still poorly understood in many developing countries and regions and is probably frequently under-estimated. Research is required to determine the true contributions from these sectors and their vulnerability to climate variability and change to ensure that planning and implementation of adaptation gives due consideration to them and does not result in undesirable negative impacts on food security.

Currently, approximate estimates of the vulnerability of countries to climate change impacts on fisheries are available. Building on this start, further research is required to improve the accuracy of these estimates and to increase the resolution of the study to identify the most vulnerable zones and communities within countries for priority action in adaptation. There is considerable general information available on what adaptive strategies will be required where fisheries and aquaculture are expected to be impacted by climate change but there are very few case studies of actual adaptation or preparation for adaptation in practice. Implementation of case studies in a range of different social and ecological contexts would enable the existing theories to be tested and revised according to lessons learned.

Possibilities for agronomic and breeding adaptations of food production to global warming are possible up to *ca*. 5ºC above pre-industrial but that the relative effectiveness of these often plateaus after about 3ºC. However, food security studies are urgently required to estimate the actual range of adaptations open to farmers and other actors in the food system especially when possible changes in climate variability are included .
From this chapter it is evident that since AR4, the production aspects of food production have continued to be studied much more comprehensively than the non-production elements of food security. Further studies require impacts and adaptation of global food security and systems in relation to global warming to be studied under a full range of radiative forcing scenarios and that these studies should be quantitative as possible. Such research should include climate impacts and adaptations of crops, livestock, fisheries, fruits and vegetables as production elements and processing, distribution and retailing and consumption patterns as the non-production but equally important elements of food security.

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 to crop production, generally reduce yields of staple cereals such as wheat, rice and maize, which, however, differs between regions and latitudes. Elevated CO_2 could benefit crops yields in short term by increasing photosynthesis rates, however, there is big uncertainty in the magnitude of the CO_2 effect and that interactions with other factors. Climate change will affect fisheries and aquaculture through gradual warming, ocean acidification and through 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.

FAQ 7.2: How could adaptation actions enhance food security and nutrition?
Over 70 per cent 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 contributing 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 should 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.

FAQ 7.3: How could climate change interact with change in fish stocks, 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: 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 which 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 Columbia in South America and some tropical Asian countries.

Cross-Chapter Boxes

Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Introduction
Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

Chemistry and Projections
The fundamental chemistry of ocean acidification has long been understood: the uptake of CO_2 into mildly alkaline ocean results in an increase in dissolved CO_2 and reductions in pH, dissolved carbonate ion, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can be projected at the global scale with high accuracy from projections of atmospheric CO_2 levels. Time series observations of changing upper ocean CO_2 chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII Figure 30.5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult; observations and models show with high certainty that fossil fuel CO_2 has penetrated at depths of 1 km and more. Importantly, the natural buffering of increased CO_2 is less in deep than in surface water and thus a greater chemical impact is projected. Additional significant CO_2 increases and pH decreases at mid-depths are expected to result from increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion

concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration).

Biological, Ecological, and Biogeochemical Impacts

The effects of ocean acidification on marine organisms and ecosystems have only recently been investigated. A wide range of sensitivities to projected rates of ocean acidification exists within and across organism groups and phyla with a trend for higher sensitivity in early life stages (*high confidence*; Kroeker et al., in press; 6.2.3-5, 6.3.4). A pattern of impacts, some positive, others negative, emerges for some processes and organisms (*high confidence*; Fig. X.C) but key uncertainties remain from organismal to ecosystem levels (Chap. 5, 6, 30). Responses to ocean acidification are exacerbated at high temperature extremes (*medium confidence*) and can be influenced by other drivers, such as oxygen concentration, nutrients, and light availability (*medium confidence*).

Experimental evidence shows that lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers such as reef-building corals (Box CC-CR, coralline algae (Raven, in press), bivalves and snails (Gazeau et al., in press) reducing their competitiveness compared to, e.g. seaweeds (Chap. 5, 6, 30). A reduced performance of these ecosystem builders would affect the other components of the ecosystem dependent on the habitats they create.

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO_2. Serious behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level responses. Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities living on the sea-floor. Shifts in community structure have been documented in rocky shore environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012). Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited evidence, high agreement*).

There is *limited evidence* and *medium agreement* that some phytoplankton and mollusks can adapt to ocean acidification, indicating that the long-term responses of these organisms to ocean acidification could be less than responses obtained in short-term experiments. However, mass extinctions during much slower rates of ocean acidification in Earth history (6.1.2) suggest that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of change (*high confidence*).

The effect of ocean acidification on global biogeochemical cycles is difficult to predict due to the species-specific responses to ocean acidification, lack of understanding of the effects on trophic interactions, and largely unexplored combined responses to ocean acidification and other climatic and non-climatic drivers, such as temperature, concentrations of oxygen and nutrients, and light availability.

