Chapter 7. Food Security and Food Production Systems

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Executive Summary

The effects of climate change are starting to be seen on food security and the food system in some regions of the world (*good evidence, good agreement*). However, climate change is not likely to be a major driver of food security for the near to medium term. With *high agreement and robust evidence* many of the elements in the human food system will be adversely affected by projected climate change from about the mid-21st century onwards. These effects will be compounded with other factors such as the rise in tropospheric ozone levels (*medium agreement, medium evidence*) and competition for water resources as between agriculture and other sectors of the economy.

Food system concepts that cover the chain from production to consumption of food are starting to be used to assess food security. Until now the overriding focus of research on food systems and climate change has been on the supply of food from the main agricultural food and fodder crops in high income countries (very high agreement, robust evidence); the food demand, processing, distribution and consumption elements of food systems contributing to food security have been much less researched, especially so in low income countries (*very high confidence*).

High agreement and robust evidence points to the importance of extreme weather events for food and fodder production, particularly for annual determinate crops in which yield is harvested as seeds. Such weather events are defined as extremely high and low temperatures and droughts and floods. There is emerging experimental and modelling evidence (*high agreement, medium evidence*) that interactions between production factors such as CO_2 and other gas levels, mean temperature and extremes, water and nitrogen can alter primary food production in complex ways. In concert with experimental results, models take more account of uncertainties, thus increasing their robustness, showing generally an ability to simulate the impacts on yields of mean changes in weather on food crops but performing less well (*good evidence, medium agreement*) in simulating yield variations.

Adaptation possibilities of food systems to climate change show a very wide range in effectiveness and with medium confidence (*good evidence, medium agreement*) point to adaptation having increased effectiveness with increasing temperature changes. Generally (*good evidence, high agreement*) adaption leads to lower reductions in yields than in its absence with a overall yield difference in adaption cases of about 20% over non-adaption cases, with more effective adaption at higher latitudes (*good evidence, medium agreement*) but with some adaptation options more effective than others.

7.1. Introduction and Context

Many definitions of food security exist. Maxwell and Smith 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 notions of food availability, food utilisation and stability over time. The definition has a focus on the under-supply 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 (Armartya Sen XXXX), 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 (Heady, 2010 IFPRI report). This link between food prices and numbers of food insecure people underscores the importance of the affordability of food in relation to food security. More than enough food is currently produced *per capita* to adequately feed the global population, yet about 925 million people remained food insecure in 2010 ((FAO, 2010)). The two overriding questions for this chapter are how far climate change adds to current issues of 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 feeding a population and relating to the *Activities* of gathering/catching, growing, harvesting, processing, packaging, transporting, marketing, consuming, and disposing of food waste and food-related items. The food system concept is not new: driven by social and political concerns, rural sociologists had promoted this approach for some years (e.g. (McMichael, 1994; Tovey, 1997)), and the food chain concept ("farm-to-fork" or "plough-to-plate") is now well established ((Maxwell and Slater, 2003); (ESF, 2009). These food system *Activities* give rise to a number of food security *Outcomes* related to availability and utilization of, and access to, food. Drawing together the extensive (yet relatively distinct) literatures built up by the food chain and food security communities, respectively, a revised 'food systems' model (Figure 7-1) has been formalised (Ericksen, 2008; Ericksen et al., 2010; Ingram, 2009). This model recognises that food systems operate within, are influenced by, and feed back to social, political, economic and environmental contexts (Figure 7-2).

[INSERT FIGURE 7-1 HERE
Figure 7-1: The components of food systems in terms of activities and outcomes for food security and environmental and social welfare (GECAFS, 2009).]

[INSERT FIGURE 7-2 HERE
Figure 7-2: Main drivers of food systems. (MAY BE REMOVED DUE TO OVERLAP WITH FIGURE 7-1)]

Understanding the interactions between food security and global climate change is highly challenging. This is nevertheless increasingly important as 50% more food will be needed by 2030 given current food consumption trends (Godfray et al., 2010b) and the risk of food insecurity will likely grow. A further challenge is developing food system adaptation pathways that are significantly more environmentally benign than current approaches. Adapting our food system activities to meet these challenges will give rise to changes in all food security outcomes to some extent (Figure 7-1) but often researchers only consider one food security element, usually food production. A meaningful adaptation discussion on food security needs consideration of how any intervention will affect all other eight elements of the food security outcomes; in principle, any intervention, even if only targeted at only one element will affect all nine (Figure 7-1).

7.1.3. The Current State of Food Security

By current estimates there are roughly one billion people in the world who lack food security (FAO, 2011). 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. For instance, Smith et al. (2006) estimated average food insecurity rates of 59% for 12 African countries, compared to 39% as estimated by FAO methods.

The highest rates of food insecurity are in Sub-Saharan Africa, where as mentioned up to 60% of people do not consume sufficient calories for an active life. The largest numbers of food insecure are found in South Asia, which has roughly 300 million undernourished. In addition to common measures of calorie availability, food security can be broadened to include nutritional aspects, which relates to the diversity of diet including not only staple foods but also vegetables, fruits, meat, milk, eggs, and fortified foods (FAO, 2011). Lack of essential micronutrients such as zinc and vitamin A affect hundreds of millions of additional people (Lopez et al., 2006).

Food insecurity is closely tied to poverty, and more detailed surveys on poverty provide insight into where the food insecure live. Globally, about one-fourth of poor people – measured using either a $1 or $2 per day standard - live in urban areas (Ravallion et al., 2007). 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. 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 (Ravallion et al., 2007).

For urban poor, who produce relatively small amounts of food, increases in food prices generally reduce food security. For the rural poor, 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. For example, Ivanic and Martin (Ivanic and Martin, 2008) used detailed data on income sources and expenditures in nine countries to examine the impact of price rises during 2007-2009, and found that they increased poverty significantly in some countries (e.g., Nicaragua, Madagascar, Pakistan) while likely lowering poverty in others (Vietnam, Peru). Overall, however, they found that increases in poverty were more common from price rises than reductions. Again, this highlights the fact that although most poor are rural, they are net buyers of food.

The effects of price volatility are distinct from the effects of gradual price rises, for two main reasons. First, rapid shifts make it difficult for the poor to adjust their activities to favor producing higher value items. Second, increased volatility leads to greater uncertainty about the future, and can dampen willingness to invest scarce resources into productivity enhancing assets, such as fertilizer purchases in the case of farmers or rural infrastructure in the case of governments.

In summary, most rural poor do not interact very much with the market, shielding them partially from effects of rapid price changes. Yet despite the largely subsistence living, they tend to spend a large share of their off-farm income on acquiring more food, which means that they are hurt by price increases in the short term. As the poorest areas slowly become more integrated with markets, they are likely to improve overall incomes and productivity, at the cost of becoming more vulnerable to price shocks.

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. As described above, these changes were primarily the result of factors other than changes in atmospheric CO_2 or climate. In fact, in many contexts the effects of past changes in weather or CO_2 are viewed as noise when trying to measure the effect of agronomic or genetic changes (Bell and Fischer, 1994). Yet understanding the effect of past CO_2 and climate shifts are a useful precursor to assessing future impacts and adaptation needs.

The sheer 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. Identifying a unique fingerprint associated with greenhouse gas emissions is therefore impractical. No studies to our knowledge, for example, simulate historical trends in food-related outcomes with and without changes in anthropogenic emissions of greenhouse gases. A possible exception was Aufhammer et al. (Auffhammer et al., 2006) who compared rice yield predictions in India using climate model simulations of temperature in the late 20th 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.

As discussed in Hegerl et al. (2010), attribution of impacts can take the form of multi-step attribution, where an outcome is related to a change in climatic conditions, and these climate conditions are in turn attributed to changes in external drivers of the climate system (i.e. greenhouse gas emissions). In this case “the assessment of the link between climate and the variable of interest may involve a process model or a statistical link” (Hegerl et al. 2010). Therefore, studies that infer an impact of changing conditions on food production or food security, for instance by using a crop model, can be considered a part of formal attribution of impacts, assuming that the change in conditions can be attributed to anthropogenic activity.

Attributions of crop changes are further complicated by the fact that models linking climate and agriculture must, implicitly or explicitly, make assumptions about farmer behavior. In most cases, models implicitly assume that farming practices or technologies did not adjust in response 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).

Many studies of cropping systems have estimated impacts of observed changes in climate over the past few decades. Based on these studies, there is *high confidence* (high agreement, robust evidence) that climate trends have negatively affected wheat and maize production for many regions, as well as *medium confidence* (high agreement, medium evidence) for negative impacts on global aggregate production of these crops (Figure 7-3). There is also *high confidence* (high agreement, robust evidence) that warming has benefitted crop production in some cold regions, such as Northeast China or England (Jaggard et al., 2007; Supit et al., 2010; Chen et al., 2011; Gregory and Marshall, 2012).

[INSERT FIGURE 7-3 HERE
Figure 7-3: 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 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 but most did not. (a) shows number of studies with different level of impact (% yield per decade), (b) shows boxplot of studies separated by modelling approach, 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), 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), 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).]

A sizable fraction of crop modeling studies were concerned with production for individual sites or provinces, scales below which the changes in climate conditions are likely attributable to anthropogenic activity (WG1, Chap x). 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 (WG 1, Chapter x.). In particular, global temperature trends over the past few decades are attributable to human activity (WG 1, Chapter x), and crop models indicate that this warming has had significant negative impacts on crop yield trends.

Figure 7-4 presents a summary of the detectability of changes in growing season climate 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 7-4 is the fact that not all major cropping regions have experienced significant climate trends in the past few decades, with the United States the most notable example.

[INSERT FIGURE 7-4 HERE
Figure 7-4: Confidence in Detection and Attribution of Observed Impacts on crop yields and growing season agroclimatic conditions. 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). References: to fill in when complete, many of the same from Figure 7-3.]

In comparison to crop food production, considerably less work has been published on non-crop food production systems, such as livestock and fisheries. 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 short- to medium-term 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 (Brander, 2007, see also Chapter 6 of this volume). 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 (Hiddink and ter Hofstede 2008). The authors report high confidence that the increase in richness has been related to rising water temperature. These trends will have mixed implications for fisheries and aquaculture with some commercial species negatively impacted and others positively (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).

Coral reef ecosystems are important sources of fish for food for local inhabitants. More than 60% of coral reefs are considered to be immediately threatened by 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 likely to continue as temperatures continue to rise (Munday et al. 2008). Ocean acidification presents an additional threat by reducing carbon accretion (see Box 5-3 for further information). 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.

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 where there is sufficient light for primary production. The study by O'Reilly et al. (2003) estimated that this would have led to a decrease of approximately 30% in fish yields, an important source of animal protein for local communities. 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).

