Chapter 7. Food Security and Food Production Systems

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Executive Summary

[to be completed]

7.1. Introduction

Many definitions of food security exist. Maxwell and Smith noted over 200 as early as 1992 ((Spring, 2009)) and more are still being 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 notion of food security has rapidly ascending policy agendas (e.g. (Defra, 2006; EU, 2011; Foresight, 2011)), science agendas (e.g. (Godfray et al., 2010a); (Science, 2010)), and the media (e.g. *Economist* 21 November 2009; 24 February 2011) worldwide. While food security has been on the development agenda for decades, this 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, including policy failures and market overreactions (von Braun and Torero, 2009). This price spike increased the number of hungry people by some 40 million (FAO, 2008). 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)). Given that food prices are again at a high level (*Economist*, 24 February 2011) there is a strong likelihood that this number will again rise.

7.1.1. 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), and is particularly suited to global environmental change research.

[INSERT FIGURES 7-1 AND 7-2 HERE; titles forthcoming….]

Understanding the interactions between food security and global environmental change is highly challenging. This is nevertheless increasingly important as 50% more food will be needed by 2030 (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.

7.1.2. 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 number 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).

Among the rural food insecure, most are net consumers of food, meaning that they consume more calories than they produce in their fields. Even net producers of food are often consuming insufficient calories, choosing instead to spend some of their income on sugar, meat, and other more expensive foods, or on non-food items such as cultural ceremonies (Banerjee and Duflo, 2007; Naylor and Falcon, 2010).

[Note (JRP): There may not be room for this entire section in the intro, so the following can be left out or shortened. In addition we need to be sure that we address as many elements in the food system as possible and the effects of climate change on each of them – ie not just food production but the other downstream elements in the food system such as processing, distribution and consumption. This still needs to be done.]

Given that the poorest of the world typically spend at least half of their income on food, the effects of changes in local food prices can be profound. Although changes in global prices are of interest, there are many reasons (government subsidies, trade restrictions, transportation costs, exchange rates) that local price variations may not reflect global conditions. In the recent episode of price volatility (2006-2008), domestic prices in many poor countries increased by only one-third or one-half as much as global prices, which are denominated in US currency (Dawe, 2008; Naylor and Falcon, 2010).

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.

[Note: (DL) Nothing on current state or future drivers of food production yet.]

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, this period used as a surrogate for climate without changes in greenhouse gases after 1960.

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.

Many studies of cropping systems have estimated impacts of observed changes in climate over the past few decades (Figure 7-3). These studies indicate that there is high confidence (high agreement, robust evidence) that climate trends have most often negatively affected crop production, particularly for wheat and maize. A sizable fraction of these 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; Lobell et al., 2011; You et al., 2009), 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.

[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., long-term experiments, 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. Studies were for China (Chen et al., 2010; Tao et al., 2008; Tao et al., 2006; Wang et al., 2008; You et al., 2009), India (Pathak et al., 2003), United States (Kucharik and Serbin, 2008), Mexico (Lobell et al., 2005), France (Brisson et al., 2010), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Lobell et al., 2011; Welch et al., 2010).]

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 (Liu et al., 2009; Zhang et al., 2008).

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). In the North Sea, within the NE Altlantic, 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, P., White, W., Gledhill, D., Hobday, A., Brown, R., Edgar, G. and Pecl, G. 2011: Long terms shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. Global Ecology and Biogeography 20, 58-72)

Coral reef ecosystems are important sources of fish for food for local inhabitants. 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. The threshold for concentration of carbonate ions between conditions favouring reef-building and those favouring net erosion is approximately 200 μmol of kg^{-1} seawater. The present estimated mean is slightly above that threshold at 210 μmol of kg^{-1} seawater which is lower than that observed during the past 420 000 years (Hoegh-Guldberg et al. 2007). De'Ath et al. (2009) estimated that that calcification in the Great Barrier Reef in Australia has declined by 14.2% since 1990, a decline which has not previously been observed in at least the last 400 years. The authors report that the causes of the decline are unknown but suggest that it could be a result of increasing temperature and declining carbonate ion concentrations. 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 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.

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 when available). 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 7-1 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 7-1). In general, we conclude with medium confidence (high agreement, medium evidence) that the major events in the past decade appear to have been more likely to occur than they otherwise would have been without anthropogenic emissions of greenhouse gases. A more complete analysis, for instance looking at major events throughout the past several decades, would be needed to assess the net effect of global warming on the overall occurrence of damaging extreme events.

[INSERT TABLE 7-1 HERE
Table 7-1: Selected extreme climate events over the past decade with impacts on food production or food security, and anticipated change in frequency due to greenhouse gas emissions.]

In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition on crops. There is 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 by a small percentage relative to non-climatic drivers of 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 (Mills et al., 2007; Morgan et al., 2006) (high agreement, robust evidence). Elevated O_3 is currently estimated to suppress global production of wheat and soybeans by roughly 10%, with values for maize and rice of 3-5% (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 1.x), 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. Trade policies 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 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

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 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. 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 work that quantifies uncertainty in both climate and its impacts, particularly for crops, and models that include crop growth as part of broader land surface and earth systems models (e.g Bondeau et al., 2007; Osborne et al., 2007). Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Baysian methods to constrain crop model parameters (Iizumi 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 (AgMIP-AFM paper; Challinor and Wheeler 2008; Kang, et al. 2009; Schlenker and Lobell 2010).

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).

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. Also maybe refer back to section 2 on observed impacts.

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 increases 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. Models have the advantage of exploring a larger number of situations, but with less certainty in the determination of the response variable. There is a contribution to uncertainty in model output from measurement error, through the calibration procedure. Greater access to accurate regional-scale crop yield data would very likely lead to decreased uncertainty in projected yields (Watson et al., AFM special issue). Given these different strengths and weaknesses, and associated dependencies, it is critical that both experimental and modeling lines of evidence, and their uncertainties, are examined carefully when drawing conclusions regarding impacts, vulnerabilities and risks. This approach to assessment is applied to each of the topics described in the rest of the chapter.

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 (2011).
More needed on non-crop experimental methods?

7.3.2. Sensitivity of Food Production to Weather and Climate

7.3.2.1. Crops

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. This 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 (Asseng et al. 2011, others). 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). However, despite this process understanding, model results tend to be specific to crops and regions and can still disagree on the sign of the response of yield to temperature (refs / example needed).

Given that many processes throughout a crop’s life cycle are sensitive to temperature, precipitation, and other meteorological conditions, the overall relationship between weather and yields is often crop and region specific, as it depends 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. For example, since 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). Since 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).

In the case of fisheries and aquaculture, the study by Mantua et al. (2010) referred to in Section 2.1 demonstrates the important impacts of seasonal variations and extremes, as opposed to means, on population responses to climate change. That study, on salmon populations in Washington State, USA, cconcluded 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 of 2ºC in excess of normal maximums for 3 to 4 weeks is sufficient to disrupt the essential relationship between endosymbiotic dinflagellates 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).

Climate and crop models have been used to make regionally-specific statements regarding which biophysical and physiological processes are likely to limit future crop productivity. A body of work for groundnut in India has highlighted, for changes in climate associated with a doubling of carbon dioxide, regions prone to decreased crop duration, and increased water and/or temperature stress. Treatments of uncertainty in these studies vary significantly, from sub-sampling of one climate model output to more recent simulations that perturb both crop and climate parameters (Challinor et al., 2009). The increased quantification of uncertainty did not significantly alter the key result for the one location studied.

[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 favor 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 subhumid 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, sugarcane), 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).

Water-stressed crops are expected to respond more strongly to elevated CO2 than well-watered crops, because of CO2 induced changes in stomatal apertures. This suggests that rainfed cropping systems will benefit more from elevated CO2 than irrigated systems, and that rainfed 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 vs wet signal (Challinor and Wheeler, 2008a).

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.

The impact of increasing CO2 concentrations on coral reefs as a result of increasing concentration of carbonic acid concentrations in the ocean reducing the availability of carbonate to the reef building organisms has been described in other parts of this chapter. 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).

Ozone in the stratosphere provides protection from lethal 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. Bing a powerful oxidant, ozone and its secondary byproducts damage vegetation by reducing photosynthesis and other important physiological functions resulting in weaker, stunted plants, inferior cop quality and decreased yields (Booker et al. 2009; Fuhrer, 2009). Ozone pollution poses a growing threat to global food security. 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 worth $11-18 billion. For the near future (Year 2030), they (Avnery et al. 2011b), under IPCC A2 scenario, showed a further yield reduction 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 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 greatest losses, in year 2000, 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, the losses reported were slightly lower than those reported by Anvery et al. (2011b) but significant losses were projected to occur in the 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) having implications for food security. 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). It is evident that any effort to reduce surface ozone concentrations provides an excellent opportunity to increase global grain yields without environmental degradation which would otherwise result from additional fertilizer application or land cultivation.

Placeholder: 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

Definition of autonomous adaptation and/or reference to Mark's Adaptation section.

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 use for irrigation, will have implications for inland fisheries and aquaculture (FAO 2009). Brander (2007) referred to

the example of the Mekong River basin where a large proportion of the 60 million inhabitants are dependent in some way on fisheries and aquaculture. Referring to an FAO publication, he reported that the impacts on human population growth, flood mitigation, increased offtake of water, changes in landuse and overfishing are likely to be greater than the impacts of climate change but that these factors are strongly interrelated.
[Placeholder: more on fresh water resources – see Chap3 ZOD 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. Observed changes in measures of suitability are described in section 2.x. [include any studies here that compare model predictions to these observations. i.e. are areas shifting in the direction expected. If not, why not] . 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).

7.3.2.2. Pests, Weeds, Diseases

[Note: (JRP) This section is a significant new development from AR4 but is too long and needs to be cut by at least a half. We would welcome suggestions from reviewers on what to include as the absolute main points.]

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?

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.

According to Oerke (2006), weeds cause much higher potential crop losses than insect pests or pathogens. However, the actual impact of weeds on global food production is frequently overlooked due to their consistent presence in agro-ecosystems. The efficacy of management also differs among regions of the world, from a total estimated reduction in losses due to pests, weeds, and diseases of 71% in Northwest Europe to 32% in East Africa and Commonwealth of Independent States (Oerke 2006). Weeds also represent a significant reduction in processing quality of crops and forages. Depending on stocking rates, livestock mortality can be significantly associated with the presence of poisonous weeds (Taylor and Ralphs 1992). Increasing occurrence of non-native (invasive) weeds can also result in significant agronomic and environmental damage with estimated losses of approximately 120 billion per year in the United States (Pimental et al. 2005).

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 7-4). 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.

[INSERT FIGURE 7-4 HERE
Figure 7-4: 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).]