Risks

Climate risk is defined as the probability that climate change will cause specific physical hazards and that those hazards will cause impacts (19.5.2). The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, includes both the probability that ocean acidification will affect key processes, and the magnitude of the resulting impacts. The changes in key processes mentioned above present significant ramifications on ecosystems and ecosystem services (Fig. 19.3). For example, ocean acidification will cause a decrease of calcification of corals, which will cause not only a reduction in the coral's ability to grow its skeleton, but also in its contribution to reef building (*high confidence*; 5.4.2.4). These changes will have consequences for the entire coral reef community and on the ecosystem services that coral reefs provide such as fisheries habitat (*medium confidence*; 19.5.2) and coastal protection (*medium confidence*; Box CC-CR). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Socioeconomic Impacts and Costs

The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key ecosystem services. The oceans will become less efficient at absorbing CO_2, hence less efficient at moderating climate change, as their CO_2 content will increase (*very high confidence*). The impacts of ocean acidification on coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited evidence, high agreement*; Box CC-CR).

There is no global estimate of the observed or projected economic costs of ocean acidification. The production of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction of US production (limited evidence, low agreement; Cooley and Doney, 2009). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a large proportion of the GDP of some regions or small island states which rely economically on coral reefs.

Adaptation and Mitigation

The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts. Climate geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification because atmospheric CO_2 would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to limit the number and the magnitude of drivers other than CO_2. There is evidence, for example, that reducing a locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally determined driver such as ocean acidification (Falkenberg et al., 2013).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.]

CC-OA References

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Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use ($kWhr/m^3$) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.,* 2008, Bazilian *et al.,* 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

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Table 7-1: Households divided into five categories of food access, indicating the impacts for them 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	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).
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-Dimelik, 2008; FAO, 2011)
Urban consumers	Growing share of population in most countries	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, whereas rural populations are more (FAO, 2008; Ivanic *et al*., 2011).

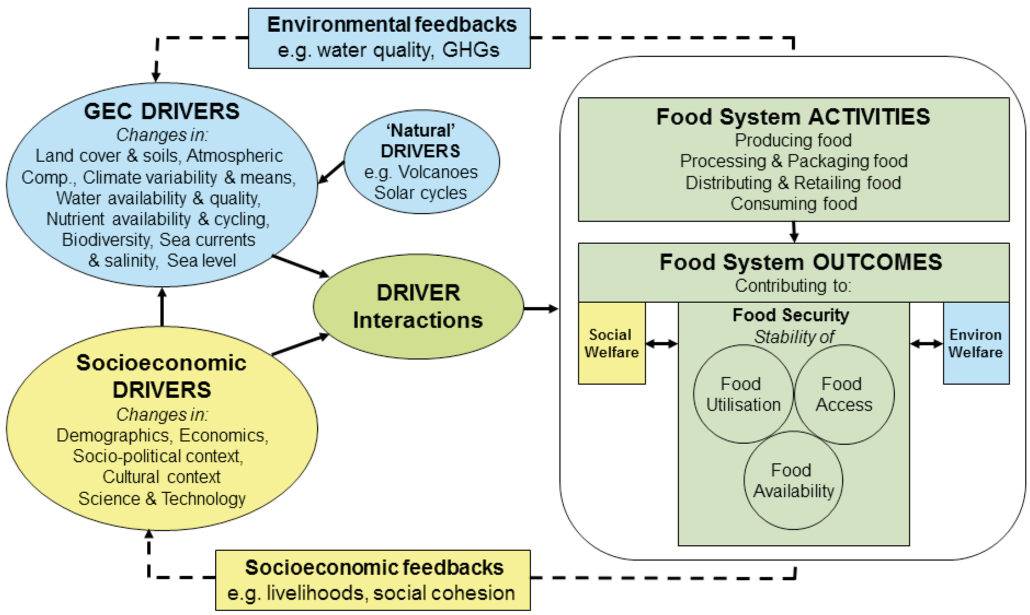

Figure 7-1: Main global environmental change (GEC) and socioeconomic drivers of food systems, the main food system activities, and the outcomes of these activities. The figure also shows the three main components of food security (circles), all of which need to be stable over time: Availability (with elements of production, distribution and trade); Access (affordability, allocation and preference); and Utilisation (nutritional value, cultural value and safety).

