

Chapter 7. Food Security and Food Production Systems**Coordinating Lead Authors**

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19 Executive Summary

20
21 The effects of climate change are starting to be seen on food security and the food system in some regions of the
22 world (*good evidence, good agreement*). However, climate change is not likely to be a major driver of food security
23 for the near to medium term. With *high agreement and robust evidence* many of the elements in the human food
24 system will be adversely affected by projected climate change from about the mid-21st century onwards. These
25 effects will be compounded with other factors such as the rise in tropospheric ozone levels (*medium agreement,*
26 *medium evidence*) and competition for water resources as between agriculture and other sectors of the economy.
27

28 Food system concepts that cover the chain from production to consumption of food are starting to be used to assess
29 food security. Until now the overriding focus of research on food systems and climate change has been on the
30 supply of food from the main agricultural food and fodder crops in high income countries (very high agreement,
31 robust evidence); the food demand, processing, distribution and consumption elements of food systems contributing
32 to food security have been much less researched, especially so in low income countries (*very high confidence*).
33

34 *High agreement and robust evidence* points to the importance of extreme weather events for food and fodder
35 production, particularly for annual determinate crops in which yield is harvested as seeds. Such weather events are
36 defined as extremely high and low temperatures and droughts and floods. There is emerging experimental and
37 modelling evidence (*high agreement, medium evidence*) that interactions between production factors such as CO₂
38 and other gas levels, mean temperature and extremes, water and nitrogen can alter primary food production in
39 complex ways. In concert with experimental results, models take more account of uncertainties, thus increasing their
40 robustness, showing generally an ability to simulate the impacts on yields of mean changes in weather on food crops
41 but performing less well (*good evidence, medium agreement*) in simulating yield variations.
42

43 Adaptation possibilities of food systems to climate change show a very wide range in effectiveness and with
44 medium confidence (*good evidence, medium agreement*) point to adaptation having increased effectiveness with
45 increasing temperature changes. Generally (*good evidence, high agreement*) adaption leads to lower reductions in
46 yields than in its absence with a overall yield difference in adaption cases of about 20% over non-adaption cases,
47 with more effective adaption at higher latitudes (*good evidence, medium agreement*) but with some adaptation
48 options more effective than others.
49

51 7.1. Introduction and Context

52
53 Many definitions of food security exist. Maxwell and Smith noted over 200 as early as 1992 (Spring, 2009) and
54 more have been formulated ((Defra, 2006)). While many of the earlier definitions centred on food production, the

1 majority of more recent definitions promote the notion of access to food. The 1996 World Food Summit definition
2 ((FAO, 1996)), which states that food security is met when “*all people, at all times, have physical and economic*
3 *access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and*
4 *healthy life*”, is still widely adopted. This definition puts the notion of access to food centre stage, also integrating
5 notions of food availability, food utilisation and stability over time. The definition has a focus on the under-supply
6 of food whereas overconsumption and obesity are also relevant as factors in global public health.
7

8 While food security has been on the development agenda for decades (Armartya Sen XXXX), world-wide attention
9 was given considerable impetus by the food ‘price spike’ in 2007-08, triggered by a complex set of long-term and
10 short-term factors (von Braun and Torero, 2009). According to some estimates the price spike increased the number
11 of hungry people by some 40 million (FAO, 2008) but other studies report a lower number (Heady, 2010 IFPRI
12 report). This link between food prices and numbers of food insecure people underscores the importance of the
13 affordability of food in relation to food security. More than enough food is currently produced *per capita* to
14 adequately feed the global population, yet about 925 million people remained food insecure in 2010 ((FAO, 2010)).
15 The two overriding questions for this chapter are how far climate change adds to current issues of food security and
16 the extent that it will do so in the future.
17

18 19 **7.1.1. Summary from AR4** 20

21 Food systems as integrated activities dealing with the impacts of climate change on the supply and demand for food
22 did not feature strongly in AR4, where the strong emphasis was on food, fibre and forest production. Summary
23 points from AR4 were that, with *medium confidence*, in mid- to high-latitude regions moderate warming will raise
24 crop and pasture yields. However, even slight warming will decrease yields in low-latitude regions. Extreme climate
25 and weather events will, with *high confidence*, reduce food production with or without changes in mean conditions.
26 The benefits of adaptation in crops such as changing varieties and/or planting times and other managements enable
27 avoidance of a 10-15% reduction in yield corresponding to 1-2°C local temperature increase. Adaptive capacity will
28 be exceeded in low-latitude areas with temperature increases of more than 3°C. Local extinctions of particular fish
29 species are expected with *high confidence* at the edges of their ranges and any slowing in the meridional overturning
30 circulation will have serious negative impacts on fisheries with a *medium confidence* level.
31

32 33 **7.1.2. Food Systems** 34

35 A food system includes all processes and infrastructure involved in feeding a population and relating to the *Activities*
36 of gathering/catching, growing, harvesting, processing, packaging, transporting, marketing, consuming, and
37 disposing of food waste and food-related items. The food system concept is not new: driven by social and political
38 concerns, rural sociologists had promoted this approach for some years (e.g. (McMichael, 1994; Tovey, 1997)), and
39 the food chain concept (“farm-to-fork” or “plough-to-plate”) is now well established ((Maxwell and Slater, 2003);
40 (ESF, 2009)). These food system *Activities* give rise to a number of food security *Outcomes* related to availability
41 and utilization of, and access to, food. Drawing together the extensive (yet relatively distinct) literatures built up by
42 the food chain and food security communities, respectively, a revised ‘food systems’ model (Figure 7-1) has been
43 formalised (Ericksen, 2008; Ericksen et al., 2010; Ingram, 2009). This model recognises that food systems operate
44 within, are influenced by, and feed back to social, political, economic and environmental contexts (Figure 7-2).
45

46 [INSERT FIGURE 7-1 HERE

47 Figure 7-1: The components of food systems in terms of activities and outcomes for food security and environmental
48 and social welfare (GECAFS, 2009).]
49

50 [INSERT FIGURE 7-2 HERE

51 Figure 7-2: Main drivers of food systems. (MAY BE REMOVED DUE TO OVERLAP WITH FIGURE 7-1)]
52

53 Understanding the interactions between food security and global climate change is highly challenging. This is
54 nevertheless increasingly important as 50% more food will be needed by 2030 given current food consumption

1 trends (Godfray et al., 2010b) and the risk of food insecurity will likely grow. A further challenge is developing food
2 system adaptation pathways that are significantly more environmentally benign than current approaches. Adapting
3 our food system activities to meet these challenges will give rise to changes in all food security outcomes to some
4 extent (Figure 7-1) but often researchers only consider one food security element, usually food production. A
5 meaningful adaptation discussion on food security needs consideration of how any intervention will affect all other
6 eight elements of the food security outcomes; in principle, any intervention, even if only targeted at only one
7 element will affect all nine (Figure 7-1).

10 7.1.3. *The Current State of Food Security*

11
12 By current estimates there are roughly one billion people in the world who lack food security (FAO, 2011).
13 Typically this is estimated based on aggregate national calorie availability and assumptions about food distribution
14 and nutritional requirements. More precise estimates are possible with detailed household surveys, which often show
15 higher incidence of food insecurity than estimated by FAO. For instance, Smith et al. (2006) estimated average food
16 insecurity rates of 59% for 12 African countries, compared to 39% as estimated by FAO methods.

17
18 The highest rates of food insecurity are in Sub-Saharan Africa, where as mentioned up to 60% of people do not
19 consume sufficient calories for an active life. The largest numbers of food insecure are found in South Asia, which
20 has roughly 300 million undernourished. In addition to common measures of calorie availability, food security can
21 be broadened to include nutritional aspects, which relates to the diversity of diet including not only staple foods but
22 also vegetables, fruits, meat, milk, eggs, and fortified foods (FAO, 2011). Lack of essential micronutrients such as
23 zinc and vitamin A affect hundreds of millions of additional people (Lopez et al., 2006).

24
25 Food insecurity is closely tied to poverty, and more detailed surveys on poverty provide insight into where the food
26 insecure live. Globally, about one-fourth of poor people – measured using either a \$1 or \$2 per day standard - live in
27 urban areas (Ravallion et al., 2007). This is partly because most poor countries have a greater fraction of people
28 living in rural areas, but also because poverty rates tend to be higher in rural settings (by slight margins in South
29 Asia and Africa, and by large margins in China). In Latin America, poverty is more skewed to urban areas, with
30 roughly two-thirds of the poor found in urban areas, a number that has been growing in the past decade. The urban
31 share of poverty has also been rising in other regions, although more slowly. It is expected that rural areas will
32 continue to have the majority of poor people for at least the next few decades, even as population growth is higher in
33 urban areas (Ravallion et al., 2007).

34
35 For urban poor, who produce relatively small amounts of food, increases in food prices generally reduce food
36 security. For the rural poor, the picture is more complicated. Much of the poor's income is from agricultural
37 activities, which stands to benefit if prices rise. As mentioned, however, the rural poor still tend to be net consumers
38 or marginal net producers. That is, they consume nearly all of what they grow and still need to buy additional food.
39 If prices are rising more quickly for crops they grow, they can sell those and buy cheaper calories, resulting in a net
40 increase in well-being. Rural wage rates may also increase in response to higher prices (for example, if workers are
41 paid with a set amount of grain), with benefits for the many who earn part of their income from working other lands.
42 Thus, the long-term welfare effects of price rises on rural poor are complex, and can vary depending on local
43 factors. For example, Ivanic and Martin (Ivanic and Martin, 2008) used detailed data on income sources and
44 expenditures in nine countries to examine the impact of price rises during 2007-2009, and found that they increased
45 poverty significantly in some countries (e.g., Nicaragua, Madagascar, Pakistan) while likely lowering poverty in
46 others (Vietnam, Peru). Overall, however, they found that increases in poverty were more common from price rises
47 than reductions. Again, this highlights the fact that although most poor are rural, they are net buyers of food.

48
49 The effects of price volatility are distinct from the effects of gradual price rises, for two main reasons. First, rapid
50 shifts make it difficult for the poor to adjust their activities to favor producing higher value items. Second, increased
51 volatility leads to greater uncertainty about the future, and can dampen willingness to invest scarce resources into
52 productivity enhancing assets, such as fertilizer purchases in the case of farmers or rural infrastructure in the case of
53 governments.

1 In summary, most rural poor do not interact very much with the market, shielding them partially from effects of
2 rapid price changes. Yet despite the largely subsistence living, they tend to spend a large share of their off-farm
3 income on acquiring more food, which means that they are hurt by price increases in the short term. As the poorest
4 areas slowly become more integrated with markets, they are likely to improve overall incomes and productivity, at
5 the cost of becoming more vulnerable to price shocks.
6
7

8 **7.2. Observed Impacts, with Detection and Attribution**

9 **7.2.1. Food Production Systems**

10 Food production systems have changed substantially over the past few decades. As described above, these changes
11 were primarily the result of factors other than changes in atmospheric CO₂ or climate. In fact, in many contexts the
12 effects of past changes in weather or CO₂ are viewed as noise when trying to measure the effect of agronomic or
13 genetic changes (Bell and Fischer, 1994). Yet understanding the effect of past CO₂ and climate shifts are a useful
14 precursor to assessing future impacts and adaptation needs.
15
16
17

18 The sheer number and strength of non-climate drivers of food systems and food security make formal detection and
19 attribution of impacts extremely difficult. Most of these confounding factors, such as fertilizer use or adoption of
20 modern hybrids in the case of crops, are not very well characterized in terms of spatial and temporal distributions,
21 and the relationships between these factors and specific outcomes of interest (e.g., crop production) are often
22 difficult to quantify. Attribution in other food production sectors is equally difficult. Identifying a unique fingerprint
23 associated with greenhouse gas emissions is therefore impractical. No studies to our knowledge, for example,
24 simulate historical trends in food-related outcomes with and without changes in anthropogenic emissions of
25 greenhouse gases. A possible exception was Auffhammer et al. (Auffhammer et al., 2006) who compared rice yield
26 predictions in India using climate model simulations of temperature in the late 20th century with yields using
27 observed temperatures for 1930-1960, the latter period used as a surrogate for climate without changes in
28 greenhouse gases after 1960. In their study, they find rice yields would have been significantly higher without
29 greenhouse gas emissions, thus attributing negative impacts to emissions.
30

31 As discussed in Hegerl et al. (2010), attribution of impacts can take the form of multi-step attribution, where an
32 outcome is related to a change in climatic conditions, and these climate conditions are in turn attributed to changes
33 in external drivers of the climate system (i.e. greenhouse gas emissions). In this case “the assessment of the link
34 between climate and the variable of interest may involve a process model or a statistical link” (Hegerl et al. 2010).
35 Therefore, studies that infer an impact of changing conditions on food production or food security, for instance by
36 using a crop model, can be considered a part of formal attribution of impacts, assuming that the change in conditions
37 can be attributed to anthropogenic activity.
38

39 Attributions of crop changes are further complicated by the fact that models linking climate and agriculture must,
40 implicitly or explicitly, make assumptions about farmer behavior. In most cases, models implicitly assume that
41 farming practices or technologies did not adjust in response climate over the period of interest. This assumption can
42 be defended in some cases based on ancillary data on practices, or based on small differences between using models
43 with and without adaptation (Schlenker and Roberts, 2009). However, in some instances the relationship between
44 climate conditions and crop production has been shown to change over time because of management changes
45 (Zhang et al., 2008; Liu et al., 2009).
46

47 Many studies of cropping systems have estimated impacts of observed changes in climate over the past few decades.
48 Based on these studies, there is *high confidence* (high agreement, robust evidence) that climate trends have
49 negatively affected wheat and maize production for many regions, as well as *medium confidence* (high agreement,
50 medium evidence) for negative impacts on global aggregate production of these crops (Figure 7-3). There is also
51 *high confidence* (high agreement, robust evidence) that warming has benefitted crop production in some cold
52 regions, such as Northeast China or England (Jaggard et al., 2007; Supit et al., 2010; Chen et al., 2011; Gregory and
53 Marshall, 2012).
54

1 [INSERT FIGURE 7-3 HERE

2 Figure 7-3: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were
3 taken from the peer-reviewed literature and used different methods (i.e., physiological crop models or statistical
4 models), spatial scales (e.g., stations, provinces, countries, or global), and time periods (median length of 29 years).
5 Some included effects of positive CO₂ trends but most did not. (a) shows number of studies with different level of
6 impact (% yield per decade), (b) shows boxplot of studies separated by modelling approach, whether CO₂ effects
7 were included, and crop. Studies were for China (Tao et al., 2006; Tao et al., 2008; Wang et al., 2008; You et al.,
8 2009; Chen et al., 2010), India (Pathak et al., 2003; Auffhammer et al., 2012), United States (Kucharik and Serbin,
9 2008), Mexico (Lobell et al., 2005), France (Brisson et al., 2010), Australia (Ludwig et al., 2009), and some studies
10 for multiple countries or global aggregates (Lobell and Field, 2007; Welch et al., 2010; Lobell et al., 2011).]

11
12 A sizable fraction of crop modeling studies were concerned with production for individual sites or provinces, scales
13 below which the changes in climate conditions are likely attributable to anthropogenic activity (WG1, Chap x).
14 Similarly, most crop studies have focused on the past few decades, a time scale shorter than most attribution studies
15 for climate. However, some focused on continental or global scales (Lobell and Field, 2007; You et al., 2009; Lobell
16 et al., 2011), at which trends in several climatic variables, including average summer temperatures, have been
17 attributed to anthropogenic activity (WG 1, Chapter x.). In particular, global temperature trends over the past few
18 decades are attributable to human activity (WG 1, Chapter x), and crop models indicate that this warming has had
19 significant negative impacts on crop yield trends.

20
21 Figure 7-4 presents a summary of the detectability of changes in growing season climate and crop yield changes, as
22 well as the ability to attribute changes to climate and CO₂ trends (in the case of yield changes) or anthropogenic
23 emissions (in the case of growing season climate changes). As discussed above, attribution of yield impacts relies on
24 multi-step attribution based on process understanding and observed climate trends. Also illustrated in Figure 7-4 is
25 the fact that not all major cropping regions have experienced significant climate trends in the past few decades, with
26 the United States the most notable example.

27
28 [INSERT FIGURE 7-4 HERE

29 Figure 7-4: Confidence in Detection and Attribution of Observed Impacts on crop yields and growing season
30 agroclimatic conditions. Yield impacts include both direct climate effects and effects of elevated CO₂, but do not
31 consider farmer adaptation. Confidence Levels were derived based on expert judgement of the available literature,
32 following the IPCC uncertainty guidance (Mastrandrea et al., 2010). References: to fill in when complete, many of
33 the same from Figure 7-3.]

34
35 In comparison to crop food production, considerably less work has been published on non-crop food production
36 systems, such as livestock and fisheries. The detection and attribution of impacts are as confounded in inland and
37 marine fisheries as in terrestrial food production systems. Overfishing, habitat modification, pollution and short- to
38 medium-term climate variability can all have impacts that are difficult to separate from those directly attributable to
39 climate change. One of the best studied areas is the North East Atlantic, where the temperature has increased rapidly
40 in recent decades, associated with a poleward shift in distribution of fish (Brander, 2007, see also Chapter 6 of this
41 volume). In the North Sea, within the NE Atlantic, the average species richness in the region, as indicated by the
42 number of species recorded per year increased by approximately 33% between 1985 and 2006 (Hiddink and ter
43 Hofstede 2008). The authors report high confidence that the increase in richness has been related to rising water
44 temperature. These trends will have mixed implications for fisheries and aquaculture with some commercial species
45 negatively impacted and others positively (Cook and Heath, 2005). There is a similar well-documented example in
46 the oceans off SE Australia with large warming trends associated with more southwards incursion of the Eastern
47 Australian Current. This has resulted in southward migration of marine species into the oceans around eastern
48 Tasmania with consequent impacts on ecosystem dynamics (Last et al. 2011).

49
50 Coral reef ecosystems are important sources of fish for food for local inhabitants. More than 60% of coral reefs are
51 considered to be immediately threatened by a range of local threats, of which overfishing is the most serious
52 followed by coastal development and pollution. The percentage under threat rises to 75% when the effect of rising
53 ocean temperatures is added to these local impacts (Burke et al. 2011). There have been ongoing incidences of coral
54 bleaching from rising sea temperatures since the 1970s which have already caused a global decline in coral reef

1 cover and the trend is likely to continue as temperatures continue to rise (Munday et al. 2008). Ocean acidification
2 presents an additional threat by reducing carbon accretion (see Box 5-3 for further information). Wilson et al. (2006)
3 demonstrated that declines in coral reef cover typically led to declines in abundance of the majority of fish species
4 associated with coral reefs, with species that depended on live coral for food and shelter most impacted while some
5 species that fed on invertebrates, algae or detritus increased.

6
7 For inland fisheries, there is evidence that increasing temperature has reduced the primary productivity of Lake
8 Tanganyika in East Africa by increasing the stability of the water column and thereby reducing upwelling of
9 nutrients into surface waters where there is sufficient light for primary production. The study by O'Reilly et al.
10 (2003) estimated that this would have led to a decrease of approximately 30% in fish yields, an important source of
11 animal protein for local communities. The Sahel region in northern Africa has historically demonstrated high
12 variability. It experienced good rainfall in the 1960s, followed by severe drought over the next 7 years and below
13 average precipitation from then until 2007. This dry period resulted in the area of Lake Chad decreasing from
14 26,000 km² in the 1960s to 1,425 km² in 2003. The decreasing area was associated with a decline in reported fish
15 catches in Chad from over 100 000t in the late 1960s to under 70 000t in the early 1990s although there is
16 considerable doubt about the accuracy of the reported catch figures, including up to the present (Welcomme, 2011).

17
18 In general, little work in food production or food security research has focused on formally attributing observed
19 changes to anthropogenic influence on the climate system. However, as the field of climate detection and attribution
20 proceeds to finer spatial and temporal scales, and as agricultural modeling studies expand to broader scales, there
21 will likely be many opportunities to link climate and crop studies in the next few years. Importantly, climate
22 attribution is increasingly documented not only for measures of average conditions over growing seasons, but also
23 for extremes. For instance, (Min et al., 2011) attribute changes in rainfall extremes to anthropogenic activity, and
24 these are widely acknowledged as important to cropping systems (Rosenzweig et al., 2002). In southern Australia,
25 crop yields, water availability and regional economics have been affected by long-term declines in rainfall. The
26 decline in rainfall is associated with a strengthening of the sub-tropical ridge which is highly correlated with global
27 temperature (Timball et al. 2009). Frost damage is an important constraint on crop growth in many crops, including
28 for various high-value crops, and significant reductions in frost occurrence have been observed and attributed to
29 greenhouse gas emissions in nearly every region of the world (Alexander et al., 2006; Zwiers et al., 2011)(add
30 SREX ref). Positive trends in the occurrence of unusually hot nights are also attributable to human activity in most
31 regions. These events are likely damaging to most crops, an effect that has been observed most commonly for rice
32 (Peng et al., 2004; Wassmann et al., 2009; Welch et al., 2010). Extremely high daytime temperatures are also
33 damaging and occasionally lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009), and trends at the
34 global scale in annual maximum daytime temperatures have been attributed to greenhouse gas emissions (Zwiers et
35 al., 2011). At regional and local scales, however, trends in daytime maximum are harder to attribute to greenhouse
36 gas emissions because of the prominent role of soil moisture and clouds in driving these trends (Christidis et al.,
37 2005; Lobell et al., 2007; Zwiers et al., 2011).

38
39 More difficult to quantify is the impact of very extreme events on cropping systems, since by definition these occur
40 very rarely and models cannot be adequately calibrated and tested. Table 18-xx lists some notable extremes over the
41 past decade, and the impacts on cropping systems as reported in production statistics. Despite the difficulty of
42 modeling the impacts of these events, they clearly have sizable impacts that are apparent immediately or soon after
43 the event, and therefore not easily confused with effects of more slowly moving factors. For a subset of these events,
44 climate research has evaluated whether anthropogenic activity has increased or decreased their likelihood, and
45 whether they are likely to become more common in the future (Table 18-xx).

46
47 In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition
48 on crops. There is *very high confidence* (high agreement, robust evidence) that the increase of atmospheric CO₂ by
49 over 100 ppm since pre-industrial times has enhanced yield growth, especially for C₃ crops, although these benefits
50 played a minor role in driving overall yield trends (Amthor, 2001; Long et al., 2006; McGrath and Lobell, 2011). As
51 described earlier, increases in carbon dioxide are expected to have negative impacts on carbon accretion in coral
52 reefs with potentially serious negative consequences for associated ecosystems and dependent social and economic
53 activities (Hoegh-Guldberg et al. 2007).