Given the importance of weeds to crop production, it is surprising to find so few assessments of how changes in CO_2/climate will alter their impact on agriculture. Yet, we are aware of only a handful of weed/crop competition studies with respect to soybean (Ziska 2000, Ziska and Goins 2006), one study with respect to rice (Alberto et al 1996) and no studies with respect to wheat, where projected changes in CO_2/climate on seed yield have been quantified. As with pests and diseases, CO_2/climate effects on weed biology and crop/weed competition represent a significant biological uncertainty with respect to predicting future yields of rice, soybean and wheat:

- 'Actual yield' results after considering the effects of pests, weeds, and disease after management to reduce their impact. 'Attainable yield' is the yield that could be obtained in the absence of the effects of pests, weeds, and disease, and is the yield often considered in evaluations of climate effects that are based primarily on crop physiological responses to environmental conditions.
- As discussed by Oerke (2006), 'The attainable yield is defined as the site-specific technical maximum, depending on abiotic growth conditions, which in general is well below the yield potential, a rather theoretical yield level that cannot be realized under practical growth conditions.'
- The focus in the extensive summary by Oerke (2006) is on pre-harvest losses. Postharvest losses have also been recognized as potentially as substantial as pre-harvest losses. Storage of food is often a problem, and one that can be exacerbated by weather conditions.
- The effects vary from one crop species to another (Table 7-2).
- Reduction in actual yield loss relies on research and extension activities to produce new crop varieties that have resistance to current pest and pathogen populations, to develop new chemical and cultural methods for management, and to make information about these technologies available to farmers. Other forms of infrastructure that support management include the development of early warning systems or decision

support systems to guide decision-making by farmers, and effective scouting methods to determine where pests and pathogens are currently present.

- Comparison of potential yield loss and actual yield loss is one measure of the success of current strategies for management. [It should be noted that most crop varieties have some level of resistance to many pathogens and pests, so estimates of potential yield loss generally take for granted that varieties are not as susceptible as would be possible.]
- The relationship between pest or pathogen abundance and yield loss is not trivial, and can also be a function of weather conditions. Research is needed to understand these relationships better.
- Effects on yield may also be on quality in addition to quantity of production, reducing the value of production. Sometimes this is in the form of cosmetic damage, for example reductions in the aesthetic qualities of fruit, which still reduces sales value. Other effects on quality can have extremely important effects on human health. Toxin production by pathogens can contaminate food and is especially problematic where infrastructure is lacking for effective food storage and for food testing prior to sale.
- Effective management of pests and diseases can also be a form of climate change mitigation, if the greenhouse gas budget for the production of a unit of food experiences a net reduction in emissions due to management.
- Beneficial microbes have an important role in low-input agricultural systems, and the associations they form with crop plants are also subject to the effects of weather.
- While the yield of food from agricultural systems is the most important short term factor for food security, the spectrum of ecosystem services provided by agriculture is also an important consideration for long-term productivity. Other ecosystem services include soil formation and water regulation. Management practices such as tillage to reduce pest and disease risk can lead to soil loss and reduced carbon sequestration, while pesticide application can affect non-target species.

[INSERT TABLE 7-2 HERE
Table 7-2: Potential yield loss and actual yield loss estimates for 2001-2003 attributable to pests, weeds, and disease (adapted from Oerke 2006).]

7.3.2.2.1. Trends in global and regional effects on production

- Oerke (2006) also provides a comparison of estimates of actual loss over time, comparing 1964/1965, 1988-1990, and 2001-2003. The total percentage loss to pests, weeds, and diseases for those time periods for wheat was 23.9, 34.0, and 28.2, respectively, and for maize was 34.8, 38.3, and 31.2, respectively.
- Oerke (2006) also makes the point that yield loss has not shown a clear downward trend over this time period, even as pesticide use has increased, but use of pesticides has offered farmers a greater range of options in some cases.
- 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 management. Plant pathologists often make reference to the disease triangle: the interaction among host susceptibility, pathogen (and vector, as relevant) competence, and environmental conduciveness to disease. Both host and pathogen traits tend to change at the same time that environmental conditions change.
- Global investments in agricultural research, extension, and teaching have generally declined during recent decades while relatively low food prices were enjoyed in many parts of the world. As food prices have increased in recent years, there is a call to increase investments, but the economic downturn may make this difficult.
- Other global change factors have particularly important effects on pest and disease risk.
  - More rapid transportation networks make movement of pests and pathogens into new regions more common. To date, this has probably had a bigger effect on agriculture than has climate change.
  - Availability of labor influences the efficacy of pest and disease management.
  - Movement of crop species to new regions can also result in new host-pathogen interactions, as appears to be the case with cassava virus diseases in East Africa.

7.3.2.2.2. Effects of climate change on pests, weeds, and diseases, and the likely knock-on impact on production

- The effects of weather on disease and pests have been studied in detail for decades, so this research forms a base for understanding the effects of climate change. There is little doubt that a change in climate will change the potential yield loss to pests and disease. Whether it changes the actual yield loss will depend on decisions by policy makers and donors, agricultural scientists and crop breeders, and by farmers, themselves.
  - Estimates of future risk are available for some pathogens and pests, and more generally for some regions.
  - For example, estimates for potato late blight are for a future increase in risk in the majority of countries where potato is an important crop.
- Most pathogens and pests have an optimal range of temperatures for reproduction, so any given location may become more or less conducive as climate change makes the most conductive temperatures more or less common. Changes in temperature can also support range expansions through changes in winter and summer extremes, and thus the potential for overwintering or oversummering. Higher temperatures may also be associated with higher rates of genetic exchange among pathogens, with implications for more rapid evolution of strains that can overcome crop genetic resistance and that have their own resistance to pesticides.
- Leaf surface wetness and humidity are very important for foliar diseases and some insects, yet tend to be given limited consideration in models of future climate scenarios. Sustained leaf surface wetness is required for infection by many pathogens, especially important fungal and oomycete pathogens, and some bacterial pathogens.
- Likewise, precipitation influences humidity, provides water for reproduction of some vectors, and influences the risk from soilborne pathogens
- Increased CO_2 concentrations have a complicated influence on disease and pests, with the potential for increasing or decreasing risk.
- Challenges for prediction for future risk include the nonlinearity of the relationship between weather and disease or pest risk, and the nonlinearity in the effects of pathogen or pest populations and yield loss. Management techniques may become more or less effective under new conditions, and the potential for movement of pests and pathogens produces correlations in risk among locations. Changes in cropping practices, such as shifts to Conservation Agriculture practices, can interact with environmental conditions to change pest and disease risk.
- The difference between potential yield loss and actual yield loss will be determined by how successful adaptation strategies are. Thus, the knock-on effect on production will depend on how effectively new management technologies have been developed and how effectively they have been deployed by farmers. If the decreased investments in agriculture over current decades continue there will likely be fewer new options available.
- Farmers tend to understand disease least of all the production components of cropping systems, and their understanding of insects is also generally lower than other components. Thus, farmers are likely to need additional extension support for adapting to new types of disease and pest problems, whether because new climatic conditions result in the presence of new pest and pathogen species, or whether the nature of old problems changes.

7.3.2.3. Biofuels and Perennials

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 transitioning economy 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). 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).

Global warming is 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) .Lobell et al, (2006) found negative impacts of future climate on almonds, walnuts, grapes, avocados and oranges in Califorrnia with projected losses ranging between 0 to >40% depending on the crop and the trajectory of climate change. 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 and these requirements 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). Climate change will affect fisheries and aquaculture through gradual warming and the associated physical (and chemical) changes as well as through changes in frequency, intensity and location of extreme events. 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 through such changes will depend on the adaptive capacity of countries and local communities. Overall, increased temperatures are likely to reduce ecosystem productivity in most tropical and subtropical oceans, seas and lakes and to increase producitivty in high latitudes. 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). 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.

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 are also likely 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 is likely to 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. Non-Production Elements and Multiple Interacting Stresses

[to be developed]

7.3.4. What is New since AR4?

This section will revisit all AR4 'new knowledge' to see if AR5 provides confirmation (see 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]

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

Scenarios, time slices, RCP, SRES/CMIP3, NAS.

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.
Will complete once literature review / table is done.

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 Ocean Acidification and Fisheries, with Regional Variation by Time Slice and Scenario

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. 2011) and global (e.g. Brander 2007, Cheung et al. 2009). 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. For example, simulation studies on skipjack and bigeye tuna in the Pacific suggest that increasing temperatures will shift the favourable habitats for both 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 (Loukos et al. 2003, Lehodey et al. 2010). These shifts would tend to favour some of the smaller Pacific Island Countries and Territories in the central Pacific which are particularly dependent on revenues from sale of tuna fishing rights (Bell 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.

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 floodingfrom major storm events and increased ocean temperatures and acidification. These physical and chemical drivers are likely to create a number of problems for the important shellfish aquaculture industry in the state through 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.

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. 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 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

For a number of development pathways. To include food prices, number of under-nourished, price volatility, food reserves, access, utilisation, socio-economic costs and benefits, prices.

Pending literature review

To include figure showing response of eg yield, food prices, food production (calories?) vs time or temperature. The x axis could be temperature, with horizontal box-plots giving time intervals – eg boxplot centred on 2oC shows the range of time within which 2oC will be reached. This emphasizes that it is not a question of 'if' , but rather a question of 'when'.

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 bigeye 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. 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.

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)

Methods of Treating Impacts in Adaptation Studies – Autonomous and Planned

The pervasiveness of climate impacts on food security and production (Section 7.2), the commitment to future climate change from past greenhouse gas emissions (WGI – section to be identified) and the high likelihood of additional climate changes from future greenhouse gas emissions (WGI section to be identified) 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. 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). Both adaptation types can occur at a range of scales from paddock to policy. There is an increasing recognition in the literature that whilst many adaptation actions are local and build off 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.

Cropping

Effective adaptation of cropping is likely to be critical in ensuring food security and sustainable livelihoods, especially in developing countries. 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). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura 2010) and this adaptation is likely to 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). 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 (draw from WG 1), 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). Flexibility in planting dates and varieties according to seasonal conditions is 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.

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 genebanks is needed to facilitate the development of cultivars with appropriate thermal time and thermal tolerance characteristics (e.g. Mercer et al. 2008, Wassman et al. 2008).

Similarly, the prospect of increasing drought conditions in many cropping regions of the world (e.g. Olesen et al. 2011) raises the need for 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).

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 are likely to 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).

(Do additional search for adaptations further down the value chain.)

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. To quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been undertaken for rice, wheat and maize. This meta-analysis indicates substantial enhancement in yields from adaptation for a 1ºC increase in mean temperatures: 10 to 12% mean increase for rice and wheat and 30% for maize. However, the yield benefit decreases with increasing temperature change, essentially becoming zero at 3ºC for all three crops. The adaptations in the meta-analysis were mostly of changes in planting times and a wider range of adaptation options may provide additional benefit at temperature increases above 1ºC.

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 transformative changes. Consequently, the potential adaptation benefits are likely to be understated and a considerable opportunity cost may emerge.

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. 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, migratory 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, especially in higher productivity systems (7.3.2.6). There is some evidence that 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 significantly 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.