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 modeling studies expand to broader scales, there will likely 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). In southern Australia, crop yields, water availability and regional economics have been affected by long-term declines in rainfall. The decline in rainfall is associated with a strengthening of the sub-tropical ridge which is highly correlated with global temperature (Timball et al. 2009). 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)(add SREX ref). Positive trends in the occurrence of unusually hot nights are also attributable to human activity in most regions. These events are likely damaging to most crops, an effect that has been observed most commonly for rice (Peng et al., 2004; Wassmann et al., 2009; Welch et al., 2010). 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).

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

In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition on crops. There is *very high confidence* (high agreement, robust evidence) that the increase of atmospheric CO_2 by over 100 ppm since pre-industrial times has enhanced yield growth, 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 negative impacts on carbon accretion in coral reefs with potentially serious negative 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). There is *high confidence* (high agreement, robust evidence) that elevated O_3 has suppressed global production of major crops, 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 in the United States in recent decades (Fishman et al., 2010).

7.2.2. Food Security

Food production is an important aspect of food security (albeit only one, see 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, particularly for poor urban consumers as well as the millions of net consumers in rural areas. Prices for major cereals, oilseeds, and other crops have exhibited an increasing trend over the past decade in a reversal of declining real prices over the previous century. The past decade has also witnessed relatively large volatility in prices, although previous periods such as the 1970's had similar levels of variability when adjusted for inflation (Naylor and Falcon, 2010; Wright, 2011). Much of these trends can be explained by changes in demand, notably increased demand via mandates for biofuel production and increases in food demand because of population and income growth (Roberts and Schlenker, 2010; Wright, 2011). Changes in global supply, defined as the combination of annual production and global stocks, have also played a role according to most analysts. In part this is evidenced by significant movements in prices following revisions of supply forecasts by the United States Department of Agriculture (Garcia et al., 1997).

The balance between global supply and demand is not the only factor affecting global prices. Macro-economic trends, such as changes in exchange rates, can be very important (Abbott et al., 2008). Most notably, changes in trade policy can cause sudden changes in prices, as witnessed with the export bans announced by several countries since 2007 (FAO, 2008). These bans are often announced after officials become concerned that domestic supplies of key grains have been imperiled by bad weather. Export bans therefore often act as an amplifier of weather-driven shocks, implying that the impacts of particular weather events or changing frequency of weather extremes because of climate change cannot be measured without specific assumptions about these trade policies.

One approach to estimate food price response to supply shocks is to examine historical correlations between supply changes and prices, taking care to consider only the component of supply changes that were not already anticipated and thus reflected in prices before the supply changed (Roberts and Schlenker, 2010). Using price elasticities of supply and demand estimated in this manner, one can estimate price responses to a given supply change. 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 include the policy responses witnessed in recent years which have amplified the price responses.

7.3. Assessing Impacts, Vulnerabilities, and Risks

7.3.1. Methods and Associated Uncertainties

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 explored as methods for presentation of uncertainty in the outcome variable (e.g. yield). In addition, greater use of historical empirical evidence of the relationship between climate and food production has been made.

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 conducted since AR4. Section 7.3.2.1.2 contains the details of these studies.

Numerical 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 for examining a large number of management and environmental conditions, such as interactions among various components of food production systems (Lonz-Weidemann, 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.

Novel developments since AR4 in the methodologies used for modeling since include more studies that quantify 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 (Bondeau et al., 2007; Osborne et al., 2007; Rötter et al., 2011). Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Bayesian methods to constrain crop model parameters (Iizumi at 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, Tao et al. 2009b, Reidsma et al., 2009, 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 (Rosenzweig et al, 2012; Challinor and Wheeler 2008; Kang, et al. 2009; Schlenker and Lobell 2010).

Increased quantification of uncertainty does not necessarily lead to less robust statements regarding climate impacts. Studies with different methods have been shown to produce convergent results for some crops and locations (e.g. Challinor et al., 2009). [Placeholder: more on this from Iizumi, Tao, forthcoming AFM special issue on the extent to which the greater focus on quantifying uncertainty has generated different results]. The methods used to describe uncertainty have also been further developed 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 (Section 7.3.2.1.1). Descriptions of uncertainty that present key processes and trade-offs, rather than ranges of outcome variables, are also new tools for understanding future impacts (EQUIP special issue papers, [forthcoming]).

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, the latter of which require many assumptions about soil and management practices, are often difficult to scale up to broad regions, and do not exist for many minor crops. 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), can readily be tested with data not used to train the model (Schlenker and Roberts, 2009), and can leverage a growing availability of crop and weather data (Welch et al. 2010 PNAS, Lobell et al. 2011). Statistical models usually exclude the direct impact of elevated CO2, 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.

Agro-climatic (e..g. Trnka et al., 2011) indices provide another alternative to process-based crop models that avoid various assumptions by focusing on accepted measures of relevance to farmers, rather than providing yield predictions *per se*. However, correlations between climate, or associated indices, and yield are not always statistically significant. (Placeholder: more studies on changes in indices [forthcoming]).

Robustness of the model results depends on data quality, model skill prediction and model complexity (Bellocchi, et al. 2010). Modeling and experiments are each subject to their own uncertainties. Measurement uncertainty is a feature of field and controlled environment experiments. For example, the magnitude of fertilizing effect of CO2 at the elevated concentrations as a result of high temperature, increased variability and several limiting factors such as soil nutrients, pests and weeds is not well understood hence a source of uncertainty (Soussana et al 2010). Also, most of the current generation crop models do not include all the effects of climate change, such as pest and disease effects, damaging effect of high surface ozone concentrations, possible decrease of glacial water supply, competing use of water by industrial sector and households (Pia0 et al. 2010), role of extreme events and interaction between biotic and abiotic factors (Soussana, et al. 2010). The uncertain projections of rainfall by different climate models further increase the uncertainty of future crop yield changes (Buytaert et al. 2010).

There are also uncertainties associated with generalizing the results of these 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. Models have the advantage of exploring a larger number of situations, but with less certainty in the determination of the responses of different genotypes to climate change (Craufurd et al. 2012, in press [forthcoming]).

Placeholders: T-FACE experiments (e.g. http://www.eurekalert.org/pub_releases/2011-02/usdo-ecc022411.phpb)
More on crops will come from a forthcoming paper Craufurd et al (2012).

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.
- Interaction between water stress and CO2: TAR/AR5 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. [Literature in prep means that this highlight will need to be revisited for the SOD]
- The relative importance of temperature and precipitation. Evidence of the greater importance of temperature over precipitation in some regions (Thornton, Lobell, Hawkins) cf AR4 conclusion paragraph 1 pg 283, and chapter figure.
- Pests weeds and diseases included more fully [this needs more detail]

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 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. Crops and Pastures

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 (e.g. Moriondo et al., 2011) confirm the importance of known physiological processes, such as the shortening of the time to maturity of a crop with increasing mean temperature, which in turn reduces yield (Iqbal et al, 2009). This observed response is 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), although temperatures above 34 °C after flowering appear to rapidly speed senescence in wheat and reduce grain set (Asseng et al. 2011, Lobell 2012: NCC). Other processes documented in AR4 include the influence of extremes of temperature and the impact of water stress, both of which have been confirmed as important by more recent research (Schlenker and Roberts 2009, Lobell et al. 2011).

Despite this process understanding, model results can still disagree on the sign of the response of yield to temperature. Many processes throughout a crop's life cycle are sensitive to temperature, precipitation, and other meteorological conditions, so that the overall relationship between weather and yields is often crop and region specific, with a dependence on 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).

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-know phenomenon in controlled environment experiments (refs, or just ref AR4). Crop models can be used to quantify abiotic stresses such as these (e.g. 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, such as those reported by Schlenker and Roberts (2009). Empirical studies of the influence of spatial variability in climate on crop yield can also result in mechanistic understanding.

Precipitation exhibits more spatial variability than temperature, temporal variations in the spatial average of precipitation tend to diminish as the spatial domain widens, and 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 greater importance of projected temperatures as the spatial scale of analysis grows wider (Lobell and Burke 2008). [Placeholder: Hawkins et al, submitted, comment on the relative importance of temperature and precipitation]. Despite this scaling issue, differences in simulated regional scale responses to precipitation can be observed: Figure 7-5 contrasts results of a meta-analysis of crop impacts studies for temperate and tropical regions. Results of these analyses show that the relationship between yield and temperature, derived from the same dataset of crop impact studies, is for most crops more robust than that between yield and precipitation (Figure 7-6). [Placeholder: more detail on this figure, depending on exactly what the final figure looks like].

[INSERT FIGURE 7-5 HERE
Figure 7-5: Reproduction of AR4 (Figure 5.2, WG II, p. 286) temperature (delta_temp) vs yield change with more up-to-date database (number of data points ca. doubled from AR4). All available data points used (cf Figure 7-7 which is where adaptation is dealt with more fully). Boxplots may be used for the final version of this figure.]

[INSERT FIGURE 7-6 HERE
Figure 7-6: Yield change vs precipitation (delta_ppt), showing a contrast between tropical and temperature regions. Redrawn from (Chettri, Lobell, Challinor, Watson – in prep). Figure contains a subset of the total envisaged final data; any conclusions are preliminary.]

[Forthcoming - AJC will add more examples of this (Refs Iizumi, Tao, forthcoming AFM special issue, others). Also something on Lobell and Field, 2007. The idea is to comment on the extent to which the greater focus on quantifying uncertainty (a trend since AR4) has resulted in different results.]

Forage (pasture/rangelands) 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. 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 (Hatfield et al, 2008).

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. Further implications for grasslands may arise from increased frequency of droughts, storms and other extreme events (Hopkins and Del Prado, 2007). Also in South America, rangelands productivity is strongly dependent of water availability. The variation in rangeland productivity is directly related with highly variable amounts and seasonal distribution of precipitation, and only secondarily controlled by other climatic variables. The relationship between primary productivity and precipitation in arid to sub-tropical ecosystems is widely similar across all geographic regions with an increment between one-half and three-fourths of a gram of production per square meter annually for each millimeter of precipitation (Yahdjian & Sala, 2008). Results from a modeling experiment in Australia indicate that increased temperature (3°C) was likely to result in a decrease in forage production for most rangeland locations, exacerbating/reducing the effects of decrease/increase in rainfall but the beneficial effects of increased CO_2 on forage production and water use efficiency enhanced forage production with increases equivalent to the decline associated with a 3°C temperature increase (McKeon et al. 2009).

7.3.2.1.2. Impact of carbon dioxide and ozone

There is further evidence since AR4 that reaction to a change in CO_2 depends on plant type; C3 or C4 (De Matta, et al. 2010). The effect of increase in carbon dioxide concentration tends to be higher on C3 plants (e.g. wheat, rice, cotton, soybean, sugar beets, and potatoes) than on C4 plants (e.g. corn, sorghum), because photosynthesis rates in C4 crops are unresponsive 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 (Hogy and Fangmeier 2009, Fleisher et al. 2008).