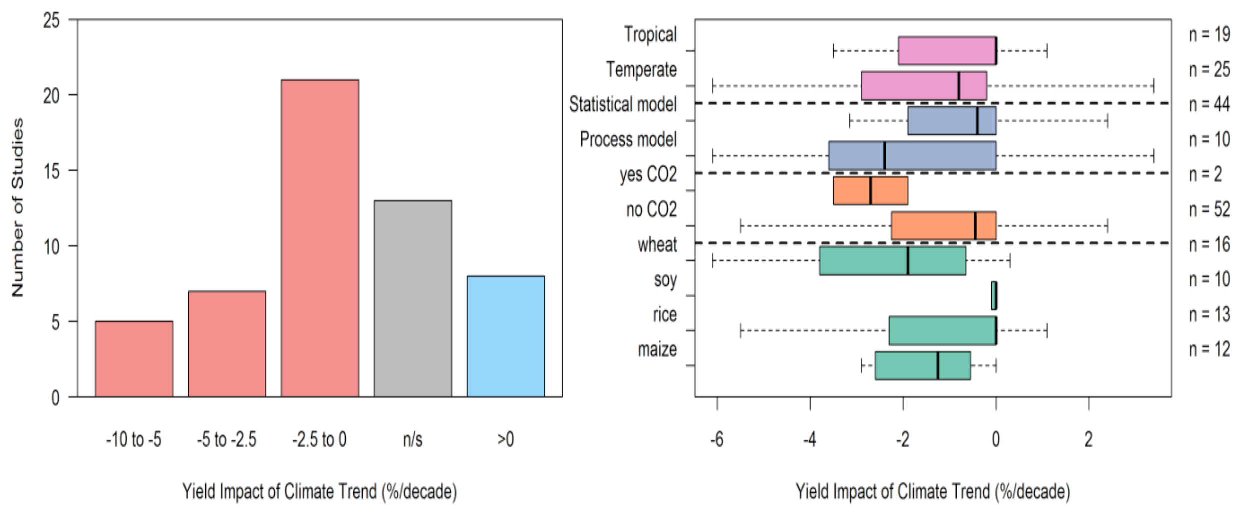

Figure 7-2: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (e.g., stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO_2 trends (see 7.3.2.1.2) but most did not. (a) shows number of studies with different level of impact (% yield per decade), (b) shows boxplot of studies separated by temperate vs. tropical regions, modelling approach (process-based vs. statistical), whether CO2 effects were included, and crop. Studies were for China (Tao *et al.*, 2006; Tao *et al.*, 2008; Wang *et al.*, 2008; You *et al.*, 2009; Chen *et al.*, 2010; Tao *et al.*, 2012), India (Pathak *et al.*, 2003; Auffhammer *et al.*, 2012), United States (Kucharik and Serbin, 2008), Mexico (Lobell *et al.*, 2005), France (Brisson *et al.*, 2010), Scotland (Gregory and Marshall, 2012) Australia (Ludwig *et al.*, 2009), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch *et al.*, 2010; Lobell *et al.*, 2011). Values from all studies were converted to percentage yield change per decade.