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 is unlikely to 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. 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. 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. Adaptive responses to climate change in fisheries should 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). Grafton (2010) identifies adaptations of catch controls (total allowable catch, dedicated catch shares, trip catch limits), input controls (vessel license controls, effort quotas. gear and vessel restrictions), technical and temporal controls (season length, fishing gear specifications, size and gender selectivity restrictions) and spatial controls (‘no take’ areas, territorial user rights in fisheries, individual vessel spatial licensing). There also opportunities for fisheries to contribute to mitigation efforts (Grafton 2010). Complementary adaptive responses including 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).

Practical Regional Experiences of Adaptation, including Lessons Learned

Given the early stages of climate change, there are relatively few unequivocal examples of adaptation (see Box 7.5.2) additional to existing climate risk management and where there have been management changes there are often conflating factors (Mertz et al. 2009, Smit and Wandel 2006). More farmers express an intention to change rather than having implemented adaptive actions 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 is likely to be devolution of the decision-making process so as to integrate local, contextual information into the adaptation decision-making (Nelson et al. 2008).

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. 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 (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. There also can be physiological limits to performance such as upper temperature limits for heat tolerance.

Facilitating adaptation and avoiding maladaptation

Adaptation actions would usually be expected to provide benefits to the farmers 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 byt 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). A recent review of adaptations however, has found that most categories of climate change adaptation options tend to reduce greenhouse gas emissions (Smith and Olesen 2010). 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 (see above) however, this may result in large opportunity costs that could arise from considering more systemic adaptation or more transformative change (Howden et al. 2010). 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 look at pro-active, planned adaptations such as structural changes (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 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. 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. These curves can be used in setting investment priorities and informing policy discussions. The local nature of many adaptation decisions and the time and climate change-sensitive nature of adaptation decisions means however, that global, time-independent curves are not feasible. The example in Fig x indicates an adaptation curve for *x* activity in *y* region (data still being synthesized by Netra Chhetri but I have enquired of other researchers regarding existing examples) it highlights that there are some options which may be more relevant and useful to consider than others and illustrates the likely scope and benefit of engaging in an adaptation assessment or establishing an adaptive management approach.

[Following the zero-order draft we can dissect the data from Netra's analysis to see if we can extend this to food systems.]

7.5.2. Well-Validated Food System Case Studies – Examples of Successful and Unsuccessful Adaptation

[Note: (JRP) We will reduce the number of examples to three – probably cases 1, 2 and 7 as being generally representative of important areas for food security. Referees comments welcome.]

Autonomous, anticipatory and planned 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: Autonomous adaptation in the Sahel

Much of the literature covers autonomous (or reactive) adaptation, but given actors are constantly adapting to changing social and economic conditions, autonomous 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 productivity. The zaï method concentrates runoff water and organic matter in small pits (20-40 cm in diameter and 10-15 cm deep) dug manually during the dry season. A handful of animal manure or compost is placed in each pit. The pits are combined with contour stone bunds that slow down runoff. By breaking the soil crust, the pits facilitate greater water infiltration, while the applied organic matter attracts termites, which have a significant positive effect on soil structure. The organic matter also improves soil nutrient status. Crop yield improves and yield variability decreases. 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: Rice-wheat systems in India

Autonomous adaptation may have undesirable impacts. This case and case 3 illustrate situations where there are undesirable impacts on GHG emissions, while case 4 shows how adaptation actions today may negatively impact the possibility of future adaptation. In the rice-wheat systems on the Indo-Gangetic plains rice is planted in July, harvested in October-November and then wheat is planted in November and harvested in April. If there are any delays in the system, or if as a result of changing weather patterns temperatures are higher, wheat yields are reduced due to increased temperature during grain filling in March and April. To avoid this, farmers need to plant wheat immediately after rice. Some farmers therefore burn rice residues to vacate fields and to plant wheat in time. This unfortunately increases GHG emissions. Minimum tillage approaches may be appropriate in these circumstances, though incentives to farmers to adopt such practices will need to be put in place.

Case 3: Potato production in the Andes

Near-surface temperature has increased significantly throughout most of the tropical Andes (Vuille et al. 2003). Late blight disease on potatoes is very sensitive to changes in temperature and humidity – how the disease spreads in relation to climate change is likely to be crucial in determining the resilience of potato systems against climate change (Forbes and Simon, 2007). Farmers have long understood the close link to weather and late blight severity, and so, for example, to avoid high disease pressure they plant at high altitudes where temperatures are lower. Late blight is one of the drivers of land cover change as farmers' move higher into the Andes (de Haan and Juarez, 2010). Unfortunately this adaptation strategy is often at the expense of carbon-rich grasslands, resulting in high GHG emissions (Segnini et al., 2010). The International Potato Centre (CIP) has initiated work to develop potato cultivars with high levels of resistance to late blight.

Case 4: 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 mean faltering forest-based income sources. This will be particularly problematic to the more vulnerable groups in the community, including women and children.

Case 5: Anticipatory 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 6: Planned adaptation in United Kingdom

In the kinds of pilot projects such as is covered in case 5, the focus is still on household responses. Linking the adaptation actions into government planning and into private sector initiatives is still in its infancy. Tompkins et al. (2010) describes adaptation actions in the UK across multiple sectors. The actions included (a) research on possible adaptation actions; (b) adaptation planning; (c) networks created (e.g. a network created to catalyse innovation in UK crop production); (d) legislative change; (e) awareness raising (f) implemented change, (g) training (e.g. in the East of England, the National Farmers Union ran a series of farmer workshops promoting efficient irrigation in response to the risks of reduced groundwater supplies, and limits on its use), and (h) advocacy. However, not a great deal of activity was found in the agricultural sector by comparison to other sectors.

Case 7: Transformational change in the primary industries of Australia
Many of the above cases 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. 2009).Transformational adaptations would involve significant changes such as relocating industries from irrigated and drying areas to higher rainfall zones or completely changing the industry mix in a specific location. The primary industries in Australia are highly sensitive to the impacts of climate change and transformational adaptation is being considered and planned for (Park submitted). CSIRO is now working with a number of pilot case study partners from wine, peanut, rice and livestock enterprises as well as two rural community groups. In 2007, the Australian Government committed $130 million over four years for the Australia's Farming Future Initiative to address the impacts of climate change - fast tracking the National Agriculture Climate Change Action Plan, preparing the sector to adequately respond to climate change; and assisting with moving farmers towards drought preparedness. In all the cases presented the focus is on production with limited attention to the whole food system. However, in the Australian example actions are also being considered across the whole food system.

[We only need 3-4 examples here as we do not have space for more. Suggest keeping cases 1, 2, 4 and 7 as this provides a cross section between poor and rich countries and well and mal-adapated examples.]

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

Sector adaptation to climate change was emphasized, and other impacts will be supplement, including some case studies.

Crop: Extending growing seasons and early sowing could be maximize production benefits and avoid to late season frosts, improving cultivar tolerance to high temperature and drought conditions could be benefits to crop yield and quality, and water use efficiency.

Livestock: Matching stocking rates pasture and water, monitoring and managing the spread of pests, weeds and diseases. Avoiding heat stress and cold disaster, breeding livestock with increased heat stress resistance apart from shading in hot days and housing in cold days.

Fisheries: Avoiding overfishing and maintaining good coastal and marine environment to improve adaptive capacity to climate change.

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.

I (JRP) think we need to include other aspects of the food system other than production in the chapter. Issues such as food safety and climate, food distribution and storms, consumption patterns as affected by heat, food storage and climate, food packaging as an adaptation to climate change, food systems and mega-cities need to be covered in the chapter and will mark out a significant change in focus from AR4. I am happy to take this on after we get the comments back on the ZOD.

Frequently Asked Questions

[to be completed]

References

[NOT COMPLETE OR IN ORDER]

Agriculture Cluster. 2010. Preliminary Damage Assessment in the Agriculture Sector for Flood-Affected Areas of Pakistan, 9-14 August, 2010 (http://www.pakresponse.info/assessments/AgricultureCluster_Preliminary%20Damage%20Assessment%20in%20the%20Agriculture%20Sector_Sep2010.pdf)

NDMA. 2010. Resilience. NDMA (National Disaster Management Authority, of Pakistan) Newsletter, 1 (#3), May – December 2010 (Web: www.ndma.gov.pk))

Barbier B, Yacouba H, Karambiri H, Zorome M, Some B. 2009. Human Vulnerability to Climate Variability in the Sahel: Farmers' Adaptation Strategies in Northern Burkina Faso. Environmental Management 43:790-803.

Berrang-Ford, L, Ford, J.D. and Paterson, J. 2010. Are we adapting to climate change? Global Environ. Change. 21: 25-33.

de Haan, S. and Juarez, H.S. 2010. Land use and potato genetic resources in Huancavelica, central Peru. Journal of Land Use Science 5: 179–195

Fatondji D., C. Martius C., Zougmoré R., Vlek P. L. G., Bielders C. L., Koala S., 2009. Decomposition of organic amendment and nutrient release under the zai technique in the Sahel. Nutrient Cycling in Agroecosystems 85:225–239

Forbes, G.A. and Simon, R. 2007. Implications for a warmer, wetter world on the late blight pathogen: How CIP efforts can reduce risk for low-input potato farmers. SAT eJournal ejournal.icrisat.org 4(1)

Mertz O, Mbow C, Reenberg A, Diouf A. 2009. Farmers' Perceptions of Climate Change and Agricultural Adaptation Strategies in Rural Sahel. Environmental Management 43:804-816.

Paavola J. 2008. Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. Environmental Science & Policy 2008,11:642-654.

Patt, A.G., Dazé, A. and Suarez, P. 2009. Gender and climate change vulnerability: what's the problem, what's the solution? In: Ruth, M. and Ibarraran, M. E. (Eds). Distributional Impacts of Climate Change and Disasters: Concepts and Cases. Cheltenham, UK: Edward Elgar Publishing Limited.

Segnini, A., Posadas, A., Quiroz, R., Milori, D.M.B.P., Saab, S.C. Neto., L.M., Vaz, C.M.P. 2010. Spectroscopic Assessment of Soil Organic Matter in Wetlands from the High Andes Soil Sci. Soc. Am. J. 74:2010

Stafford-Smith, M., Horrocks, L., Harvey, A., and Hamilton, C. 2011. Rethinking adaptation for a 4°C world. Phil. Trans. R. Soc. 369: 196-216.

Speranza, C.I. (2010): Drought coping and adaptation strategies: understanding adaptations to climate change in agro-pastoral livestock production in Makueni District, Kenya. European Journal of Development Research 22: 623-642

Tompkins, E.L., Adger, W.N., Boyd, E., Nicholson-Cole, S., Weatherhead, K., and Arnell, N. 2010. Observed adaptation to climate change: UK evidence of transition to a well-adapting society. Global Environmental Change 20: 627–635

Vuille, M., Bradley, R.S., Werner, M. And Keimig, F. 2003. 20th century climate change in the tropical Andes: Observations and model results. Climatic Change 59: 75–99, 2003

Zougmoré R., Mando A., Stroosnijder L., 2010. Benefits of integrated soil fertility and water management in semi-arid West Africa: an example study in Burkina Faso. Nutrient Cycling in Agroecosystems 88, 1: 17-27.