Rain-fed cropping systems will benefit more from elevated CO2 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 analysis supports this notion by demonstrating that the rate of yield gains in rainfed systems is higher for dry years than for wet years (McGrath and Lobell, 2011). However, this response is not seen consistently across models and Free-Air CO2 Enrichment (FACE) meta-analyses and there is some suggestion that the relationship between water stress and assimilation may vary with spatial scale, with regional scales showing a reversal of the expected dry versus wet signal (Challinor and Wheeler, 2008a). FACE studies have shown that the impact of elevated CO2 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., in press). Water-stressed crops are expected to respond more strongly to elevated CO2 than well-watered crops, because of CO2 induced changes in stomatal apertures.

There remains some controversy since the AR4 over 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 responses than non-FACE studies. Although some authors have claimed that the results of the two are statistically indistinct (Tubiello et al. 2007), 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). That is, comparisons between different methodologies must take care to control for differences in water stress levels. Moreover, recent FACE results continue to show no significant response of maize to elevated CO_2, even when water stress is sufficiently high to affect photosynthesis rates (Marketz et al. 2011). Unfortunately, the number of FACE studies are still quite low, which limits statistical power when evaluating the average yield effects of elevated CO2 or interactions with temperature and moisture.

Ozone in the stratosphere provides protection from short-wave solar ultraviolet radiation, but in the troposphere it is both an air pollutant and a greenhouse gas. Ozone precursors are emitted by vehicles, power plants, biomass burning and other sources of combustion. Being a powerful oxidant, ozone and its secondary by-products damage vegetation by reducing photosynthesis and other important physiological functions resulting in reduced crop quality and decreased yields (Booker et al. 2009; Fuhrer, 2009). Current and future estimates of global yield losses of key crops due to surface ozone exposure have been made. Avnery et al. (2011a) reported losses of soybean, wheat and maize, in the year 2000, to range from 8.5-14% for soybean, 3.9-15% for wheat and 2.2-5.5% for maize with total global production losses of 79-120 million metric tons. For the near future (2030), they (Avnery et al. 2011b), under IPCC A2 scenario, showed a further yield reductions of 0.9-11% in soybean, 1.5-10% in wheat and 2.1-3.2% in maize, over their respective values in 2000, with total global losses worth $17-35 billion (an increase of $6-17 billion for year 2000). Under the SRES B1 scenario, less severe but substantial reduction was projected; a further reduction of 0.7-1% for soybean, 0.1-1.8% for wheat and 0.3-0.5% for maize, with total losses worth $12-21 billion (an increase of $1-3 billion over year 2000). Van Dingenen et al. (2009) reported losses of wheat in India (28%) and China (19%) and of soybean (20-27%) in Europe due to ozone exposure; maize was the least affected across all regions. For 2030, losses reported were slightly lower than those reported by Anvery et al. (2011b) but significant losses were projected to occur in developing nations. In China, relative grain losses due to increased levels of ozone pollution were projected to increase by 3-22% for wheat, 8-18% for rice and 9-30% for maize over the next decades (Piao, et al, 2010). In other reports, O_3 concentrations predicted for 2050 are likely to increase transpiration and reduce drought tolerance by altering hormonal regulation of stomata and leaf growth (Mills et al. 2009). Negative impacts of O_3 have also been reported on crop quality (Aggarwal 2007) and on protein content of crop yields (Pikki et al. 2007). Ozone may have direct effect on reproductive process, leading to reduced seed and fruit development and abortion of developing fruit (Royal Society 2009).

[Forthcoming: Further recent refs to include (with a brief summary of main point): Fishman, J. et al., 2010. An investigation of widespread ozone damage to the soybean crop in the upper Midwest determined from ground-based and satellite measurements. Atmospheric Environment, 44(18): 2248-2256. -ozone shows clear effect on soy yields in us, based on regression of county yield and ozone data Van Dingenen, R. et al., 2009. The global impact of ozone on agricultural crop yields under current and future air quality legislation. Atmospheric Environment, 43(3): 604-618. - gives numbers on current cost and future increase in ozone losses.]

7.3.2.1.3. Land use change and autonomous adaptation

As noted in the AR4, adjusting the location of crop production is a potential adaptation response to changes in mean temperature and other aspects of 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).between spring and autumn frost will lengthen (medium evidence, high agreement.). 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.

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) (Fischer et al. 2005, Jones and Thornton 2009 ESP, Zhang and Cai 2011 ERL). 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 check). 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.

[More on the AEZ methods that have been used to assess this (ecocrop, IIASA, Osborne, Olieson)].

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). Changes in water use, including increased water diversion and development to meet increasing water demand, and increased dam building will 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.

[Placeholder: more on fresh water resources – see Chap3 FOD when available]

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. 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 & 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, 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 el al, 2009).

7.3.2.1.4. Framing adaptation

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 naturally 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 adaptation are discussed in section 7.5. The interaction between water resources and agriculture is projected 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).

7.3.2.2. Pests, Weeds, Diseases

As a world-wide average, the potential crop yield loss to animal pests and (non-virus) pathogens 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 (e.g., 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. Expanding knowledge of the gamut of plant responses to environment, including potential faster loss of pest or disease resistance at higher temperatures, is being synthesized so that it can be ‘scaled up’ to contribute to climate change scenario analysis (Garrett et al. 2006). 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 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).

Certainly it is reasonable to expect that climate stability with respect to temperature and precipitation is likely 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 likely to respond differently to increasing temperature, with possible reductions in insect predation (i.e. greater insect numbers). Unfortunately, while there is evidence suggesting that insect damage could increase as a function of climate; specific experimental results related to rice, soybean and wheat remain scarce. Similarly, while we recognize plant-pathogen interactions 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 since specific experimental data are not available.

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 (e.g. Holm et al. 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, 2003). If weeds are not managed such losses may exceed any observed stimulation in crop yield associated with elevated [CO_2] (Ziska 2000, 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 et al. 2010). Climate change may be a factor in extending the northward migration of agronomic and invasive weeds (e.g. Ziska et al. 2011a, 2011b). 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 (Rejmanek 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 C3 and C4 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) (Figure 7-X). 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 (see figure 1 in Ziska et al. 2004). To date, studies on physical, cultural or biological weed control are lacking.

[Possible Figure 7-X: Changes in herbicide efficacy determined as changes in growth (g day^{-1}) following application for weeds grown at either current (A) or projected (~700 ppm) (B) levels of carbon dioxide. Herbicide was glyphosate in all cases, except [1], which was glufosinate. (See also Manea et al. 2011). Not included in FOD.]

7.3.2.2.2. 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). 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., in review). Luck et al. (2011) summarized the mixed results for the qualitative effects of climate change on pathogens that cause disease of four major food crops - wheat, rice, soybean and potato - where some diseases increased in risk while others decreased under climate change scenarios. In syntheses, there is a tendency for risk of insect damage to plants to increase (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).

7.3.2.3. Perennials

Changes in temperature are already affecting fruits and nuts production because of the decreasing accumulation of winter chill hours all around the world. 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 General Circulation Models annual winter chill loss by 2050 compared to 1970 would amount 17.7 % to 22.6 % in Egypt (Farag et al, 2010). Assessing climate change impacts on fruit production in California towards 2050, Lobell & field 2011 found a slightly positive trend (some 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 without the effect of elevated CO2, future climate change is projected to decrease apple production by 1%, 3%, and 4% for the 2020, 2040, and 2080 scenarios, respectively but when the effect of CO2 is added, yields are projected to increase by 6% (2020s), 9% (2040s), and 16% (2080s) (Stockle et al 2010). Sugarcane production will be benefited in Brazil, as warming could permit the expansion of planted areas towards the south, where currently low temperatures are a limiting factor (Pinto et al, 2008). Increases in crop productivity could attain 6% in Sao Paulo state towards 2040 (Marin et al., 2009). On the other hand, the warming up to 5.8 °C foreseen for 2070 would make unfeasible the coffee crop in the Southeast region of Brazil (Minas Gerais and Sao Paulo States). In 2070 the coffee crop will migrate for the South region (Parana, Santa Catarina and Rio Grande do Sul), where frost risk will be much lower (Pinto et al 2007). However, warming exceeding 3ºC will impact negatively coffee production in south Brazil (Jurandir et al, 2011)

7.3.2.4. Food and Fodder Quality and Human Health

The climate change that is occurring at present will have, and is already having, an adverse impact on food production and food quality. The adverse effect is the consequence of expected increased frequency of some abiotic stresses, such as heat and drought, and of biotic stresses, such pests and diseases (Caracelli, et al. 2010). The reported decreased concentration of protein and altered lipid composition as a result of climate change (De Matta, et al. 2010; Pikki et al. 2007), and micronutrient deficiency (e.g. Zn, Fe, Se, B, I) as a result of soil degradation aggravate malnutrition and hidden hunger that affects 3.7 billion people, especially children (Lal, 2009). High and low temperature even for a short duration at the reproductive phenostage can cause pollen sterility and shriveling of grain in wheat with consequent reduction in yield. Rice is sensitive to daylight extreme temperature and humidity during flowering and also to high night-time temperature causing reduction in assimilates accumulation and yield (Wassmann et al. 2009). The effect of surface concentartaions of ozone on quality of a number of crops in India was reported by Aggarwal (2007). The crown root disease of wheat caused by stubble-borne pathogen, *Fusarium pseudograminearum* may become more severe at high CO_2 concentrations with increased biomass (Melloy, et al. 2010). Maize plant was found to be susceptible to drought stress around anthesis (Bamabas, et al. 2008). Soil degradation, an allied impact of climate change, affects quantity and quality of food production with consequent adverse effects on human nutrition and health. Soil degradation increases susceptibility of crops to drought stress and imbalance of nutrient elements.

7.3.2.5. 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. 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.

7.3.2.5.1. Mean and extremes of temperature and precipitation

There is high confidence 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, Chapter 6) and Australia (Hobday 2010, 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 of 30–70% increase in fisheries yield from high-latitude regions (>50o 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). The seasonality of biological and ecological processes in many aquatic ecosystems is already being affected but the likely consequences for fish production are generally still poorly understood (FAO 2009).

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.

7.3.2.5.2. 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 has been described in other parts of this chapter and in Box 5-3. Other organisms that produce aragonite will also be affected (Feeley et al. 2004). The most important from a food production perspective will be marine mollusc species which make important contributions to capture fisheries and aquaculture production in many regions (e.g. De Silva and Soto 2009, Huppert et al. 2009).

7.3.2.5.3. 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).