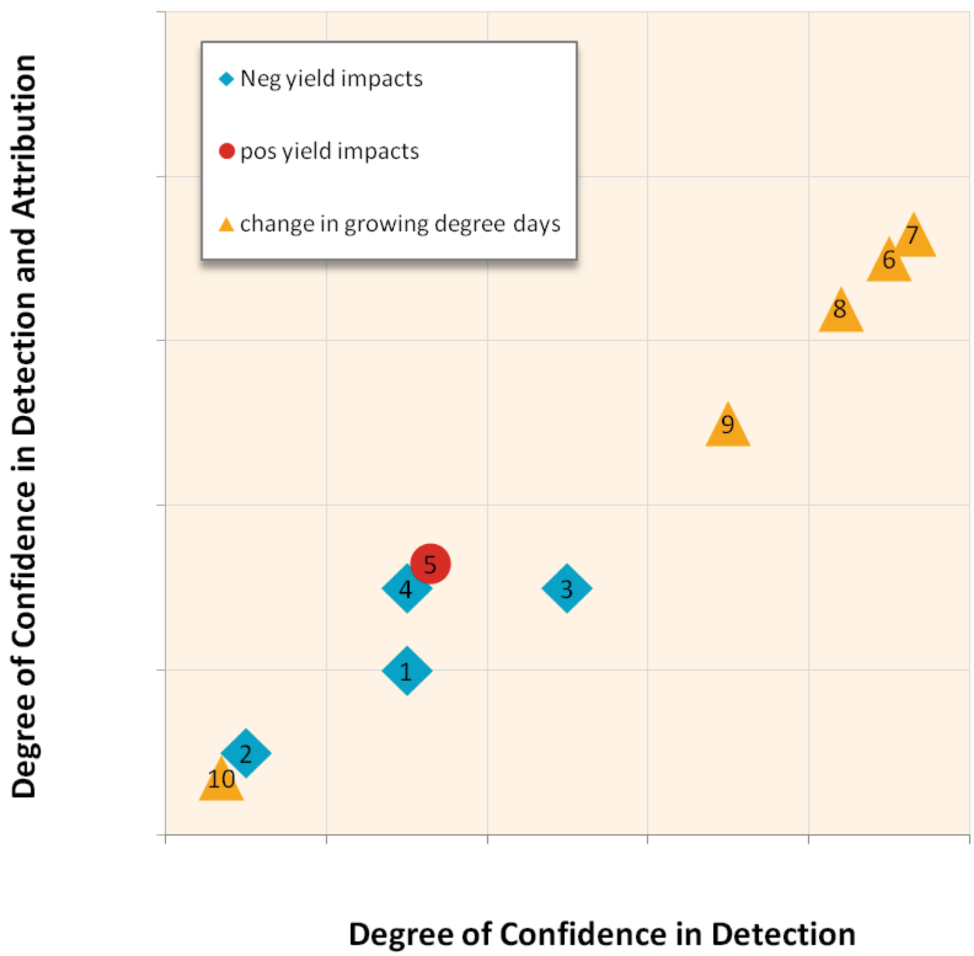

Figure 7-3: Confidence in detection and attribution of observed impacts on crop yields and growing season degree days. Yield impacts include both direct climate effects and effects of elevated CO_2, but do not consider farmer adaptation. Confidence Levels were derived based on expert judgement of the available literature, following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010). Negative yield impacts: 1= Global maize , 2= Global wheat, 3= South Asia wheat; 4 = China maize and wheat; Positive yield impacts: 5 = UK wheat, sugarbeet, and potato. Increase in growing degree days: 6 = South Asia, main crops; 7 = China, main crops; 8 = Europe, main crops; 9 = Latin America, main crops; 10 = North America, maize and soybean. Yield impact confidence based on studies listed in Figure 7-2. Growing degree day confidence based on detection and attribution of trends in growing season temperatures (IPCC 2013, WG1, Chapter 10).

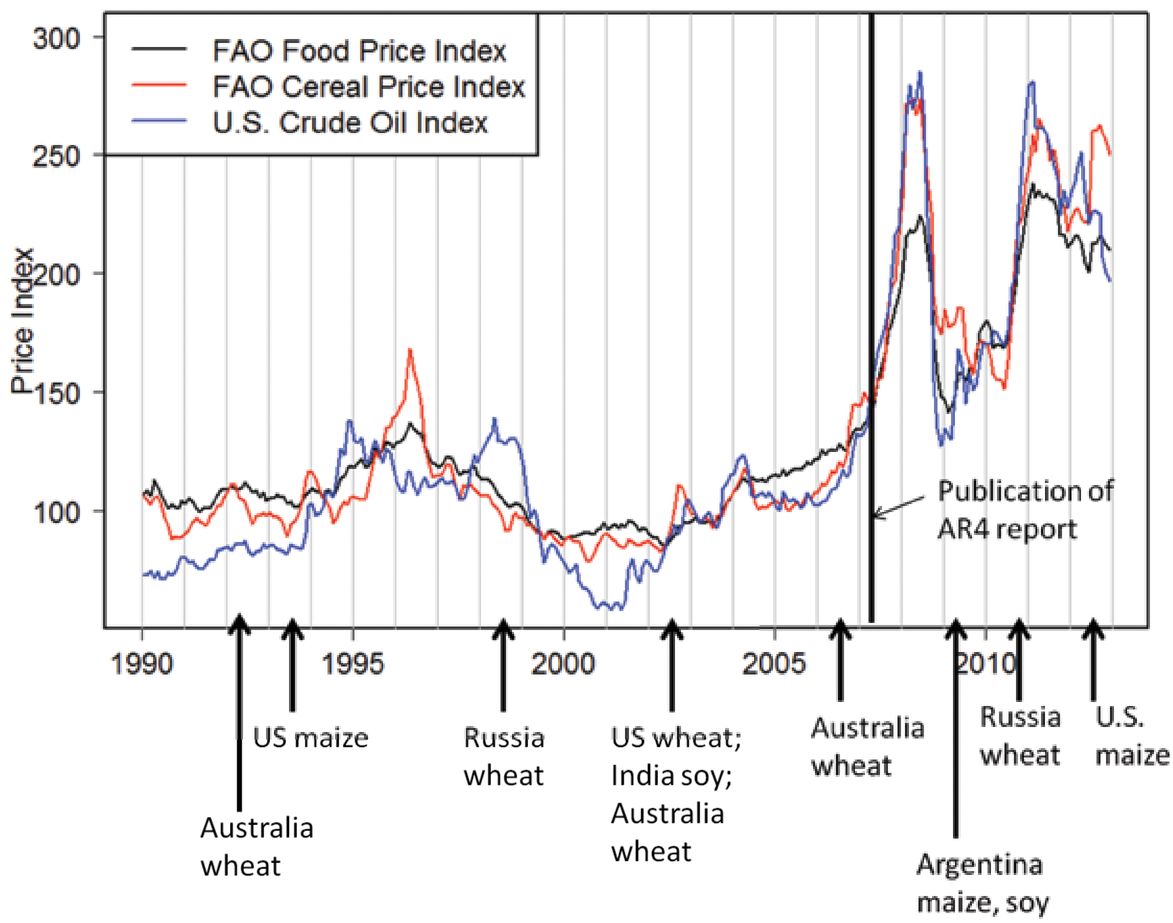

Figure 7-4: Since the AR4 report, food prices have reversed historical downward trend. Plot shows history of FAO food and cereal price index, along with events when a top 5 producer of a crop had yields 25% below trend line (indicative of a big weather effect). Australia is included despite not being 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, perhaps reflecting the importance of interactions with global storage levels and rapid growth in crop demand. At the same time, because of increased biofuel demand, food prices are also increasingly linked to the price of crude oil, shown in the blue line (data available at http://www.eia.gov). Therefore, 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.