Aggarwal, M. 2007. Experimental evidence of O_3 impacts on crop yield and quality in India. Royal Society Workshop onGround-level ozone, May 2007 (http://royalsociety.org/document.asp?id=1170).

E.H., Allison L. Perry, Marie-Caroline Badjeck, W. Neil Adger, Katrina Brown, Declan Conway, Ashley S. Halls, Graham M. Pilling, John D. Reynolds, Neil L. Andrew & Nicholas K. Dulvy. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. FISH and FISHERIES , 10, 173–196

Avnery, S., D.L. Mauzerall, J. Liu and L.W. Horowitz. 2011a. Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. Atmospheric Environment, **45**, 2264-2296.

Avnery, S., D.L. Mauzerall, J. Liu and L.W. Horowitz. 2011b. Global crop yield reductions due to surface ozone exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O3 pollution. Atmospheric Environment, **45**, 2296-2309.
Bamabas, B.A.T., K. Jager, and A. Feher. 2008. The effect of heat and drought stress on reproductive process in cereals. Plant Cell Environ. **31**, 11-39.
Bell, J., M. Batty, A. Ganachaud, P. Gehrke, A. Hobday, O. Hoegh-Guldberg, J. Johnson, R. Le Borgne, P. Lehodey, J. Lough, T. Pickering, M. Pratchett, M. Sheaves, M. Waycott. 2011 -*in press*. Preliminary Assessment of the Effects of Climate Change on Fisheries and Aquaculture in the Pacific. To be published in 'The Contribution of Fisheries to the Economies of Pacific Island Countries and Territories'. Pacific Studies Series (Asian Development Bank)
Bellocchi, G., M. Rivington, M. Donatelli and K. Mathew. 2010. Validation of biophysical models: issues and methodologies. A review. Agron. Sustain. Dev., **30**, 109-130.
Booker, F., R. Muntiferg, M. McGrath, et al. 2009. The ozone components of global change: Potential effects on agricultural and horticultural plant yield, product quality and interaction with invasive species. J. Integr.Plant Biol., **51**,337-351.
Bondeau, A., P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein and B. Smith (2007) Modeling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13, 679-706
Brown, C.J., Fulton, E.A., Hobday, A.J., Matear, R.J., Possingham, H.P., Bulman, C., Christensen, V., Forrest, R.E., Gehrke, P.C., Gribble, N.A., Griffiths, S.P., Lozano-Montes, H., Martin, J.M., Metcalf, S., Okey, T.A., Watson, R. and Richardson, A.J. 2010. Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. Global Change Biology: 16, 1194–1212.
Burke, M. B., Lobell, D. B., Guarino, L. (2009). Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. Global Environmental Change - Human and Policy Dimensions 19 (3): 317-325.
Buytaert,.W , M. Vuille A. Dewulf R. Urrutia A. Karmalkar and R. C´elleri (Uncertainties in climate change projections and regional downscaling in the tropical Andes: implications for water resources management. Hydrol. Earth Syst. Sci., 14, 1247–1258, 2010
Caracelli, S., S. Grando, M. Maattougi, M. Michael, M. Slash and M. Nachit.2010. Plant breeding and climate changes. J. Agr. Sci. (Cambridge), **148**, 627-637.
Cassman, K.G., P. Grassini and J. van Wart. 2010. Crop yield potential, yield trends, and global food security in a changing climate. Chapter 3 in Handbook of Climate change and Agroecosystems, pp 37-51.
Chavas, D.R.,R.C. Izaurralde, A.M. Thomson and X.J. Gao. 2009. Long term climate change impacts on agricultural productivity in eastern China. Agric. For. Meteorol. 149, doi: 10.1016./.j.agrformet.2009.02.001
Challinor, A. J., E. S. Simelton, E. D. G. Fraser, D. Hemming and M. Collins(2010) Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. Environ. Res. Lett. 5 (2010) 034012
Challinor, A. J., T. R. Wheeler, D. Hemming and H. D. Upadhyaya (2009). Ensemble yield simulations: crop and climate uncertainties, sensitivity to temperature and genotypic adaptation to climate change. Climate Research, 38 117-127
Challinor, A. J. and T. R. Wheeler (2008). Use of a crop model ensemble to quantify CO2 stimulation of water-stressed and well-watered crops. Agric. For. Meteorol, 148 1062-1077
Craufurd, P. Q. and T. R. Wheeler (2009). "Climate change and the flowering time of annual crops." Journal of Experimental Botany 60(9): 2529-2539.
De Silva, S.S. and Soto, D. 2009. Climate change and aquaculture: potential impacts, adaptation and mitigation. In: Eds. Cochrane, K., De Young, C. Soto, D. and Bahri, T. Climate change implications for fisheries and aquaculture. Overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper 530. Rome, FAO. 151-212.
De Matta, F.M., A. Grandis, B.C. Arenque and M.S. Buckeridge. 2010. Impact of climate change on crop physiology and food quality. Food Res. Int., **43**, 1814-1823.
Ewing, M., Msangi, S. 2009. Biofuels production in developing countries: assessing tradeoffs in welfare and food security. Environmental Science & Policy 12: 520 – 528
FAO, 2008. The state of food and agriculture 2008. Biofuels: prospects, risks and opportunities.

Fischer, G. , E. Hizsnyik, S. Prieler, M. Shah and H. van Velthuizen. 2009 . Biofuels and Food Security. Final Report to Sponsor: The OPEC Fund for International Development (OFID), Vienna, Austria (March 2009). IIASA Contract No. 08-134
FAO. 2009a. Introduction. In: Eds. Cochrane, K., De Young, C. Soto, D. and Bahri, T. Climate change implications for fisheries and aquaculture. Overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper 530. Rome, FAO. 212pp.
Feely, R.A., Sabine, C.L., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J. and Millero, F.J. 2004. Impact of Anthropogenic CO2 on the CaCO3 System in the Oceans. Science 305, 362-366.
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**, 2248-2256.
Fraser, E., Termansen, M., Sun, N., Guan, D., Simelton, E., Dodds, P., Feng, K. & Yu, Y. (2008) Quantifying socio economic characteristics of drought sensitive regions: Evidence from chinese provincial agricultural data. Comptes Rendus Geosciences, 340, 679-688.
Fuhrer, J. 2009. Ozone risk for crops and pastures in present and future climate. Naturwissenschaften, **96**, 173-194.
Hatfield, J., K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, and D. Wolfe. 2008. Agriculture. In *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. Washington, DC: U.S. Climate Change Science Program and the Subcommittee on Global Change Research, pp. 21–74.
Hopkins, A. and A. Del Prado. 2007. Implications of climate change for grassland in Europe: impacts, adaptations and mitigation options: a review. Grass and Forage Science, 62, 118–126
Humaira, S., N. Ali, M.M. Iqbal and A. M. Khan. 2009. Vulnerability and adaptability of wheat production in different climatic zones of Pakistan under climate change scenarios. Climatic Change. **94**, 123-142.
Huppert DD, Moore A, Dyson K (2009) Impacts of climate change on the coasts of Washington State. Chapter 8 in The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate, Climate Impacts Group, University of Washington, Seattle, Washington
Iizumi, T., M. Yokozawaa and M. Nishimoria (2009). Parameter estimation and uncertainty analysis of a large-scale crop model for paddy rice: Application of a Bayesian approach. Agricultural and Forest Meteorology 149 (2) 333-348.
Iqbal, M. M., M. A. Goheer and A. M. Khan. 2009. Climate-change aspersions on food security of Pakistan. Science Vision, **15**, 15-23.
Kang, Y.M., S. Khan and X.Y. Ma. 2009. Climate change impacts on crop yield, crop water productivity and food security: A review. Prog. Nat. Sci., **19**, 1665-1674.
Lehodey, P., I. Senina, J. Sibert, L. Bopp, B. Calmettes, J. Hampton andMurtugudde. 2010. Preliminary forecasts of Pacific bigeye tuna population trends under te A2 IPCC scenario. Progress in Oceanography 86: 302–315
Loukos, H., P. Monfray, L. Boppi and P. Lehodey. 2003. Potential changes in skipjack tuna (Katsuwonus pelamis) habitat from a global warming scenario: modelling approach and preliminary results. Fish. Oceanogr. 12: 474–482
Schroth, G., Peter Laderach, Jan Dempewolf, Stacy Philpott, Jeremy Haggar et al. 2009. Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. Mitigation and Adaptation Strategies for Global Change 14, Issue: 7, 605-625
Jaggard et al. (2010). Possible changes to arable crop yields by 2050. Phil Trans B. 2010 365, 2835-2851.
Lal, R. 2009. Soil degradation as a reason for inadequate human nutrition. Food Secur. **1**, 45-57.
Li, Y. P., W. Ye, et al. (2009). "Climate change and drought: a risk assessment of crop-yield impacts." Climate Research 39(1): 31-46.
Lobell and Burke 2010 AFM150
Lobell, D. B. and M. B. Burke (2008). Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environmental Research Letters 3 (3): Art No. 034007.
Lobell, D.B., and C. B. Field (2007) Global scale climate-crop yield relationships and the impacts of recent warming. Environmental Research Letters 2, 014002
Lobell, D.B., M. Banziger, C. Mogorokosho and B. Vivek. 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Climate Change, /doi: 10. 1038/nclimate 1043
Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, R. L. Naylor (2008). Prioritizing Climate Change Adaptation Needs for Food Security in 2030. Science 319 (5863), 607 – 610.
Lonz-Weidemann, V.S., C.W. Klar and K. Schneider. 2010. Development and testing of a crop growth model for