7.3.2.6. Livestock

Impacts of climate change on feed crops and grazing systems include changes in herbage growth brought about by changes in atmospheric CO2 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 are not likely to compensate for the declines in forage quality that accompany projected temperature increases, and cattle are likely to experience greater nutritional stress in the future (Craine et al., 2010).

Izaurralde et al. (2011) found that both pastureland and rangeland species in the USA may experience accelerated metabolism and advanced development with rising temperature, often resulting in a longer growing season, although soil resources will often constrain temperature effects. They conclude that increases in CO2 concentrations and precipitation will enhance rangeland net primary production whereas increased air temperatures will either increase or decrease it (Izaurralde et al., 2011). The consensus is that increases in CO2 will benefit C3 species, although warmer temperatures and drier conditions will tend to favour C4 species (Hatfield 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 C4 grasses (Archimède et al., 2011).

In Australian rangelands, projected changes in rainfall and temperature generally appear small when compared with year-to-year variability, but even so, impacts on rangeland production systems are expected to be important in terms of required managerial and enterprise adaptations (McKeon et al., 2009). In these systems, increases in temperature, which are likely to result in a decrease in forage production, may exacerbate or reduce the effects of a decrease or increase in rainfall, respectively; at the same time, the effects of increased CO_2 concentrations may enhance forage production and water use efficiency. These opposing effects emphasise the importance of the uncertainties in quantifying the impacts of these components of climate change (McKeon et al., 2009). In South America as in other regions, future changes in rangeland productivity will be strongly dependent on water availability as a result of shifts in rainfall amounts and patterns. Response is estimated to be widely similar across all geographic regions: a change of 0.5-0.75 g m-2 production per mm change in precipitation (Yahdjian and Sala, 2008).

Some of these components remain uncertain. 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 southern and 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).

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 (Stokes et al. reference, Nowak et al. reference), 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). We still lack comprehensive studies of climate change impacts on pastureland and rangeland ecosystems that include assessment of the mediating effects of management as well as changes in water, carbon, and nutrient cycling (McKeon et al., 2009; Izaurralde et al., 2011).

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 therefore result in animals with lower heat tolerance (Hoffman, 2010). Recent work adds to previous understanding (AR4 Chapter 5) and indicate 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 milk yields will be reduced and mortality increased because of heat stress. 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 are likely to change their ranges because of climate change. Species diversity 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 (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 are likely to expand their range 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 are all likely to be affected by climate change (Gilbert et al., 2008). The changing frequency of extreme weather events is likely to 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. At the same time, a decline is likely 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 are very likely to 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).

7.3.3. Sensitivity of Food Security to Weather and Climate

7.3.3.1. Non-Production Food Security Elements

[Forthcoming: In terms of food security you might mention two papers done in mali that show climate change almost doubles the risk of hunger but that adaptation can reduce this back almost to current levels Butt, T.A., B.A. McCarl, and A.O. Kergna, "Policies For Reducing Agricultural Sector Vulnerability To Climate Change In Mali", Climate Policy, Volume 5, 583-598, 2006. Butt, T.A., B.A. McCarl, J.P. Angerer, P.R. Dyke, and J.W. Stuth, "Food Security Implications of Climate Change in Developing Countries: Findings from a Case Study in Mali", Climatic Change, volume 68(3), February, 355-378, 2005 (McCarl, Bruce, Texas A&M University) – also recent study by Ingram and CCAFS people (Campbell et al)]

7.3.3.2. Accessibility, Utilization, and Stability

Given the hypothesis that climate change will increase the price of food the vulnerability of households to climate change induced changes on agricultural productivity and food prices thus depends on their channel of food access (FAO 2012). Five key categories can be defined:

Self-sufficient households without access to markets: This includes subsistence farmers, herders, fishers and forest-dependent population that are dependent on own production or gathering provisions from the wild for subsistence. They are vulnerable to production risks and loss of natural resources (land, water, fish). They constitute a small share of the population (Karfakis *et al.,* 2011).

Food producing households that are net sellers of food. These households will tend to benefit from increases in food prices, although they are vulnerable to loss of access to natural resources, and productivity shocks. This too is a relatively small group: Results from an analysis of 9 developoing countries show that on average only 23 percent of all households and 32 percent of rural households were net food sellers (Aksoy and Sid-Dikmelik 2008).

Food producing households that are net buyers of food. Most farming households in developing countries are both buyers and sellers of food, using markets to supplement a lack of quantity or variety in domestic production or to bridge seasonal periods of food shortage. They are vulnerable to market as well as production risks. Lack of storage (or vulnerability of storage facilities to climate risks) increases their vulnerability (Brown et. al. 2009).

Rural landless and non-farm rural households. The access to food in this group depends on relative changes in incomes and in food prices. As non-producers, they are not directly affected by production risks, although their employment prospects and incomes often depend on agricultural-based sources and thus they too can be vulnerable to production shocks (FAO 2011; Aksoy and Sid-Dikmelik 2008).

Poor urban households. Their food security depends on relative changes in incomes and food prices. Urban consumers are especially vulnerable to changes in global food prices, as they are more likely to consume staple foods derived from tradable commodities, whereas rural populations consume more traditional staples such as roots or tubers. (FAO, 2008a).

The variation in the vulnerability across these household types indicates the complexity of assessing food security impacts of climate change at future time periods where the distribution of households by category may be expected to change.

Climate change impacts on stability. In terms of stability, climate extremes will become more frequent (SREX 2011). In terms of availability, greater uncertainty 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 risk, in the absence of well-functioning insurance markets, leads to: 1) greater emphasis on low-return but low-risk subsistence crops (Heltberg & Tarp 2002; Sadoulet & de Janvry, Chpt. 5, 1996; Fafchamps, 1992; Roe & Graham-Tomasi, 1986;), 2) a lower likelihood of applying purchased inputs such as fertilizer (Dercon & Christiaensen, 2011; Kassie et al. 2008), 3) a lower likelihood of adopting new technologies (Feder et al., 1985; Antle & Crissman, 1990), and 4) lower investments (Skees et al., 1999). All of these responses generally lead to both lower current and future farm profits (Hurley, 2010; Rosenzweig & Binswanger 1993).

In terms of accessibility, climate change-induced increases in agricultural production losses are likely to translate into less accessbility to rural producers via lower incomes, and to the rural landless and urban residents through higher and more volatile food prices. It is 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 (Prakash, 2011; Dercon, 2004; Dercon et al., 2006; Vargas-Hill et al., 2009; Fafchamps, 2009; Udry et al, 2004; Skoufias & Quisumbing, 2005). Any increases in climate extremes will exacerbate the vulnerability of these smallholders. Currently, smallholders rely to a large extent on increasing labor off-farm where possible (Kazianga & Udry, 2006; McPeak, 2004; Fafchamps, 1999), but also by decreasing both food consumption and non-food expenditures, such as those on education and healthcare (Skoufias & Quisumbing, 2005; Frankenberg, 1999).

Reductions in food consumption, education and healthcare can have long-term losses in terms of income-generation and thus to future food security (Hoddinot & Maluccio, 2002; Skoufias & Quisumbing, 2005; Frankenger et al., 1999). Furthermore, some evidence also suggests that poorer households are more likely to reduce consumption, while wealthier households liquidate assets to cover current deficits (Carter & Lybbert, 2012; Kazianga & Udry, 2006; McPeak, 2004; Kurasaki & Fafchamps, 2002). Households currently vulnerable to climate shocks have limited opportunities to smooth these shocks through reliance on informal networks and reallocation of labor, and thin or non-existent credit and insurance mechanisms mean that poor households are faced with difficult choices between consumption and asset smoothing in response to a climate shock. Increased uncertainty of future climate conditions and increases in climate extremes will increase food insecurity unless these significant barriers to consumption smoothing can be addressed.

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 agricultural products as well as other factors such as food safety, storage and distribution systems. In this section we focus on the first two. 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 (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 (Hatfield et. al. 2011; Ainsworth and McGrath 2010; Erda et. al., 2010).

7.3.4. Summary

This section will revisit all AR4 'new knowledge' to see if AR5 provides confirmation (see AR4 pg 284):

- Impacts of climate change on irrigated water requirement may be large
- Stabilisation of CO2 concentrations reduces damage to crop production in the long term
- Including effects of trade lowers regional and global impacts

Notes for further development of text; confirmation:

- Internnual variability in yield is likely to rise across many regions. [Cf AR4 "Increases in frequency of climate extremes may lower crop yields beyond the impacts of mean climate change" (pg 284)]

New knowledge:

- Crops: Water stress x CO2 response: TAR/AR5 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.
- Crops: Impact of the advances presented in methodology presented in the first section, e.g. increased quantification of uncertainty results in more robust statements (even if the message itself doesn't change). This could be linked to the table that David and Andy are preparing
- Crops: accurate yield data would improve projections [Andy, based on Hansen, Watson work]
- Greater use of technology (RS/GIS techniques) in assessing food security
- Better understanding of mechanisms of heat effects
- Evidence of the importance of temperature over precip in some regions (Thornton, Lobell) cf AR4 conclusion paragraph 1 pg 283
- Clearer evidence for ozone effects
- Pests weeds and diseases included more fully

7.4. Projected Integrated Climate Change Impacts

[This section is spatially and temporally specific, asking what the synthesis knowledge is on impacts of climate change on [crops, livestock, pests, etc] and knock on effect on food production and food security. This section is likely to be less well developed at ZOD than the section above - we may need to wait until we see what the community do with CMIP5,3 , SRES etc., and also what the region-specific chapter say about food production. Additional useful references are Cho et al (2011), and Calzadilla et al. (2010): Calzadilla, Alvaro, Rehdanz, Katrin, Betts, Richard, Falloon, Pete, Wiltshire, Andy and Tol, Richard S.J., (2010), Climate Change Impacts on Global Agriculture, No FNU-185, Working Papers, Research unit Sustainability and Global Change, Hamburg University, http://econpapers.repec.org/RePEc:sgc:wpaper:185 . Abstract of Calzadilla et al 2011 below: Based on predicted changes in the magnitude and distribution of global precipitation, temperature and river flow under the IPCC SRES A1B and A2 scenarios, this study assesses the potential impacts of climate change and CO2 fertilization on global agriculture. The analysis uses the new version of the GTAP-W model, which distinguishes between rainfed and irrigated agriculture and implements water as an explicit factor of production for irrigated agriculture. Future climate change is likely to modify regional water endowments and soil moisture. As a consequence, the distribution of harvested land would change, modifying production and international trade patterns. The results suggest that a partial analysis of the main factors through which climate change will affect agricultural productivity lead to different outcomes. Our results show that global food production, welfare and GDP fall in the two time periods and SRES scenarios. Higher food prices are expected. Independently of the SRES scenario, expected losses in welfare are marked in the long term. They are larger under the SRES A2 scenario for the 2020s andunder the SRES A1B scenario for the 2050s. The results show that countries are not only influenced by regional climate change, but also by climate-induced changes in competitiveness. (Falloon, Peter, Met Office Hadley Centre). Conclusion is that we are waiting on the RCPs]

7.4.1. Food Systems and Food Security with Regional Variation by Scenario and Time Slice

When assessing impacts, it is important to be clear about the extent to which these autonomous adaptations are accounted for. It is also important to account for potential future changes in agricultural systems. For example, projections of the yield technology trend out to 2050 suggest the potential for significant increases in crop yield in many regions across the globe (Jaggard et al., 2010). The way in which new crop varieties interact with future climates is inherently difficult to predict with any precision.