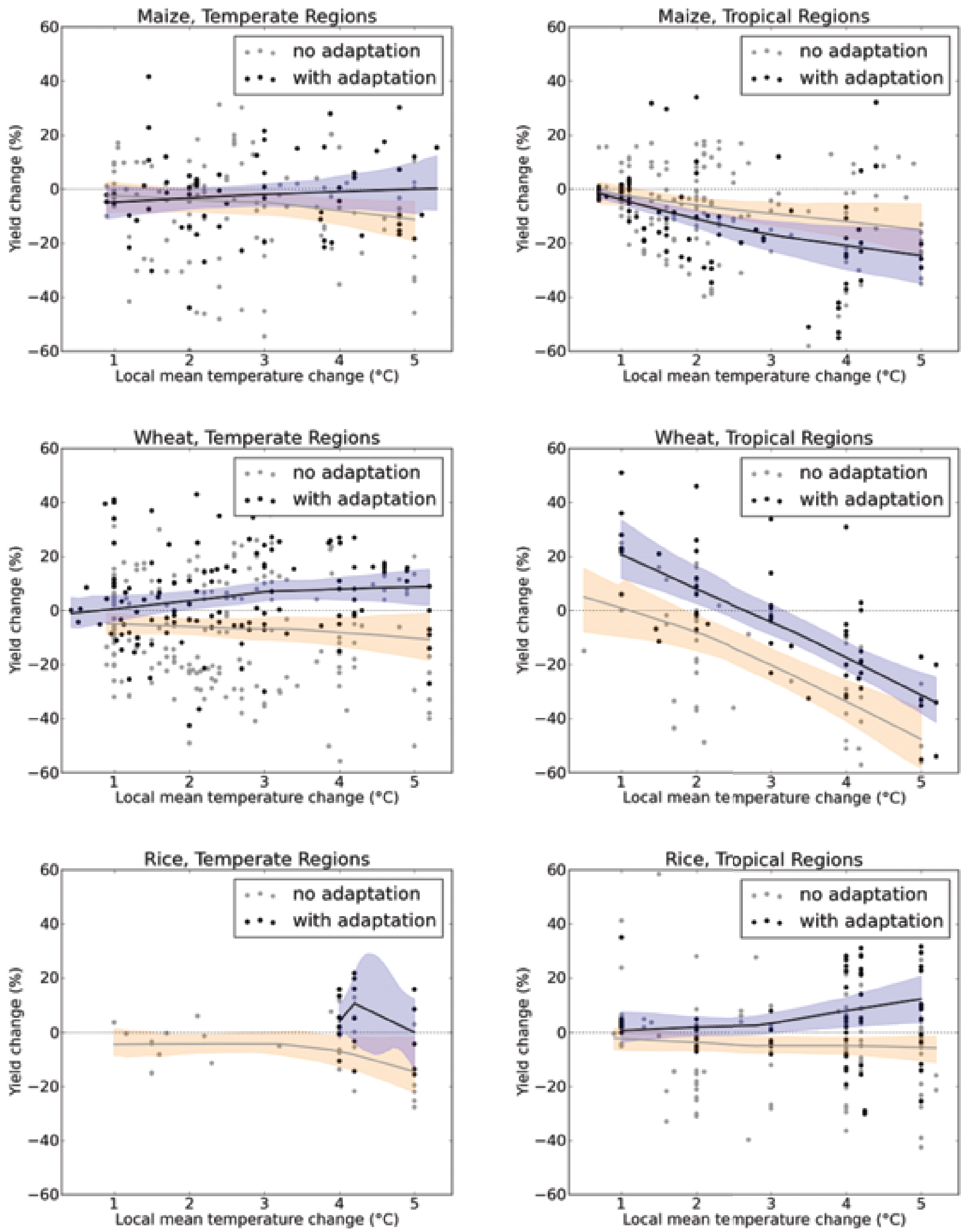

Figure 7-5: Percentage simulated yield change as a function of local temperature change temperature for the three major crops and for temperate and tropical regions. Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, which are separated according to the presence (blue) or absence (red) of adaptation. Note that 10 of the 1125 datapoints across all six panels are outside the yield change range shown. These were omitted for clarity.