application with a Global change decision support system. Ecol. Model. **221**, 314-329.
McKeon, G. M. , G. S. Stone, J. I. Syktus, J. O. Carter, N. R. Flood, D. G. Ahrens, D. N. Bruget, C. R. Chilcott, D. H. Cobon, R. A. Cowley, S. J. Crimp, G. W. Fraser, S. M. Howden, P. W. Johnston, J. G. Ryan, C. J. Stokes, K. A. Day. 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. The Rangeland Journal, Vol. 31 No. 1 Pages 1 - 29
Melloy, P., G. Hollaway, G. Luck, R. Norton, E. Aiken and S. Chakraborty. 2010. Production and fitness of Fusarium pseudograminearum inoculation at elevated carbon dioxide in FACE. Global Change Biol. **16**, 3363-3373.
Mills, G., F. Hayes, S. Wilkinson and J.W. Davies. 2009. Chronic exposure to background ozone impairs stomatal functioning in grassland species. Global Change Biol., **15**, 1522-1533.
Misselhorn, A., A. Challinor, P. Thornton, J. W. Jones, R. Schaldach and V. Plocq-Fichelet (2010). Chapter 20: Surprises and Possibilities. In J. Ingram, P. Ericksen and D. Liverman (Eds) Food Security and Global Environmental Change. Earthscan ISBN 9781849711289.
Mo, X.G., S.X. Liu, Z.H. Lin and R.P. Guo. 2009. Regional crop yield, water consumption and water use efficiency and their responses to climate change in the North China Plain. Agric. Ecosyst. Environ. **134**, 67-68.
Moriondo, M, C. Giannakopoulos and M. Bindi, 2011, Climate change impact assessment: the role of climate extremes in crop yield simulation. Climatic Change 104 (3-4): 679-701
Nandone, A., B. Ronchi, N. Lacetera, M.S. Ranieri and U. Bernabucci. 2010. Effect of climate change on animal production and sustainability of livestock systems. Livest. Sci., **130**, 57-69.
Ortiz, R., K. D. Sayre, et al. (2008). "Climate change: Can wheat beat the heat?" Agriculture Ecosystems & Environment 126(1-2): 46-58.
Osborne, T. M., D. M. Lawrence, A. J. Challinor, J. M. Slingo, T. R. Wheeler (2007). Development and assessment of a coupled crop-climate model. Global Change Biology 13 169-183.
Piao, S., P. Ciais, Y. Huang, Z. She, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, Y., Ding, P. Friedlingstein, C. Liu, K. Tan, Y. Yu, T. Zhang and J. Fang. 2010. The impacts of climate change on water resources and agriculture in China. Nature, **467**, 43-51.
Pikki, K., V. Vorne, K. Ojanpera and H. Pleijet. 2007. Impact of elevated O3 and CO2 exposure on potato (Solanum tuberosum L. cv. Bintje) tuber macronutrients (N, P. K. Mg, Ca). Agric. Ecosyst. Environ., **118**, 55-84.
Reidsma, P., Ewert, F., Oude Lansink, A. and Leemans, R., 2009. Vulnerability and adaptation of European farmers: a multi-level analysis of yield and income responses to climate variability. Regional Environmental Change 9: 25-40
Royal Society. 2009. Reaping the harvest (RS/Policy Document 11/09). The Royal Society, London.
Soltani, A. and G. Hoogenboom. 2007. Assessing crop management options with crop simulation models based on generated weather data. Field Crops Res. **105**, 198-207.
Soussana, J.F., A.I. Graux and F.N. Tubiello. 2010. Improving the use of modelling for projections of climate change impacts on crops and pastures. J. Ext. Bot. **61**, 2217-2228.
Schlenker, W and M. J. Roberts (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. Proceedings of the National Academy of Science of the United States of America 106 (37): 15594-15598.
Thornton, P. K. *et al*. *Global Environmental Change* **19** (1), 54-65 (2009).
Thornton, P. K., P. G. Jones, P. Ericksen and A. J. Challinor (2010) Agriculture and food systems in sub-Saharan Africa in a four-plus degree world. Phil. Trans. Roy. Soc .A. 369 117-136 doi:10.1098/rsta.2010.0246
Trnka et al., 2011. Agroclimatic conditions in Europe under climate change. Global Change Biology DOI: 10.1111/j.1365-2486.2011.02396.x
Tao, F., M. Yokozawa, et al. (2009). "Modelling the impacts of weather and climate variability on crop productivity over a large area: A new process-based model development, optimization, and uncertainties analysis." Agricultural and Forest Meteorology 149(5): 831-850.
Tao, F., M. Yokozawa, et al. (2009). "Climate change, land use change, and China's food security in the twenty-first century: an integrated perspective." Climatic Change 93(3-4): 433-445.
von Braun, J. 2009. Addressing the food crisis: governance, market functioning, and investment in public goods. Food Sec. 1:9–15 DOI 10.1007/s12571-008-0001-z
Tubiello, F.N., J.S. Amthor, K.J. Boote,Donatelli, W. Easterling, G. Fischer, R.M. Gifford, M. Howden, J. Reilly, and C. Rosenzweig, 2007: Crop response to elevated CO_2 and world food supply: A comment on "Food for Thought." by Long et al., Science 312:1918-1921, 2006. *Euro. J. Agron*., **26**, 215-223, doi:10.1016/j.eja.10.002.

Wassmann, R. S.V.K. Jagdish, S. Heur, A. Ismail, E. Redona, R. Serraj, R.K. Singh, G. Howell, H. Pathak and K. Sumfleth. 2009. Climate change affecting rice production: The physiological and agronomic basis for possible adaptation strategies. Advanc. Agron.**101,** 59-122. Academic Press, San Diego, CA, USA.
Welch, J. R., Jeffrey R. Vincentb,1, Maximilian Auffhammerc,d, Piedad F. Moyae, Achim Dobermannf, and David Daweg, 2010. Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. www.pnas.org/cgi/doi/10.1073/pnas.1001222107
Xiong, W. et al. 2009. Future cereal production in China: Modelling the interaction of climate change, water availability and socio-economic scenarios. In The impacts of Climate Change on Chinese Agriculture – Phase II Final Report (AEA Group, 2008).
Yahdjian, L. & O. Sala, 2008. Climate Change Impacts on South American Rangelands. Rangelands, June 2008, pp 33-39
Zhang, T. Zhu, J., Wassmann R. (2010) Responses of rice yields to recent climate change in China: An empirical assessment based on long-term observations at different spatial scales (1981–2005). Agricultural and Forest Meteorology 150: 1128–1137
Baldocchi, D.& S.Wong . Accumulated winter chill is decreasing in the fruit growing regions of California. Climatic Change (2008) 87 (Suppl 1):S153–S166
Farag A.A, A.A. Khalil and M.K Hassanein. 2010. Chilling requirement for deciduous fruits under climate change in Egypt. Research Journal of Agriculture and Biological Sciences, 6(6): 815-822.
Lobell, D.B., Ch. B. Field, K. N. Cahill, C. Bonfils. 2006. Impacts of future climate change on California perennial crop yields. Model projections with climate and crop uncertainties *Agricultural and Forest Meteorology*, *Volume 141, Issues 2-4*, *20 December 2006*, *Pages 208-218*
Marin, F, G. Q. Pellegrino; E. D. Assad; D. S. P. Nassif;M. S. Viana; F. A.Soares; L. L. Cabral; D.Guiatto. 2009. FUTURE SCENARIOS FOR SUGARCANE IN THE STATE OF SAO PAULO BASED ON REGIONLIZED CLIMATE CHANGE PROJECTIONS
XVI Congresso Brasileiro de Agrometeorologia – Belo Horizonte – MG- Brazil
PINTO, H. S. ; ZULLO JR, J.; ASSAD, E. D. ; EVANGELISTA, B. A. . 2007. O aquecimento global e a cafeicultura brasileira. Boletim da Sociedade Brasileira de Meteorologia, v. 30, p. 65-72, 2007.
PINTO, H. S.; ASSAD, E. D.; JUNIOR, J .Z.; EVANGELISTA, S. R. M.; OTAVIAN, A. F.; ÁVILA, A. M. H.; EVANGELISTA, B.; MARIN, F. R.; JUNIOR, C. M.; PELLEGRINO, G. Q.; COLTRI, P. P.; CORAL, G. Aquecimento global e a nova geografia da produção agrícola no Brasil. Embrapa, São Paulo, 2008.
Stöckle, C.O., R.L. Nelson, S. Higgins, J.Brunner, G.Grove, R. Boydston, M.Whiting, Ch. Kruger. 2010. Assessment of climate change impact on Eastern Washington agriculture
Climatic Change (2010) 102:77–102
Zullo Jr., J., H.Silveira Pinto, E. Delgado Assad , A. M. Heuminski de Ávila. 2011. Potential for growing Arabica coffee in the extreme south of Brazil in a warmer world. Climatic Change DOI 10.1007/s10584-011-0058-0. Published online: 09 April 2011
Abbott, P.C., Hurt, C. and Tyner, W.E., 2008. What's Driving Food Prices?
Alexander, L.V. et al., 2006. Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res, 111: D05109, doi:10.1029/2005JD006290.
Amthor, J.S., 2001. Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO2 concentration. Field Crops Research, 73(1): 1-34.
Auffhammer, M., Ramanathan, V. and Vincent, J.R., 2006. Integrated model shows that atmospheric brown clouds and greenhouse gases have reduced rice harvests in India. Proceedings of the National Academy of Sciences, 103(52): 19668-19672.
Banerjee, A.V. and Duflo, E., 2007. The economic lives of the poor. The journal of economic perspectives: a journal of the American Economic Association, 21(1): 141.
Bell, M.A. and Fischer, R.A., 1994. Using Yield Prediction Models to Assess Yield Gains - a Case Study For Wheat. Field Crops Research, 36(2): 161-166.
Brisson, N. et al., 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Research, 119(1): 201-212.
Chen, C., Wang, E., Yu, Q. and Zhang, Y., 2010. Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain. Climatic Change, 100(3): 559-578.
Christidis, N., Stott, P.A., Brown, S., Hegerl, G.C. and Caesar, J., 2005. Detection of changes in temperature extremes during the second half of the 20th century. Geophys. Res. Lett, 32.

CSIRO, 2010. Climate variability and change in south-eastern Australia: A synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI).
Dawe, D., 2008. Have recent increases in international cereal prices been transmitted to domestic economies? The experience in seven large Asian countries, FAO, Rome.
Ding, Y., Wang, Z., Song, Y. and Zhang, J., 2008. Causes of the unprecedented freezing disaster in January 2008 and its possible association with the global warming. Acta Meteorologica Sinica, 665: 809-825.
Dole, R. et al., 2011. Was there a basis for anticipating the 2010 Russian heat wave? Geophysical Research Letters, 38(6): L06702.
Easterling, W. et al., 2007. Chapter 5: Food, Fibre, and Forest Products. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J.v.d. Linden and C.E. Hanson (Editors), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp. 273-313.
FAO, 2008. Policy measures taken by government to reduce the impact of soaring prices. Global Information and Early Warning System.
FAO, 2010. Food and Agriculture Organization of the United Nations (FAO), FAO Statistical Databases.
FAO, 2011. The State of Food Insecurity in the World 2010, FAO, Rome, Italy.
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.
Garcia, P., Irwin, S.H., Leuthold, R.M. and Yang, L., 1997. The value of public information in commodity futures markets. Journal of Economic Behavior & Organization, 32(4): 559-570.
Ivanic, M. and Martin, W., 2008. Implications of higher global food prices for poverty in low-income countries.
Kucharik, C.J. and Serbin, S.P., 2008. Impacts of recent climate change on Wisconsin corn and soybean yield trends. Environmental Research Letters, 3: 034003.
Liu, Y., Wang, E., Yang, X. and Wang, J., 2009. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. Global Change Biology, 9999(999A).
Lobell, D.B., Bonfils, C. and Duffy, P.B., 2007. Climate change uncertainty for daily minimum and maximum temperatures: a model inter-comparison. Geophysical Research Letters, 34: L05715, doi:10.1029/2006GL028726.
Lobell, D.B. and Field, C.B., 2007. Global scale climate-crop yield relationships and the impacts of recent warming. Environmental Research Letters, 2: 004000 (7pp).
Lobell, D.B. et al., 2005. Analysis of wheat yield and climatic trends in Mexico. Field Crops Research, 94(2-3): 250-256.
Lobell, D.B., Schlenker, W.S. and Costa-Roberts, J., 2011. Climate trends and global food production since 1980. Science, science express website.
Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nosberger, J. and Ort, D.R., 2006. Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO2 Concentrations. Science, 312(5782): 1918-1921.
Lopez, A.D., Mathers, C.D., Ezzati, M., Jamison, D.T. and Murray, C.J.L., 2006. Global and regional burden of disease and risk factors, 2001: systematic analysis of population health data. The Lancet, 367(9524): 1747-1757.
McGrath, J. and Lobell, D.B., 2011. An independent method of deriving the carbon dioxide fertilization effect in dry conditions using historical yield data from wet and dry years. Global Change Biology, in press.
Mills, G. et al., 2007. A synthesis of AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops. Atmospheric Environment, 41(12): 2630-2643.
Min, S.-K., Zhang, X., Zwiers, F.W. and Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. Nature, 470(7334): 378-381.
Morgan, P.B., Mies, T.A., Bollero, G.A., Nelson, R.L. and Long, S.P., 2006. Season long elevation of ozone concentration to projected 2050 levels under fully open air conditions substantially decreases the growth and production of soybean. New Phytologist, 170(2): 333-343.
Naylor, R.L. and Falcon, W.P., 2010. Food Security in an Era of Economic Volatility. Population and Development Review, 36(4): 693-723.
Pathak, H. et al., 2003. Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. Field Crops Research, 80(3): 223-234.
Peng, S. et al., 2004. Rice yields decline with higher night temperature from global warming. Proceedings of the