1 Emissions of CO₂ have also been associated with ozone (O₃) precursors that have driven a rise in tropospheric O₃
2 that harms crop yields (Morgan et al., 2006; Mills et al., 2007). There is *high confidence* (high agreement, robust
3 evidence) that elevated O₃ has suppressed global production of major crops, with estimated losses of roughly 10%
4 for wheat and soybean and 3-5% for maize and rice (Van Dingenen et al., 2009). Impacts are most severe over India
5 and China, but are also evident for soybean in the United States in recent decades (Fishman et al., 2010).
6
7

8 **7.2.2. Food Security**

9

10 Food production is an important aspect of food security (albeit only one, see section 7.1), and the evidence that
11 climate change has affected food production implies some effect on food security. Yet quantifying this effect is an
12 extremely difficult task, requiring assumptions about the many non-climate factors that interact with climate to
13 determine food security. There is thus limited direct evidence that unambiguously links climate change to impacts
14 on food security.
15

16 One important aspect of food security is global food prices, particularly for poor urban consumers as well as the
17 millions of net consumers in rural areas. Prices for major cereals, oilseeds, and other crops have exhibited an
18 increasing trend over the past decade in a reversal of declining real prices over the previous century. The past decade
19 has also witnessed relatively large volatility in prices, although previous periods such as the 1970's had similar
20 levels of variability when adjusted for inflation (Naylor and Falcon, 2010; Wright, 2011). Much of these trends can
21 be explained by changes in demand, notably increased demand via mandates for biofuel production and increases in
22 food demand because of population and income growth (Roberts and Schlenker, 2010; Wright, 2011). Changes in
23 global supply, defined as the combination of annual production and global stocks, have also played a role according
24 to most analysts. In part this is evidenced by significant movements in prices following revisions of supply forecasts
25 by the United States Department of Agriculture (Garcia et al., 1997).
26

27 The balance between global supply and demand is not the only factor affecting global prices. Macro-economic
28 trends, such as changes in exchange rates, can be very important (Abbott et al., 2008). Most notably, changes in
29 trade policy can cause sudden changes in prices, as witnessed with the export bans announced by several countries
30 since 2007 (FAO, 2008). These bans are often announced after officials become concerned that domestic supplies of
31 key grains have been imperiled by bad weather. Export bans therefore often act as an amplifier of weather-driven
32 shocks, implying that the impacts of particular weather events or changing frequency of weather extremes because
33 of climate change cannot be measured without specific assumptions about these trade policies.
34

35 One approach to estimate food price response to supply shocks is to examine historical correlations between supply
36 changes and prices, taking care to consider only the component of supply changes that were not already anticipated
37 and thus reflected in prices before the supply changed (Roberts and Schlenker, 2010). Using price elasticities of
38 supply and demand estimated in this manner, one can estimate price responses to a given supply change. In a study
39 of global production responses to climate trends, (Lobell et al., 2011) estimated a price increase of 19% due to the
40 impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of
41 increased CO₂ over the study period were considered. Since the price models were developed for a period ending in
42 2003, these estimates do not include the policy responses witnessed in recent years which have amplified the price
43 responses.
44

45 **7.3. Assessing Impacts, Vulnerabilities, and Risks**

46

47 **7.3.1. Methods and Associated Uncertainties**

48

49 Methods developed or extended since AR4 have resulted in more robust statements on climate impacts through
50 improved quantification and presentation of uncertainty. Descriptions of processes and trade-offs, and expression of
51 uncertainty in the temporal dimension, are two methods that have been explored as methods for presentation of
52 uncertainty in the outcome variable (e.g. yield). In addition, greater use of historical empirical evidence of the
53 relationship between climate and food production has been made.
54

1
2 The methods used for field and controlled environment experiments remain similar to those at the time of AR4.
3 There has been a greater interest in the use of Remote Sensing (RS)/Geographic information System (GIS)
4 techniques for assessing temporal and spatial changes in land use particularly in agricultural land use for assessment
5 of food security status (Fishman et al, 2010). There has also been an increase in the number of Free Air
6 Concentration Enrichment (FACE) studies that examine ozone instead of, or in addition to, carbon dioxide. A
7 number of meta-analyses of experimental studies, in particular (FACE) studies have been conducted since AR4.
8 Section 7.3.2.1.2 contains the details of these studies.
9

10 Numerical models can be used to investigate a larger number of possible environmental and management conditions
11 than physical experiments. This in turn enables a broader range of statements regarding the response of food
12 production systems to climate variability and change. Previous assessment reports have documented new knowledge
13 resulting from numerical simulation of the response of food production to climate change. AR4 noted the increasing
14 number of regional studies, which is a trend that has continued to date (Challinor et al., 2009). Since AR4, crop
15 models have been used for examining a large number of management and environmental conditions, such as
16 interactions among various components of food production systems (Lonz-Weidemann, et al. 2010), determination
17 of optimum crop management practices (Soltani and Hoogenboom, 2007), vulnerability and adaptability
18 assessments (Humaira, et al. 2009), evaluation of water consumption and water use efficiency (Mo et al. 2009; Kang
19 et al. 2009), estimation of changes and uncertainties (Bellocchi, et al. 2010) and fostering communication between
20 scientists, managers, policymakers and planners.
21

22 Novel developments since AR4 in the methodologies used for modeling since include more studies that quantify
23 uncertainty in both climate and its impacts, particularly for crops, and models that include crop growth as part of
24 broader land surface and earth systems models (Bondeau et al., 2007; Osborne et al., 2007; Rötter et al., 2011).
25 Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Bayesian
26 methods to constrain crop model parameters (Iizumi et al., 2009, Tao et al., 2009a). It is also increasingly common
27 to assess both bio-physical and socio-economic drivers of crop productivity within the same study (Fraser et al 2008,
28 Tao et al. 2009b, Reidsma et al., 2009, Challinor et al., 2010). Finally, an important recent development is the
29 systematic comparison of results from different modelling and experimental approaches for providing insights into
30 model uncertainties as well as to develop risk management (Rosenzweig et al, 2012; Challinor and Wheeler 2008;
31 Kang, et al. 2009; Schlenker and Lobell 2010).
32

33 Increased quantification of uncertainty does not necessarily lead to less robust statements regarding climate impacts.
34 Studies with different methods have been shown to produce convergent results for some crops and locations (e.g.
35 Challinor et al., 2009). [Placeholder: more on this from Iizumi, Tao, forthcoming AFM special issue on the extent to
36 which the greater focus on quantifying uncertainty has generated different results]. The methods used to describe
37 uncertainty have also been further developed since AR4. The projected range of global and local temperature
38 changes can be described by quantifying uncertainty in the temporal dimension, rather than that in temperature itself
39 (Joshi et al. 2011), and a similar approach can be used for crop yield (Section 7.3.2.1.1). Descriptions of uncertainty
40 that present key processes and trade-offs, rather than ranges of outcome variables, are also new tools for
41 understanding future impacts (EQUIP special issue papers, [forthcoming]).
42

43 A considerable body of work since AR4 has used extensive datasets of country-, regional- and farm- level crop
44 yield together with observed and/or simulated weather time series in order to assess the sensitivity of food
45 production to weather and climate. These statistical models offer a complement to more process-based model
46 approaches, the latter of which require many assumptions about soil and management practices, are often difficult to
47 scale up to broad regions, and do not exist for many minor crops. The regional-scale statistical models that have
48 been developed in recent years can thus produce more widely applicable results than field and controlled
49 environment experiments, whilst avoiding the need for assumptions regarding management and planting dates.
50 Although statistical models forfeit some of the process knowledge embedded in other approaches, they can often
51 reproduce the behavior of other models (Iglesias et al. 2000, Lobell and Burke 2010), can readily be tested with data
52 not used to train the model (Schlenker and Roberts, 2009), and can leverage a growing availability of crop and
53 weather data (Welch et al. 2010 PNAS, Lobell et al. 2011). Statistical models usually exclude the direct impact of
54 elevated CO₂, making multi-decadal prediction problematic. Similarly, technological progress and its interaction

1 with climatic variability are not simulated by statistical models. Regional-scale process-based models tend to include
2 at least some of these processes.

3
4 Agro-climatic (e.g. Trnka et al., 2011) indices provide another alternative to process-based crop models that avoid
5 various assumptions by focusing on accepted measures of relevance to farmers, rather than providing yield
6 predictions *per se*. However, correlations between climate, or associated indices, and yield are not always
7 statistically significant. (Placeholder: more studies on changes in indices [forthcoming]).

8
9 Robustness of the model results depends on data quality, model skill prediction and model complexity (Bellocchi, et
10 al. 2010). Modeling and experiments are each subject to their own uncertainties. Measurement uncertainty is a
11 feature of field and controlled environment experiments. For example, the magnitude of fertilizing effect of CO₂ at
12 the elevated concentrations as a result of high temperature, increased variability and several limiting factors such as
13 soil nutrients, pests and weeds is not well understood hence a source of uncertainty (Soussana et al 2010). Also,
14 most of the current generation crop models do not include all the effects of climate change, such as pest and disease
15 effects, damaging effect of high surface ozone concentrations, possible decrease of glacial water supply, competing
16 use of water by industrial sector and households (Piao et al. 2010), role of extreme events and interaction between
17 biotic and abiotic factors (Soussana, et al. 2010). The uncertain projections of rainfall by different climate models
18 further increase the uncertainty of future crop yield changes (Buytaert et al. 2010).

19
20 There are also uncertainties associated with generalizing the results of these experiments, since each one has been
21 conducted relatively few times under a relatively small range of environmental and management conditions and for
22 a limited number of genotypes. Models have the advantage of exploring a larger number of situations, but with less
23 certainty in the determination of the responses of different genotypes to climate change (Craufurd et al. 2012, in
24 press [forthcoming]).

25
26 Placeholders: T-FACE experiments (e.g. http://www.eurekalert.org/pub_releases/2011-02/usdo-ec022411.php)
27 More on crops will come from a forthcoming paper Craufurd et al (2012).

28 29 30 **7.3.2. Sensitivity of Food Production to Weather and Climate**

31
32 Since AR4, understanding of the impacts of a range of biophysical processes and associated outcomes has been
33 improved:

- 34 • Heat stress effects have been better quantified at regional and local scales. There is no evidence that the
35 response is uniform across spatial scale.
- 36 • Interaction between water stress and CO₂: TAR/AR5 states that water stressed crops may benefit more than
37 well-watered crops from elevated CO₂. Work since then suggests this may not consistently be the case.
38 [Literature in prep means that this highlight will need to be revisited for the SOD]
- 39 • The relative importance of temperature and precipitation. Evidence of the greater importance of
40 temperature over precipitation in some regions (Thornton, Lobell, Hawkins) of AR4 conclusion paragraph
41 1 pg 283, and chapter figure.
- 42 • Pests weeds and diseases included more fully [this needs more detail]

43
44 The majority of research into the sensitivity of food production to weather and climate remains focussed on crops.
45 The majority of that work is focussed on impacts on major annual crops such as maize, wheat and rice, a focus that
46 is commensurate with the area harvested of these crops (White et al., 2011). Whilst there are many other crops of
47 importance to food systems, the crops discussed here reflect both the availability of research and the global remit of
48 this chapter.

1 7.3.2.1. *Crops and Pastures*

3 7.3.2.1.1. *Mean and extremes of temperature and precipitation*

5 Both statistical and process-based models have widely been used since AR4 to assess the response of crop yield to
6 temperature. Model results (e.g. Moriondo et al., 2011) confirm the importance of known physiological processes,
7 such as the shortening of the time to maturity of a crop with increasing mean temperature, which in turn reduces
8 yield (Iqbal et al, 2009). This observed response is well-understood for temperatures up to the optimum temperature
9 for development. The impacts of prolonged periods of temperatures beyond the optimum for development are not as
10 well understood (Craufurd and Wheeler, 2009), although temperatures above 34 °C after flowering appear to rapidly
11 speed senescence in wheat and reduce grain set (Asseng et al. 2011, Lobell 2012: NCC). Other processes
12 documented in AR4 include the influence of extremes of temperature and the impact of water stress, both of which
13 have been confirmed as important by more recent research (Schlenker and Roberts 2009, Lobell et al. 2011).

15 Despite this process understanding, model results can still disagree on the sign of the response of yield to
16 temperature. Many processes throughout a crop's life cycle are sensitive to temperature, precipitation, and other
17 meteorological conditions, so that the overall relationship between weather and yields is often crop and region
18 specific, with a dependence on the duration and timing of crop exposure to various conditions. For example, rice
19 yields in China have been found to be positively correlated with temperature in some regions and negatively
20 correlated in others (Zhang et al., 2010). This difference may be due to positive correlation between temperature and
21 solar radiation in the former case, and negative correlation between temperature and water stress in the latter case.
22 Similarly, although studies consistently show spikelet sterility in rice for daytime temperatures exceeding 33 °C
23 (Jadadish et al. 2007, Wassmann et al. 2009), some statistical studies find a positive effect of daytime warming on
24 yields because these extremes are not reached frequently enough to affect yields (Welch et al. 2010).

26 The relative importance of temperature and water stress for crop productivity can be assessed using models, and can
27 vary according to the criteria used for assessment (Challinor et al., 2010). There are also some cases where the sign
28 of a correlation depends on the direction of the change. For example, Thornton et al. (2009) found that the response
29 crop yields to climate change in the drylands of East Africa is insensitive to rainfall, since wetter climates are
30 associated with warmer temperatures that act to reduce yields. Variation in crop-climate relationships can also result
31 from the analytical methods used and/or the spatial scale of the analysis (e.g. Challinor and Wheeler, 2008). For
32 example, increases in daily maximum temperature have been found to increase the yield of rice at a number of sites
33 across Asia (Welch et al., 2010), whilst negative responses due to spikelet sterility are a well-know phenomenon in
34 controlled environment experiments (refs, or just ref AR4). Crop models can be used to quantify abiotic stresses
35 such as these (e.g. Challinor et al., 2009), although only by hypothesizing that the functional responses to weather
36 derived from experiments are valid at regional scales. Thus, whilst many fundamental bio-physical processes are
37 understood at the plant or field scale, it remains difficult to quantify the extent to which these mechanisms are
38 responsible for the observed regional-scale relationships between crop yield and weather, such as those reported by
39 Schlenker and Roberts (2009). Empirical studies of the influence of spatial variability in climate on crop yield can
40 also result in mechanistic understanding.

42 Precipitation exhibits more spatial variability than temperature, temporal variations in the spatial average of
43 precipitation tend to diminish as the spatial domain widens, and as a result precipitation becomes less important as a
44 predictor of crop yields at broad scales (Lobell and Field 2007, Li et al. 2010). Similarly, projected changes in
45 precipitation from climate models tend to be more spatially variable than temperature, leading to greater importance
46 of projected temperatures as the spatial scale of analysis grows wider (Lobell and Burke 2008). [Placeholder:
47 Hawkins et al, submitted, comment on the relative importance of temperature and precipitation]. Despite this scaling
48 issue, differences in simulated regional scale responses to precipitation can be observed: Figure 7-5 contrasts results
49 of a meta-analysis of crop impacts studies for temperate and tropical regions. Results of these analyses show that the
50 relationship between yield and temperature, derived from the same dataset of crop impact studies, is for most crops
51 more robust than that between yield and precipitation (Figure 7-6). [Placeholder: more detail on this figure,
52 depending on exactly what the final figure looks like].

1 [INSERT FIGURE 7-5 HERE

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

5
6 [INSERT FIGURE 7-6 HERE

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

10
11 [Forthcoming - AJC will add more examples of this (Refs Iizumi, Tao, forthcoming AFM special issue, others).
12 Also something on Lobell and Field, 2007. The idea is to comment on the extent to which the greater focus on
13 quantifying uncertainty (a trend since AR4) has resulted in different results.]

14
15 Forage (pasture/rangelands) response to climate change is complex because, in addition to the major climatic drivers
16 (CO₂ concentration, temperature, and precipitation), other plant and management factors affect this response (e.g.,
17 plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions). Projected increases
18 in temperature and the lengthening of the growing season should extend forage production into late fall and early
19 spring, thereby decreasing the need for accumulation of forage reserves during the winter season in USA. In
20 addition, water availability may play a major role in the response of pasturelands to climate change although there
21 are differences in species response. There is general consensus that increases in CO₂ will benefit C₃ species,
22 however warmer temperatures and drier conditions will tend to favour C₄ species (Hatfield et al, 2008).

23
24 Projected scenarios for Europe indicate that increased temperatures and CO₂ concentrations have the potential to
25 increase herbage growth and to favour legumes more than grasses, but changes in seasonal precipitation would
26 reduce these benefits particularly in areas with low summer rainfall. Further implications for grasslands may arise
27 from increased frequency of droughts, storms and other extreme events (Hopkins and Del Prado, 2007). Also in
28 South America, rangelands productivity is strongly dependent of water availability. The variation in rangeland
29 productivity is directly related with highly variable amounts and seasonal distribution of precipitation, and only
30 secondarily controlled by other climatic variables. The relationship between primary productivity and precipitation
31 in arid to sub-tropical ecosystems is widely similar across all geographic regions with an increment between one-
32 half and three-fourths of a gram of production per square meter annually for each millimeter of precipitation
33 (Yahdjian & Sala, 2008). Results from a modeling experiment in Australia indicate that increased temperature (3°C)
34 was likely to result in a decrease in forage production for most rangeland locations, exacerbating/reducing the
35 effects of decrease/increase in rainfall but the beneficial effects of increased CO₂ on forage production and water use
36 efficiency enhanced forage production with increases equivalent to the decline associated with a 3°C temperature
37 increase (McKeon et al. 2009).

38 39 40 7.3.2.1.2. *Impact of carbon dioxide and ozone*

41
42 There is further evidence since AR4 that reaction to a change in CO₂ depends on plant type; C₃ or C₄ (De Matta, et
43 al. 2010). The effect of increase in carbon dioxide concentration tends to be higher on C₃ plants (e.g. wheat, rice,
44 cotton, soybean, sugar beets, and potatoes) than on C₄ plants (e.g. corn, sorghum), because photosynthesis rates in
45 C₄ crops are unresponsive to increases in ambient CO₂ (Leakey 2009). The highest fertilization responses have been
46 observed in tuber crops, which have large capacity to store extra carbohydrates in belowground organs (Hogy and
47 Fangmeier 2009, Fleisher et al. 2008).

48
49 Rain-fed cropping systems will benefit more from elevated CO₂ than irrigated systems, and that rain-fed systems in
50 drier regions or years will benefit more than in wetter conditions. This expectation has been cited in TAR and AR4,
51 and new evidence based on historical analysis supports this notion by demonstrating that the rate of yield gains in
52 rainfed systems is higher for dry years than for wet years (McGrath and Lobell, 2011). However, this response is not
53 seen consistently across models and Free-Air CO₂ Enrichment (FACE) meta-analyses and there is some suggestion
54 that the relationship between water stress and assimilation may vary with spatial scale, with regional scales showing

1 a reversal of the expected dry versus wet signal (Challinor and Wheeler, 2008a). FACE studies have shown that the
2 impact of elevated CO₂ varies according to temperature and availability of water and nutrients; yet there is a strong
3 geographical bias of FACE studies towards temperate zone (Leakey et al., in press). Water-stressed crops are
4 expected to respond more strongly to elevated CO₂ than well-watered crops, because of CO₂ induced changes in
5 stomatal apertures.
6

7 There remains some controversy since the AR4 over the disparities between results from FACE experiments and
8 non-FACE experiments, such as in open-top chambers or greenhouses. As reported in AR4, FACE studies tend to
9 show lower responses than non-FACE studies. Although some authors have claimed that the results of the two are
10 statistically indistinct (Tubiello et al. 2007), others have argued that the results are only similar when the FACE
11 experiments are grown under considerably more water stress than non-FACE experiments (Ainsworth et al. 2008).
12 That is, comparisons between different methodologies must take care to control for differences in water stress levels.
13 Moreover, recent FACE results continue to show no significant response of maize to elevated CO₂, even when water
14 stress is sufficiently high to affect photosynthesis rates (Marketz et al. 2011). Unfortunately, the number of FACE
15 studies are still quite low, which limits statistical power when evaluating the average yield effects of elevated CO₂
16 or interactions with temperature and moisture.
17

18 Ozone in the stratosphere provides protection from short-wave solar ultraviolet radiation, but in the troposphere it is
19 both an air pollutant and a greenhouse gas. Ozone precursors are emitted by vehicles, power plants, biomass burning
20 and other sources of combustion. Being a powerful oxidant, ozone and its secondary by-products damage vegetation
21 by reducing photosynthesis and other important physiological functions resulting in reduced crop quality and
22 decreased yields (Booker et al. 2009; Fuhrer, 2009). Current and future estimates of global yield losses of key crops
23 due to surface ozone exposure have been made. Avnery et al. (2011a) reported losses of soybean, wheat and maize,
24 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
25 production losses of 79-120 million metric tons. For the near future (2030), they (Avnery et al. 2011b), under IPCC
26 A2 scenario, showed a further yield reductions of 0.9-11% in soybean, 1.5-10% in wheat and 2.1-3.2% in maize,
27 over their respective values in 2000, with total global losses worth \$17-35 billion (an increase of \$6-17 billion for
28 year 2000). Under the SRES B1 scenario, less severe but substantial reduction was projected; a further reduction of
29 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
30 of \$1-3 billion over year 2000). Van Dingenen et al. (2009) reported losses of wheat in India (28%) and China
31 (19%) and of soybean (20-27%) in Europe due to ozone exposure; maize was the least affected across all regions.
32 For 2030, losses reported were slightly lower than those reported by Anvery et al. (2011b) but significant losses
33 were projected to occur in developing nations. In China, relative grain losses due to increased levels of ozone
34 pollution were projected to increase by 3-22% for wheat, 8-18% for rice and 9-30% for maize over the next decades
35 (Piao, et al, 2010). In other reports, O₃ concentrations predicted for 2050 are likely to increase transpiration and
36 reduce drought tolerance by altering hormonal regulation of stomata and leaf growth (Mills et al. 2009). Negative
37 impacts of O₃ have also been reported on crop quality (Aggarwal 2007) and on protein content of crop yields (Pikki
38 et al. 2007). Ozone may have direct effect on reproductive process, leading to reduced seed and fruit development
39 and abortion of developing fruit (Royal Society 2009).
40

41 [Forthcoming: Further recent refs to include (with a brief summary of main point): Fishman, J. et al., 2010. An
42 investigation of widespread ozone damage to the soybean crop in the upper Midwest determined from ground-based
43 and satellite measurements. *Atmospheric Environment*, 44(18): 2248-2256. -ozone shows clear effect on soy yields
44 in us, based on regression of county yield and ozone data Van Dingenen, R. et al., 2009. The global impact of ozone
45 on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment*, 43(3): 604-
46 618. - gives numbers on current cost and future increase in ozone losses.]
47
48