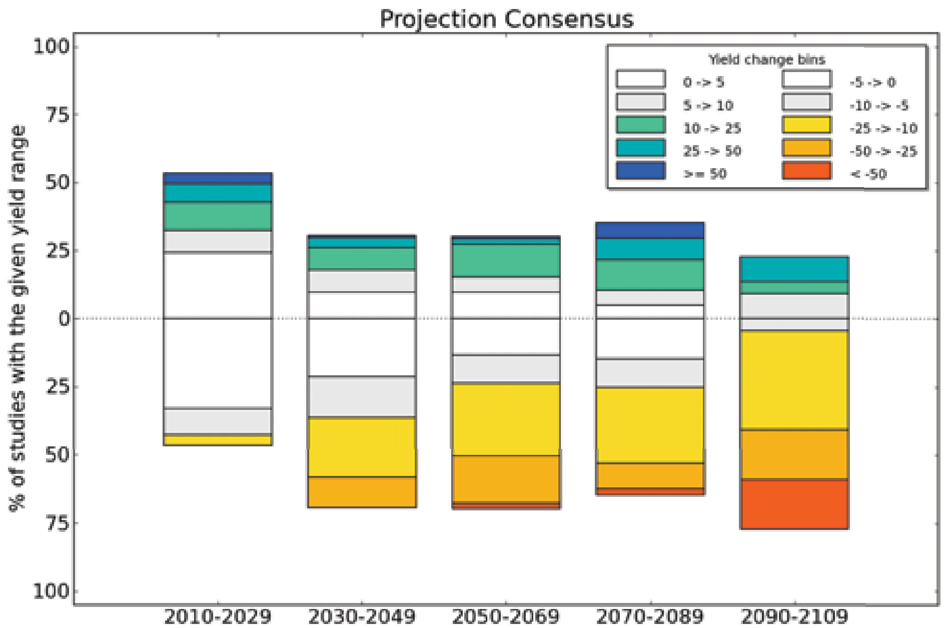

Figure 7-6: Projected changes in crop yield as a function of time. The y-axis indicates degree of consensus and the colours denote percentage change in crop yield. Data are plotted according to the 20-year period in which the centre point of the projection period falls. Taken from (Challinor *et al*., 2013).

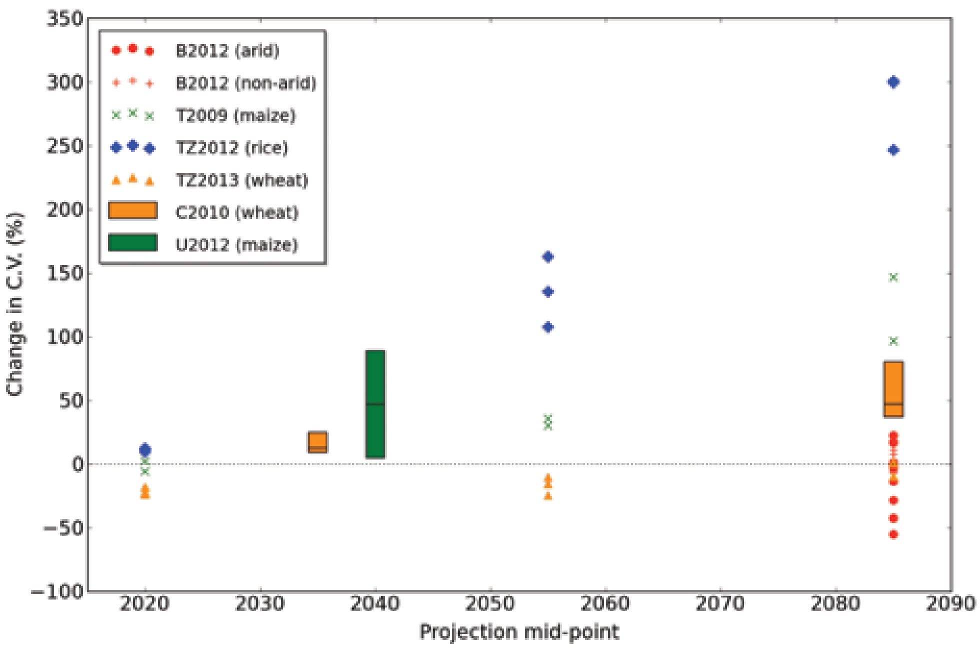

Figure 7-7: Projected percentage change in coefficient of variation (CV) for wheat (gold), maize (green), rice (blue) and C4 crops (red) taken from C2010 (Challinor *et al*., 2010), B2012 (Berg et al., 2012), T2009 (Tao et al., 2009), TZ2013 (Tao and Zhang, 2010), TZ2012 (Tao and Zhang, 2011) and U2012 (Urban et al., 2012). U2012 and C2012 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in CV. For C2012 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. The studies used a range of scenarios (SRES A1B, A2, A1F1 and B1). B2012 is a global study, U2012 is for the US, and the remaining studies are for China.