National Academy of Sciences of the United States of America, 101(27): 9971-9975.
Porter, J.R. and Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. European Journal of Agronomy, 10(1): 23-36.
Ravallion, M., Chen, S. and Sangraula, P., 2007. New evidence on the urbanization of global poverty. Population and Development Review, 33(4): 667-701.
Roberts, M. and Schlenker, W., 2010. Identifying Supply and Demand Elasticities of Agricultural Commodities: Implications for the US Ethanol Mandate, NBER Working Paper No. 15921.
Rosenzweig, C., Tubiello, F.N., Goldberg, R., Mills, E. and Bloomfield, J., 2002. Increased crop damage in the US from excess precipitation under climate change. Global Environmental Change-Human and Policy Dimensions, 12(3): 197-202.
Schlenker, W. and Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proceedings of the National Academy of Sciences, 106(37): 15594-15598
Stott, P.A., Stone, D.A. and Allen, M.R., 2004. Human contribution to the European heatwave of 2003. Nature, 432(7017): 610-614.
Tao, F., Yokozawa, M., Liu, J. and Zhang, Z., 2008. Climate–crop yield relationships at provincial scales in China and the impacts of recent climate trends. Clim Res, 38(1): 83-94.
Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y. and Zhang, Z., 2006. Climate changes and trends in phenology and yields of field crops in China, 1981-2000. Agricultural and Forest Meteorology, 138(1-4): 82-92.
USDA, 2007. Wheat Situation and Outlook Yearbook. U.S. Department of Agriculture, Washington, D.C.
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.
Wang, H.L. et al., 2008. Phenological trends in winter wheat and spring cotton in response to climate changes in northwest China. Agricultural and Forest Meteorology, 148(8-9): 1242-1251.
Wassmann, R. et al., 2009. Climate change affecting rice production: the physiological and agronomic basis for possible adaptation strategies. Advances in Agronomy.
Welch, J.R. et al., 2010. Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. Proceedings of the National Academy of Sciences, 107(33): 14562.
Wright, B.D., 2011. The Economics of Grain Price Volatility. Applied Economic Perspectives and Policy, 33(1): 32.
You, L., Rosegrant, M., Wood, S. and Sun, D., 2009. Impact of growing season temperature on wheat productivity in China. Agricultural and Forest Meteorology, 149(6-7): 1009-1014.
Zhang, T., Zhu, J., Yang, X. and Zhang, X., 2008. Correlation changes between rice yields in North and Northwest China and ENSO from 1960 to 2004. Agricultural and Forest Meteorology, 148(6-7): 1021-1033.
Zwiers, F.W., Zhang, X. and Feng, Y., 2011. Changes in the extremes of the climate simulated by CCC GCM2 under CO2 doubling. Journal of Climate: in press.
Defra, 2006. Food Security and the UK: An Evidence and Analysis Paper. Food Chain Analysis Group.
Ericksen, P.J., 2008. Conceptualizing Food Systems for Global Environmental Change Research. Global Environmental Change, 18: 234-245.
Ericksen, P.J. et al., 2010. The Value of a Food System Approach. In: J. Ingram, P. Ericksen and D. Liverman (Editors), Security and Global Environmental Change. Earthscan, London.
ESF, 2009. European Food Systems in a Changing World, Strasbourg.
EU, 2011. Food security under threat: global response needed.
FAO, 1996. Rome Declaration and World Food Summit Plan of Action, FAO, Rome.
FAO, 2008
FAO, 2010. The State of Food Insecurity in the World (SOFI): Addressing food insecurity in protracted crises, Rome.
Foresight, 2011. The Future of Food and Farming. Final Project Report. The Government Office for Science, London.
Godfray, H.C.J. et al., 2010a. Food security: feeding the world in 2050 - Theme Issue September 2010.
Godfray, H.C.J. et al., 2010b. Food Security: The Challenge of Feeding 9 Billion People. Science, 327: 812-818.
Ingram, J.S.I., 2009. Food system concepts. In: R. Rabbinge and A. Linneman (Editors), ESF/COST Forward Look on European Food Systems in a Changing World. European Science Foundation, Strasbourg.
Maxwell, S. and Slater, R., 2003. Food Policy Old and New. Development Policy Review, 21(5-6): 531-553.
McMichael, P. (Editor), 1994. The Global Restructuring of Agro-Food Systems. Cornell University Press, New York, US.

Science, 2010. Special Issue 12 February 2010: Food Security.
Spring, Ú.O., 2009. Food as a New Human and Livelihood Security Challenge. In: H.G. Brauch et al. (Editors), Facing Global Environmental Change. Hexagon Series on Human and Environmental Security and Peace. Springer Berlin Heidelberg, pp. 471-500.
Tovey, H., 1997. Food, Environmentalism and Rural Sociology: On the Organic Farming Movement in Ireland. Sociologia Ruralis, 37(1): 21-37.
von Braun and Torero, 2009
Leakey, A.D.B., 2009. Rising atmospheric carbon dioxide concentration and the future of C4 crops for food and fuel. Proceedings of the Royal Society B: Biological Sciences: doi: 10.1098/rspb.2008.1517.
Högy, P. and Fangmeier, A., 2009. Atmospheric CO2 enrichment affects potatoes: 1. Aboveground biomass production and tuber yield. European Journal of Agronomy, 30(2): 78-84.
Fleisher, D.H., Timlin, D.J. and Reddy, V.R., 2008. Interactive Effects of Carbon Dioxide and Water Stress on Potato Canopy Growth and Development. Agronomy journal, 100(3): 711.
Markelz, R.J.C., Strellner, R.S. and Leakey, A.D.B., 2011. Impairment of C4 photosynthesis by drought is exacerbated by limiting nitrogen and ameliorated by elevated [CO2] in maize. Journal of Experimental Botany.
McGrath, J. and Lobell, D.B., 2011. An independent method of deriving the carbon dioxide fertilization effect in dry conditions using historical yield data from wet and dry years. Global Change Biology, in press.
Ainsworth, E.A., Leakey, A.D.B., Ort, D.R. and Long, S.P., 2008. FACE-ing the facts: inconsistencies and interdependence among field, chamber and modeling studies of elevated CO2 impacts on crop yield and food supply. New Phytologist, 179(1): 5-9.
Archimède H., M. Eugène, C. Marie Magdeleine, M. Boval, C. Martin, D.P. Morgavi, P. Lecomte, M. Doreau, 2011. Comparison of methane production between C3 and C4 grasses and legumes. Animal Feed Science and Technology, doi:10.1016/j.anifeedsci.2011.04.003
Barati F., B. Agung, P. Wongsrikeao, M. Taniguchi, T. Nagai, T. Otoi, 2008. Meiotic competence and DNA damage of porcine oocytes exposed to an elevated temperature. Theriogenology 69, 767-772.
Blackwell P.J., 2010. East Africa's pastoralist emergency: is climate change the straw that breaks the camel's back? Third World Quarterly 31 (8), 1321-1338.
Bohmanova J., I. Misztal, S. Tsuruta, H.D. Norman, T.J. Lawlor, 2008. Genotype by environment interaction due to heat stress. Journal of Diary Science 91, 840-846.
Burke M.B., D.B. Lobell, L. Guarino, 2009. Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. Global Environmental Change 19, 317-325.
Craine J.M., A.J. Elmore, K.C. Olson, D Tolleson, 2010. Climate change and cattle nutritional stress. Global Change Biology 16, 2901-2911.
Cutler S.J., A.R. Fooks, W.H. van der Poel, 2010. Public health threat of new, re-emerging, and neglected zoonoses in the industrialized world. Emerging Infectious Diseases 16, 1-7.
Descheemaeker K., T. Amede, A. Haileslassie, 2010. Improving water productivity in mixed crop–livestock farming systems of sub-Saharan Africa. Agricultural Water Management 97, 579-586.
De Fraiture C., D. Wichelns, 2010. Satisfying future water demands for agriculture. Agricultural Water management 97, 502-511.
De Fraiture C., D. Molden, D. Wichelns, 2010. Investing in water for food, ecosystems, and
livelihoods: An overview of the comprehensive assessment of water management in agriculture. Agricultural Water Management 97, 495-501.
Dikmen S., P.J. Hansen, 2009. Is the temperature-humidity index the best indicator of heat stress in lactating dairy cows in a subtropical environment? Journal of Dairy Science 92, 109-16.
Doherty R.M., S. Sitch, B. Smith, S.L. Lewis, P.K. Thornton, 2010. Implications of future climate and atmospheric CO2 content for regional biogeochemistry, biogeography and ecosystem services across East Africa. Global Change Biology 16 (2), 617-640.
Ericksen P.J., J.S.I. Ingram, D. Liverman, 2009. Food security and global environmental change: emerging challenges. Environmental Science and Policy 12, 373-377.
Feng J., M. Zhang, S. Zheng, P. Xie, A. Ma, 2008. Effects of high temperature on multiple parameters of broilers in vitro and in vivo. Poultry Science 87, 2133-2139.
Fuhrer J., 2009. Ozone risks for crops and pastures in present and future climates. Naturwissenschaften 96, 173-194.
Gilbert M., J. Slingenbergh, X. Xiao, 2008. Climate change and avian influenza. Revue Scientifique et Technique - Office International des Epizooties 27, 459-466.