49 7.3.2.1.3. *Land use change and autonomous adaptation*

50

51 As noted in the AR4, adjusting the location of crop production is a potential adaptation response to changes in mean
52 temperature and other aspects of climate change. Studies since the AR4 have confirmed that high latitude locations
53 are likely to become more suitable as the total time regions (Iqbal et al., 2009).between spring and autumn frost will
54 lengthen (medium evidence, high agreement.). Trnka et al (2011), for example, examined projections of eleven

1 agro-climatic indices across Europe, and found that declines in frost occurrence will lead to longer growing seasons,
2 although temperature and moisture stress will likely lead to greater inter-annual variability in crop suitability.
3

4 For tropical systems where moisture availability or extreme heat rather than frost limits the length of the growing
5 season, there is a likelihood that the length of the growing season and overall suitability for crops will decline
6 (medium evidence, medium agreement) (Fischer et al. 2005, Jones and Thornton 2009 ESP, Zhang and Cai 2011
7 ERL). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat
8 stressed by the 2050s, whilst temperate wheat environments are likely to expand northwards as climate changes
9 (Ortiz et al., 2008 check). Similarly, by 2050, the majority of African countries will experience climates over at least
10 half of their current crop area that lie outside the range currently experienced within the country (Burke et al., 2009).
11 The majority of these novel climates have analogues in other African countries.
12

13 [More on the AEZ methods that have been used to assess this (ecocrop, IIASA, Osborne, Olieson)].
14

15 In mountainous regions, where temperature varies significantly across topography, changes in crop suitability can be
16 inferred from the variation of temperature across topography. The resulting vertical zones of increasing, decreasing
17 and unchanging suitability can be relatively robust in the face of uncertainty in future climate (Schroth et al., 2009).
18 The interaction between water resources and agriculture is likely to be increasingly important as climate changes.
19 For example, whilst projected changes in crop productivity in China are uncertain, even within a single emissions
20 scenario, irrigation has significant adaptation potential (Piao et al., 2010). Changes in water use, including increased
21 water diversion and development to meet increasing water demand, and increased dam building will have
22 implications for inland fisheries and aquaculture, and therefore for the people dependent on them (Ficke et al. 2007,
23 FAO 2009). In the case of the Mekong River basin, a large proportion of the 60 million inhabitants are dependent in
24 some way on fisheries and aquaculture which will be seriously impacted by human population growth, flood
25 mitigation, increased offtake of water, changes in land use and overfishing, as well as by climate change (Brander
26 2007). Ficke et al. (2007) reported that at that time there were 46 large dams planned or already under construction
27 in the Yangtze River basin, the completion of which would have detrimental effects on those dependent on fish for
28 subsistence and recreation.
29

30 [Placeholder: more on fresh water resources – see Chap3 FOD when available]
31

32 The models used in projections of land suitability and cropland expansion discussed above rely on assumptions
33 about non-climatic constraints on crop productivity, such as soil quality and access to markets. These assumptions
34 are increasingly amenable to testing as the climate system shifts, by comparing observed changes in cropland area
35 with model predictions. The location of the margin between cropping land and extensive grazing in southern
36 Australia has varied with decadal climate conditions and is projected to shift towards the coast with hotter and drier
37 conditions, notwithstanding the positive impacts of elevated CO₂ (Nidumolu et al. 2011). Recent trends in climate
38 have seen reductions in cropping activity consistent with these projections (Nidumolu et al. 2011).
39

40 The application of first-generation biofuel conversion technologies have expanded the uses for traditional
41 commodities such as maize, oil seeds, and sugarcane, enabling farmers to market their crops beyond the traditional
42 food, feed or industrial food-processing uses. There are a number of developing countries that are relatively food
43 secure, and have a higher demand for fossil-based fuels – Brazil, Malaysia, Peru, Argentina, and Thailand–. A
44 number of these countries which are export-oriented and have relatively large areas of land available are currently
45 expanding biofuel production in order to meet both domestic and international demand (Ewing & Msangi, 2009).
46 However, the expansion of biofuel production has created new linkages, trade-offs, and competition between the
47 agricultural and energy sectors. It has also introduced new food-security risks and new challenges for the poor,
48 particularly when natural-resource constraints have led to trade-offs between food and biofuel production and also to
49 rising food prices (FAO, 2008; von Braun, 2009; Chum et al, 2011). The current food crop based biofuels are of
50 concern as their development will also exacerbate food insecurity particularly in many of developing countries.
51 Biofuels targets imply that an additional 140 and 150 million people may be at risk of hunger by 2020. Africa and
52 South Asia will account for over two-thirds of those people most affected (Fischer et al, 2009).
53
54

1 7.3.2.1.4. *Framing adaptation*
2

3 Adaptation occurs on a range of timescales and by a range of actors. Incremental adaptation, such as a change in
4 crop management, can occur relatively naturally within farming systems. It is the type of adaptation most commonly
5 assessed in the impacts literature, and it is the only form of adaptation discussed in sections 7.3 and 7.4. Systemic
6 and transformational adaptation are discussed in section 7.5. The interaction between water resources and
7 agriculture is projected to be increasingly important as climate changes. For example, whilst projected changes in
8 crop productivity in China are uncertain, even within a single emissions scenario, irrigation has significant
9 adaptation potential (Piao et al., 2010).
10

11
12 7.3.2.2. *Pests, Weeds, Diseases*
13

14 As a world-wide average, the potential crop yield loss to animal pests and (non-virus) pathogens is estimated at 18%
15 and 16%, respectively (Oerke, 2006). Although physical changes associated with climate uncertainty are recognized
16 and assessed, (e.g. drought, water, temperature) in the context of agricultural productivity, less attention has focused
17 on biological interactions and climate, even though it is universally recognized that weeds, insects and diseases have
18 limited crop yield potential. A fair question then is to ask whether such limitations will increase or decrease in
19 response to future changes in CO₂/climate?
20

21 The effects of weather on important diseases and pests, including optimal temperature and moisture conditions, have
22 been studied in detail for decades (e.g., De Wolf and Isard 2007). This research forms a base for understanding that
23 climate change will change potential losses to many pests and diseases. Changes in temperature can support range
24 expansions through changes in winter and summer extremes, and thus the potential for overwintering or summer
25 survival. Expanding knowledge of the gamut of plant responses to environment, including potential faster loss of
26 pest or disease resistance at higher temperatures, is being synthesized so that it can be ‘scaled up’ to contribute to
27 climate change scenario analysis (Garrett et al. 2006). CO₂ and ozone can either increase or decrease plant disease,
28 and can exhibit important interactions in effects, suggesting incorporation of these risk factors in analyses may need
29 to be system specific (Chakraborty et al. 2008, Eastburn et al. 2011). It is challenging to estimate the extent to which
30 observed changes in effects may be due to climate change because of the many factors that interact to result in pest
31 and disease risk and management decisions (Chakraborty and Newton 2011, Garrett et al. 2011). Interactions with
32 landscape effects may be particularly important in such perennial agricultural systems as forests and grasslands
33 (Pautasso et al. 2010).
34

35 The rarity of long-term studies of plant diseases and pests is a problem for the evaluation of climate change effects,
36 but there are some examples of the potential for such analyses available. Studies of a wheat experiment at
37 Rothamsted maintained for over 160 years have revealed shifts in foliar wheat pathogens linked to rainfall,
38 temperature, and SO₂ emissions (Bearchell et al. 2005, Shaw et al. 2008). Wheat rust risk has been observed to
39 respond to ENSO (Scherm and Yang 1995). Over almost seven decades, earlier and more frequent epidemics of
40 potato late blight, and more frequent pesticide use, were observed in Finland, associated with changing climate
41 conditions and lack of crop rotation (Hannukkala et al. 2007). Up to a point, adaptation to climate change will be
42 similar to adaptation to other new scenarios as agricultural systems have moved around the world (Coakley et al.
43 1999, Juroszek and von Tiedemann 2011). As an example of the effect of climate on management efficacy, higher
44 diversity potato systems designed for management of potato late blight had lower utility in climatic zones where
45 potato growing seasons were longer and presumably there were higher regional pathogen loads (Garrett et al. 2009).
46

47 Certainly it is reasonable to expect that climate stability with respect to temperature and precipitation is likely to
48 affect the range of specific species of insects and diseases for a given crop growing region. For example, Cannon
49 (1998) has suggested that migratory insects could colonize crops over a larger range in response to temperature
50 increases, with subsequent reductions in yield. Guitierrez (2000) has suggested that predator and insect herbivores
51 are likely to respond differently to increasing temperature, with possible reductions in insect predation (i.e. greater
52 insect numbers). Unfortunately, while there is evidence suggesting that insect damage could increase as a function
53 of climate; specific experimental results related to rice, soybean and wheat remain scarce. Similarly, while we
54 recognize plant-pathogen interactions as a factor affecting crop yields, our ability to predict CO₂/climate change

1 impacts on pathogen biology and subsequent changes on yield of rice, soybean, wheat inter alia is tenuous at best
2 since specific experimental data are not available.
3

4 Ostensibly, since many agricultural weeds are C₄, and soybean, wheat and rice, C₃, increasing CO₂ should reduce
5 crop losses due to weedy competition since the C₃ pathway, in general, shows a stronger response to rising carbon
6 dioxide levels. However, the argument that rising CO₂ will reduce weedy competition because the C₄ photosynthetic
7 pathway is over-represented among weed species (e.g. Holm et al. 1977) does not consider the range of available C₃
8 and C₄ weed species present within the agronomic seed bank. For example, in the United States, every crop, on
9 average, competes with an assemblage of 8-10 weed species (Bridges 1992). In addition, CO₂, and/or climate, can
10 also affect weed demographics. For example, with field grown soybean, elevated CO₂ per se appeared to be a factor
11 in increasing the relative proportion of C₃ to C₄ weedy species with subsequent reductions in soybean yields (Ziska
12 and Goins 2006). For rice and barnyard grass (C₄), increasing CO₂ favored rice, but if both temperature and CO₂
13 increased simultaneously, the C₄ weed was favored, primarily because higher temperatures resulted in increased
14 seed yield loss for rice (Alberto *et al.* 1996). Overall, rising atmospheric [CO₂] can increase the extent of crop losses
15 due to a greater response of the weed relative to the crop (Ziska 2000, 2003). If weeds are not managed such losses
16 may exceed any observed stimulation in crop yield associated with elevated [CO₂] (Ziska 2000, 2003). For weeds
17 that share physiological, morphological, or phenological traits with the crop, including those weeds that are wild
18 relatives of the domesticated crop species, (often among the “worst” weeds in agronomic situations, e.g. rice and red
19 rice) the decrease in seed yield from weeds may, in fact, be greater in response to increasing atmospheric CO₂ (Ziska
20 et al. 2010). Climate change may be a factor in extending the northward migration of agronomic and invasive weeds
21 (e.g. Ziska et al. 2011a, 2011b). The projected warming may be exceeding maximum rates of plant migration
22 observed in post-glacial time periods (Malcolm et al. 2002), resulting in preferential selection for the most mobile
23 plant species. A number of characteristics associated with long-distance dispersal are commonly found among
24 weeds (Rejmanek 1996) suggesting that they will be among the fastest to migrate with increasing temperatures
25 (Dukes and Mooney 1999). In addition, climate (e.g. precipitation) and/or temperature may change the
26 demographics of C₃ and C₄ weed species in crop production (e.g. Ziska and Goins 2006, McDonald et al. 2009).
27

28 Initial studies indicate a potential decline in herbicide efficacy with rising [CO₂] and/or temperature for some weeds
29 (Ziska and Goins 2006, Archambault 2007, Manea et al. 2011) (Figure 7-X). For Canada thistle, increasing [CO₂]
30 appears to have induced greater below-ground growth of roots, diluting the active ingredient of the herbicide and
31 making chemical control less effective (see figure 1 in Ziska et al. 2004). To date, studies on physical, cultural or
32 biological weed control are lacking.
33

34 [Possible Figure 7-X: Changes in herbicide efficacy determined as changes in growth (g day⁻¹) following application
35 for weeds grown at either current (A) or projected (~700 ppm) (B) levels of carbon dioxide. Herbicide was
36 glyphosate in all cases, except ¹, which was glufosinate. (See also Manea et al. 2011). Not included in FOD.]
37
38

39 7.3.2.2.2. *Effects of climate change on pests, weeds, and diseases*

40

41 Climate change scenario analyses are available for some pests and diseases. For example, range expansion has been
42 predicted for the destructive *Phytophthora cinnamomi* in Europe (Bergot et al. 2004). Increased generations under
43 climate change for the coffee nematode have been predicted for the coffee nematode in Brazil (Ghini et al. 2008).
44 Walnut pests in California are predicted to experience increased numbers of generations under climate change
45 scenarios (Luedeling et al. 2011). Potato late blight risk increases in some areas of the world, and decreases in
46 others, under climate change scenarios (Sparks et al., in review). Luck et al. (2011) summarized the mixed results
47 for the qualitative effects of climate change on pathogens that cause disease of four major food crops - wheat, rice,
48 soybean and potato - where some diseases increased in risk while others decreased under climate change scenarios.
49 In syntheses, there is a tendency for risk of insect damage to plants to increase (Deutsch et al. 2008, Paulson et al.
50 2009). Typical scenario analyses are limited by simplistic assumptions, and work remains to evaluate how
51 conclusions will change as more complete scenarios, such as those including migration and invasion patterns and
52 other types of global change, are considered (Savary et al. 2005, Garrett et al. 2011). Effects on soil communities
53 represent an area that needs more attention (Pritchard 2011). Mycotoxins and pesticide residues in food are an

1 important concern for food safety in many parts of the world, and identified as an important issue for climate change
2 effects in Europe (Miraglia et al., 2009).

3 4 5 7.3.2.3. *Perennials*

6
7 Changes in temperature are already affecting fruits and nuts production because of the decreasing accumulation of
8 winter chill hours all around the world. Observed trends in winter chill range between -50 and -260 chill hours per
9 decade in California and predicted rates of reduced winter chill, for the period between 1950 and 2100, are on the
10 order of -40 h per decade (Baldocchi and Wong, 2008). Averaging over three General Circulation Models annual
11 winter chill loss by 2050 compared to 1970 would amount 17.7 % to 22.6 % in Egypt (Farak et al, 2010). Assessing
12 climate change impacts on fruit production in California towards 2050, Lobell & field 2011 found a slightly positive
13 trend (some 5%) for almonds and negative trends for table grapes (5%), berries (10%) and cherries (20%) as
14 compared to 2000. Also in eastern Washington in US without the effect of elevated CO₂, future climate change is
15 projected to decrease apple production by 1%, 3%, and 4% for the 2020, 2040, and 2080 scenarios, respectively but
16 when the effect of CO₂ is added, yields are projected to increase by 6% (2020s), 9% (2040s), and 16% (2080s)
17 (Stockle et al 2010). Sugarcane production will be benefited in Brazil, as warming could permit the expansion of
18 planted areas towards the south, where currently low temperatures are a limiting factor (Pinto et al, 2008). Increases
19 in crop productivity could attain 6% in Sao Paulo state towards 2040 (Marin et al., 2009). On the other hand, the
20 warming up to 5.8 °C foreseen for 2070 would make unfeasible the coffee crop in the Southeast region of Brazil
21 (Minas Gerais and Sao Paulo States). In 2070 the coffee crop will migrate for the South region (Parana, Santa
22 Catarina and Rio Grande do Sul), where frost risk will be much lower (Pinto et al 2007). However, warming
23 exceeding 3°C will impact negatively coffee production in south Brazil (Jurandir et al, 2011)

24 25 26 7.3.2.4. *Food and Fodder Quality and Human Health*

27
28 The climate change that is occurring at present will have, and is already having, an adverse impact on food
29 production and food quality. The adverse effect is the consequence of expected increased frequency of some abiotic
30 stresses, such as heat and drought, and of biotic stresses, such pests and diseases (Caracelli, et al. 2010). The
31 reported decreased concentration of protein and altered lipid composition as a result of climate change (De Matta, et
32 al. 2010; Pikki et al. 2007), and micronutrient deficiency (e.g. Zn, Fe, Se, B, I) as a result of soil degradation
33 aggravate malnutrition and hidden hunger that affects 3.7 billion people, especially children (Lal, 2009). High and
34 low temperature even for a short duration at the reproductive phenostage can cause pollen sterility and shriveling of
35 grain in wheat with consequent reduction in yield. Rice is sensitive to daylight extreme temperature and humidity
36 during flowering and also to high night-time temperature causing reduction in assimilates accumulation and yield
37 (Wassmann et al. 2009). The effect of surface concentrations of ozone on quality of a number of crops in India was
38 reported by Aggarwal (2007). The crown root disease of wheat caused by stubble-borne pathogen, *Fusarium*
39 *pseudograminearum* may become more severe at high CO₂ concentrations with increased biomass (Melloy, et al.
40 2010). Maize plant was found to be susceptible to drought stress around anthesis (Bamabas, et al. 2008). Soil
41 degradation, an allied impact of climate change, affects quantity and quality of food production with consequent
42 adverse effects on human nutrition and health. Soil degradation increases susceptibility of crops to drought stress
43 and imbalance of nutrient elements.

44 45 46 7.3.2.5. *Fisheries and Aquaculture*

47
48 The fisheries and aquaculture sector differs from mainstream agriculture and is characterized by distinct interactions
49 and needs in relation to climate change. Capture fisheries in particular, comprising the largest remaining example of
50 harvesting natural, wild resources, are strongly influenced by global ecosystem processes. The social, economic and
51 nutritional requirements of the growing human population are already driving heavy exploitation of capture fisheries
52 and rapid development of aquaculture. This demand will increase over the next 20 to 30 years at least. Climate
53 change is an additional threat to the sustainability of capture fisheries and aquaculture development, adding to the
54 threats of over-fishing and other environmental impacts (FAO, 2009). Expected changes in the intensity, frequency

1 and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification and
2 changes in precipitation with associated changes in groundwater and river flows are expected to result in significant
3 changes across a wide range of aquatic ecosystem types and regions.
4

6 7.3.2.5.1. *Mean and extremes of temperature and precipitation*

7

8 There is high confidence that, under most emission scenarios, increasing mean temperatures will lead to changes in
9 the distribution of marine fish and invertebrate species. In general, the distribution of species will shift towards the
10 poles as has already been observed in, for example, the North Sea (Brander 2007, Chapter 6) and Australia (Hobday
11 2010, Chapter 6 of this volume). These shifts will result in positive and negative impacts on fisheries production
12 with the direction of change varying from locality to locality and species to species. Overall, increased temperatures
13 are expected to reduce ecosystem productivity in most tropical and subtropical oceans, seas and lakes and to
14 increase productivity in high latitudes. Projections based on a dynamic bioclimate envelope model under the SRES
15 A1B scenario suggested that climate change could lead to an average of 30–70% increase in fisheries yield from
16 high-latitude regions (>50° N in the northern hemisphere), but a decrease of up to 40% in the tropics by 2055
17 compared to yields obtained in 2005 (Cheung et al. 2010). The seasonality of biological and ecological processes in
18 many aquatic ecosystems is already being affected but the likely consequences for fish production are generally still
19 poorly understood (FAO 2009).
20

21 The changes in marine yields projected by Cheung et al. (2010) result from changes in distribution of important fish
22 stocks. In the case of freshwater fisheries, natural boundaries will frequently restrict the ability of species to change
23 distribution. Endemic species, those in fragmented habitats and those in aquatic systems with a predominantly east–
24 west orientation will be particularly restricted (Ficke et al. 2007), as will food production systems dependent on
25 them.
26

27 Many aquatic species are routinely subjected to large daily and seasonal fluctuations in temperature and are able to
28 cope with them. For example, temperatures in shallow coastal habitats in the tropical Pacific can vary by more than
29 14°C diurnally (Pratchett et al. 2011). Nevertheless, changes in temperature extremes are expected to have impacts
30 in some cases. For example, a study on salmon populations in Washington State, USA by Mantua et al. (2010)
31 demonstrated the important impacts of seasonal variations and extremes, as opposed to means, on population
32 responses to climate change. The study concluded that warming in winter and spring would have some positive
33 impacts while increased summertime stream temperatures, seasonal low flows and changes in the peak and base
34 flows would have negative impacts. Coral reefs are particularly susceptible to extremes in temperature: temperatures
35 1 or 2°C in excess of normal maximums for 3 to 4 weeks are sufficient to disrupt the essential relationship between
36 endosymbiotic dino-flagellates and their coral hosts leading to coral bleaching. Large scale bleaching of coral reefs
37 has increased in recent decades both in intensity and frequency (Hoegh-Guldberg et al. 2007, Box 5-3).
38

39 Reliable fine scale projections are not available at present because of the ecological complexity of the responses as
40 well as the potential role of human adaptation in minimising risks and taking advantage of new opportunities.
41

43 7.3.2.5.2. *Impact of ocean acidification*

44

45 The impact of increasing CO₂ concentrations on coral reefs as a result of higher concentrations of carbonic acid in
46 the ocean reducing the availability of carbonate to the reef building organisms has been described in other parts of
47 this chapter and in Box 5-3. Other organisms that produce aragonite will also be affected (Feeley et al. 2004). The
48 most important from a food production perspective will be marine mollusc species which make important
49 contributions to capture fisheries and aquaculture production in many regions (e.g. De Silva and Soto 2009, Huppert
50 et al. 2009).
51
52
53

1 7.3.2.5.3. *Combined impacts on fish and seafood production*
2

3 Climate change is modifying the distribution of marine and freshwater species with a general displacement towards
4 the poles and is leading to changes in the size and productivity of suitable aquatic habitats. This will have a mixture
5 of negative and potentially positive impacts which will vary from locality to locality. The ability to take advantage
6 of new opportunities brought about by these changes will depend on the adaptive capacity of countries and local
7 communities.
8

9 Where these ecological changes are significant, countries and communities will need to adapt through, for example,
10 changes in fishing and aquaculture practices and operations. Given the proximity of fishing and aquaculture sites to
11 oceans, seas and riparian environments, extreme events can be expected to have impacts on the associated
12 infrastructure and to affect safety at sea and for communities, with those living in low-lying areas at particular risk.
13 In areas that experience water stress and competition for water resources, aquaculture operations and inland fisheries
14 production will be at risk. The impacts of climate change on the fisheries and aquaculture sector will have
15 implications for the four dimensions of food security i.e. availability of aquatic foods, stability of supply, access to
16 aquatic foods, and utilization of aquatic products (FAO, 2009).
17
18

19 7.3.2.6. *Livestock*
20

21 Impacts of climate change on feed crops and grazing systems include changes in herbage growth brought about by
22 changes in atmospheric CO₂ concentrations and rainfall and temperature regimes, and changes in the composition of
23 pastures and in herbage quality. The interactions among climate, plants, livestock grazing and land management
24 practices are complex, and evaluating the impacts of climate change on these elements is difficult (Craine et al.,
25 2010). In North American cattle production systems, future increases in precipitation are not likely to compensate
26 for the declines in forage quality that accompany projected temperature increases, and cattle are likely to experience
27 greater nutritional stress in the future (Craine et al., 2010).
28

29 Izaurralde et al. (2011) found that both pastureland and rangeland species in the USA may experience accelerated
30 metabolism and advanced development with rising temperature, often resulting in a longer growing season, although
31 soil resources will often constrain temperature effects. They conclude that increases in CO₂ concentrations and
32 precipitation will enhance rangeland net primary production whereas increased air temperatures will either increase
33 or decrease it (Izaurralde et al., 2011). The consensus is that increases in CO₂ will benefit C₃ species, although
34 warmer temperatures and drier conditions will tend to favour C₄ species (Hatfield et al., 2011). Similar effects are
35 projected for European grasslands, many of which may be mediated via management - sometimes with impacts on
36 mitigation too: ruminants fed tropical legumes produced 20% less methane than those fed C₄ grasses (Archimède et
37 al., 2011).
38

39 In Australian rangelands, projected changes in rainfall and temperature generally appear small when compared with
40 year-to-year variability, but even so, impacts on rangeland production systems are expected to be important in terms
41 of required managerial and enterprise adaptations (McKeon et al., 2009). In these systems, increases in temperature,
42 which are likely to result in a decrease in forage production, may exacerbate or reduce the effects of a decrease or
43 increase in rainfall, respectively; at the same time, the effects of increased CO₂ concentrations may enhance forage
44 production and water use efficiency. These opposing effects emphasise the importance of the uncertainties in
45 quantifying the impacts of these components of climate change (McKeon et al., 2009). In South America as in other
46 regions, future changes in rangeland productivity will be strongly dependent on water availability as a result of shifts
47 in rainfall amounts and patterns. Response is estimated to be widely similar across all geographic regions: a change
48 of 0.5-0.75 g m⁻² production per mm change in precipitation (Yahdjian and Sala, 2008).
49

50 Some of these components remain uncertain. IPCC emission scenarios for many cropland regions project elevated
51 ozone concentrations in the atmosphere to the 2050s and beyond. At the same time, crop sensitivity may decline in
52 areas where warming is accompanied by drying, such as in southern and central Europe (Soussana et al., 2010).
53 Parameters in models for ozone risk assessment are uncertain and model improvements will be needed to identify
54 regions most at risk from ozone in future climates (Fuhrer, 2009). At this stage, more experiments using free-air

1 ozone enrichment will be needed across different habitats, climates and productivity levels before generalisations
2 about the sensitivity of pastures to ozone can be made (Fuhrer, 2009).