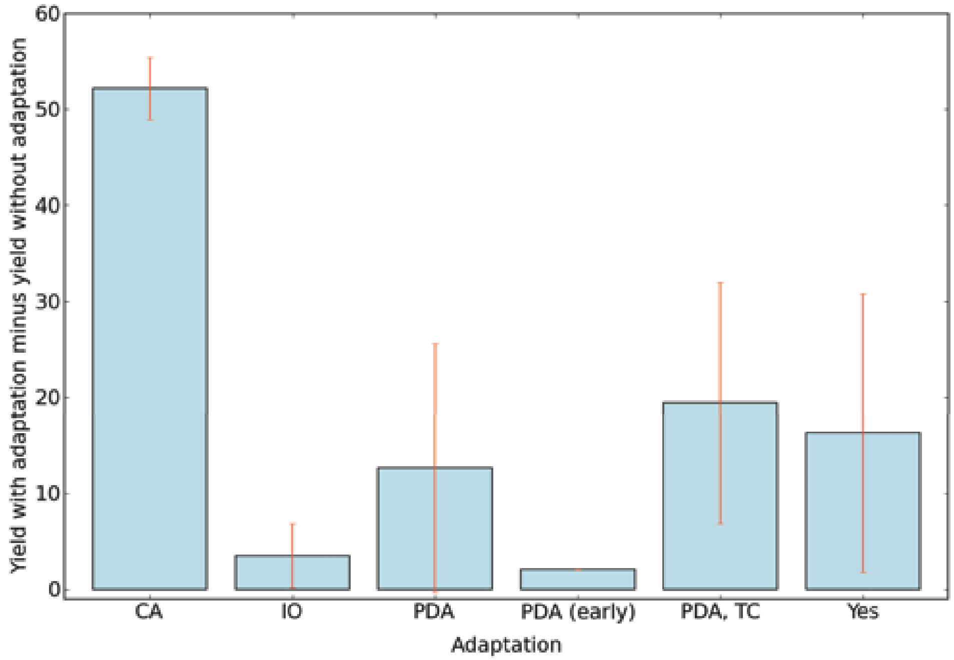

Figure 7-8: The benefit (% difference from baseline) for different crop management adaptations (CA – cultivar adjustment; IO – irrigation optimisation; PDA – planting date adjustment; PDA early – adjusting planting date earlier; yes – other treatments). The bars indicate ± SE.

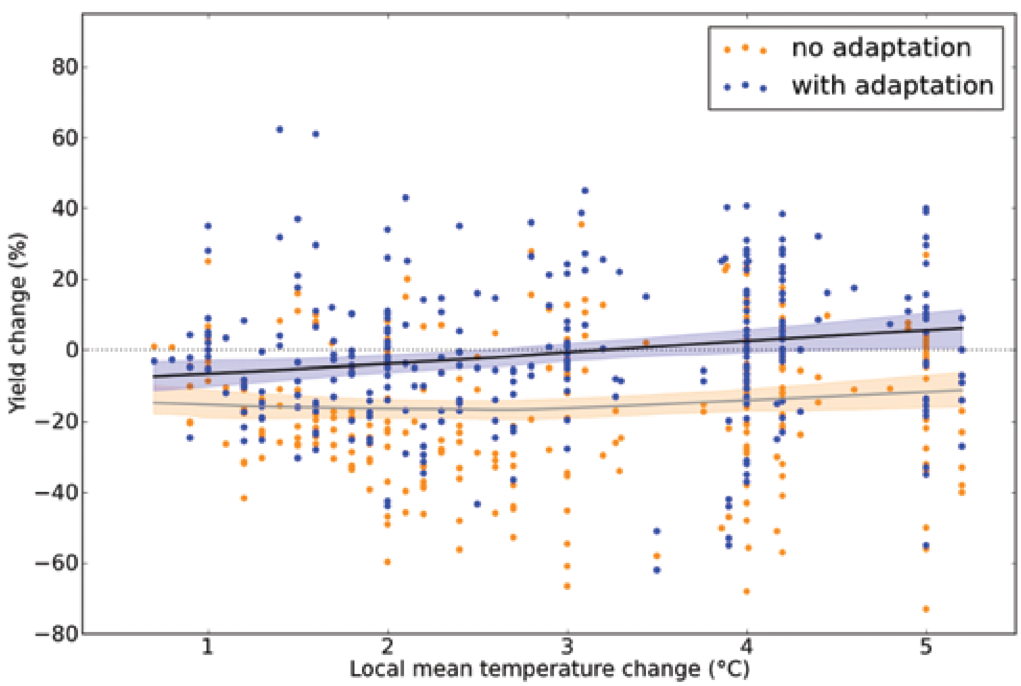

Figure 7-9: Yield change (% difference from baseline) as affected by temperature aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a 'no adaptation' and an 'adaptation' scenario are used.