Gummow B., 2010. Challenges posed by new and re-emerging infectious diseases in livestock production, wildlife and humans. Livestock Science 130, 41-46.
Hassan R., 2010. Implications of climate change for agricultural sector performance in
Africa: policy challenges and research agenda. Journal of African Economies 19 (supplement 2), ii77-ii105.
Hatfield J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, D. Wolfe, 2011. Climate Impacts on agriculture: implications for crop production. Agronomy Journal 103, 351-370.
Hayes B.J., P.J. Bowman, A.J. Chamberlain, K. Savin, C.P. van Tassell, T.S. Sonstegard, M.E. Goddard, 2009. A validated genome wide association study to breed cattle adapted to an environment altered by climate change. PLoS ONE 4(8), e6676. doi:10.1371/journal.pone.0006676
Herrero M., P.K. Thornton, R.L. Kruska, R.S. Reid, 2008. Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. Agriculture, Ecosystems and Environment 126, 122–37.
Hoffmann I., 2010. Climate change and the characterization, breeding and conservation
of animal genetic resources. Animal Genetics, 41 (Suppl. 1), 32-46.
Howden S.M., S.J. Crimp, C.J. Stokes, 2008. Climate change and Australian livestock systems : impact, research and policy issues. Australian Journal of Experimental Agriculture 48, 780-788.
Izaurralde R.C., A.M. Thomson, J.A. Morgan, P.A. Fay, H.W. Polley, J.L. Hatfield, 2011. Climate impacts on agriculture: implications for forage and rangeland production. Agronomy Journal 103, 371-381.
Jones P.G., P.K. Thornton, 2009. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. Environmental Science and Policy 12, 427–37.
Lazzarotto P., P. Calanca, J. Fuhrer, 2009. Dynamics of grass–clover mixtures. An analysis of the response to management with the productive grassland simulator (PROGRASS). Ecological Modelling 220, 703-724.
Lobell D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, R.L. Naylor, 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319, 607-610.
Masike S., P. Urich, 2008. Vulnerability of traditional beef sector to drought and the challenges of climate change: the case of Kgatleng District, Botswana. Journal of Geography and Regional Planning 1 (1), 12-18.
McKeon G.M., G.S. Stone, J.I. Syktus, J.O. Carter, N.R. Flood, D.G. Ahrens, D.N. Bruget, C.R. Chilcott, D.H. Cobon, R.A. Cowley, S.J. Crimp, G.W. Fraser, S.M. Howden, P.W. Johnston, J.G. Ryan, C.J. Stokes, K.A. Day, 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues. The Rangeland Journal 31, 1-29.
Mills J. N., K.L. Gage, A.S. Khan, 2010. Potential influence of climate change on vector-borne and zoonotic diseases: a review and proposed research plan. Environmental Health Perspectives 118, 1507-1514.
Molden D., T. Oweis, P. Steduto, P. Bindraban, M.A. Hanjra, J. Kijne, 2010. Improving agricultural water productivity: between optimism and caution. Agricultural Water Management 97, 528-535.
Mortensen C.J., Y.H. Choi, K. Hinrichs, N.H. Ing, D.C. Kraemer, S.G. Vogelsang, M.M Vogelsang, 2009. Embryo recovery from exercised mare. Animal Reproduction Science 110, 237-244.
Nardone A., B. Ronchi, N. Lacetera, M.S. Ranieri, U. Bernabucci, 2010. Effects of climate changes on animal production and sustainability of livestock systems. Livestock Science 130, 57-69.
Ostfeld R.S., 2009. Climate change and the distribution and intensity of infectious diseases. Ecology 90, 903-905.
Palmer M.A., C.A. Reidy Liermann, C. Nilsson, M. Flörke, J. Alcamo, P.S. Lake, N. Bond, 2008. Climate change and the world's river basins: anticipating management options. Frontiers in Ecology and the Environment 6, 81-89. doi:10.1890/060148
Pfeffer M, G. Dobler, 2010. Emergence of zoonotic arboviruses by animal trade and migration. Parasites and Vectors 3, 35.
Rocque S.D.L., J.A. Rioux, J. Slingenbergh, 2008. Climate change: effects on animal disease systems and implications for surveillance and control. Revue Scientifique et Technique - Office International des Epizooties 27, 339-354.
Rosegrant M.W., M. Fernandez, A. Sinha, J. Alder, H. Ahammad, C. de Fraiture, B. Eickhout, J. Fonseca, J. Huang, O. Koyama, A.M. Omezzine, P. Pingali, R. Ramirez, C. Ringler, S. Robinson, P. Thornton, D. van Vuuren, H. Yana-Shapiro, 2009. Looking into the future for agriculture and AKST (Agricultural Knowledge Science and Technology). Pp 307-376 in Agriculture at a Crossroads (eds. B.D. McIntyre, H.R. Herren, J. Wakhungu, R.T. Watson), Island Press, Washington DC.
Rosenthal J., 2009. Climate change and the geographic distribution of infectious diseases. Ecohealth 6, 489-495.
Seo S.N., R. Mendelsohn, 2008. Measuring impacts and adaptations to climate change: a structural Ricardian model of African livestock management. Agricultural Economics 38, 151–65.

Soussana J.-F., A-I Graux, F.N. Tubiello, 2010. Improving the use of modelling for projections of climate change impacts on crops and pastures. Journal of Experimental Botany 61 (8), 2217-2228.
Tabachnick W.J., 2010. Challenges in predicting climate and environmental effects on vector-borne disease episystems in a changing world. Journal of Experimental Biology 213, 946-954.
Thornton P.K., P.G. Jones, T. Owiyo, R.L. Kruska, M. Herrero, P. Kristjanson, A. Notenbaert, N. Bekele, A. Omolo, 2008. Climate change and poverty in Africa: mapping hotspots of vulnerability. African Journal of Agricultural and Resource Economics 2 (1), 24-44.
Thornton P.K., P.G. Jones, G. Alagarswamy, J. Andresen, M. Herrero, 2010. Adapting to climate change: agricultural system and household impacts in East Africa. Agricultural Systems 103, 73-82.
Thornton P.K., P.G. Jones, P. Ericksen, A.J. Challinor, 2011. Agriculture and food systems in sub-Saharan Africa in a four-plus degree world. Philosophical Transactions of the Royal Society Series A 369, 117-136.
Vitali A., M. Segnalini, L. Bertocchi, U. Bernabucci, A. Nardone, N. Lacetera, 2009. Seasonal pattern of mortality and relationships between mortality and temperature-humidity index in dairy cows. Journal of Dairy Science 92, 3781-3790.
Wall E., A. Wreford, K. Topp, D. Moran, 2010. Biological and economic consequences of heat stress due to a changing climate on UK livestock. Advances in Animal Biosciences 1, 53.
Yahdjian L., O.E. Sala, 2008. Climate change impacts on South American rangelands. Rangelands 30(3), 34-39.
Zumbach B., I. Misztal, S. Tsuruta, J.P. Sanchez, M. Azain, W. Herring, J. Holl, T. Long, M. Culbertson, 2008. Genetic components of heat stress in finishing pigs: development of a heat load function. Journal of Animal Science 86, 2082-2088.
Archambault DJ 2007. Efficacy of herbicides under elevated temperature and CO_2. In: *Agroecosystems in a Changing Climate*, (Newton PCD, Carran A, Edwards GR, Niklaus PA, eds.), CRC Press, Boston, MA , pp 262-279.
Bridges DC. 1992. *Crop Losses Due to Weeds in the United States*. Weed Science Society of America, Champaign, IL, 403 pp.
Bunce JA, Ziska LH 2000. Crop/Weed Interactions. **In**: *Climate Change and Global Crop Productivity*, (eds. KR Reddy, HF Hodges), CABI International Press, pp 333-348.
Dukes JS, Mooney HA 2000. Does global change increase the success of biological invaders? *Trends in Ecology and Evolution,* 14, 135-139.
Oerke EC. 2006. Crop losses to pests. *J. Agric. Sci.* **144**:31–43.
MacDonald AJ, Riha SJ, DiTommaso A, DeGaetano AT. 2009. Climate change and the geography of weed damage: analysis of U.S. maize systems suggests the potential for significant range transformations. *Agric. Ecosyst. Enviorn.* **130**:131–140.
Malcolm JR, Markham A, Neilson RP, Garaci M 2002. Estimated migration rates under scenarios of global climate change. *J Biogeo* 29:835-849.
Manea A, Leishman MR, Downey PO 2011. Exotic C4 Grasses have increased tolerance to glyphosate under elevated carbon dioxide. *Weed Science* 59:28-36.
Pimentel D, Zuniga R, Morison D 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics* 52:273-288.
Rejmanek M 1996. A theory of seed plant invasiveness: the first sketch. *Biol Conserv* 78:171-181.
Taylor CA, Ralphs, MH. 1992. Reducing livestock losses from poisonous plants through grazing management. *Journal of Range Management* 45: 9-12.
Ziska LH, Faulkner SS, Lydon J. 2004. Changes in biomass and root:shoot ratio of field-grown Canada thistle (Cirsium arvense), a noxious, invasive weed, with elevated CO_2: implications for control with glyphosate. Weed Science 52:584-588.
Ziska LH, Reeves JB III, Blank R. 2005. The impact of recent increases in atmospheric CO2 on biomass production and vegetative retention of Cheatgrass (Bromus tectorum): implications for fire disturbance. *Global Change Biol.* **11**:1325–1332.
Ziska LH, Goins EW. 2006. Elevated atmospheric carbon dioxide and weed populations in glyphosate treated soybean. *Crop Sci.* **46**:1354–1359.
Ziska, L.H., Tomecek, M., and D.R. Gealy 2010. Competitive interactions between cultivated and red rice as a function of recent and projected increases in atmospheric carbon dioxide. *Agronomy J* 102:118-123.
Ziska LH, Blumenthal DM, Runion GB, Hunt Jr. ER, Diaz-Soltero H. 2011a. Invasive species and climate change:

an agronomic perspective. *Climatic Change* 105:13-42.
Ziska LH. 2000. The impact of elevated carbon dioxide on yield loss from a C3 and C4 weed in field grown soybean. *Global Change Biol*. **6**:899–905.
Ziska LH. 2003. Evaluation of yield loss in field sorghum from a C3 and C4 weed with increasing CO2. *Weed Sci*. **51**:914–918.

Table 7-1: Selected extreme climate events over the past decade with impacts on food production or food security, and anticipated change in frequency due to greenhouse gas emissions.

Extreme Event (Year, Location, Event)	Impacts on Food Systems	Expected Change in Frequency with Greenhouse Gas Emissions (+/-/0/?)	Studies on detection and attribution, and relevant sections in SIMEX
2003, Europe, Heat Wave	Reductions of yields in many crops by 30% or more (Easterling et al., 2007)	+	(Stott et al., 2004)
2006-2007, Australia, Drought	Wheat, rice, and cotton production reduced by 50% or more (FAO, 2010; USDA, 2007)	+	(CSIRO, 2010)
2008, China, Freezing Rain	0.8 Mha crops destroyed	?	(Ding et al., 2008)
2010, Pakistan, Floods	More than 1.3M ha of crops flooded, and 270,000 livestock killed. Total damage to agriculture of roughly $5B		
2010, Russia, Heat Wave	To complete once more specific statistics available	+	(Dole et al., 2011)

Table 7-2: Potential yield loss and actual yield loss estimates for 2001-2003 attributable to pests, weeds, and disease (adapted from Oerke 2006).