Africa: Mueller et al (2011) review: Projected changes of −100% to +168% (econometric)−84% to +62% (models) and −57% to +30% (statistical). Despite this uncertainty, risk of negative impacts is clear and existing agricultural systems will have to change to meet future demand.

Globally, the fraction of cropland affected by drought is projected to increase by a factor of 2-4 by 2100 (the average value from 20 GCMS is 44%, from a baseline value of 15.4%; see Li et al., 2009). 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. However, ongoing increases in potential yield across the globe due to crop improvements may act to mitigate negative impacts such as these (Jaggard et al., 2011).

7.4.2. Projected Impacts on Fisheries and Aquaculture, with Regional Variation by Time Slice and Scenario

7.4.2.1. Capture Fisheries

There have been a number of studies on the probable impacts of climate change on capture fisheries. 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 ter Hofstede 2008, the Pacific island countries and territories: Bell et al. 2011a) and global (e.g. Brander 2007, Cheung et al. 2009, 2010). All of them make considerable effort to minimise uncertainties but inevitably rely on underlying assumptions and retain considerable residual uncertainty. As a general rule, their outcomes can be considered to be characterized by medium evidence and medium agreement. The forecast impacts vary widely depending on the specific characteristics of each taxonomic group and ecosystem.

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 there is lower confidence in these results than for the other scenarios (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. 2011a).

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. 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 of coastal fisheries as a whole in 2035 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 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 primary production in the ocean around Australia will increase 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 likely 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 (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, that will vary according to species, including through 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. 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. Thresholds and Irreversible Changes

Any reduction in the number of options for food production could also be irreversible. Thornton et al. (2010) found that the changes in crop and livestock production associated with four degree increase in global mean temperature (e.g. projected changes in growing season length) result in diminishing options for agricultural growth and food security in Africa. Much of the literature on projected climate impacts and adaptation can be interpreted in terms of changes to the number of options for agricultural productivity.

Food price spikes and their relationship to climate change, perhaps in the broader context of: The food price spikes of the early 21st century demonstrate that unanticipated changes in food systems may be important in the future. Such changes may be prompted by an unpredictable climatic extreme in a given location, or by a predictable trend (e.g. greater uptake of a particular crop variety) with unpredictable consequences. Nonlinear interactions in food systems may mean that thresholds are reached through unexpected 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).

7.4.4. Projected Impacts on Food Availability and Food Security

Figure 7-7 shows the time evolution of crop yield from a meta-analysis of impacts studies. It demonstrates that the consensus across the range of crop responses found in the literature is that mean crop yields are [hopefully use calibrated language here] likely to fall by at least X% by the year 20XX, and that the latest date at which this will occur is likely 20ZZ.

[INSERT FIGURE 7-7 HERE
Figure 7-7: Summary of yield projections, demonstrating when decreases in mean yields of e.g. 40% are likely. Redrawn from (Chettri, Lobell, Challinor, Watson – in prep). Figure contains a subset of the total envisaged final data; any conclusions are preliminary. The widths of the boxes indicate the projection time period, and their heights illustrate the mean yield change across studies of this precise period. The bars show the standard deviation. The form of presentation may change, pending a current analysis.]

[The likelihood statement will depend on the accuracy of the models. The need for a traceable account suggests we have one statement contingent on 100% accurate models, and another that takes into account expert opinion on how accurate the crop models are]

Weeds and Food Security: Projected Impacts: It is likely that weed populations and demographics will change, with an overall poleward migration (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, is likely to be adversely affected, with increasing economic and environmental costs.

Number of under-nourished: Lloyd (2011) used models 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).

The main focus of recent models projecting impacts on non-availability dimensions of food security focus on access, building on estimated impacts of climate change on productivity and food security (Nelson et. al. 2009; Hertel et. al. 2010; Calzadilla et al 2011). Nelson et. al. 2009 develop 15 scenarios for climate change based on 3 economic development and five climate change scenarios find that up to 2050 economic growth has a much greater effect on food security than climate change, although climate change does augment negative impacts. They project increases in the number of malnourished children due to changes in per capita calorie availability driven by varying economic growth and climate change scenarios. They find increases ranging from 8.5 to 10.3 percent over the baseline scenario. Their findings also indicate that up to 2050, changes in global food trade patterns can mitigation negative effects of climate change. Hertel et. al. 2010 use a computable general equilibrium model to analyse food security impacts of climate change, focusing on the tails of the distribution of projected climate change impacts on yields up to 2030. The results highlight the importance of income source in determining food security impacts: scenarios with high yield impacts also generated increases in food prices that benefitted net exporters/sellers. Conversely, high productivity growth scenarios lead to reductions in food prices that had differential impacts on sellers and buyers.

Two modeling studies focus on the relative impacts on key inputs to agricultural production in estimating global welfare effects. Calzadilla et. al. 2010 distinguish climate change impacts on irrigated and rainfed agricultural systems for two periods: 2020s and 2050s using a CGE model and the equivalent variation[1] to measure welfare impacts. They find significantly larger negative impacts of climate change on welfare in 2050s compared with the earlier period, with a high number of developing countries in South and Southeast Asia, as well as Middle East and North Africa adversely affected. Sub-Saharan Africa shows net positive welfare gains, albeit relatively small in both periods. Roson and VansMensbrugge 2010 include the effects on labor productivity arising from adverse health impacts of climate change in assessing with and without climate change scenarios up to 2100. Their findings indicate that climate change impacts on labor productivity are always negative, and particularly significant in China, India and most developing countries.

[INSERT FOOTNOTE 1: The equivalent variation measures the welfare impact of a policy change in monetary terms. It is defined as the change in regional household income at constant prices that is equivalent to the proposed change (Calzadilla et. al., 2010).]

There is little modeling work on climate change impacts on the stability and utilization dimensions of food security. Battisti and Naylor 2009 show a probability of over 90% that temperatures in the tropics and subtropics will exceed even the most extreme seasonal temperatures recorded from 1900 to 2006 and note the strong adverse effects this will have on human health in these areas of high population densities. They also conclude that these projected temperature changes will generate global stress on crops and livestock production that will be difficult to balance with global food trade.

7.4.5. Key Findings from Impacts – Confidence Limits, Agreement, and Level of Evidence

Regional climate change impacts were emphasized, and other impacts will be supplement, including CO2 fertilizer effects. Model simulation showed that future climate change has, though varied large range, risk of negative impacts on agricultural systems in Africa. Taking the global as whole, cropland drought will be strengthened by 2100, in South Asia and Southern Africa in particular.

Studies showed that (medium evidence) increasing temperature in the Pacific will shift the favourable habitats for both skipjack and big-eye tuna species tending to improve conditions east of the date line for both species while the temperature is forecast to become too warm for bigeye tuna in the Western Central Atlantic. And primary production in the ocean around Australia will increase as a result of small increases in nutrient availability from changes in ocean stratification and temperature. Changes in crop and livestock production associated with four degree increase in global mean temperature result in diminishing options for agricultural growth and food security in Africa.

Confirmation of the generally positive effects of elevated CO_2 levels on primarily C_3 crops although the CO_2 signal is often superseded by other impacts such as improvements in agricultural technology and breeding. It is difficult only to ascribe changes in cropping and yield to changes in climate as there are many other interacting factors, some of which, such as extreme droughts and temperatures, are in agreement with the climatic consequences of climate change. Such a conclusion also applies to fisheries.

Work since AR4 has tried to move the scope of modelling to larger geographical scales whilst recognizing that the process models that may be better suited to predicting future impacts rather than analyzing current and historical patterns, require overhaul to bring them up to date with the latest experimental findings. New parameter estimation methods such as Bayesian analysis that allow better quantification of the uncertainties implicit in models are a welcome development since AR4.

[A summary of this section will need a figure with agreement (H,M,L) on one axis and confidence (H, M, L) on the other axis with the nine so formed boxes completed with impacts. (DL is working on this with Chapter 18 on attribution and detection).]

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. 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) although this response is not ubiquitous (Bryan et al. 2009). There are a large number of potential adaptations for cropping systems, many of them enhancements of existing climate risk management.

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. 2011). 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. 2011, Cho et al. 2011). 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 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 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 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 (*medium agreement, limited evidence*). 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, Bindi & Olesen 2011, Dronin and Kirilenko 2011, Kulshreshtha 2011, Kvalvik et al. 2011, Tchebakova et al. 2011). In many of these cases, the northerly range expansion may only offset the reduction in southerly cropping areas and yields due to lower rainfall, water shortages and high temperatures (*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 (Krishnan et al. 2007; Challinor 2009; Luo et al. 2009; Shimono et al. 2010; Stockle et al. 2010, Wassman et al. 2008). 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 to be integrated with *in situ* conservation of local varieties (IAASTD 2010).

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 (Mutekwa 2009, Naylor et al. 2007, Tao and Zhang 2010), 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 and more effective decision support (Connor et al. 2009, Olesen et al 2011, Thomas 2008, Falloon and Betts 2010, Luo et al. 2009, Lioubimtseva and 2009, Piao et al. 2010). 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 (Figures 7-9 and 7-10) 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 (Lioubimtseva and 2009, Thornton et al. 2010). Reidsma and Ewert (2008) 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 (2011) 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. In some cases, increased diversification outside of agriculture may be favoured (e.g. Coulthard 2008, Mary and Majule 2009, Mertz et al. 2009).

[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 (this is a subset of the data points in Figure 7-5). For the final figure, we'd envisage shading the area between the two regressions – this quantifies the benefit of adaptation according to the modelling studies. The figure contains a subset of the total envisaged final data; any conclusions are preliminary.]

[INSERT FIGURE 7-10 HERE
Figure 7-10: The benefit of crop management adaptations as a function of global temperature change expressed as the difference between yield change between the adapted and non-adapted cases 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 (this is a subset of the data points in Figure 7-5).]

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 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 18% of current yields for a temperature increase of 5ºC (Figure 7-10). This response is, however, extremely variable, ranging from negligible benefit to very substantial. The responses are similar between wheat, maize and rice but 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%).

Potential increased variability of crop production means there is high confidence (*high agreement, medium evidence*) that that food reserve, storage and distribution policies and systems may need to be enhanced (IAASTD 2010) 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 (*medium agreement, limited evidence*).