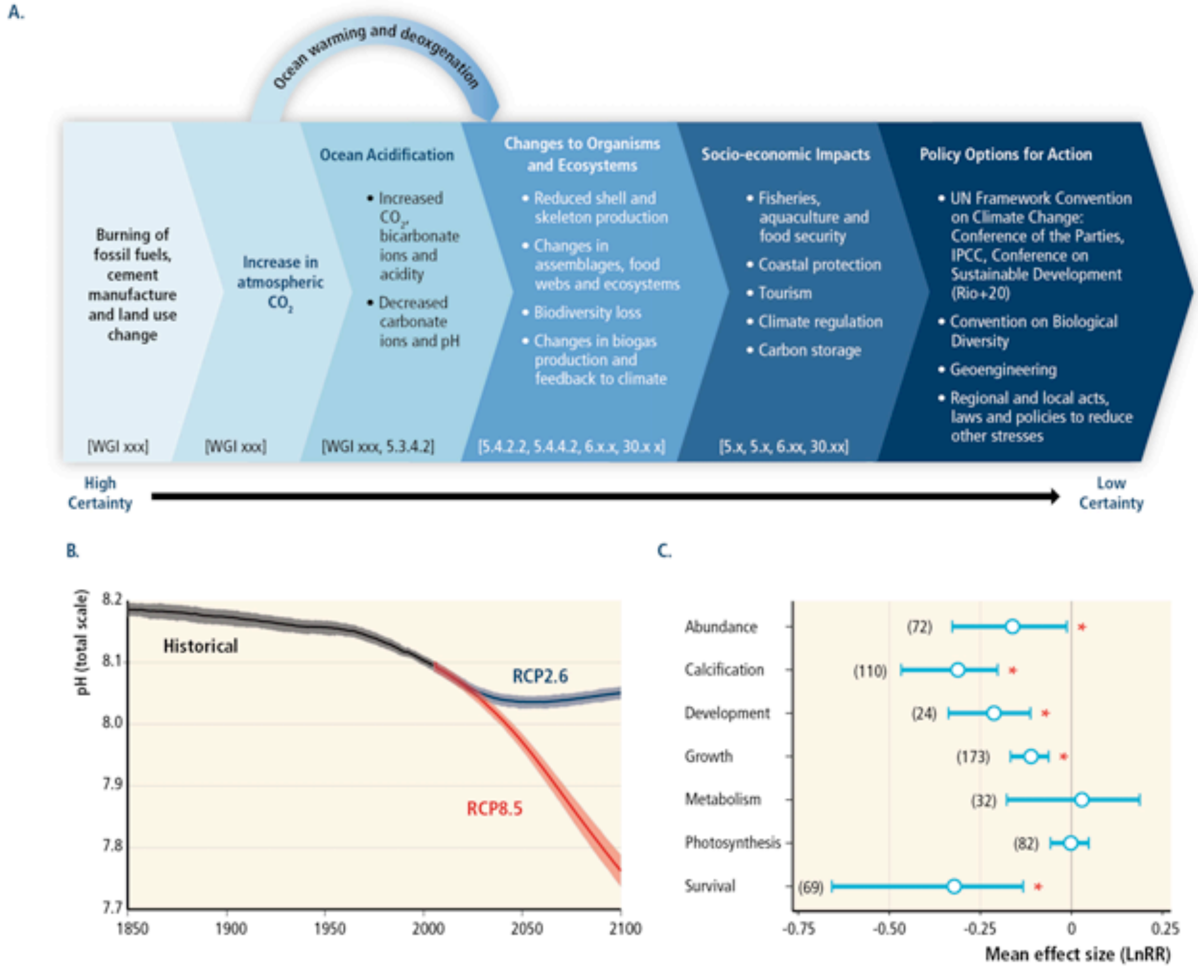

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.

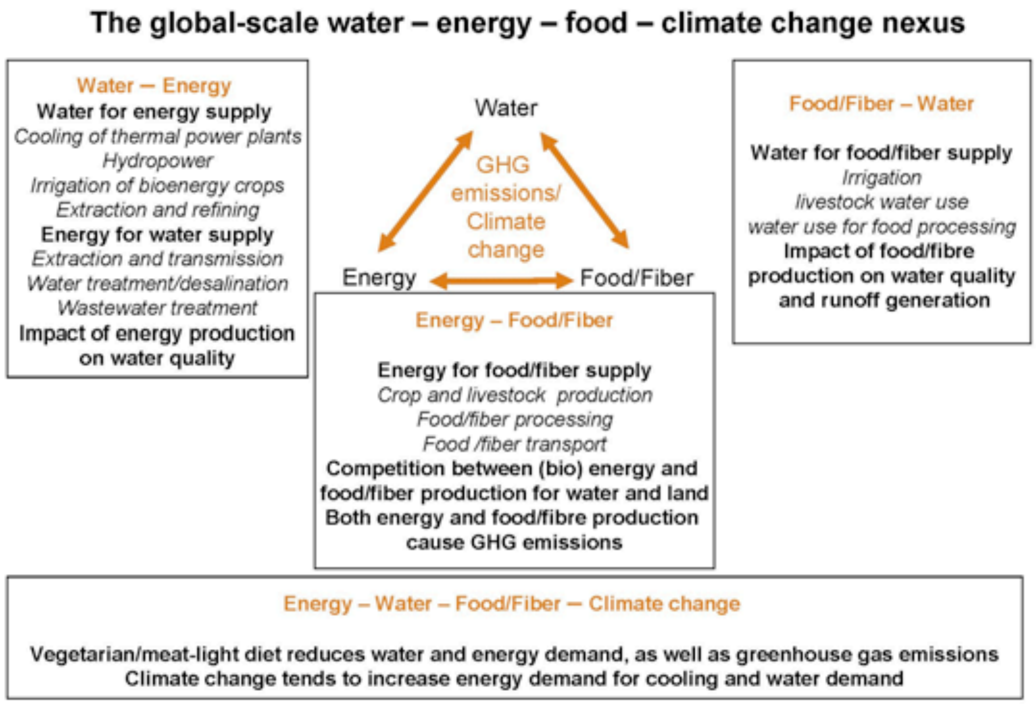

Figure WE-1: The water-energy-food nexus as related to climate change.