3
4 While elevated atmospheric CO₂ concentrations reduce sensitivity to lower precipitation in grassland ecosystems
5 and can reduce mortality and increase recovery during severe water stress events (Stokes et al. reference, Nowak et
6 al. reference), it is still unclear how general this result is (Soussana et al., 2010). Evaluating the differential responses
7 of plant species to elevated CO₂ will require models to include mechanisms of resource capture and use among plant
8 functional types (Lazzarotto et al., 2009; Soussana et al., 2010). We still lack comprehensive studies of climate
9 change impacts on pastureland and rangeland ecosystems that include assessment of the mediating effects of
10 management as well as changes in water, carbon, and nutrient cycling (McKeon et al., 2009; Izaurralde et al., 2011).

11
12 As livestock productivity increases, be it increasing milk yield in dairy cattle or higher growth rates and leanness in
13 pigs or poultry, so metabolic heat production increases and the capacity to tolerate elevated temperatures declines
14 (Zumbach et al., 2008; Dikmen and Hansen, 2009). Over the long term, single-trait selection for productivity will
15 therefore result in animals with lower heat tolerance (Hoffman, 2010). Recent work adds to previous understanding
16 (AR4 Chapter 5) and indicate that heat stress in dairy cows can be responsible for the increase in mortality and
17 economic losses (Vitali et al., 2009); it affects a wide range of parameters in broilers (Feng et al., 2008); it impairs
18 embryonic development and reproductive efficiency in pigs (Barati et al., 2008); and affects ovarian follicle
19 development and ovulation in horses (Mortensen et al., 2009). The impacts of a changing UK climate on dairy cow
20 production were analysed by Wall et al. (2010), who showed that milk yields will be reduced and mortality
21 increased because of heat stress. Given that there is a genotype-by-environment interaction on the impacts of heat
22 stress (Bohmanova et al., 2008), breeding goals that focus on production traits tend to reduce heat tolerance.
23 Breeding goals that aim to reduce greenhouse gas emissions need to take possible future climatic conditions into
24 account (Hoffmann, 2010). Tools to do this in developed country situations are becoming available (e.g. Hayes et
25 al., 2009). Developing countries may be more reliant on local breeds, most of which are not well characterized,
26 although such breeds may be not only heat tolerant but also tolerant of poor seasonal nutrition and parasites and
27 diseases (Hoffmann, 2010).

28
29 Host and pathogen systems are likely to change their ranges because of climate change. Species diversity may
30 decrease in lowland tropical areas as temperatures increase (Mills et al., 2010). The temperate regions may become
31 more suitable for tropical vector-borne diseases (Rocque et al., 2008). An overall increase in suitable conditions for
32 pathogens and vectors is expected, rather than just a shift in distribution, because minimum temperatures are
33 increasing more than maximum temperatures (Ostfeld, 2009). Vector-borne diseases of livestock such as African
34 horse sickness and bluetongue are likely to expand their range because rising temperatures increase the development
35 rate and winter survival of vectors and pathogens (Cutler et al., 2010). Diseases such as West Nile virus and
36 schistosomiasis are projected to expand into new areas (Rosenthal, 2009). The distribution, composition and
37 migration of wild bird populations that harbour the genetic pool of Avian Influenza viruses are all likely to be
38 affected by climate change (Gilbert et al., 2008). The changing frequency of extreme weather events is likely to
39 affect diseases too. For example, outbreaks of Rift Valley fever in East Africa are associated with increased rainfall
40 and flooding due to El Niño-Southern Oscillation events (Gummow, 2010; Pfeffer and Dobler, 2010). In general, the
41 impacts of climate change on livestock diseases remain difficult to predict and highly uncertain (Mills et al., 2010;
42 Tabachnick, 2010).

43
44 Current trends in consumption, production and environmental patterns will lead to water crises in many parts of the
45 world (De Fraiture et al., 2010). Every populated river basin in the world will experience changes in river discharge,
46 and large human and livestock populations will experience water stress such that proactive or reactive management
47 interventions will almost certainly be required (Palmer et al., 2008). Climate change will affect the water resources
48 available for livestock production and keeping via impacts on runoff and groundwater. In Kgatleng District,
49 Botswana, climate change could lead to an annual increase of more than 20% in cattle water demand by 2050
50 because of increased temperatures. At the same time, a decline is likely in the contribution of surface pan water to
51 cattle water supply, leading to substantial increases in the abstraction of groundwater for cattle (Masike and Urich,
52 2008). Such problems of water supply for increasing livestock populations are very likely to be exacerbated by
53 climate change in many places in sub-Saharan Africa and South Asia. Nevertheless, there are sufficient water
54 resources available to satisfy global food demands during the next 50 years, but only if water is managed more

1 effectively (De Fraiture and Wichelns, 2010). There is ample scope to improve livestock water productivity
2 considerably (Molden et al., 2010); for example, in mixed crop-livestock systems of sub-Saharan Africa via feed,
3 water and animal management (Descheemaeker et al., 2010).

6 **7.3.3. Sensitivity of Food Security to Weather and Climate**

8 **7.3.3.1. Non-Production Food Security Elements**

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

19 **7.3.3.2. Accessibility, Utilization, and Stability**

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

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

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

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

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

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

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

1 Climate change impacts on stability. In terms of stability, climate extremes will become more frequent (SREX
2 2011). In terms of availability, greater uncertainty mitigates incentives to invest in agricultural production,
3 potentially offsetting positive impacts from increasing food price trends. This is particularly true for poor
4 smallholders with limited or no access to credit and insurance. Greater exposure to risk, in the absence of well-
5 functioning insurance markets, leads to: 1) greater emphasis on low-return but low-risk subsistence crops (Heltberg
6 & Tarp 2002; Sadoulet & de Janvry, Chpt. 5, 1996; Fafchamps, 1992; Roe & Graham-Tomasi, 1986;), 2) a lower
7 likelihood of applying purchased inputs such as fertilizer (Dercon & Christiaensen, 2011; Kassie et al. 2008), 3) a
8 lower likelihood of adopting new technologies (Feder et al., 1985; Antle & Crissman, 1990), and 4) lower
9 investments (Skees et al., 1999). All of these responses generally lead to both lower current and future farm profits
10 (Hurley, 2010; Rosenzweig & Binswanger 1993).

11
12 In terms of accessibility, climate change-induced increases in agricultural production losses are likely to translate
13 into less accessibility to rural producers via lower incomes, and to the rural landless and urban residents through
14 higher and more volatile food prices. It is well documented that in many rural areas, smallholders in particular do
15 not have the capacity to smooth consumption in the face of climate shocks, particularly generalized shocks that
16 affect a majority of households in the same location (Prakash, 2011; Dercon, 2004; Dercon et al., 2006; Vargas-Hill
17 et al., 2009; Fafchamps, 2009; Udry et al, 2004; Skoufias & Quisumbing, 2005). Any increases in climate extremes
18 will exacerbate the vulnerability of these smallholders. Currently, smallholders rely to a large extent on increasing
19 labor off-farm where possible (Kazianga & Udry, 2006; McPeak, 2004; Fafchamps, 1999), but also by decreasing
20 both food consumption and non-food expenditures, such as those on education and healthcare (Skoufias &
21 Quisumbing, 2005; Frankenberg, 1999).

22
23 Reductions in food consumption, education and healthcare can have long-term losses in terms of income-generation
24 and thus to future food security (Hoddinot & Maluccio, 2002; Skoufias & Quisumbing, 2005; Frankenger et al.,
25 1999). Furthermore, some evidence also suggests that poorer households are more likely to reduce consumption,
26 while wealthier households liquidate assets to cover current deficits (Carter & Lybbert, 2012; Kazianga & Udry,
27 2006; McPeak, 2004; Kurasaki & Fafchamps, 2002). Households currently vulnerable to climate shocks have
28 limited opportunities to smooth these shocks through reliance on informal networks and reallocation of labor, and
29 thin or non-existent credit and insurance mechanisms mean that poor households are faced with difficult choices
30 between consumption and asset smoothing in response to a climate shock. Increased uncertainty of future climate
31 conditions and increases in climate extremes will increase food insecurity unless these significant barriers to
32 consumption smoothing can be addressed.

33
34 Climate change impacts on utilization. Climate change impacts on utilization may come about through changes in
35 consumption patterns in response to shocks, as well as changes in nutrient content of agricultural products as well as
36 other factors such as food safety, storage and distribution systems. In this section we focus on the first two.
37 Rationing consumption to prioritize calorie-rich, but nutrient poor foods is another common response (Bloem et. al.
38 2010) The effects are a decrease in dietary quality as well as quantity, which are magnified by pre-existing
39 vulnerabilities – and lead to long term loss of health, productivity capacity and low incomes (Bloem et. al. 2010;
40 Alderman 2010; Brinkman et. al. 2010; Campbell et.al. 2010; Sari et. al. 2010). The biological effects of climate
41 change on nutrient content of foods is one of main pathways for effects on utilization. A summary of recent
42 literature on the impacts of climate change on the composition of nutrients in food items is given in HLPE 2012.
43 Research on grains generally shows lowering of protein content with elevated temperature and CO₂ levels (Hatfield
44 et. al. 2011; Ainsworth and McGrath 2010; Erda et. al., 2010).

45 46 47 **7.3.4. Summary**

48
49 This section will revisit all AR4 ‘new knowledge’ to see if AR5 provides confirmation (see AR4 pg 284):

- 50 • Impacts of climate change on irrigated water requirement may be large
 - 51 • Stabilisation of CO₂ concentrations reduces damage to crop production in the long term
 - 52 • Including effects of trade lowers regional and global impacts
- 53
54

1 Notes for further development of text; confirmation:

- 2 • Internnual variability in yield is likely to rise across many regions. [Cf AR4 “Increases in frequency of
3 climate extremes may lower crop yields beyond the impacts of mean climate change” (pg 284)]
4

5 New knowledge:

- 6 • Crops: Water stress x CO2 response: TAR/AR5 states that water stressed crops may benefit more than
7 well-watered crops from elevated CO2. Work since then suggests this may not consistently be the case.
8 • Crops: Impact of the advances presented in methodology presented in the first section, e.g. increased
9 quantification of uncertainty results in more robust statements (even if the message itself doesn’t change).
10 This could be linked to the table that David and Andy are preparing
11 • Crops: accurate yield data would improve projections [Andy, based on Hansen, Watson work]
12 • Greater use of technology (RS/GIS techniques) in assessing food security
13 • Better understanding of mechanisms of heat effects
14 • Evidence of the importance of temperature over precip in some regions (Thornton, Lobell) cf AR4
15 conclusion paragraph 1 pg 283
16 • Clearer evidence for ozone effects
17 • Pests weeds and diseases included more fully
18
19

20 **7.4. Projected Integrated Climate Change Impacts**

21
22 [This section is spatially and temporally specific, asking what the synthesis knowledge is on impacts of climate
23 change on [crops, livestock, pests, etc] and knock on effect on food production and food security. This section is
24 likely to be less well developed at ZOD than the section above - we may need to wait until we see what the
25 community do with CMIP5,3 , SRES etc., and also what the region-specific chapter say about food production.
26 Additional useful references are Cho et al (2011), and Calzadilla et al. (2010): Calzadilla, Alvaro, Rehdanz, Katrin,
27 Betts, Richard, Falloon, Pete, Wiltshire, Andy and Tol, Richard S.J., (2010), Climate Change Impacts on Global
28 Agriculture, No FNU-185, Working Papers, Research unit Sustainability and Global Change, Hamburg University,
29 <http://econpapers.repec.org/RePEc:sgc:wpaper:185> . Abstract of Calzadilla et al 2011 below: Based on predicted
30 changes in the magnitude and distribution of global precipitation, temperature and river flow under the IPCC SRES
31 A1B and A2 scenarios, this study assesses the potential impacts of climate change and CO2 fertilization on global
32 agriculture. The analysis uses the new version of the GTAP-W model, which distinguishes between rainfed and
33 irrigated agriculture and implements water as an explicit factor of production for irrigated agriculture. Future climate
34 change is likely to modify regional water endowments and soil moisture. As a consequence, the distribution of
35 harvested land would change, modifying production and international trade patterns. The results suggest that a
36 partial analysis of the main factors through which climate change will affect agricultural productivity lead to
37 different outcomes. Our results show that global food production, welfare and GDP fall in the two time periods and
38 SRES scenarios. Higher food prices are expected. Independently of the SRES scenario, expected losses in welfare
39 are marked in the long term. They are larger under the SRES A2 scenario for the 2020s and under the SRES A1B
40 scenario for the 2050s. The results show that countries are not only influenced by regional climate change, but also
41 by climate-induced changes in competitiveness. (Falloon, Peter, Met Office Hadley Centre). Conclusion is that we
42 are waiting on the RCPs]
43
44

45 **7.4.1. Food Systems and Food Security with Regional Variation by Scenario and Time Slice**

46
47 When assessing impacts, it is important to be clear about the extent to which these autonomous adaptations are
48 accounted for. It is also important to account for potential future changes in agricultural systems. For example,
49 projections of the yield technology trend out to 2050 suggest the potential for significant increases in crop yield in
50 many regions across the globe (Jaggard et al., 2010). The way in which new crop varieties interact with future
51 climates is inherently difficult to predict with any precision.
52

1 Africa: Mueller et al (2011) review: Projected changes of –100% to +168% (econometric)–84% to +62% (models)
2 and –57% to +30% (statistical). Despite this uncertainty, risk of negative impacts is clear and existing agricultural
3 systems will have to change to meet future demand.
4

5 Globally, the fraction of cropland affected by drought is projected to increase by a factor of 2-4 by 2100 (the average
6 value from 20 GCMS is 44%, from a baseline value of 15.4%; see Li et al., 2009). Lobell et al. (2008) used a
7 statistical crop model with 20 GCMs and identified South Asia and Southern Africa as two regions that, in the
8 absence of adaptation, would likely suffer negative impacts on several important crops. However, ongoing increases
9 in potential yield across the globe due to crop improvements may act to mitigate negative impacts such as these
10 (Jaggard et al., 2011).
11
12

13 **7.4.2. Projected Impacts on Fisheries and Aquaculture, with Regional Variation by Time Slice and Scenario**

14 **7.4.2.1. Capture Fisheries**

15
16
17 There have been a number of studies on the probable impacts of climate change on capture fisheries. These take the
18 form of studies on single-species (e.g. tuna species: Loukos et al. 2003, Lehodey et al. 2010, and cod: Drinkwater
19 2005), ecologically significant taxonomic groups (e.g. coral reefs: Hoegh-Guldberg et al. 2007, Munday et al. 2008),
20 geographical regions (e.g. Australia: Brown et al. 2010, North Sea: Cook and Heath 2005, Hiddink and ter Hofstede
21 2008, the Pacific island countries and territories: Bell et al. 2011a) and global (e.g. Brander 2007, Cheung et al.
22 2009, 2010). All of them make considerable effort to minimise uncertainties but inevitably rely on underlying
23 assumptions and retain considerable residual uncertainty. As a general rule, their outcomes can be considered to be
24 characterized by medium evidence and medium agreement. The forecast impacts vary widely depending on the
25 specific characteristics of each taxonomic group and ecosystem.
26

27 Simulation studies on skipjack and bigeye tuna in the Pacific under the B1 and A2 scenarios suggest that the
28 vulnerability of skipjack tuna to climate impacts in 2035 is low under both scenarios but moderate under B1 and
29 high under A2 by 2100. Projections under the A2 scenario suggest a 32% decrease in biomass of skipjack in the
30 western and 50% increase in the eastern Pacific Ocean by 2100 compared to biomasses in 2000, but there is lower
31 confidence in these results than for the other scenarios (Lehodey 2011). For bigeye tuna, the results are broadly
32 similar. These shifts in distribution would tend to favour some of the smaller Pacific Island Countries and Territories
33 (PICTs) in the central Pacific which are particularly dependent on revenues from sale of tuna fishing rights (Bell et
34 al. 2011a).
35

36 Coastal fisheries make significant contributions to food security and livelihoods of rural and urban populations in
37 the PICTs where, for the majority of them, average fish consumption is more than 50 kg.person⁻¹.year⁻¹. The food
38 requirements of the human population of this area are predicted to increase by between 20 and 60% over the next 20
39 years. Climate change is expected to impact directly on the productivity of coastal fisheries in the PICTs through
40 increased sea surface temperature and ocean acidification and indirectly through climate-driven damage to coral
41 reefs, mangroves, sea-grasses and intertidal flats (Pratchett et al. 2011). Extreme events such as increased severity of
42 tropical cyclones could also impact on some species. Under both B1 and A2 emissions scenarios, the vulnerability of
43 coastal fisheries as a whole in 2035 is considered to be low. Under the B1 emissions scenario, the overall
44 vulnerability of coastal fisheries is considered to be moderate in the PICTs in the west of the region and low for
45 those in the East. The high emissions A2 scenario is expected to lead to major changes in the tropical Pacific, for
46 example through deterioration of coral reef habitats and weakening of the South Equatorial Current and Counter
47 Current. The net result is forecast to be a reduction in coastal fisheries production by 20-35% in the west and 10-
48 30% in the east, leading to an estimated vulnerability of moderate to high in the west and moderate in the east
49 (Pratchett et al. 2011).
50

51 In a broad-based modelling study Brown et al. (2010) forecast that primary production in the ocean around Australia
52 will increase as a result of small increases in nutrient availability from changes in ocean stratification and
53 temperature, although the authors acknowledge considerable model uncertainty. This increase is forecast, in general,

1 to benefit fisheries catch and value. As another example, described in Section 2.1, impacts on fish and fisheries in
2 the North Sea are likely to vary from area to area and species to species.
3
4

5 *7.4.2.2. Aquaculture*

6

7 Complementing the study by Mantua et al. (2010) on the impacts of climate change on salmon populations in
8 Washington State, USA, Huppert et al. (2009) considered the impacts on the coast of that state. They concluded that
9 there would be a number of physical and chemical consequences including inundation of low-lying coastal areas
10 from sea level rise, coastal flooding from major storm events and increased ocean temperatures and acidification.
11 These physical and chemical drivers are forecast to create a number of problems for the important shellfish
12 aquaculture industry in the state arising from reduced growth and reproductive rates as a result of increased
13 temperatures, inundation of existing shellfish habitats from sea level rise, increased incidence of harmful algal
14 blooms and higher rates of mortality as a result of greater acidity of sea water and resulting decreased calcification
15 rates in skeleton and shell formation. The authors report that the socio-economic impacts cannot be quantified at this
16 stage but are considered to be substantial.
17

18 Aquaculture is considered to be under-developed in the island states and territories of the tropical Pacific. At present
19 just over 20 000 people are estimated to be employed in aquaculture enterprises throughout the region, including the
20 culture of black pearls in French Caledonia. Starting from this low base, pond aquaculture is seen as an important
21 contributor to meeting the shortage of fish required for food security in the region. Using a structured vulnerability
22 framework which uses the B1 and A2 emission scenarios (Bell et al. 2011b), it was concluded that production of
23 freshwater species such as tilapia, carp and milkfish will probably benefit from the expected climate changes while
24 coastal enterprises are expected to encounter problems, that will vary according to species, including through
25 changes to temperature, rainfall and sea-level rise (Pickering et al. 2011)

26 *7.4.2.3 National and Regional Vulnerability*

27

28 The consequences of the many and diverse impacts on capture fisheries and aquaculture, both positive and negative,
29 on food security are more difficult to estimate than the biological and ecological consequences. A preliminary but
30 informative study by Allison et al. (2009) attempted to estimate the vulnerability of the economies of 132 countries
31 to climate change impacts on fisheries in 2050 under the A1FI and B2 scenarios. They estimated vulnerability as a
32 composite of three components: exposure to the physical effects of climate change, the sensitivity of the country to
33 impacts on fisheries (measured by total fisheries production, contribution of fisheries to national employment,
34 export income and dietary protein) and adaptive capacity within the country (a composite index derived from life
35 expectancy, indicators of education levels, various indicators of governance effectiveness and size of economy).
36 This analysis suggested that under both scenarios several of the least developed countries were also amongst the
37 most vulnerable. They included countries in central and western Africa, Peru and Columbia in South America and
38 four tropical Asian countries. Food security will be a major consideration in these vulnerable countries.
39
40

41 *7.4.3. Thresholds and Irreversible Changes*

42

43 Any reduction in the number of options for food production could also be irreversible. Thornton et al. (2010) found
44 that the changes in crop and livestock production associated with four degree increase in global mean temperature
45 (e.g. projected changes in growing season length) result in diminishing options for agricultural growth and food
46 security in Africa. Much of the literature on projected climate impacts and adaptation can be interpreted in terms of
47 changes to the number of options for agricultural productivity.
48

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

1 prediction, and building resilience into food systems, are likely to be two key tools in avoiding the negative impacts
2 resulting from these interactions (Misselhorn et al., 2010).