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, providing 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). 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. Ash et al. 2007). 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 production systems there is a range of barriers to adaptation which could be addressed 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 agreement, robust evidence*), especially in higher productivity systems (7.3.2.6). For example, some graziers in Africa are already make 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. 2011b). In warmer climates 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 (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 (Alison 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, Hobday 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).

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 adaptation. Bell et al. (2011c) 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 (Ford 2009, Alessa 2008), 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., 2011McDowell & 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 & Thomas 2011) [Cross reference to Chapters 22 and 9]. 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. 2011, Salick & Ross 2009, Kalanda et al. 2011; Green et al. 2010), although IK can differ according to gender and age in some communities (Rengalakshmi 2007, 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: cross reference to WGI and IPCC Extremes SR) the confidence in 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 (*high agreement, medium evidence*). Moreover, 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. 2011) (*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 (e.g. Battaglini et al. 2009) although in some regions there appears to be adaptation to climate change that is happening now (Olesen et al. 2011). Activities to build adaptive capacity to better manage climate change are more widespread (e.g. 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 (Adger et al. 2005) and there can be barriers (restrictions that can be addressed) and limits in all these factors (high agreement, ???? 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, financial constraints including access to credit, insufficient fertile land, infrastructure, lack of functioning markets and insurance systems (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. 2010). 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 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 2010). 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 agreement, medium evidence*). These adaptations include measures that reduce soil erosion or reduce leaching of nitrogen and phosphorus, 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, 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 both farmers and policymakers in evaluating transformative, pro-active, planned adaptations such as structural changes (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. 2011).

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 example in Figure 7.10 indicates 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. 2010, 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, as well as with local organisations to build their capacity to support communities to adapt. The initial stage in their work involves participatory assessment of vulnerability and adaptive capacity. 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). CSIRO is 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 [still to be revised]

There have been many studies of crop adaptation since the AR4. In aggregate these show that adaptations to changed temperature and precipitation are likely to bring substantial benefit with some adaptations (e.g. cultivar adaptation) being more effective than others (e.g. irrigation optimisation). Changing planting dates and associated decisions to match evolving growing seasons could maximize production benefits whilst improving cultivar tolerance to high temperature, drought conditions and elevated CO_2 levels could be beneficial to crop yield and quality and water use efficiency.

Livestock and fisheries systems have available a large range of possible adaptations often tailored to local conditions but there is not adequate information to aggregate the likely value of these adaptations. 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. 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.

Indigenous knowledge has been important for food security in many parts of the world but climate and other changes are causing re-thinking as to how to best apply it.

There is some evidence that decision-makers along the food security chain are starting to adapt to climate changes but this response is not ubiquitous.

Most adaptation studies focus on the farm level and on productivity measures with relatively few addressing value chains or economic measures.

The focus on incremental adaptations and few studies on more systemic and transformational adaptation or adaptation along the value chain mean that there may be underestimation of adaptation opportunities and benefits. 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.

7.6. Research and Data Gaps – Food Security as a Cross-Sector Activity, Malnutrition, Research Capacity, and its Regional Variation

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 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 food production impact models, the need to create integrated food systems models at the regional and global scales and geared to including climate change effects on the global food system.

Frequently Asked Questions

FAQ 7.1: How could climate change result in reduced food production?
Observations and many experimental studies show with high confidence that a warming climate has a generally reducing effect on yields of staple cereals such as wheat, rice and maize, especially at low latitudes. Warming can have a stimulatory effect on yields of perennial crops such as grass. Crop models have generally indicated that climate warming has negative impacts on crop yield. However, the impacts differ between regions, with low latitudes more negatively affected than high latitudinal areas. Climate change will affect fisheries and aquaculture through gradual warming, ocean acidification and through changes in the frequency, intensity and location of extreme events. Overall, it will lead to a mixture of negative and potentially positive impacts on fishery and aquaculture production which will vary with locality. 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 do elevated CO_2 levels affect crops?
Stabilization of CO_2 concentration reduces temperature damage to crop production in the long term. Generally, elevated CO_2 benefits C_3 species more than C_4 species by increasing photosynthetic rates. CO_2 can also improve yields in dry conditions for both C3 and C4 species, because CO_2 induced reductions in stomatal apertures help to reduce water loss. However, there is big uncertainty in the magnitude of the CO_2 effect and that interactions with other factors such as nutrient fertilization highly influence crop responses to CO_2, as does the effect of other gases such as tropospheric ozone in combination with CO_2.

FAQ 7.3: What type of climate extremes matter for agriculture?
Low and high temperature and moisture extremes are generally harmful to agriculture. Frost damage is an important constraint on crop growth in high latitudes, and reduced frost occurrence from climate change will likely benefit crops in these regions. Extreme high temperatures can reduce leaf longevity and photosynthesis rates, increase water loss, and directly damage plant cells, with especially high sensitivity during flowering period. Increased high temperature extremes are expected, and indeed are already occurring, in both low and high latitudes. Heavy rainfall

affects farming in many ways, including flooding, waterlogging, and washing away nutrients. Experience of climate extremes reduces the productivity of animals and their welfare.

FAQ 7.4: How could adaptation actions avoid the loss of food production?

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 7.5: Where do the food insecure live?

Most small island nations are vulnerable to climate change will face more food insecure, poor countries and poor people also have more challenge because they are lack of adaptation capacity.

FAQ 7.6: How could climate change interact with declining fish stocks, ocean acidification?

Millions of people rely on fish and aquatic invertebrates for their food security and as an important source of protein. .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.

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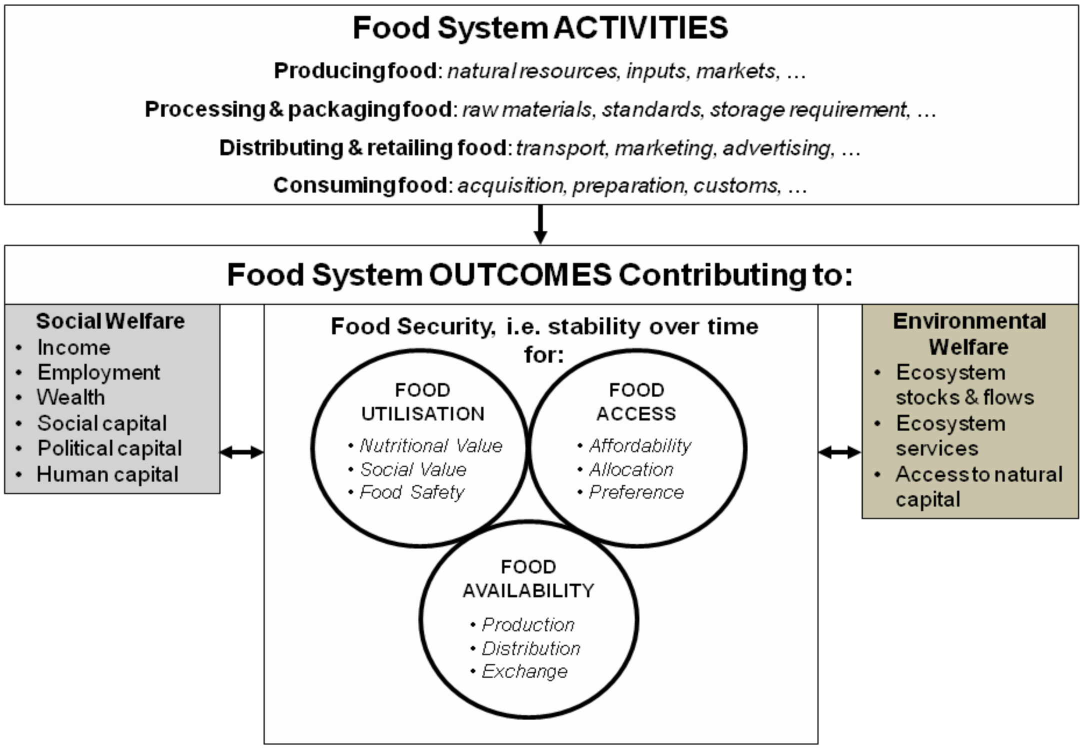

Figure 7-1: The components of food systems in terms of activities and outcomes for food security and environmental and social welfare (GECAFS, 2009).

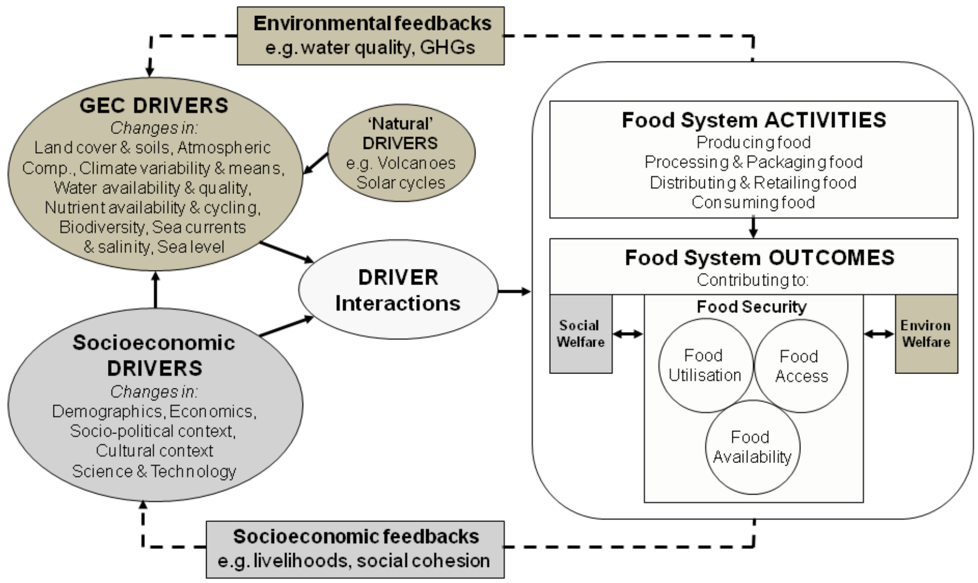

Figure 7-2: Main drivers of food systems. (MAY BE REMOVED DUE TO OVERLAP WITH FIGURE 7-1)

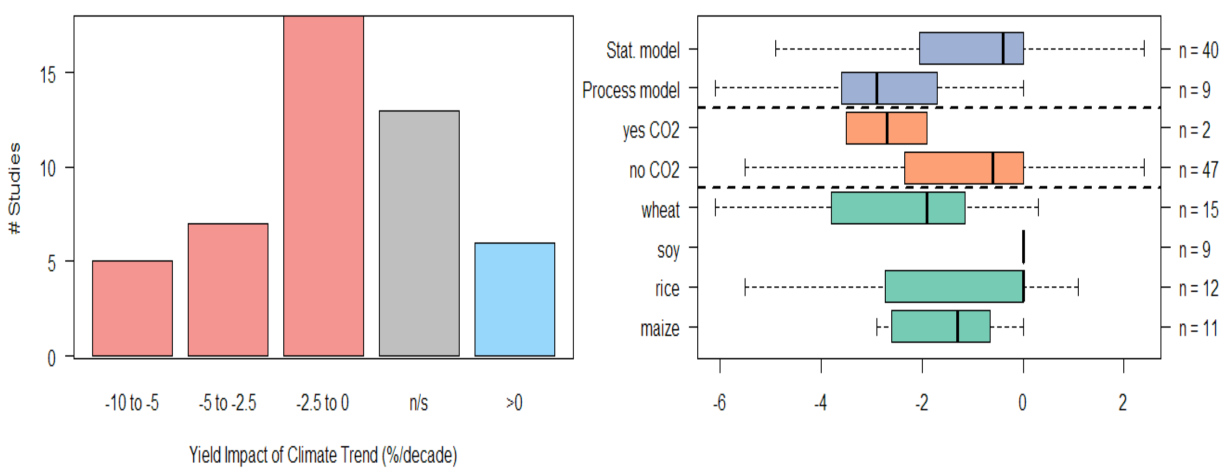

Figure 7-3: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological crop models or statistical models), spatial scales (e.g., stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO_2 trends but most did not. (a) shows number of studies with different level of impact (% yield per decade), (b) shows boxplot of studies separated by modelling approach, 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), 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), 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).