Wheat		
	Potential yield loss	Actual yield loss
Weeds	23.0	7.7
Animal pests	8.7	7.9
Pathogens	15.6	10.2
Viruses	2.5	2.4
Rice		
	Potential yield loss	Actual yield loss
Weeds	37.1	10.2
Animal pests	24.7	15.1
Pathogens	13.5	10.8
Viruses	1.7	1.4
Maize		
	Potential yield loss	Actual yield loss
Weeds	40.3	10.5
Animal pests	15.9	9.6
Pathogens	9.4	8.5
Viruses	2.9	2.7
Potato		
	Potential yield loss	Actual yield loss
Weeds	30.2	8.3
Animal pests	15.3	10.9
Pathogens	21.2	14.5
Viruses	8.1	6.6
Soybean		
	Potential yield loss	Actual yield loss
Weeds	37.0	7.5
Animal pests	10.7	8.8
Pathogens	11.0	8.9
Viruses	1.4	1.2

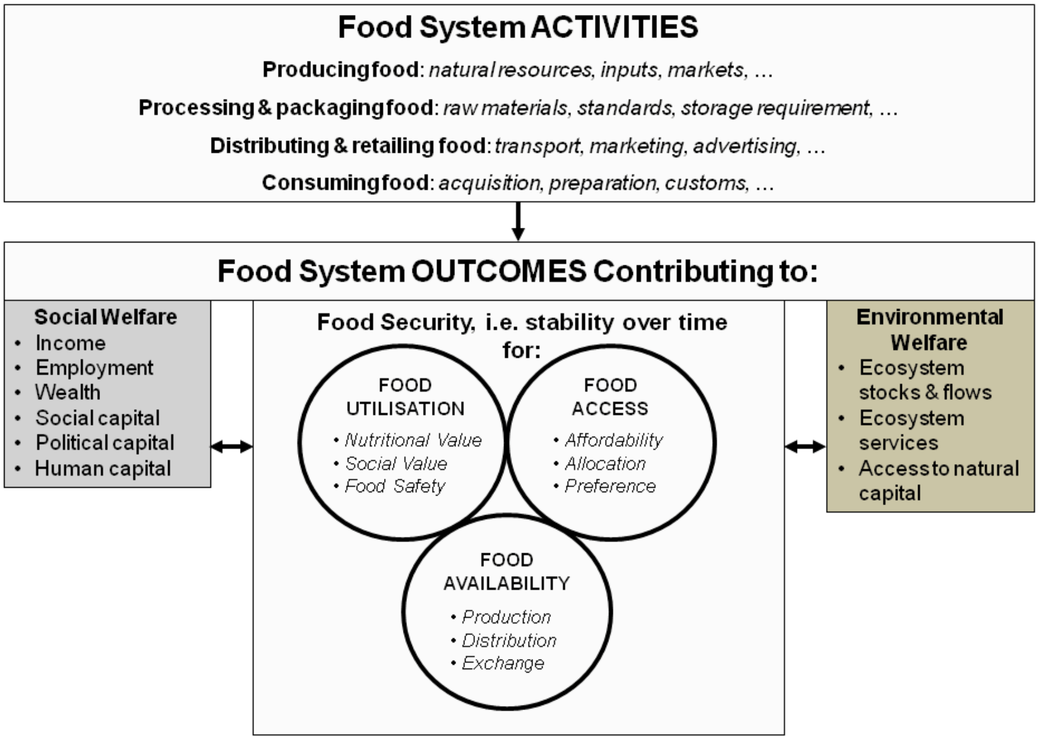

Figure 7-1: Title?

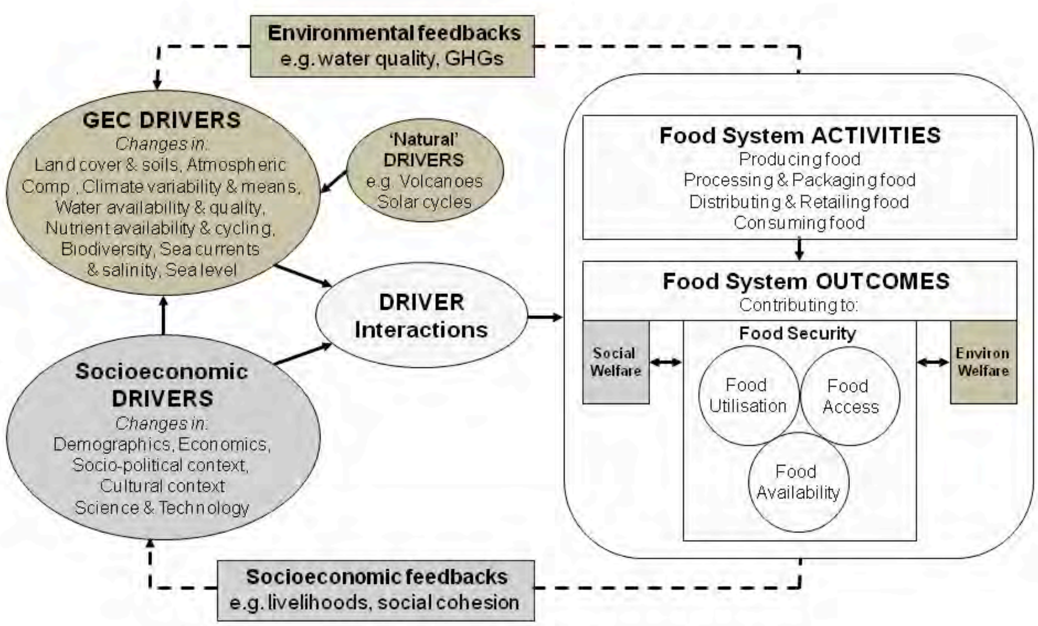

Figure 7-2: Title?

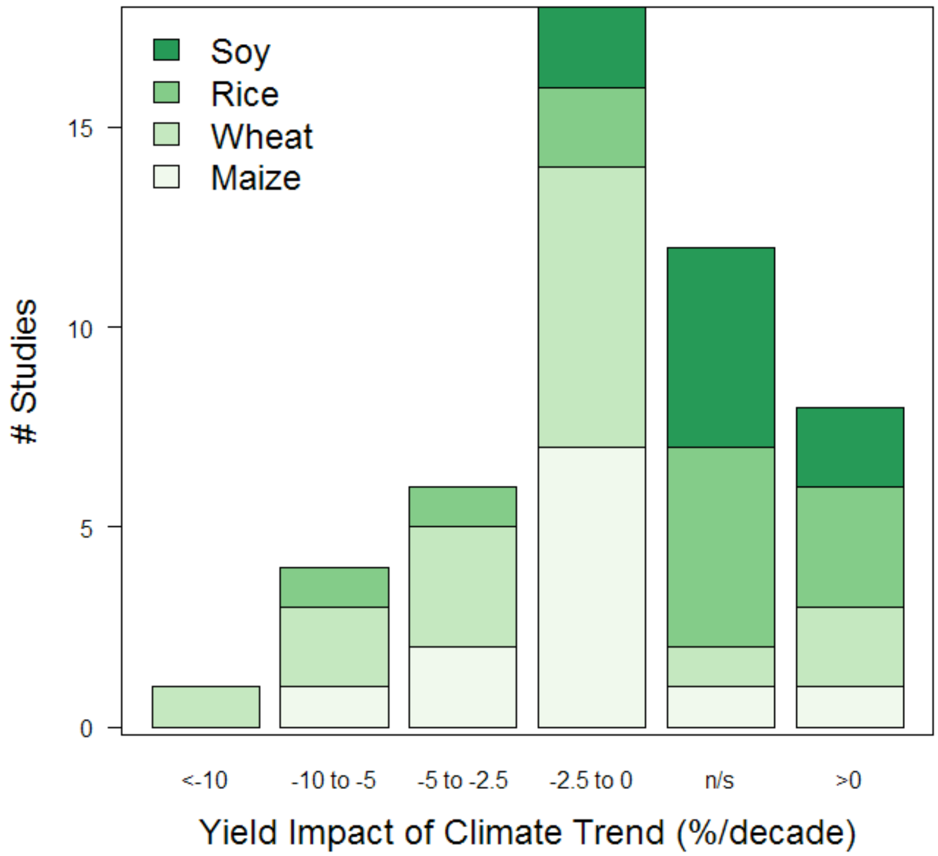

Figure 7-3: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., long-term experiments, physiological crop models, or statistical models),spatial scales (e.g., stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO_2 trends but most did not. Studies were for China (Chen et al., 2010; Tao et al., 2008; Tao et al., 2006; Wang et al., 2008; You et al., 2009), India (Pathak et al., 2003), United States (Kucharik and Serbin, 2008), Mexico (Lobell et al., 2005), France (Brisson et al., 2010), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Lobell et al., 2011; Welch et al., 2010).

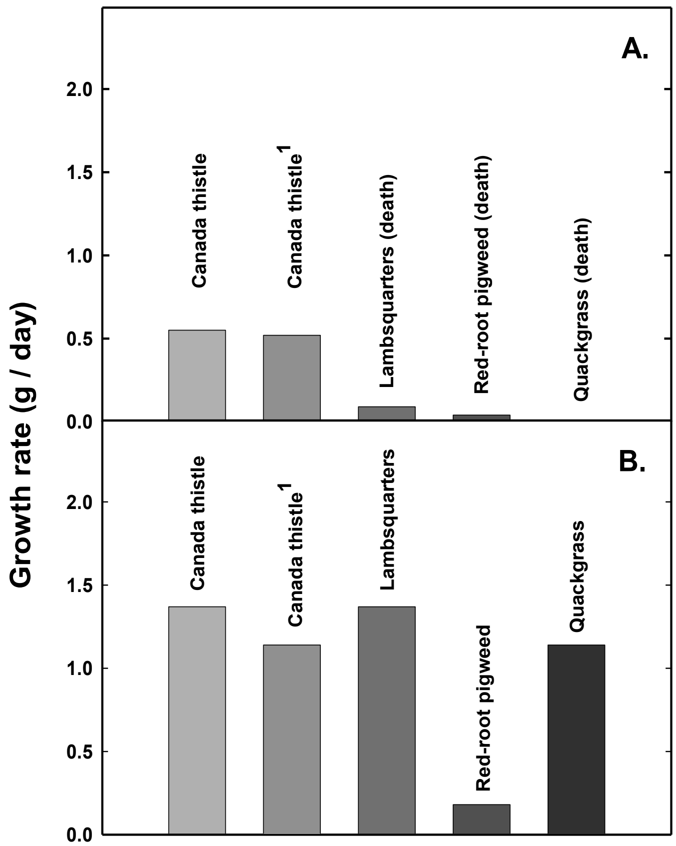

Figure 7-4: Changes in herbicide efficacy determined as changes in growth (g day^{-1}) following application for weeds grown at either current (A) or projected (~700 ppm) (B) levels of carbon dioxide. Herbicide was glyphosate in all cases, except [1], which was glufosinate. (See also Manea et al. 2011)