5 **7.4.4. Projected Impacts on Food Availability and Food Security**

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

11 [INSERT FIGURE 7-7 HERE

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

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

23 Weeds and Food Security: Projected Impacts: It is likely that weed populations and demographics will change, with
24 an overall poleward migration (Ziska et al. 2011). An overview of crop and weed competitive studies indicate that
25 weeds could limit crop yields to a greater extent with rising levels of carbon dioxide per se (Ziska 2010). This may
26 be related to the greater degree of phenotypic and genotypic plasticity associated with weedy species relative to the
27 uniformity inherent in large cropping systems (Treharne 1989); such plasticity, in turn, would be advantageous in a
28 rapidly changing climate. Finally, chemical control of weeds, which is the preferred management method for large-
29 scale farms, is likely to be adversely affected, with increasing economic and environmental costs.

31 Number of under-nourished: Lloyd (2011) used models to project the impact of climate change on human nutrition,
32 estimating a relative increase in moderate stunting of 1–29% in 2050 compared with a future without climate
33 change. Severe stunting was projected to increase by 23% (central SSA) to 62% (South Asia).

35 The main focus of recent models projecting impacts on non-availability dimensions of food security focus on access,
36 building on estimated impacts of climate change on productivity and food security (Nelson et. al. 2009; Hertel et. al.
37 2010; Calzadilla et al 2011). Nelson et. al. 2009 develop 15 scenarios for climate change based on 3 economic
38 development and five climate change scenarios find that up to 2050 economic growth has a much greater effect on
39 food security than climate change, although climate change does augment negative impacts. They project increases
40 in the number of malnourished children due to changes in per capita calorie availability driven by varying economic
41 growth and climate change scenarios. They find increases ranging from 8.5 to 10.3 percent over the baseline
42 scenario. Their findings also indicate that up to 2050, changes in global food trade patterns can mitigation negative
43 effects of climate change. Hertel et. al. 2010 use a computable general equilibrium model to analyse food security
44 impacts of climate change, focusing on the tails of the distribution of projected climate change impacts on yields up
45 to 2030. The results highlight the importance of income source in determining food security impacts: scenarios with
46 high yield impacts also generated increases in food prices that benefitted net exporters/sellers. Conversely, high
47 productivity growth scenarios lead to reductions in food prices that had differential impacts on sellers and buyers.

49 Two modeling studies focus on the relative impacts on key inputs to agricultural production in estimating global
50 welfare effects. Calzadilla et. al. 2010 distinguish climate change impacts on irrigated and rainfed agricultural
51 systems for two periods: 2020s and 2050s using a CGE model and the equivalent variation¹ to measure welfare
52 impacts. They find significantly larger negative impacts of climate change on welfare in 2050s compared with the
53 earlier period, with a high number of developing countries in South and Southeast Asia, as well as Middle East and
54 North Africa adversely affected. Sub-Saharan Africa shows net positive welfare gains, albeit relatively small in both

1 periods. Roson and VansMensbrugge 2010 include the effects on labor productivity arising from adverse health
2 impacts of climate change in assessing with and without climate change scenarios up to 2100. Their findings
3 indicate that climate change impacts on labor productivity are always negative, and particularly significant in China,
4 India and most developing countries.

5
6 [INSERT FOOTNOTE 1: The equivalent variation measures the welfare impact of a policy change in monetary
7 terms. It is defined as the change in regional household income at constant prices that is equivalent to the proposed
8 change (Calzadilla et. al., 2010).]
9

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

16 17 18 **7.4.5. Key Findings from Impacts – Confidence Limits, Agreement, and Level of Evidence** 19

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

24
25 Studies showed that (medium evidence) increasing temperature in the Pacific will shift the favourable habitats for
26 both skipjack and big-eye tuna species tending to improve conditions east of the date line for both species while the
27 temperature is forecast to become too warm for bigeye tuna in the Western Central Atlantic. And primary
28 production in the ocean around Australia will increase as a result of small increases in nutrient availability from
29 changes in ocean stratification and temperature. Changes in crop and livestock production associated with four
30 degree increase in global mean temperature result in diminishing options for agricultural growth and food security in
31 Africa.
32

33 Confirmation of the generally positive effects of elevated CO₂ levels on primarily C₃ crops although the CO₂ signal
34 is often superseded by other impacts such as improvements in agricultural technology and breeding. It is difficult
35 only to ascribe changes in cropping and yield to changes in climate as there are many other interacting factors, some
36 of which, such as extreme droughts and temperatures, are in agreement with the climatic consequences of climate
37 change. Such a conclusion also applies to fisheries.
38

39 Work since AR4 has tried to move the scope of modelling to larger geographical scales whilst recognizing that the
40 process models that may be better suited to predicting future impacts rather than analyzing current and historical
41 patterns, require overhaul to bring them up to date with the latest experimental findings. New parameter estimation
42 methods such as Bayesian analysis that allow better quantification of the uncertainties implicit in models are a
43 welcome development since AR4.
44

45 [A summary of this section will need a figure with agreement (H,M,L) on one axis and confidence (H, M, L) on the
46 other axis with the nine so formed boxes completed with impacts. (DL is working on this with Chapter 18 on
47 attribution and detection).]
48
49
50

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

7.5.1. Adaptation Needs and Gaps (based on Assessed Impacts and Vulnerabilities)

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

The pervasiveness of climate impacts on food security and production (Section 7.2), the commitment to future climate change from past greenhouse gas emissions (cross reference to WGI) and the very high likelihood of additional climate changes from future greenhouse gas emissions (cross reference to WGI) means that some level of adaptation of food systems to climate change will be necessary. Here we take adaptation to mean reductions in risk and vulnerability through the actions of adjusting practices, processes and capital in response to the actuality or threat of climate change. This often involves changes in the decision environment, such as social and institutional structures, and altered technical options that can affect the potential or capacity for these actions to be realized. Adaptation can also enhance opportunities from climate change (IPCC AR4 Chapters 5 and 17). These adaptations will need to be taken in the context of a range of other pressures on food security such as increasing demand as a result of population growth and increasing per capita consumption (Section 7.1).

In the period since the AR4 the literature on adaptation and food production has increased substantially, although there has been less focus on adaptations to food systems and on value chains: the linked sets of activities that progressively add value as inputs are converted into products the market demands. Many adaptation frameworks or approaches have been published, informing the approach in the AR4 which addressed both autonomous and planned adaptations. Autonomous adaptations are incremental changes in the existing system including through the ongoing implementation of extant knowledge and technology in response to the changes in climate experienced. They include coping responses and are reactive in nature. Planned adaptations are proactive and can either adjust the broader system or transform it (Howden et al. 2010). Adaptations can occur at a range of scales from field to policy. There is an increasing recognition in the literature that whilst many adaptation actions are local and build on past climate risk management experience, effective adaptation will often require changes in institutional arrangements and policies to strengthen the conditions favourable for effective adaptation including investment in new technologies and infrastructure. Building adaptive capacity by decision-makers at all scales (e.g. Nelson et al. 2008) is an increasingly important part of the adaptation discourse which has also further addressed costs, benefits, barriers and limits of adaptation (e.g. Adger et al. 2009).

The sector-specific nature of many adaptations means that sectors will initially be addressed separately below.

7.5.1.1.1. Cropping

Effective adaptation of cropping could be critical in enhancing food security and sustainable livelihoods, especially in developing countries (Chapter 5 AR4). There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times and crop cultivars and species (e.g. Olesen et al. (2011) although this response is not ubiquitous (Bryan et al. 2009). There are a large number of potential adaptations for cropping systems, many of them enhancements of existing climate risk management.

The possibility of extended growing seasons because of higher temperatures increasing growth in cooler months means that changing planting dates is a frequently identified option for cereals and oilseeds (Krishnan et al, 2007; Magrin et al., 2009; Travasso et al., 2009; Laux et al., 2010; Stockle et al., 2010; Shimono et al., 2010, Deressa et al. 2009. Van de Giesen et al. 2008, Mary and Majule 2009, Meza and Silva 2009, Olesen et al. 2011, Tao and Zhang 2010, Tingem and Rivington 2010, Cho et al. 2011). Aggregated across studies changing planting dates may increase yields by a mean of 13% but with substantial variation (Figure 7-8). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura 2010), seedling transplanting and seed priming and these adaptations can be integrated with varieties with greater thermal time requirements so as to maximize production benefits and to avoid late season frosts (e.g. Tingem and Rivington 2010, Crimp et al. 2011, Cho et al. 2011). In some situations early sowing may allow double cropping where currently

1 only a single crop is feasible. For example, this could occur for irrigated maize in central Chile (Meza et al., 2008)
2 and the southern pampas of Argentina (Monzon et al, 2007), increasing productivity per unit land although
3 increasing nitrogen and water demand at the same time. However, in Mediterranean climates, early sowing of
4 cereals is dependent on adequate planting rains in autumn and climate projections indicate that this may decrease in
5 many regions (WG 1 cross-reference), limiting the effectiveness of this adaptation and possibly resulting in later
6 sowings than are currently practiced. In such circumstances, use of short duration cultivars could be desirable so as
7 to reduce exposure to end of season droughts and high temperature events (Orlandini et al. 2008; Walter et al. 2010).
8 There is medium confidence (high agreement, medium evidence) that optimisation of crop varieties appears to be an
9 effective adaptation, increasing yields by around 50% compared with the use of current varieties and planting
10 schedules when aggregated across studies (Figure 7-8). Flexibility in planting dates and varieties according to
11 seasonal conditions could be increasingly important with ongoing climate change (Meza and Silva 2009, Deressa et
12 al 2009). Approaches that integrate climate forecasts at a range of scales in some cases are able to better inform crop
13 risk (e.g. Cooper et al. 2008; Challinor 2009, Baethgen 2010, Li et al. 2010) although care is needed to ensure that
14 the provision of forecasts does not increase existing inequities in farming or fishing communities.

15
16 [INSERT FIGURE 7-8 HERE

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

20
21 Warmer conditions may also allow range expansion of cropping activities polewards in regions where low
22 temperature has been a past limitation (*medium agreement, limited evidence*). This may particularly occur in Russia,
23 Canada and the Scandinavian nations although the potential may be less than earlier analyses indicated due to
24 increased climate extremes, water limitations and various institutional barriers (Alcamo et al. 2007, Bindi & Olesen
25 2011, Dronin and Kirilenko 2011, Kulshreshtha 2011, Kvalvik et al. 2011, Tchebakova et al. 2011). In many of
26 these cases, the northerly range expansion may only offset the reduction in southerly cropping areas and yields due
27 to lower rainfall, water shortages and high temperatures (*high agreement, limited evidence*).

28
29 Improving cultivar tolerance to high temperature is a frequently identified adaptation for almost all crops and
30 environments worldwide as high temperatures are known to reduce grain number, fill and quality (Krishnan et al.
31 2007; Challinor 2009; Luo et al. 2009; Shimono et al. 2010; Stockle et al. 2010, Wassman et al. 2008). Improving
32 gene conservation and access to gene banks could facilitate the development of cultivars with appropriate thermal
33 time and thermal tolerance characteristics (e.g. Mercer et al. 2008, Wassman et al. 2008) as well as to take
34 advantage of increasing atmospheric CO₂ concentrations (Ziska et al. 2012) and respond to changing pest, disease
35 and weed threats with these developments needing to be integrated with *in situ* conservation of local varieties
36 (IAASTD 2010).

37
38 Similarly, the prospect of increasing drought conditions in many cropping regions of the world (e.g. Olesen et al.
39 2011) raises the need for breeding additional drought-tolerant crop varieties (Mutekwa 2009, Naylor et al. 2007, Tao
40 and Zhang 2010), for enhanced storage and access to irrigation water, more efficient delivery systems, improved
41 irrigation technologies such as deficit irrigation, more effective water harvesting, agronomy that increases soil water
42 retention through practices such as minimum tillage and canopy management and more effective decision support
43 (Connor et al. 2009, Olesen et al 2011, Thomas 2008, Falloon and Betts 2010, Luo et al. 2009, Lioubimtseva and
44 2009, Piao et al. 2010). There is medium confidence (*high agreement, limited evidence*) that crop adaptations can
45 lead to moderate yield benefits under persistently drier conditions (about 10% from aggregation of studies (Figures
46 7-9 and 7-10) and that irrigation optimisation for changed climate can increase yields by about 4% (Figure 7-8).
47 Diversification of activities is another climate adaptation option for cropping systems (Lioubimtseva and 2009,
48 Thornton et al. 2010). Reidsma and Ewert (2008) found that regional farm diversity reduces the risk that is currently
49 associated with unfavourable climate conditions in Europe. Diversification of activities often seeks to incorporate
50 higher value activities or those that increase efficiency of a limited resource such as through increased water use
51 efficiency (Thomas 2008). For future conditions, Seo (2011) assessed that under climate predictions for 2060,
52 integrated crop-livestock farms could increase in number in Africa at the expense of specialized crop or livestock
53 systems. The analysis indicated that the net revenue of the specialized farms could decrease by up to 75% compared

1 with only 10% for the mixed farm. In some cases, increased diversification outside of agriculture may be favoured
2 (e.g. Coulthard 2008, Mary and Majule 2009, Mertz et al. 2009).

3
4 [INSERT FIGURE 7-9 HERE

5 Figure 7-9: Yield change (% difference from baseline) as affected by temperature aggregated across all crops for
6 paired non-adapted and adapted cases. Only studies that examine both a 'no adaptation' and an 'adaptation' scenario
7 are used (this is a subset of the data points in Figure 7-5). For the final figure, we'd envisage shading the area
8 between the two regressions – this quantifies the benefit of adaptation according to the modelling studies. The figure
9 contains a subset of the total envisaged final data; any conclusions are preliminary.]

10
11 [INSERT FIGURE 7-10 HERE

12 Figure 7-10: The benefit of crop management adaptations as a function of global temperature change expressed as
13 the difference between yield change between the adapted and non-adapted cases aggregated across all crops for
14 paired non-adapted and adapted cases. Only studies that examine both a 'no adaptation' and an 'adaptation' scenario
15 are used (this is a subset of the data points in Figure 7-5).]

16
17 The above adaptations, either singly or in combination, could significantly reduce negative impacts of climate
18 change and increase the benefit of positive changes as found in AR4 (*high agreement, medium evidence*). To
19 quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been undertaken for wheat,
20 rice and maize (see Section 7.5.2). This meta-analysis adds more recent studies to that undertaken in the AR4
21 (Chapter 5). It indicates that the average benefit (the yield difference between the adapted and non-adapted cases) of
22 adapting crop management increases approximately linearly with increasing temperature change being equivalent to
23 about 18% of current yields for a temperature increase of 5°C (Figure 7-10). This response is, however, extremely
24 variable, ranging from negligible benefit to very substantial. The responses are similar between wheat, maize and
25 rice but differ markedly between adaptation management options (Figure 7-8). For example, cultivar adaptation is
26 assessed by several studies as providing substantially more benefit (mean of over 50%) than changing planting dates
27 (13%) or optimizing irrigation to the new climatic conditions (4%).

28
29 Potential increased variability of crop production means there is high confidence (*high agreement, medium*
30 *evidence*) that that food reserve, storage and distribution policies and systems may need to be enhanced (IAASTD
31 2010) along with a range of broader issues such as provision of effective insurance markets, clarity in property
32 rights, building adaptive capacity and developing effective participatory research cultures that apply to more than
33 just farming systems (Chapter 9, AR4 Chapter 5).

34
35 It is notable that most of the above adaptations raised above and used in this analysis are essentially either
36 incremental changes to existing agricultural systems or are systemic changes which integrate new aspects into
37 current systems. Few could be considered to be transformative changes. Consequently, the potential adaptation
38 benefits could be understated and a considerable opportunity cost may emerge (*medium agreement, limited*
39 *evidence*).

40 41 42 7.5.1.1.2. Livestock

43
44 Extensive livestock systems occur over a huge range of biophysical and socio-ecological systems, with a consequent
45 large range of potential adaptations. In many cases, these livestock systems are highly adapted to past climate risk,
46 providing a sound starting point for climate change adaptation (*high agreement, medium evidence*). These
47 adaptations include matching stocking rates with pasture production, adjusting herd and water point management to
48 altered seasonal and spatial patterns of forage production, managing diet quality (using diet supplements, legumes,
49 choice of introduced pasture species and pasture fertility management), more effective use of silage, pasture spelling
50 and rotation, fire management to control woody thickening, using more suitable livestock breeds or species,
51 migratory pastoralist activities and a wide range of biosecurity activities to monitor and manage the spread of pests,
52 weeds and diseases (Fitzgerald et al. 2008, Howden et al. 2008, Nardone et al. 2010). In some regions, these
53 activities can in part be informed by climate forecasts at differing time-scales to enhance opportunities and reduce
54 risks including soil degradation (e.g. Ash et al. 2007). Many livestock systems are integrated with or compete for

1 land with cropping systems and one climate adaptation may be to change these relationships. For example, with
2 increased precipitation, farmers in Africa may need to reduce their livestock holdings in favour of crops, but with
3 rising temperatures, they may need to substitute small ruminants in place of cattle with small temperature increases
4 or reduce stocking rates with larger temperature rises (Kabubo-Mariara 2009, Seo 2010, Thornton et al. 2010). As
5 with other production systems there is a range of barriers to adaptation which could be addressed by changes in
6 infrastructure, establishment of functioning markets, improved access to credit, improved access to water and water
7 management technologies, enhanced animal health services and enhanced knowledge adoption and information
8 systems (Howden et al. 2008, Kabubo-Mariara 2009, Mertz et al. 2009).

9
10 Heat stress is an existing issue for livestock in some regions (*high agreement, robust evidence*), especially in higher
11 productivity systems (7.3.2.6). For example, some graziers in Africa are already make changes to stock holdings in
12 response to shorter term variations in temperatures (Seo et al. 2008). Breeding livestock with increased heat stress
13 resistance is an adaptation often identified but there are usually trade-offs with productivity (Nardone et al. 2010)
14 and so this option needs careful evaluation. Increased shade provision through trees or cost-effective structures can
15 substantially reduce the incidence of high heat stress days (Nidumolu et al. 2011b). In warmer climates there might
16 be lesser need for winter housing and feed stocks.

17 18 19 7.5.1.1.3. Fisheries

20
21 The resources for capture fisheries are largely already fully or overexploited with an estimated 32 percent of stocks
22 being overexploited and 53% being fully exploited (FAO 2010). Comparable global statistics are not available for
23 inland fisheries but the status of those stocks may not be any better. Overfishing is widely regarded as the primary
24 pressure on marine fishery resources but other human activities including coastal and offshore mining, oil and gas
25 extraction, coastal zone development, land-based pollution and other activities are also negatively impacting status
26 and production (Rosenberg and MacLeod 2005, Cochrane et al. 2009). For inland fisheries, overfishing is also
27 widespread but the majority of impacts on the integrity of freshwater ecosystems and their resources originate from
28 outside the sector (Welcomme et al. 2010). Climate change adds another compounding influence in both cases.

29
30 The vulnerability of fisheries and fishing communities to climate change will depend on their exposure to its
31 physical and ecological effects, their dependence on the fishery and their sensitivity to physical effects, and their
32 adaptive capacity (Allison et al. 2009). Adaptive responses to climate change in fisheries could include:
33 management approaches and policies that strengthen the livelihood asset base, improved understanding of the
34 existing response mechanisms to climate variability to assist in planning adaptation, recognising and responding to
35 new opportunities brought about by climate change, monitoring biophysical, social and economic indicators linked
36 to management and policy responses and adoption of multi-sector adaptive strategies to minimise negative impacts
37 (Alison et al. 2009, Badjeck et al. 2010, MacNeil et al. 2010). A wide range of management tools and strategies
38 have been developed to manage fisheries. However, Grafton (2010) points out that this array of tools is necessary
39 but not sufficient for adaptation to climate change in fisheries. He argues that the standard tools for fisheries
40 management were developed to control fishing mortality and to maintain adequate levels of recruitment to fishery
41 stocks but without necessarily addressing the needs for resilience to change or to be able to function under changing
42 climates. He therefore proposes that these conventional management tools must be used within processes that i) have
43 a core objective to encourage ecosystems that are resilient to change and ii) that explicitly take into account
44 uncertainties about future conditions and the effect of adaptation, and make use of models to explore the
45 implications of these (Grafton 2010). There are also opportunities for fisheries to contribute to mitigation efforts
46 (Grafton 2010). Complementary adaptive responses include occupational flexibility, changing target species and
47 fishing operations, protecting key functional groups, developing early warning systems for extreme events and the
48 establishment of insurance schemes (Coulthard 2008, FAO 2009a, Daw et al. 2009, MacNeil et al. 2010, Hobday et
49 al. 2011). Governance and management of fisheries will need to follow an ecosystem approach to maximise
50 resilience of the ecosystem, and to be adaptive and flexible to allow for rapid responses to climate induced change
51 (FAO 2009a, Daw et al. 2009).