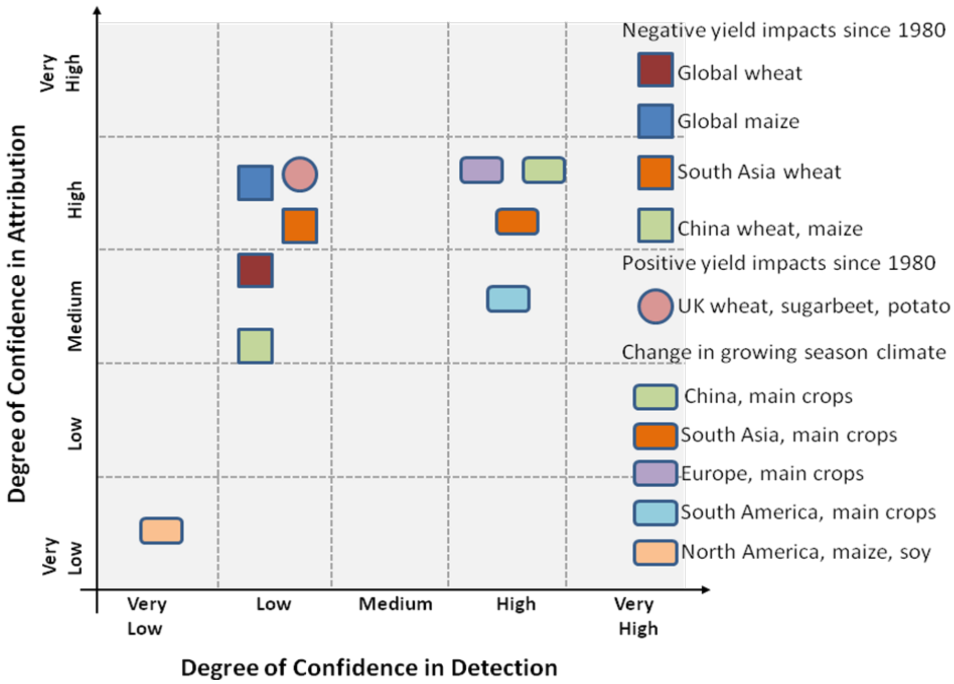

Figure 7-4: Confidence in Detection and Attribution of Observed Impacts on crop yields and growing season agroclimatic conditions. Yield impacts include both direct climate effects and effects of elevated CO_2, but do not consider farmer adaptation. Confidence Levels were derived based on expert judgement of the available literature, following the IPCC uncertainty guidance (Mastrandrea et al., 2010). References: to fill in when complete, many of the same from Figure 7-3.

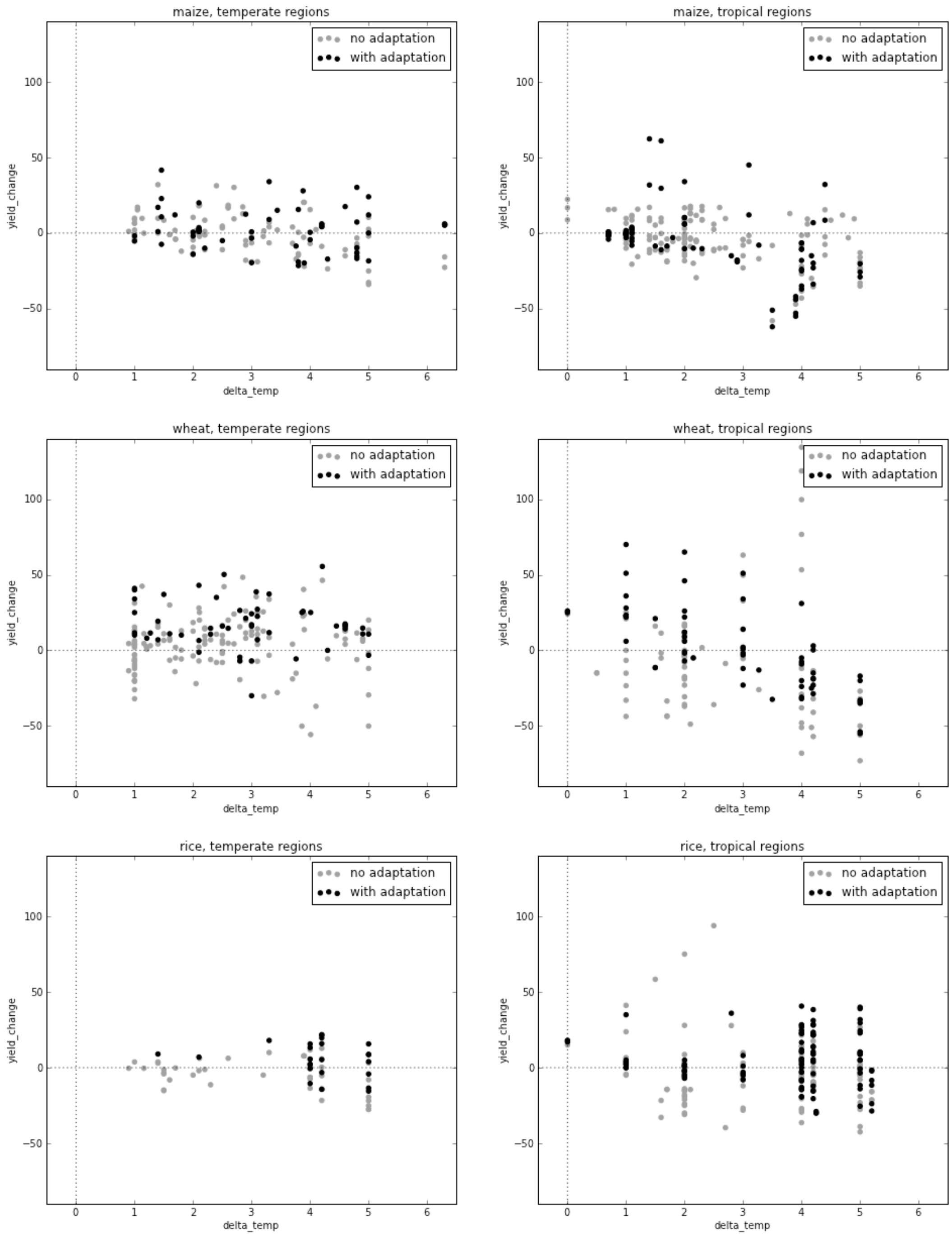

Figure 7-5: Reproduction of AR4 (Figure 5.2, WG II, p. 286) temperature (delta_temp) vs yield change with more up-to-date database (number of data points ca. doubled from AR4). All available data points used (cf Figure 7-7 which is where adaptation is dealt with more fully). Boxplots may be used for the final version of this figure.

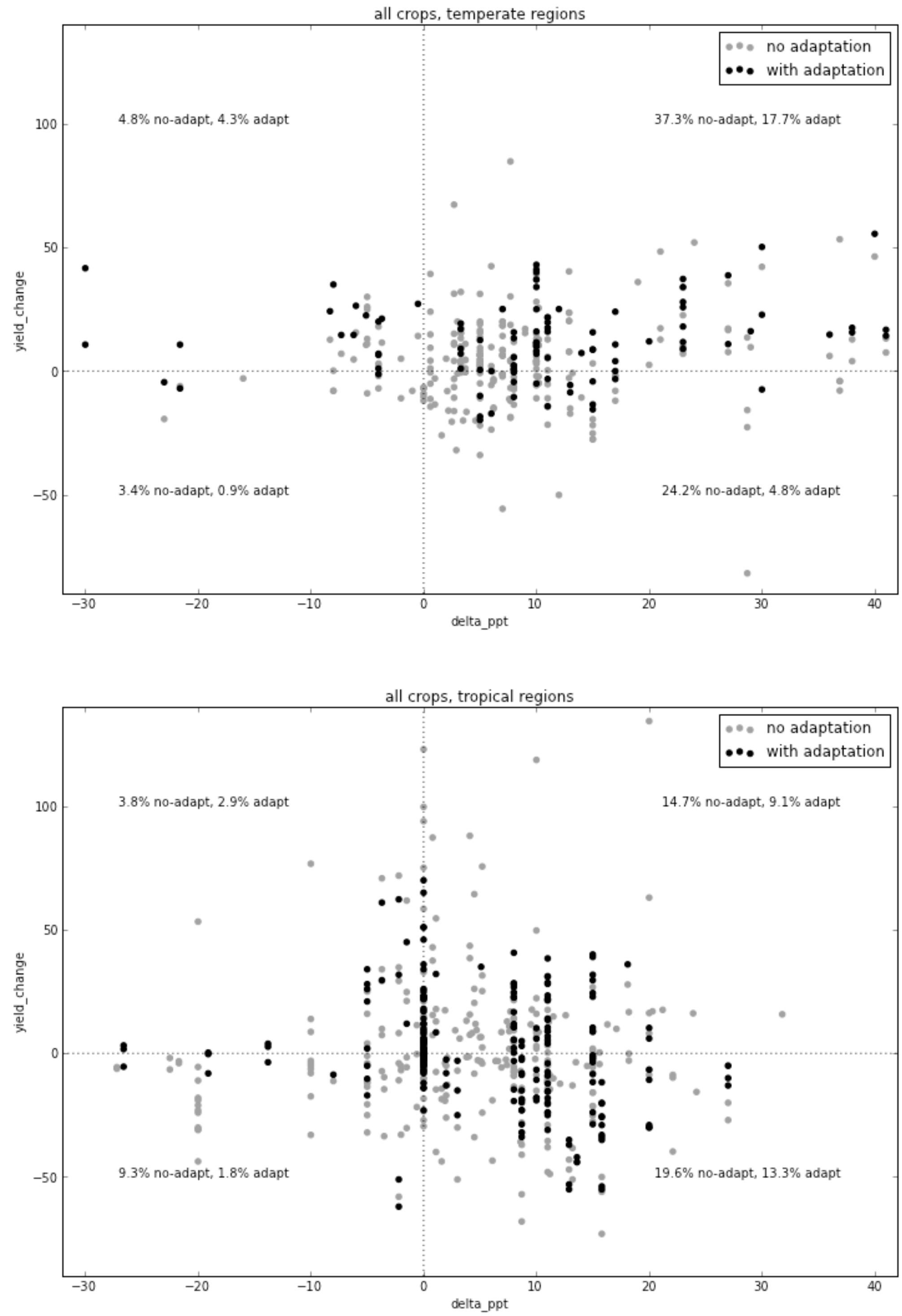

Figure 7-6: Yield change vs precipitation (delta_ppt), showing a contrast between tropical and temperature regions. Redrawn from (Chettri, Lobell, Challinor, Watson – in prep). Figure contains a subset of the total envisaged final data; any conclusions are preliminary.