52
53 In contrast to capture fisheries, aquaculture is estimated to be the fastest-growing animal-food-producing sector and
54 is outpacing human population growth. Per capita supply from aquaculture increased at an average annual growth

1 rate of 6.6 percent from 1970 to 2008 (FAO, 2010). Adaptive responses in aquaculture include use of improved
2 feeds and selective breeding for higher temperature tolerance strains to cope with increasing temperatures (De Silva
3 and Soto 2009) and shifting to more tolerant strains of molluscs to cope with increased acidification (Huppert et al.
4 2009). Better planning and improved site selection to take into account expected changes in water availability and
5 quality; integrated water use planning that recognises and takes into account the water requirements and social and
6 economic importance of fisheries and aquaculture in addition to other sectors; and improving the efficiency of water
7 use in aquaculture operations are other adaptation options (De Silva and Soto 2009). Integrated water use planning
8 will require making trade-offs between different land and water uses in the watershed (e.g. Mantua et al. 2010). De
9 Silva and Soto (2009) also describe the need for insurance schemes accessible to small-scale producers so as to
10 increase their resilience. In some near-shore locations there may be a need to shift property lines as the mean high
11 water mark is displaced landwards by rising sea level (Huppert et al. 2009).

12
13 There are no simple, generic recipes for adaptation. Bell et al. (2011c) suggest a list of 24 separate, but inter-related,
14 actions that could be taken to adapt fisheries and aquaculture in the tropical Pacific to climate change. They break
15 these management steps into three categories according to the primary objective: economic development and
16 government revenue; maintaining the contribution of fish to food security; and maximising sustainable livelihoods.
17 These authors also point out that actions and policies for adaptation in fisheries and aquaculture must complement
18 those for other sectors. They suggest that the greater the number of different production systems to which
19 communities have access, the greater the chance that some systems available to them will not be negatively
20 impacted and that some may even benefit from climate change. Similar case-by-case, integrated planning will be
21 required in all other regions and at scales from community to regional to achieve clearly defined adaptation goals.

22 23 24 7.5.1.1.4. *Indigenous knowledge*

25
26 Indigenous Knowledge (IK) has developed to cope with climate hazards contributing to food security in many parts
27 of the world. Examples in the Americas include Alaska, where the Inuit knowledge of climate variability assured the
28 source of food to hunters (Ford 2009, Alessa 2008), down to the southern Andes where the Inca traditions of crop
29 diversification, genetic diversity, raised bed cultivation, agroforestry, weather forecasting and water harvesting are
30 still used in agriculture (Goodman-Elgar 2008, Renard et al., 2011 McDowell & Hess 2012). In Africa, weather
31 forecasting, diversity of crops and agropastoralism strategies have been useful in the Sahel (Nyong et al. 2007).
32 Rainwater harvesting has been a common practice in Sub-Saharan Africa (Biazin et al. 2011) to cope with dry spells
33 and improve crop productivity, while strategies from agropastoralists in Kenya are related to drought forecasting
34 based on the fauna, flora, moon, winds and other factors (Speranza et al. 2010). In South Africa, farmer's early
35 warming indicators of wet or dry periods in Namibia based on animals, plants and climate observations contributed
36 to deal with climatic variability (Newsham & Thomas 2011) [Cross reference to Chapters 22 and 9]. In the same
37 way, in Asia and Australia IK plays an important role to assure food security of certain groups (Marin, 2010,
38 Speranza et al. 2010; Biazin et al. 2011, Salick & Ross 2009, Kalanda et al. 2011; Green et al. 2010), although IK
39 can differ according to gender and age in some communities (Rengalakshmi 2007, Kalanda et al. 2011) leading to
40 distinct adaptive capacities and options.

41
42 However, because of changes already occurring in climate (seasonal changes, changes in extreme events: cross
43 reference to WGI and IPCC Extremes SR) the confidence in IK could be reduced (Kalanda et al. 2011; Speranza et
44 al. 2009, McDowell & Hess 2012) affecting the adaptive capacity of a number of peoples globally (*high agreement,*
45 *medium evidence*). Moreover, some policies and regulations leading to limit the access to territories, promoting
46 sedentarization, the substitution of traditional livelihoods, reduced genetic diversity and harvesting opportunities as
47 well as loss of transmission of IK, may contribute to limit the adaptation to climate change in many regions
48 (Nakashima et al. 2011) (*medium agreement, medium evidence*).

49 50 51 7.5.1.2. *Practical Regional Experiences of Adaptation, including Lessons Learned*

52
53 Given the early stages of climate change, there are relatively few unequivocal examples of adaptation (see Section
54 7.5.2) additional to existing climate risk management. Where there have been management changes these have often

1 been in response to several driving variables of which climate is only one (Smit and Wandel 2006, Mertz et al. 2009,
2 Chen et al. 2011, Odgaard et al. 2011). More farmers express an intention to change rather than having implemented
3 adaptive actions (e.g. Battaglini et al. 2009) although in some regions there appears to be adaptation to climate
4 change that is happening now (Olesen et al. 2011). Activities to build adaptive capacity to better manage climate
5 change are more widespread (e.g. Twomlow et al. 2008) but there remain questions as to how this capacity will
6 evolve and be maintained (Nelson et al. 2009). Crucial in this will be devolution of the decision-making process so
7 as to integrate local, contextual information into adaptation decision-making (Nelson et al. 2008).

10 7.5.1.2.1. *Observed and expected barriers and limits to adaptation*

11
12 Adaptation is strongly influenced by factors including institutional, technological, informational and economic
13 (Adger et al. 2005) and there can be barriers (restrictions that can be addressed) and limits in all these factors (high
14 agreement, ??? evidence). Several barriers to adaptation of food systems have been raised including inadequate
15 information on the climate, climate impacts and on the risks and benefits of the adaptation options, lack of adaptive
16 capacity, inadequate extension, institutional inertia, financial constraints including access to credit, insufficient
17 fertile land, infrastructure, lack of functioning markets and insurance systems (Bryan et al. 2009, de Bruin and de
18 Link 2011, Deressa et al. 2009, Kabubo-Mariara 2009). Limits to adaptation can occur for example where crop
19 yields drop below the level required to sustain critical infrastructure such as sugar or rice mills (Park et al. 2010). In
20 some cases, these can be effectively irreversible. Some studies have shown that access to climate information is not
21 the principal limitation to improving decision making and it can result in perverse outcomes, increasing inequities
22 and widening gender gaps (Coles and Scott 2009). Incomplete adoption of adaptations may also occur,

23
24 Lack of technical options can also be a barrier to adaptation. New varieties of crops or breeds of livestock are
25 assessed as providing possible core adaptations of production systems (*high agreement, medium evidence*) (Mercer
26 et al. 2008, Tingem and Rivington 2010) however, there is substantial investment needed to develop these along
27 with delays before they are available, both of which can act as adaptation barriers. This may be addressed in part by
28 investments to improve local crop varieties or livestock breeds that are easily adopted (IAASTD 2010). There also
29 can be physiological limits to performance such as upper temperature limits for heat tolerance (AR4 WGII 5.2.1).

32 7.5.1.2.2. *Facilitating adaptation and avoiding maladaptation*

33
34 Adaptation actions would usually be expected to provide benefits to farmers, the food industry along the value chain
35 or perhaps to a broader community. However, there are possible maladaptations that arise from adapting too early or
36 too late, by changing the incorrect elements of the food system or changing them by the incorrect amount. A key
37 maladaptation would be one which increased emissions of greenhouse gases, this making the underlying problem
38 worse (Smith and Olesen 2010; AR5 WGIII Chapter 11, *high agreement, robust evidence*). A recent review of
39 agricultural adaptations however, has found that most categories of climate change adaptation options tend to reduce
40 greenhouse gas emissions (Smith and Olesen 2010, Falloon and Betts 2010) (*medium agreement, medium evidence*).
41 These adaptations include measures that reduce soil erosion or reduce leaching of nitrogen and phosphorus,
42 measures for conserving soil moisture and reducing temperature extremes by increasing vegetative cover.

43
44 There is a strong focus on incremental adaptation of existing food systems in the literature since AR4 (see above)
45 however, this may result in large opportunity costs that could arise from not considering more systemic adaptation
46 or more transformative change (Kates et al. 2012; Howden et al. 2010) (*high agreement, limited evidence*). For
47 example, in the USA, changes in farming systems (i.e. the combination of crops) have been assessed as providing
48 significant adaptation benefit in terms of net farm income (Prato et al. 2010). There is a need to also engage both
49 farmers and policymakers in evaluating transformative, pro-active, planned adaptations such as structural changes
50 (McCrum et al. 2009, Olesen et al. 2011). This could involve changes in land allocation and farming systems,
51 breeding of functionally-different crop varieties, new land management techniques and new classes of service from
52 lands such as ecosystem services (Howden et al. 2010). In Australia, industries including the wine, rice and peanut
53 industries are already adopting transformative changes such as change in location so as to be early adopters of what
54 are perceived as opportunities arising from change (Park et al. 2011).

1
2 There is substantial commonality in adaptation actions within different agricultural systems. For example, changing
3 varieties and planting times are incremental adaptations found in studies of many different cropping systems as
4 evidenced by the sample size in the meta-analysis. Collating information on the array of adaptation options available
5 for farmers, their relative cost and benefit and their broad applicability could be a way of initiating engagement with
6 decision-makers. In the climate mitigation domain, this has been attempted using marginal abatement cost curves
7 which identify mitigation options, their relative cost and the potential size of emission-reductions (IPCC WG3).
8 These curves can be used in setting investment priorities and informing policy discussions. The local nature of many
9 adaptation decisions, their interactions with other highly contextual driving factors and the time and climate change-
10 sensitive nature of adaptation decisions means however, that global, time-independent curves are not feasible. The
11 example in Figure 7.10 indicates that there some options which may be more relevant and useful to consider than
12 others. These results however, illustrate the potential scope and benefit of developing effective crop adaptation
13 options if implemented in an adaptive management approach.
14
15

16 **7.5.2. Food System Case Studies – Examples of Successful and Unsuccessful Adaptation**

17

18 Incremental, systemic and transformational adaptation to climate change is beginning to be documented, though the
19 peer-reviewed literature largely covers vulnerability assessments and intentions to act, not adaptation actions
20 (Berang-Ford et al. 2010).
21

22 *Case 1: Incremental adaptation in the Sahel*

23 Much of the literature covers incremental, reactive adaptation, but given actors are constantly adapting to changing
24 social and economic conditions, incremental adaptation to climate change is difficult to distinguish from other
25 actions (Berang-Ford et al. 2010, Speranza 2010)), and in fact is usually a response to a complex of factors. This
26 case, of the zaï soil management practice in the Sahel region, is an example where a complex of factors drives local
27 actions, and factors such as growing land scarcity and new market opportunities, rather than climate, may be the
28 primary factors (Barbier et al. 2010, Mertz et al. 2010). Inherent poor soil quality and human activities have resulted
29 in soil degradation – crusting, sealing, erosion by water and wind, and hardpan formation (Zougmore et al. 2010,
30 Fatondji et al. 2009). Zaï, a traditional integrated soil and water management practice, can combat land degradation
31 and improve yield and decrease yield variability by concentrating runoff water and organic matter in small pits (20-
32 40 cm in diameter and 10-15 cm deep) dug manually during the dry season and combined with contour stone bunds
33 to slow runoff. A handful of animal manure or compost is placed in each pit. . By breaking the soil crust, the pits
34 facilitate greater water infiltration, while the applied organic matter improves soil nutrient status and attracts
35 termites, which have a positive effect on soil structure.. The zaï technique is very labour intensive requiring some 60
36 days of labour per hectare. Innovations to the system, involving animal-drawn implements, can reduce labour
37 substantially.
38

39 *Case 2: Mixed farming systems in Tanzania*

40 In Morogoro, Tanzania, farming households have adapted in many ways to climatic and other stresses (Paavola
41 2008). They have extended cultivation through forest clearance or reducing the length of the fallow period.
42 Intensification is under way, through change in crop choices, increased fertiliser use and irrigation, and especially
43 greater labour inputs. Livelihood diversification has been the main adaptation strategy – this has involved more non-
44 farm income-generating activities, tapping into natural resources for subsistence and cash income (e.g. charcoal
45 production), and has included artisanal gold and gemstone mining. Households have also altered their cropping
46 systems, for example, by changing planting times. Migration is another frequently used strategy – with farmers
47 moving to gain land, access markets or get employment. Parents also send children to cities to work for upkeep and
48 cash income to reduce the household numbers that need to be supported by uncertain agricultural income. While
49 many of these strategies help in terms of the short-term needs, in the longer term they may be reducing the capacity
50 of households to cope. For instance, land cover change has negative impacts on future water supplies for irrigation,
51 and deforestation and forest degradation means faltering forest-based income sources. This will be particularly
52 problematic to the more vulnerable groups in the community, including women and children.
53
54

1 *Case 3: Planning for adaptation in a CARE project*

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

17 *Case 4 Transformational change in the primary industries of Australia*

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

30 **7.5.3. Key Findings from Adaptations – Confidence Limits, Agreement, and Level of Evidence**

31 *[still to be revised]*

32 There have been many studies of crop adaptation since the AR4. In aggregate these show that adaptations to
33 changed temperature and precipitation are likely to bring substantial benefit with some adaptations (e.g. cultivar
34 adaptation) being more effective than others (e.g. irrigation optimisation). Changing planting dates and associated
35 decisions to match evolving growing seasons could maximize production benefits whilst improving cultivar
36 tolerance to high temperature, drought conditions and elevated CO₂ levels could be beneficial to crop yield and
37 quality and water use efficiency.

38 Livestock and fisheries systems have available a large range of possible adaptations often tailored to local conditions
39 but there is not adequate information to aggregate the likely value of these adaptations. Key livestock adaptations
40 include matching stocking rates with pasture availability, water management, monitoring and managing the spread
41 of pests, weeds and diseases, livestock breeding and adjusting to changed frequencies of heat stress and cold
42 conditions. Fishery adaptations include management approaches and policies that strengthen the livelihood asset
43 base, take an ecosystem approach to managing the resource and adoption of multi-sector adaptive strategies to
44 minimise negative impacts. Importantly, there is an emerging recognition that existing fishery management tools
45 and strategies are necessary but not sufficient for adaptation to climate.

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

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

3
4 Most adaptation studies focus on the farm level and on productivity measures with relatively few addressing value
5 chains or economic measures.

6
7 The focus on incremental adaptations and few studies on more systemic and transformational adaptation or
8 adaptation along the value chain mean that there may be underestimation of adaptation opportunities and benefits. In
9 addition to this, there is a range of limits and barriers to adaptation and many of these could be addressed by
10 devolution of the decision-making process so as to integrate local, contextual information into adaptation decision-
11 making.

14 **7.6. Research and Data Gaps – Food Security as a Cross-Sector Activity, Malnutrition, Research** 15 **Capacity, and its Regional Variation**

16
17 Research and data gaps are seen mainly in the fact that most work since AR4 has concentrated on food production
18 and not included other aspects of the food system that connects climate change to food security. Features such as
19 food processing, distribution, access and consumption have become areas of research interest in their own right but
20 only tangentially attached to climate change.

21
22 Other areas of neglect include food quality and nutritional aspects of climate change, the need to update food
23 production impact models, the need to create integrated food systems models at the regional and global scales and
24 geared to including climate change effects on the global food system.

27 **Frequently Asked Questions**

29 ***FAQ 7.1: How could climate change result in reduced food production?***

30 Observations and many experimental studies show with high confidence that a warming climate has a generally
31 reducing effect on yields of staple cereals such as wheat, rice and maize, especially at low latitudes. Warming can
32 have a stimulatory effect on yields of perennial crops such as grass. Crop models have generally indicated that
33 climate warming has negative impacts on crop yield. However, the impacts differ between regions, with low
34 latitudes more negatively affected than high latitudinal areas. Climate change will affect fisheries and aquaculture
35 through gradual warming, ocean acidification and through changes in the frequency, intensity and location of
36 extreme events. Overall, it will lead to a mixture of negative and potentially positive impacts on fishery and
37 aquaculture production which will vary with locality. The relationship between climate change and food production
38 depends to a large degree on when and which adaptation actions are taken. Other links in the food chain from
39 production to consumption are sensitive to climate but such impacts are much less well known.

41 ***FAQ 7.2: How do elevated CO₂ levels affect crops?***

42 Stabilization of CO₂ concentration reduces temperature damage to crop production in the long term. Generally,
43 elevated CO₂ benefits C₃ species more than C₄ species by increasing photosynthetic rates. CO₂ can also improve
44 yields in dry conditions for both C₃ and C₄ species, because CO₂ induced reductions in stomatal apertures help to
45 reduce water loss. However, there is big uncertainty in the magnitude of the CO₂ effect and that interactions with
46 other factors such as nutrient fertilization highly influence crop responses to CO₂, as does the effect of other gases
47 such as tropospheric ozone in combination with CO₂.

49 ***FAQ 7.3: What type of climate extremes matter for agriculture?***

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

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

3
4 **FAQ 7.4: How could adaptation actions avoid the loss of food production?**

5 Effective adaptation of cropping can help ensure food production and thereby contributing to food security and
6 sustainable livelihoods in developing countries, by enhancing current climate risk management. There is increasing
7 evidence that farmers in some regions are already adapting to observed climate changes in particular altering
8 cultivation and sowing times and crop cultivars and species. Adaptive responses to climate change in fisheries
9 should include: management approaches and policies that maximize resilience of the exploited ecosystems, ensuring
10 fishing and aquaculture communities have the opportunity and capacity to respond to new opportunities brought
11 about by climate change, and the use of multi-sector adaptive strategies to reduce the consequence of negative
12 impacts in any particular sector. However, these adaptations will not necessarily reduce all of the negative impacts
13 of climate change, and the effectiveness of adaptations could diminish at the higher end of warming projections.

14
15 **FAQ 7.5: Where do the food insecure live?**

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

18
19 **FAQ 7.6: How could climate change interact with declining fish stocks, ocean acidification?**

20 Millions of people rely on fish and aquatic invertebrates for their food security and as an important source of
21 protein. However, climate change will affect fish stocks and other aquatic species: increasing temperatures will lead
22 to increased production of important fishery resources in some areas but decreased production in others while
23 increases in acidification will have negative impacts on important invertebrate species, including species responsible
24 for building coral reefs which provide essential habitat for many fished species in these areas. The poorest fishers
25 and others dependent on fisheries and subsistence aquaculture will be the most vulnerable to these changes,
26 including those in small-island developing States, central and western African countries, Peru and Columbia in
27 South America and some tropical Asian countries.

28
29
30 **References**

31 [to be consolidated]

32
33 Agriculture Cluster. 2010. Preliminary Damage Assessment in the Agriculture Sector for Flood-Affected Areas of
34 Pakistan, 9-14 August, 2010

35 (http://www.pakresponse.info/assessments/AgricultureCluster_Preliminary%20Damage%20Assessment%20in%20the%20Agriculture%20Sector_Sep2010.pdf)

36
37 NDMA. 2010. Resilience. NDMA (National Disaster Management Authority, of Pakistan) Newsletter, 1 (#3), May
38 – December 2010 (Web: www.ndma.gov.pk)

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

41 Berrang-Ford, L, Ford, J.D. and Paterson, J. 2010. Are we adapting to climate change? *Global Environ. Change*. 21:
42 25-33.

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

45 Fatondji D., C. Martius C., Zougmore R., Vlek P. L. G., Biolders C. L., Koala S., 2009. Decomposition of organic
46 amendment and nutrient release under the zai technique in the Sahel. *Nutrient Cycling in Agroecosystems*
47 85:225–239

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

50 Last et , P., White, W., Gledhill, D., Hobday, A., Brown, R., Edgar, G. and Pecl, G. 2011: Long terms shifts in
51 abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global*
52 *Ecology and Biogeography* 20, 58-72.

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

- 1 Paavola J. 2008. Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental*
2 *Science & Policy* 2008,11:642-654.
- 3 Patt, A.G., Dazé, A. and Suarez, P. 2009. Gender and climate change vulnerability: what's the problem, what's the
4 solution? In: Ruth, M. and Ibarraran, M. E. (Eds). *Distributional Impacts of Climate Change and Disasters:*
5 *Concepts and Cases*. Cheltenham, UK: Edward Elgar Publishing Limited.
- 6 Segnini, A., Posadas, A., Quiroz, R., Milori, D.M.B.P., Saab, S.C. Neto., L.M., Vaz, C.M.P. 2010. Spectroscopic
7 Assessment of Soil Organic Matter in Wetlands from the High Andes *Soil Sci. Soc. Am. J.* 74:2010
- 8 Stafford-Smith, M., Horrocks, L., Harvey, A., and Hamilton, C. 2011. Rethinking adaptation for a 4°C world. *Phil.*
9 *Trans. R. Soc.* 369: 196-216.
- 10 Speranza, C.I. (2010): Drought coping and adaptation strategies: understanding adaptations to climate change in
11 agro-pastoral livestock production in Makueni District, Kenya. *European Journal of Development Research* 22:
12 623-642
- 13 Tompkins, E.L., Adger, W.N., Boyd, E., Nicholson-Cole, S., Weatherhead, K., and Arnell, N. 2010. Observed
14 adaptation to climate change: UK evidence of transition to a well-adapting society. *Global Environmental*
15 *Change* 20: 627–635
- 16 Vuille, M., Bradley, R.S., Werner, M. And Keimig, F. 2003. 20th century climate change in the tropical Andes:
17 Observations and model results. *Climatic Change* 59: 75–99, 2003
- 18 Zougmore R., Mando A., Stroosnijder L., 2010. Benefits of integrated soil fertility and water management in semi-
19 arid West Africa: an example study in Burkina Faso. *Nutrient Cycling in Agroecosystems* 88, 1: 17-27.
- 20 Aggarwal, M. 2007. Experimental evidence of O₃ impacts on crop yield and quality in India. Royal Society
21 Workshop on Ground-level ozone, May 2007 (<http://royalsociety.org/document.asp?id=1170>).
- 22 E.H., Allison L. Perry, Marie-Caroline Badjeck, W. Neil Adger, Katrina Brown, Declan Conway, Ashley S. Halls,
23 Graham M. Pilling, John D. Reynolds, Neil L. Andrew & Nicholas K. Dulvy. 2009. Vulnerability of national
24 economies to the impacts of climate change on fisheries. *FISH and FISHERIES* , 10, 173–196
- 25 Avnery, S., D.L. Mauzerall, J. Liu and L.W. Horowitz. 2011a. Global crop yield reductions due to surface ozone
26 exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment*, **45**,
27 2264-2296.
- 28 Avnery, S., D.L. Mauzerall, J. Liu and L.W. Horowitz. 2011b. Global crop yield reductions due to surface ozone
29 exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O₃
30 pollution. *Atmospheric Environment*, **45**, 2296-2309.
- 31 Badjeck, M.-C., Allison, E. H., Halls, A.S. and Dulvey, N.K. (2010). Impacts of climate variability and change on
32 fishery-based livelihoods. *Marine Policy* 34, 375–383.
- 33 Bamabas, B.A.T., K. Jager, and A. Feher. 2008. The effect of heat and drought stress on reproductive process in
34 cereals. *Plant Cell Environ.* **31**, 11-39.
- 35 Bell, J., M. Batty, A. Ganachaud, P. Gehrke, A. Hobday, O. Hoegh-Guldberg, J. Johnson, R. Le Borgne, P.
36 Lehodey, J. Lough, T. Pickering, M. Pratchett, M. Sheaves, M. Waycott. 2011a. Preliminary Assessment of the
37 Effects of Climate Change on Fisheries and Aquaculture in the Pacific. To be published in 'The Contribution of
38 Fisheries to the Economies of Pacific Island Countries and Territories'. Pacific Studies Series (Asian
39 Development Bank)
- 40 Bell, J., T.J.H. Adams, J.E. Johnson, A.J. Hobday and A.S. Gupta. 2011b. Pacific communities, fisheries,
41 aquaculture and climate change: an introduction. In J.D. Bell, J.E. Johnson and A.J. Hobday: *Vulnerability of*
42 *tropical Pacific fisheries and aquaculture to climate change*. Secretariat of the Pacific Community, Noumea,
43 New Caledonia. Pp1-47.
- 44 Bell, J., N.L. Andrew, M.J. Batty and 17 co-authors. 2011c. Adapting tropical Pacific fisheries and aquaculture to
45 climate change: management measures, policies and investments. In J.D. Bell, J.E. Johnson and A.J. Hobday:
46 *Vulnerability of tropical Pacific fisheries and aquaculture to climate change*. Secretariat of the Pacific
47 Community, Noumea, New Caledonia. Pp803-876.
- 48 Bellocchi, G., M. Rivington, M. Donatelli and K. Mathew. 2010. Validation of biophysical models: issues and
49 methodologies. A review. *Agron. Sustain. Dev.*, **30**, 109-130.
- 50 Booker, F., R. Muntiferg, M. McGrath, et al. 2009. The ozone components of global change: Potential effects on
51 agricultural and horticultural plant yield, product quality and interaction with invasive species. *J. Integr.Plant*
52 *Biol.*, **51**,337-351.
- 53 Bondeau, A., P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller,
54 M. Reichstein and B. Smith (2007) Modeling the role of agriculture for the 20th century global terrestrial

- 1 carbon balance. *Global Change Biology* 13, 679-706
- 2 Brander, K.M. 2007. Global fish production and climate change. *Proc.Nat.Academy Sci.* 104: 19709-19714
- 3 Brown, C.J., Fulton, E.A., Hobday, A.J., Matear, R.J., Possingham, H.P., Bulman, C., Christensen, V., Forrest, R.E.,
4 Gehrke, P.C., Gribble, N.A., Griffiths, S.P., Lozano-Montes, H., Martin, J.M., Metcalf, S., Okey, T.A., Watson,
5 R. and Richardson, A.J. 2010. Effects of climate-driven primary production change on marine food webs:
6 implications for fisheries and conservation. *Global Change Biology*: 16, 1194–1212.
- 7 Burke, M. B., Lobell, D. B., Guarino, L. (2009). Shifts in African crop climates by 2050, and the implications for
8 crop improvement and genetic resources conservation. *Global Environmental Change - Human and Policy*
9 *Dimensions* 19 (3): 317-325.
- 10 Burke, L., Reynter, K., Spalding, M., Perry, A. 2011. Reefs at risk revisited, Executive Summary. World Resources
11 Institute, Washington DC. 11pp.
- 12 Buytaert, W., Vuille A., Dewulf R., Urrutia A., Karmalkar and R. C'elleri (Uncertainties in climate change
13 projections and regional downscaling in the tropical Andes: implications for water resources management.
14 *Hydrol. Earth Syst. Sci.*, 14, 1247–1258, 2010
- 15 Caracelli, S., S. Grando, M. Maattougi, M. Michael, M. Slash and M. Nachit. 2010. Plant breeding and climate
16 changes. *J. Agr. Sci. (Cambridge)*, **148**, 627-637.
- 17 Cassman, K.G., P. Grassini and J. van Wart. 2010. Crop yield potential, yield trends, and global food security in a
18 changing climate. Chapter 3 in *Handbook of Climate change and Agroecosystems*, pp 37-51.
- 19 Chavas, D.R., R.C. Izaurralde, A.M. Thomson and X.J. Gao. 2009. Long term climate change impacts on
20 agricultural productivity in eastern China. *Agric. For. Meteorol.* 149, doi: 10.1016./j.agrformet.2009.02.001
- 21 Challinor, A. J., E. S. Simelton, E. D. G. Fraser, D. Hemming and M. Collins (2010) Increased crop failure due to
22 climate change: assessing adaptation options using models and socio-economic data for wheat in China.
23 *Environ. Res. Lett.* 5 (2010) 034012
- 24 Challinor, A. J., T. R. Wheeler, D. Hemming and H. D. Upadhyaya (2009). Ensemble yield simulations: crop and
25 climate uncertainties, sensitivity to temperature and genotypic adaptation to climate change. *Climate Research*,
26 38 117-127
- 27 Challinor, A. J. and T. R. Wheeler (2008). Use of a crop model ensemble to quantify CO2 stimulation of water-
28 stressed and well-watered crops. *Agric. For. Meteorol.* 148 1062-1077
- 29 Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson and D. Pauly, 2009: Projecting global
30 marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, 10(3), 235-251.
- 31 Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, D. Zeller and D. Pauly, 2010: Large scale
32 redistribution of maximum fisheries catch in the global ocean under climate change. *Global Change Biology*,
33 16, 24-35.
- 34 Cook, R.M. and M.R. Heath. 2005. The implications of warming climate for the management of North Sea demersal
35 fisheries. *ICES Journal of Marine Science*, 62: 1322-1326.
- 36 Craufurd, P. Q. and T. R. Wheeler (2009). "Climate change and the flowering time of annual crops." *Journal of*
37 *Experimental Botany* 60(9): 2529-2539.
- 38 Daw, T., W.N. Adger, K. Brown and M-C. Badjeck. Climate change and capture fisheries: potential impacts,
39 adaptation and mitigation. In *Climate change implications for fisheries and aquaculture. Overview of current*
40 *scientific knowledge. FAO Fisheries and Aquaculture Technical Paper 530. Rome, FAO. pp 107-150.*
- 41 De'ath, G., J.M. Lough and K.E. Fabricius (2009). Declining coral calcification on the Great Barrier Reef. *Science*
42 323: 116-119.
- 43 De Silva, S.S. and Soto, D. 2009. Climate change and aquaculture: potential impacts, adaptation and mitigation. In:
44 Eds. Cochrane, K., De Young, C. Soto, D. and Bahri, T. *Climate change implications for fisheries and*
45 *aquaculture. Overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper 530.*
46 *Rome, FAO. 151-212.*
- 47 De Matta, F.M., A. Grandis, B.C. Arenque and M.S. Buckeridge. 2010. Impact of climate change on crop
48 physiology and food quality. *Food Res. Int.*, **43**, 1814-1823.
- 49 Drinkwater, K. F. 2005. The response of Atlantic cod (*Gadus morhua*) to future climate change. *ICES Journal of*
50 *Marine Science*, 62: 1327-1337.
- 51 Ewing, M., Msangi, S. 2009. Biofuels production in developing countries: assessing tradeoffs in welfare and food
52 security. *Environmental Science & Policy* 12: 520 – 528
- 53 FAO, 2008. *The state of food and agriculture 2008. Biofuels: prospects, risks and opportunities.*
- 54 Fischer, G., E. Hiznyik, S. Prieler, M. Shah and H. van Velthuisen. 2009. *Biofuels and Food Security. Final*

- 1 Report to Sponsor: The OPEC Fund for International Development (OFID), Vienna, Austria (March 2009).
2 IIASA Contract No. 08-134
- 3 FAO. 2009a. Introduction. In: Eds. Cochrane, K., De Young, C. Soto, D. and Bahri, T. Climate change implications
4 for fisheries and aquaculture. Overview of current scientific knowledge. FAO Fisheries and Aquaculture
5 Technical Paper 530. Rome, FAO. 212pp.
- 6 Feely, R.A., Sabine, C.L., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J. and Millero, F.J. 2004. Impact of
7 Anthropogenic CO₂ on the CaCO₃ System in the Oceans. *Science* 305, 362-366.
- 8 Ficke, A.D., C.A. Myrick and L. J. Hansen. 2007. Potential impacts of global climate change on freshwater
9 fisheries. *Rev Fish Biol Fisheries*, 17:581–613
- 10 Fishman, J. et al. 2010. An investigation of widespread ozone damage to the soybean crop in the upper Midwest
11 determined from ground-based and satellite measurements. *Atmospheric Environment*, **44**, 2248-2256.
- 12 Fraser, E., Termansen, M., Sun, N., Guan, D., Simelton, E., Dodds, P., Feng, K. & Yu, Y. (2008) Quantifying socio
13 economic characteristics of drought sensitive regions: Evidence from chinese provincial agricultural data.
14 *Comptes Rendus Geosciences*, 340, 679-688.
- 15 Fuhrer, J. 2009. Ozone risk for crops and pastures in present and future climate. *Naturwissenschaften*, **96**, 173-194.
- 16 Hatfield, J., K. Boote, P. Fay, L. Hahn, C. Izaurrealde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A.
17 Thomson, and D. Wolfe. 2008. Agriculture. In *The Effects of Climate Change on Agriculture, Land Resources,*
18 *Water Resources, and Biodiversity*. Washington, DC: U.S. Climate Change Science Program and the
19 Subcommittee on Global Change Research, pp. 21–74.
- 20 Hiddink, J.G. and R.ter Hofstede. 2008. Climate induced increases in species richness of marine fishes. *Global*
21 *Change Biology* 14, 453–460.
- 22 Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale,
23 A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A.
24 Dubi, M. E. Hatziolos. 2007. Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science* 318,
25 1737-1742.
- 26 Hopkins, A. and A. Del Prado. 2007. Implications of climate change for grassland in Europe: impacts, adaptations
27 and mitigation options: a review. *Grass and Forage Science*, 62, 118–126
- 28 Humaira, S., N. Ali, M.M. Iqbal and A. M. Khan. 2009. Vulnerability and adaptability of wheat production in
29 different climatic zones of Pakistan under climate change scenarios. *Climatic Change*. **94**, 123-142.
- 30 Huppert DD, Moore A, Dyson K (2009) Impacts of climate change on the coasts of Washington State. Chapter 8 in
31 *The Washington Climate Change Impacts Assessment: Evaluating Washington’s Future in a Changing Climate*,
32 Climate Impacts Group, University of Washington, Seattle, Washington
- 33 Iizumi, T., M. Yokozawaa and M. Nishimoria (2009). Parameter estimation and uncertainty analysis of a large-scale
34 crop model for paddy rice: Application of a Bayesian approach. *Agricultural and Forest Meteorology* 149 (2)
35 333-348.
- 36 Iqbal, M. M., M. A. Goheer and A. M. Khan. 2009. Climate-change aspersions on food security of Pakistan. *Science*
37 *Vision*, **15**, 15-23.
- 38 Kang, Y.M., S. Khan and X.Y. Ma. 2009. Climate change impacts on crop yield, crop water productivity and food
39 security: A review. *Prog. Nat. Sci.*, **19**, 1665-1674.
- 40 Last, P., White, W., Gledhill, D., Hobday, A., Brown, R., Edgar, G. and Pecl, G. 2011: Long terms shifts in
41 abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global*
42 *Ecology and Biogeography* 20, 58-72)
- 43 Lehodey, P., J. Hampton, R.W. Brill and 11 co-authors. 2011. Chapter 8. Vulnerability of oceanic fisheries in the
44 tropical Pacific to climate change. In J.D. Bell, J.E. Johnson and A.J. Hobday: *Vulnerability of tropical Pacific*
45 *fisheries and aquaculture to climate change*. Secretariat of the Pacific Community, Noumea, New Caledonia.
46 Pp433-492.
- 47 Lehodey, P., I. Senina, J. Sibert, L. Bopp, B. Calmettes, J. Hampton and Murtugudde. 2010. Preliminary forecasts of
48 Pacific bigeye tuna population trends under the A2 IPCC scenario. *Progress in Oceanography* 86: 302–315
- 49 Loukos, H., P. Monfray, L. Boppi and P. Lehodey. 2003. Potential changes in skipjack tuna (*Katsuwonus pelamis*)
50 habitat from a global warming scenario: modelling approach and preliminary results. *Fish. Oceanogr.* 12: 474–
51 482
- 52 Schroth, G., Peter Laderach, Jan Dempewolf, Stacy Philpott, Jeremy Hagggar et al. 2009. Towards a climate change
53 adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. *Mitigation*
54 *and Adaptation Strategies for Global Change* 14, Issue: 7, 605-625

- 1 Jaggard et al. (2010). Possible changes to arable crop yields by 2050. *Phil Trans B.* 2010 365, 2835-2851.
- 2 Lal, R. 2009. Soil degradation as a reason for inadequate human nutrition. *Food Secur.* **1**, 45-57.
- 3 Li, Y. P., W. Ye, et al. (2009). "Climate change and drought: a risk assessment of crop-yield impacts." *Climate*
4 *Research* 39(1): 31-46.
- 5 Lobell and Burke 2010 AFM150
- 6 Lobell, D. B. and M. B. Burke (2008). Why are agricultural impacts of climate change so uncertain? The importance
7 of temperature relative to precipitation. *Environmental Research Letters* 3 (3): Art No. 034007.
- 8 Lobell, D.B., and C. B. Field (2007) Global scale climate-crop yield relationships and the impacts of recent
9 warming. *Environmental Research Letters* 2, 014002
- 10 Lobell, D.B., M. Banziger, C. Mogorokosho and B. Vivek. 2011. Nonlinear heat effects on African maize as
11 evidenced by historical yield trials. *Nature Climate Change*, /doi: 10. 1038/nclimate 1043
- 12 Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, R. L. Naylor (2008). Prioritizing Climate
13 Change Adaptation Needs for Food Security in 2030. *Science* 319 (5863), 607 – 610.
- 14 Lonz-Weidemann, V.S., C.W. Klar and K. Schneider. 2010. Development and testing of a crop growth model for
15 application with a Global change decision support system. *Ecol. Model.* **221**, 314-329.
- 16 Mantua, N., I.M. Tohver, A.F. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime
17 stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Clim*
18 *Change*.102:187–223.
- 19 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.
20 H. Cobon, R. A. Cowley, S. J. Crimp, G. W. Fraser, S. M. Howden, P. W. Johnston, J. G. Ryan, C. J. Stokes, K.
21 A. Day. 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: a review
22 of issues. *The Rangeland Journal*, Vol. 31 No. 1 Pages 1 - 29
- 23 Melloy, P., G. Hollaway, G. Luck, R. Norton, E. Aiken and S. Chakraborty. 2010. Production and fitness of
24 *Fusarium pseudograminearum* inoculation at elevated carbon dioxide in FACE. *Global Change Biol.* **16**, 3363-
25 3373.
- 26 Mills, G., F. Hayes, S. Wilkinson and J.W. Davies. 2009. Chronic exposure to background ozone impairs stomatal
27 functioning in grassland species. *Global Change Biol.*, **15**, 1522-1533.
- 28 Misselhorn, A., A. Challinor, P. Thornton, J. W. Jones, R. Schaldach and V. Plocq-Fichelet (2010). Chapter 20:
29 Surprises and Possibilities. In J. Ingram, P. Ericksen and D. Liverman (Eds) *Food Security and Global*
30 *Environmental Change*. Earthscan ISBN 9781849711289.
- 31 Mo, X.G., S.X. Liu, Z.H. Lin and R.P. Guo. 2009. Regional crop yield, water consumption and water use efficiency
32 and their responses to climate change in the North China Plain. *Agric. Ecosyst. Environ.* **134**, 67-68.
- 33 Moriondo, M, C. Giannakopoulos and M. Bindi, 2011, Climate change impact assessment: the role of climate
34 extremes in crop yield simulation. *Climatic Change* 104 (3-4): 679-701
- 35 Munday, P.L., G.P. Jones, M.S. Pratchett, A.J. William. 2008. Climate change and the future for coral reef fishes.
36 *Fish and Fisheries*, 9: 261–285.
- 37 Nandone, A., B. Ronchi, N. Lacetera, M.S. Ranieri and U. Bernabucci. 2010. Effect of climate change on animal
38 production and sustainability of livestock systems. *Livest. Sci.*, **130**, 57-69.
- 39 O'Reilly, C.M, Alin, S.R., Plisnier, P-D., Cohen, A.S. and McKee, B.A. 2003. Climate change decreases aquatic
40 ecosystem productivity of Lake Tanganyika, Africa. *Nature*. 424: 766-768.
- 41 Ortiz, R., K. D. Sayre, et al. (2008). "Climate change: Can wheat beat the heat?" *Agriculture Ecosystems &*
42 *Environment* 126(1-2): 46-58.
- 43 Osborne, T. M., D. M. Lawrence, A. J. Challinor, J. M. Slingo, T. R. Wheeler (2007). Development and assessment
44 of a coupled crop-climate model. *Global Change Biology* 13 169-183.
- 45 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.
46 Tan, Y. Yu, T. Zhang and J. Fang. 2010. The impacts of climate change on water resources and agriculture in
47 China. *Nature*, **467**, 43-51.
- 48 Last, P., White, W., Gledhill, D., Hobday, A., Brown, R., Edgar, G. and Pecl, G. 2011: Long terms shifts in
49 abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. *Global*
50 *Ecology and Biogeography* 20, 58-72)
- 51 Lehodey, P., J. Hampton, R.W. Brill and 11 co-authors. 2011. Chapter 8. Vulnerability of oceanic fisheries in the
52 tropical Pacific to climate change. In J.D. Bell, J.E. Johnson and A.J. Hobday: *Vulnerability of tropical Pacific*
53 *fisheries and aquaculture to climate change*. Secretariat of the Pacific Community, Noumea, New Caledonia.
54 Pp433-492.

- 1 Pikki, K., V. Vorne, K. Ojanpera and H. Pleijet. 2007. Impact of elevated O₃ and CO₂ exposure on potato (*Solanum*
2 *tuberosum* L. cv. Bintje) tuber macronutrients (N, P, K, Mg, Ca). *Agric. Ecosyst. Environ.*, **118**, 55-84.
- 3 Pratchett, M.S., P.L. Munday, N.J. Graham and 13 co-authors. 2011. Chapter 9. Vulnerability of coastal fisheries in
4 the tropical Pacific to climate change. In J.D. Bell, J.E. Johnson and A.J. Hobday: *Vulnerability of tropical*
5 *Pacific fisheries and aquaculture to climate change*. Secretariat of the Pacific Community, Noumea, New
6 Caledonia. Pp493-573.
- 7 Reidsma, P., Ewert, F., Oude Lansink, A. and Leemans, R., 2009. Vulnerability and adaptation of European farmers:
8 a multi-level analysis of yield and income responses to climate variability. *Regional Environmental Change* 9:
9 25-40
- 10 Royal Society. 2009. Reaping the harvest (RS/Policy Document 11/09). The Royal Society, London.
- 11 Soltani, A. and G. Hoogenboom. 2007. Assessing crop management options with crop simulation models based
12 on generated weather data. *Field Crops Res.* **105**, 198-207.
- 13 Soussana, J.F., A.I. Graux and F.N. Tubiello. 2010. Improving the use of modelling for projections of climate
14 change impacts on crops and pastures. *J. Ext. Bot.* **61**, 2217-2228.
- 15 Schlenker, W and M. J. Roberts (2009). Nonlinear temperature effects indicate severe damages to US crop yields
16 under climate change. *Proceedings of the National Academy of Science of the United States of America* 106
17 (37): 15594-15598.
- 18 Thornton, P. K. *et al.* *Global Environmental Change* **19** (1), 54-65 (2009).
- 19 Thornton, P. K., P. G. Jones, P. Ericksen and A. J. Challinor (2010) Agriculture and food systems in sub-Saharan
20 Africa in a four-plus degree world. *Phil. Trans. Roy. Soc .A.* 369 117-136 doi:10.1098/rsta.2010.0246
- 21 Trnka et al., 2011. Agroclimatic conditions in Europe under climate change. *Global Change Biology* DOI:
22 10.1111/j.1365-2486.2011.02396.x
- 23 Tao, F., M. Yokozawa, et al. (2009). "Modelling the impacts of weather and climate variability on crop productivity
24 over a large area: A new process-based model development, optimization, and uncertainties analysis."
25 *Agricultural and Forest Meteorology* 149(5): 831-850.
- 26 Tao, F., M. Yokozawa, et al. (2009). "Climate change, land use change, and China's food security in the twenty-first
27 century: an integrated perspective." *Climatic Change* 93(3-4): 433-445.
- 28 von Braun, J. 2009. Addressing the food crisis: governance, market functioning, and investment in public goods.
29 *Food Sec.* 1:9-15 DOI 10.1007/s12571-008-0001-z
- 30 Tubiello, F.N., J.S. Amthor, K.J. Boote, Donatelli, W. Easterling, G. Fischer, R.M. Gifford, M. Howden, J. Reilly,
31 and C. Rosenzweig, 2007: Crop response to elevated CO₂ and world food supply: A comment on "Food for
32 Thought." by Long et al., *Science* 312:1918-1921, 2006. *Euro. J. Agron.*, **26**, 215-223, doi:10.1016/j.eja.10.002.
- 33 Wassmann, R. S.V.K. Jagdish, S. Heur, A. Ismail, E. Redona, R. Serraj, R.K. Singh, G. Howell, H. Pathak and K.
34 Sumfleth. 2009. Climate change affecting rice production: The physiological and agronomic basis for possible
35 adaptation strategies. *Advanc. Agron.* **101**, 59-122. Academic Press, San Diego, CA, USA.
- 36 Welch, J. R., Jeffrey R. Vincent, Maximilian Auffhammer, Piedad F. Moyae, Achim Dobermann, and David
37 Daweg, 2010. Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and
38 maximum temperatures. www.pnas.org/cgi/doi/10.1073/pnas.1001222107
- 39 Welcomme, R. 2011. Review of the State of the World Fishery Resources: Inland Fisheries. *FAO Fisheries and*
40 *Aquaculture Circular No. 942, Rev. 2.* Rome, FAO. 2011. 97 pp.
- 41 Wilson, S.K., Graham, N.A.J., Pratchett, M.S., Jones, G.P. and Polunin, V.C. 2006. Multiple disturbances and the
42 global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology*: 2220-2234.
- 43 Xiong, W. et al. 2009. Future cereal production in China: Modelling the interaction of climate change, water
44 availability and socio-economic scenarios. In *The impacts of Climate Change on Chinese Agriculture – Phase II*
45 *Final Report* (AEA Group, 2008).
- 46 Yahdjian, L. & O. Sala, 2008. Climate Change Impacts on South American Rangelands. *Rangelands*, June 2008, pp
47 33-39
- 48 Zhang, T. Zhu, J., Wassmann R. (2010) Responses of rice yields to recent climate change in China: An empirical
49 assessment based on long-term observations at different spatial scales (1981-2005). *Agricultural and Forest*
50 *Meteorology* 150: 1128-1137
- 51 Baldocchi, D. & S. Wong. Accumulated winter chill is decreasing in the fruit growing regions of California. *Climatic*
52 *Change* (2008) 87 (Suppl 1):S153-S166
- 53 Farag A.A., A.A. Khalil and M.K Hassanein. 2010. Chilling requirement for deciduous fruits under climate change
54 in Egypt. *Research Journal of Agriculture and Biological Sciences*, 6(6): 815-822.