[Possible Figure 7-X: Changes in herbicide efficacy determined as changes in growth (g day^{-1}) following application for weeds grown at either current (A) or projected (~700 ppm) (B) levels of carbon dioxide. Herbicide was glyphosate in all cases, except [1], which was glufosinate. (See also Manea et al. 2011). Not included in FOD.]

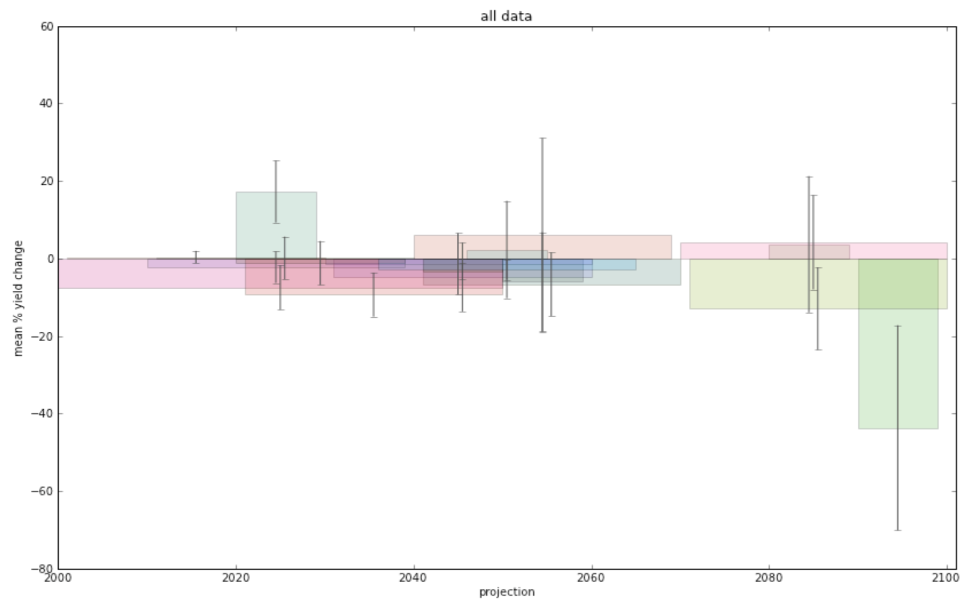

Figure 7-7: Summary of yield projections, demonstrating when decreases in mean yields of e.g. 40% are likely. Redrawn from (Chettri, Lobell, Challinor, Watson – in prep). Figure contains a subset of the total envisaged final data; any conclusions are preliminary. The widths of the boxes indicate the projection time period, and their heights illustrate the mean yield change across studies of this precise period. The bars show the standard deviation. The form of presentation may change, pending a current analysis.

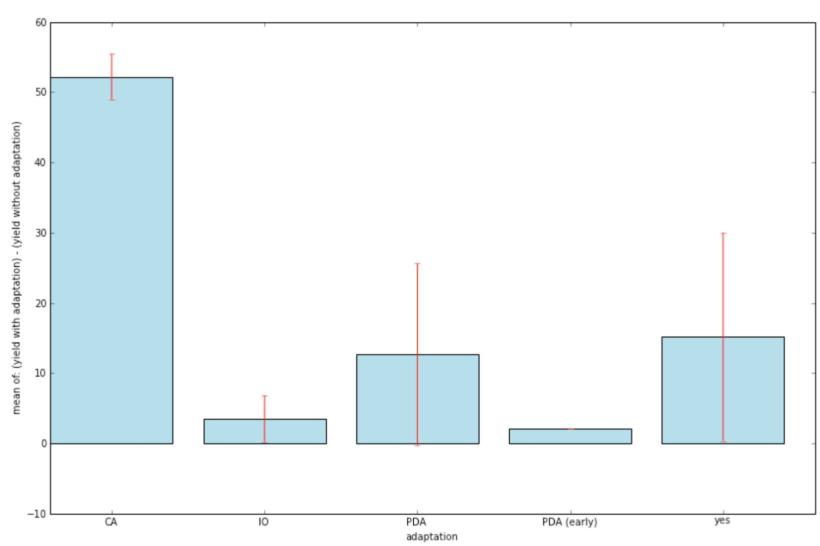

Figure 7-8: The benefit (% difference from baseline) for different crop management adaptations (CA – cultivar adjustment; IO – irrigation optimisation; PDA – planting date adjustment; PDA early – adjusting planting date earlier; yes – other treatments). The bars indicate ± SE.

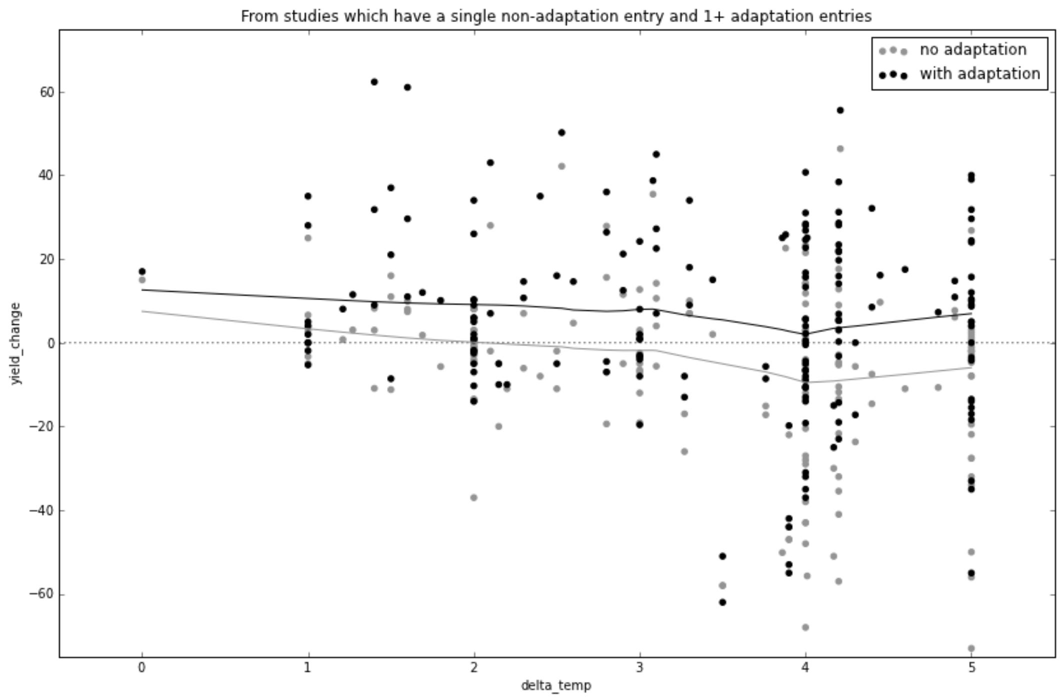

Figure 7-9: Yield change (% difference from baseline) as affected by temperature aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a 'no adaptation' and an 'adaptation' scenario are used (this is a subset of the data points in fig 7.5). For the final figure, we'd envisage shading the area between the two regressions – this quantifies the benefit of adaptation according to the modelling studies. The figure contains a subset of the total envisaged final data; any conclusions are preliminary.

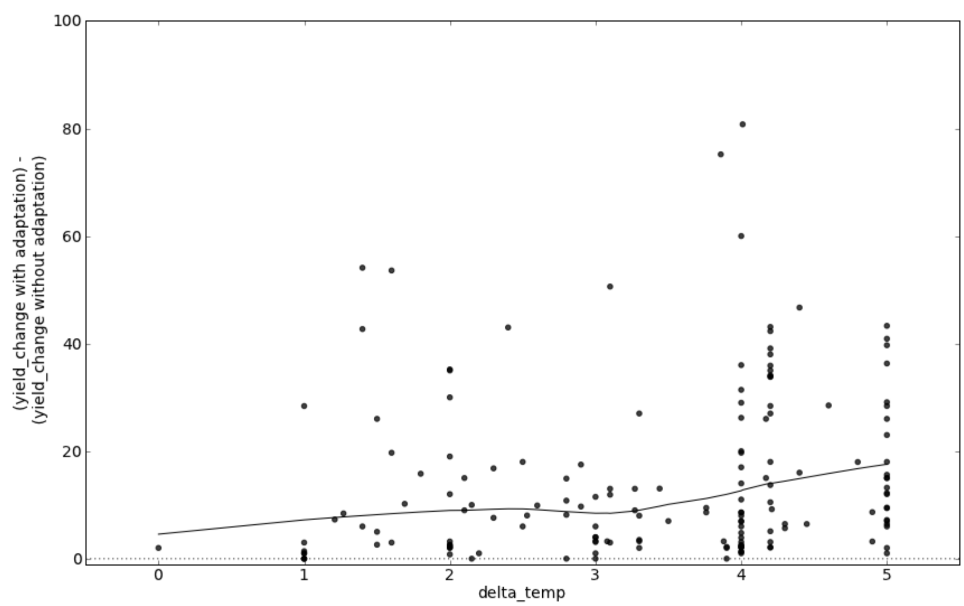

Figure 7-10: The benefit of crop management adaptations as a function of global temperature change expressed as the difference between yield change between the adapted and non-adapted cases aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a 'no adaptation' and an 'adaptation' scenario are used (this is a subset of the data points in fig 7.5).