- 1 Lobell, D.B., Ch. B. Field, K. N. Cahill, C. Bonfils. 2006. Impacts of future climate change on California perennial
2 crop yields. Model projections with climate and crop uncertainties *Agricultural and Forest Meteorology*,
3 Volume 141, Issues 2-4, 20 December 2006, Pages 208-218
- 4 Marin, F, G. Q. Pellegrino; E. D. Assad; D. S. P. Nassif; M. S. Viana; F. A. Soares; L. L. Cabral; D. Guiatto. 2009.
5 FUTURE SCENARIOS FOR SUGARCANE IN THE STATE OF SAO PAULO BASED ON REGIONLIZED
6 CLIMATE CHANGE PROJECTIONS
7 XVI Congresso Brasileiro de Agrometeorologia – Belo Horizonte – MG- Brazil
- 8 PINTO, H. S. ; ZULLO JR, J.; ASSAD, E. D. ; EVANGELISTA, B. A. . 2007. O aquecimento global e a
9 cafeicultura brasileira. *Boletim da Sociedade Brasileira de Meteorologia*, v. 30, p. 65-72, 2007.
- 10 PINTO, H. S.; ASSAD, E. D.; JUNIOR, J. Z.; EVANGELISTA, S. R. M.; OTAVIAN, A. F.; ÁVILA, A. M. H.;
11 EVANGELISTA, B.; MARIN, F. R.; JUNIOR, C. M.; PELLEGRINO, G. Q.; COLTRI, P. P.; CORAL, G.
12 Aquecimento global e a nova geografia da produção agrícola no Brasil. Embrapa, São Paulo, 2008.
- 13 Stöckle, C.O., R.L. Nelson, S. Higgins, J. Brunner, G. Grove, R. Boydston, M. Whiting, Ch. Kruger. 2010.
14 Assessment of climate change impact on Eastern Washington agriculture
15 *Climatic Change* (2010) 102:77–102
- 16 Zullo Jr., J., H. Silveira Pinto, E. Delgado Assad, A. M. Heuminski de Ávila. 2011. Potential for growing Arabica
17 coffee in the extreme south of Brazil in a warmer world. *Climatic Change* DOI 10.1007/s10584-011-0058-0.
18 Published online: 09 April 2011
- 19 Abbott, P.C., Hurt, C. and Tyner, W.E., 2008. What's Driving Food Prices?
- 20 Alexander, L.V. et al., 2006. Global observed changes in daily climate extremes of temperature and precipitation. *J.*
21 *Geophys. Res.*, 111: D05109, doi:10.1029/2005JD006290.
- 22 Amthor, J.S., 2001. Effects of atmospheric CO₂ concentration on wheat yield: review of results from experiments
23 using various approaches to control CO₂ concentration. *Field Crops Research*, 73(1): 1-34.
- 24 Auffhammer, M., Ramanathan, V. and Vincent, J.R., 2006. Integrated model shows that atmospheric brown clouds
25 and greenhouse gases have reduced rice harvests in India. *Proceedings of the National Academy of Sciences*,
26 103(52): 19668-19672.
- 27 Banerjee, A.V. and Duflo, E., 2007. The economic lives of the poor. *The journal of economic perspectives: a journal*
28 *of the American Economic Association*, 21(1): 141.
- 29 Bell, M.A. and Fischer, R.A., 1994. Using Yield Prediction Models to Assess Yield Gains - a Case Study For
30 Wheat. *Field Crops Research*, 36(2): 161-166.
- 31 Brisson, N. et al., 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France.
32 *Field Crops Research*, 119(1): 201-212.
- 33 Chen, C., Wang, E., Yu, Q. and Zhang, Y., 2010. Quantifying the effects of climate trends in the past 43 years
34 (1961–2003) on crop growth and water demand in the North China Plain. *Climatic Change*, 100(3): 559-578.
- 35 Christidis, N., Stott, P.A., Brown, S., Hegerl, G.C. and Caesar, J., 2005. Detection of changes in temperature
36 extremes during the second half of the 20th century. *Geophys. Res. Lett.*, 32.
- 37 CSIRO, 2010. Climate variability and change in south-eastern Australia: A synthesis of findings from Phase 1 of the
38 South Eastern Australian Climate Initiative (SEACI).
- 39 Dawe, D., 2008. Have recent increases in international cereal prices been transmitted to domestic economies? The
40 experience in seven large Asian countries, FAO, Rome.
- 41 Ding, Y., Wang, Z., Song, Y. and Zhang, J., 2008. Causes of the unprecedented freezing disaster in January 2008
42 and its possible association with the global warming. *Acta Meteorologica Sinica*, 665: 809-825.
- 43 Dole, R. et al., 2011. Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters*,
44 38(6): L06702.
- 45 Easterling, W. et al., 2007. Chapter 5: Food, Fibre, and Forest Products. In: M.L. Parry, O.F. Canziani, J.P.
46 Palutikof, P.J. v.d. Linden and C.E. Hanson (Editors), *Climate Change 2007: Impacts, Adaptation and*
47 *Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental*
48 *Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY,*
49 *USA., pp. 273-313.*
- 50 FAO, 2008. Policy measures taken by government to reduce the impact of soaring prices. *Global Information and*
51 *Early Warning System.*
- 52 FAO, 2010. Food and Agriculture Organization of the United Nations (FAO), *FAO Statistical Databases.*
- 53 FAO, 2011. *The State of Food Insecurity in the World 2010*, FAO, Rome, Italy.
- 54 Fishman, J. et al., 2010. An investigation of widespread ozone damage to the soybean crop in the upper Midwest

- 1 determined from ground-based and satellite measurements. *Atmospheric Environment*, 44(18): 2248-2256.
- 2 Garcia, P., Irwin, S.H., Leuthold, R.M. and Yang, L., 1997. The value of public information in commodity futures
3 markets. *Journal of Economic Behavior & Organization*, 32(4): 559-570.
- 4 Ivanic, M. and Martin, W., 2008. Implications of higher global food prices for poverty in low-income countries.
- 5 Kucharik, C.J. and Serbin, S.P., 2008. Impacts of recent climate change on Wisconsin corn and soybean yield
6 trends. *Environmental Research Letters*, 3: 034003.
- 7 Liu, Y., Wang, E., Yang, X. and Wang, J., 2009. Contributions of climatic and crop varietal changes to crop
8 production in the North China Plain, since 1980s. *Global Change Biology*, 9999(999A).
- 9 Lobell, D.B., Bonfils, C. and Duffy, P.B., 2007. Climate change uncertainty for daily minimum and maximum
10 temperatures: a model inter-comparison. *Geophysical Research Letters*, 34: L05715,
11 doi:10.1029/2006GL028726.
- 12 Lobell, D.B. and Field, C.B., 2007. Global scale climate-crop yield relationships and the impacts of recent warming.
13 *Environmental Research Letters*, 2: 004000 (7pp).
- 14 Lobell, D.B. et al., 2005. Analysis of wheat yield and climatic trends in Mexico. *Field Crops Research*, 94(2-3):
15 250-256.
- 16 Lobell, D.B., Schlenker, W.S. and Costa-Roberts, J., 2011. Climate trends and global food production since 1980.
17 *Science*, science express website.
- 18 Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nosberger, J. and Ort, D.R., 2006. Food for Thought: Lower-Than-
19 Expected Crop Yield Stimulation with Rising CO₂ Concentrations. *Science*, 312(5782): 1918-1921.
- 20 Lopez, A.D., Mathers, C.D., Ezzati, M., Jamison, D.T. and Murray, C.J.L., 2006. Global and regional burden of
21 disease and risk factors, 2001: systematic analysis of population health data. *The Lancet*, 367(9524): 1747-
22 1757.
- 23 McGrath, J. and Lobell, D.B., 2011. An independent method of deriving the carbon dioxide fertilization effect in dry
24 conditions using historical yield data from wet and dry years. *Global Change Biology*, in press.
- 25 Mills, G. et al., 2007. A synthesis of AOT40-based response functions and critical levels of ozone for agricultural
26 and horticultural crops. *Atmospheric Environment*, 41(12): 2630-2643.
- 27 Min, S.-K., Zhang, X., Zwiers, F.W. and Hegerl, G.C., 2011. Human contribution to more-intense precipitation
28 extremes. *Nature*, 470(7334): 378-381.
- 29 Morgan, P.B., Mies, T.A., Bollero, G.A., Nelson, R.L. and Long, S.P., 2006. Season long elevation of ozone
30 concentration to projected 2050 levels under fully open air conditions substantially decreases the growth and
31 production of soybean. *New Phytologist*, 170(2): 333-343.
- 32 Naylor, R.L. and Falcon, W.P., 2010. Food Security in an Era of Economic Volatility. *Population and Development
33 Review*, 36(4): 693-723.
- 34 Pathak, H. et al., 2003. Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic
35 Plains. *Field Crops Research*, 80(3): 223-234.
- 36 Peng, S. et al., 2004. Rice yields decline with higher night temperature from global warming. *Proceedings of the
37 National Academy of Sciences of the United States of America*, 101(27): 9971-9975.
- 38 Porter, J.R. and Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. *European
39 Journal of Agronomy*, 10(1): 23-36.
- 40 Ravallion, M., Chen, S. and Sangraula, P., 2007. New evidence on the urbanization of global poverty. *Population
41 and Development Review*, 33(4): 667-701.
- 42 Roberts, M. and Schlenker, W., 2010. Identifying Supply and Demand Elasticities of Agricultural Commodities:
43 Implications for the US Ethanol Mandate, NBER Working Paper No. 15921.
- 44 Rosenzweig, C., Tubiello, F.N., Goldberg, R., Mills, E. and Bloomfield, J., 2002. Increased crop damage in the US
45 from excess precipitation under climate change. *Global Environmental Change-Human and Policy Dimensions*,
46 12(3): 197-202.
- 47 Schlenker, W. and Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields
48 under climate change. *Proceedings of the National Academy of Sciences*, 106(37): 15594-15598
- 49 Stott, P.A., Stone, D.A. and Allen, M.R., 2004. Human contribution to the European heatwave of 2003. *Nature*,
50 432(7017): 610-614.
- 51 Tao, F., Yokozawa, M., Liu, J. and Zhang, Z., 2008. Climate-crop yield relationships at provincial scales in China
52 and the impacts of recent climate trends. *Clim Res*, 38(1): 83-94.
- 53 Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y. and Zhang, Z., 2006. Climate changes and trends in phenology and
54 yields of field crops in China, 1981-2000. *Agricultural and Forest Meteorology*, 138(1-4): 82-92.

- 1 USDA, 2007. Wheat Situation and Outlook Yearbook. U.S. Department of Agriculture, Washington, D.C.
- 2 Van Dingenen, R. et al., 2009. The global impact of ozone on agricultural crop yields under current and future air
3 quality legislation. *Atmospheric Environment*, 43(3): 604-618.
- 4 Wang, H.L. et al., 2008. Phenological trends in winter wheat and spring cotton in response to climate changes in
5 northwest China. *Agricultural and Forest Meteorology*, 148(8-9): 1242-1251.
- 6 Wassmann, R. et al., 2009. Climate change affecting rice production: the physiological and agronomic basis for
7 possible adaptation strategies. *Advances in Agronomy*.
- 8 Welch, J.R. et al., 2010. Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum
9 and maximum temperatures. *Proceedings of the National Academy of Sciences*, 107(33): 14562.
- 10 Wright, B.D., 2011. The Economics of Grain Price Volatility. *Applied Economic Perspectives and Policy*, 33(1): 32.
- 11 You, L., Rosegrant, M., Wood, S. and Sun, D., 2009. Impact of growing season temperature on wheat productivity
12 in China. *Agricultural and Forest Meteorology*, 149(6-7): 1009-1014.
- 13 Zhang, T., Zhu, J., Yang, X. and Zhang, X., 2008. Correlation changes between rice yields in North and Northwest
14 China and ENSO from 1960 to 2004. *Agricultural and Forest Meteorology*, 148(6-7): 1021-1033.
- 15 Zwiers, F.W., Zhang, X. and Feng, Y., 2011. Changes in the extremes of the climate simulated by CCC GCM2
16 under CO2 doubling. *Journal of Climate*: in press.
- 17 Defra, 2006. Food Security and the UK: An Evidence and Analysis Paper. Food Chain Analysis Group.
- 18 Ericksen, P.J., 2008. Conceptualizing Food Systems for Global Environmental Change Research. *Global
19 Environmental Change*, 18: 234-245.
- 20 Ericksen, P.J. et al., 2010. The Value of a Food System Approach. In: J. Ingram, P. Ericksen and D. Liverman
21 (Editors), *Security and Global Environmental Change*. Earthscan, London.
- 22 ESF, 2009. *European Food Systems in a Changing World*, Strasbourg.
- 23 EU, 2011. *Food security under threat: global response needed*.
- 24 FAO, 1996. *Rome Declaration and World Food Summit Plan of Action*, FAO, Rome.
- 25 FAO, 2008
- 26 FAO, 2010. *The State of Food Insecurity in the World (SOFI): Addressing food insecurity in protracted crises*,
27 Rome.
- 28 Foresight, 2011. *The Future of Food and Farming. Final Project Report*. The Government Office for Science,
29 London.
- 30 Godfray, H.C.J. et al., 2010a. Food security: feeding the world in 2050 - Theme Issue September 2010.
- 31 Godfray, H.C.J. et al., 2010b. Food Security: The Challenge of Feeding 9 Billion People. *Science*, 327: 812-818.
- 32 Ingram, J.S.I., 2009. Food system concepts. In: R. Rabbinge and A. Linneman (Editors), *ESF/COST Forward Look
33 on European Food Systems in a Changing World*. European Science Foundation, Strasbourg.
- 34 Maxwell, S. and Slater, R., 2003. Food Policy Old and New. *Development Policy Review*, 21(5-6): 531-553.
- 35 McMichael, P. (Editor), 1994. *The Global Restructuring of Agro-Food Systems*. Cornell University Press, New
36 York, US.
- 37 Science, 2010. Special Issue 12 February 2010: Food Security.
- 38 Spring, Ú.O., 2009. Food as a New Human and Livelihood Security Challenge. In: H.G. Brauch et al. (Editors),
39 *Facing Global Environmental Change. Hexagon Series on Human and Environmental Security and Peace*.
40 Springer Berlin Heidelberg, pp. 471-500.
- 41 Tovey, H., 1997. Food, Environmentalism and Rural Sociology: On the Organic Farming Movement in Ireland.
42 *Sociologia Ruralis*, 37(1): 21-37.
- 43 von Braun and Torero, 2009
- 44 Leakey, A.D.B., 2009. Rising atmospheric carbon dioxide concentration and the future of C4 crops for food and
45 fuel. *Proceedings of the Royal Society B: Biological Sciences*: doi: 10.1098/rspb.2008.1517.
- 46 Högy, P. and Fangmeier, A., 2009. Atmospheric CO2 enrichment affects potatoes: 1. Aboveground biomass
47 production and tuber yield. *European Journal of Agronomy*, 30(2): 78-84.
- 48 Fleisher, D.H., Timlin, D.J. and Reddy, V.R., 2008. Interactive Effects of Carbon Dioxide and Water Stress on
49 Potato Canopy Growth and Development. *Agronomy journal*, 100(3): 711.
- 50 Markelz, R.J.C., Strellner, R.S. and Leakey, A.D.B., 2011. Impairment of C4 photosynthesis by drought is
51 exacerbated by limiting nitrogen and ameliorated by elevated [CO2] in maize. *Journal of Experimental Botany*.
- 52 McGrath, J. and Lobell, D.B., 2011. An independent method of deriving the carbon dioxide fertilization effect in dry
53 conditions using historical yield data from wet and dry years. *Global Change Biology*, in press.
- 54 Ainsworth, E.A., Leakey, A.D.B., Ort, D.R. and Long, S.P., 2008. FACE-ing the facts: inconsistencies and

- 1 interdependence among field, chamber and modeling studies of elevated CO₂ impacts on crop yield and food
2 supply. *New Phytologist*, 179(1): 5-9.
- 3 Archimède H., M. Eugène, C. Marie Magdeleine, M. Boval, C. Martin, D.P. Morgavi, P. Lecomte, M. Doreau,
4 2011. Comparison of methane production between C₃ and C₄ grasses and legumes. *Animal Feed Science and*
5 *Technology*, doi:10.1016/j.anifeedsci.2011.04.003
- 6 Barati F., B. Agung, P. Wongsrikeao, M. Taniguchi, T. Nagai, T. Otoi, 2008. Meiotic competence and DNA damage
7 of porcine oocytes exposed to an elevated temperature. *Theriogenology* 69, 767-772.
- 8 Blackwell P.J., 2010. East Africa's pastoralist emergency: is climate change the straw that breaks the camel's back?
9 *Third World Quarterly* 31 (8), 1321-1338.
- 10 Bohmanova J., I. Misztal, S. Tsuruta, H.D. Norman, T.J. Lawlor, 2008. Genotype by environment interaction due to
11 heat stress. *Journal of Dairy Science* 91, 840-846.
- 12 Burke M.B., D.B. Lobell, L. Guarino, 2009. Shifts in African crop climates by 2050, and the implications for crop
13 improvement and genetic resources conservation. *Global Environmental Change* 19, 317-325.
- 14 Craine J.M., A.J. Elmore, K.C. Olson, D. Tolleson, 2010. Climate change and cattle nutritional stress. *Global Change*
15 *Biology* 16, 2901-2911.
- 16 Cutler S.J., A.R. Fooks, W.H. van der Poel, 2010. Public health threat of new, re-emerging, and neglected zoonoses
17 in the industrialized world. *Emerging Infectious Diseases* 16, 1-7.
- 18 Descheemaeker K., T. Amede, A. Hailelassie, 2010. Improving water productivity in mixed crop–livestock farming
19 systems of sub-Saharan Africa. *Agricultural Water Management* 97, 579-586.
- 20 De Fraiture C., D. Wichelns, 2010. Satisfying future water demands for agriculture. *Agricultural Water management*
21 97, 502-511.
- 22 De Fraiture C., D. Molden, D. Wichelns, 2010. Investing in water for food, ecosystems, and
23 livelihoods: An overview of the comprehensive assessment of water management in agriculture. *Agricultural Water*
24 *Management* 97, 495-501.
- 25 Dikmen S., P.J. Hansen, 2009. Is the temperature-humidity index the best indicator of heat stress in lactating dairy
26 cows in a subtropical environment? *Journal of Dairy Science* 92, 109-16.
- 27 Doherty R.M., S. Sitch, B. Smith, S.L. Lewis, P.K. Thornton, 2010. Implications of future climate and atmospheric
28 CO₂ content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global*
29 *Change Biology* 16 (2), 617-640.
- 30 Ericksen P.J., J.S.I. Ingram, D. Liverman, 2009. Food security and global environmental change: emerging
31 challenges. *Environmental Science and Policy* 12, 373-377.
- 32 Feng J., M. Zhang, S. Zheng, P. Xie, A. Ma, 2008. Effects of high temperature on multiple parameters of broilers in
33 vitro and in vivo. *Poultry Science* 87, 2133-2139.
- 34 Fuhrer J., 2009. Ozone risks for crops and pastures in present and future climates. *Naturwissenschaften* 96, 173-194.
- 35 Gilbert M., J. Slingenbergh, X. Xiao, 2008. Climate change and avian influenza. *Revue Scientifique et Technique -*
36 *Office International des Epizooties* 27, 459-466.
- 37 Gummow B., 2010. Challenges posed by new and re-emerging infectious diseases in livestock production, wildlife
38 and humans. *Livestock Science* 130, 41-46.
- 39 Hassan R., 2010. Implications of climate change for agricultural sector performance in
40 Africa: policy challenges and research agenda. *Journal of African Economies* 19 (supplement 2), ii77-ii105.
- 41 Hatfield J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, D. Wolfe, 2011.
42 Climate Impacts on agriculture: implications for crop production. *Agronomy Journal* 103, 351-370.
- 43 Hayes B.J., P.J. Bowman, A.J. Chamberlain, K. Savin, C.P. van Tassell, T.S. Sonstegard, M.E. Goddard, 2009. A
44 validated genome wide association study to breed cattle adapted to an environment altered by climate change.
45 *PLoS ONE* 4(8), e6676. doi:10.1371/journal.pone.0006676
- 46 Herrero M., P.K. Thornton, R.L. Kruska, R.S. Reid, 2008. Systems dynamics and the spatial distribution of methane
47 emissions from African domestic ruminants to 2030. *Agriculture, Ecosystems and Environment* 126, 122–37.
- 48 Hoffmann I., 2010. Climate change and the characterization, breeding and conservation
49 of animal genetic resources. *Animal Genetics*, 41 (Suppl. 1), 32-46.
- 50 Howden S.M., S.J. Crimp, C.J. Stokes, 2008. Climate change and Australian livestock systems : impact, research
51 and policy issues. *Australian Journal of Experimental Agriculture* 48, 780-788.
- 52 Izaurralde R.C., A.M. Thomson, J.A. Morgan, P.A. Fay, H.W. Polley, J.L. Hatfield, 2011. Climate impacts on
53 agriculture: implications for forage and rangeland production. *Agronomy Journal* 103, 371-381.
- 54 Jones P.G., P.K. Thornton, 2009. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to

- 1 climate change. *Environmental Science and Policy* 12, 427–37.
- 2 Lazzarotto P., P. Calanca, J. Fuhrer, 2009. Dynamics of grass–clover mixtures. An analysis of the response to
3 management with the productive grassland simulator (PROGRASS). *Ecological Modelling* 220, 703-724.
- 4 Lobell D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, R.L. Naylor, 2008. Prioritizing climate
5 change adaptation needs for food security in 2030. *Science* 319, 607-610.
- 6 Masike S., P. Urich, 2008. Vulnerability of traditional beef sector to drought and the challenges of climate change:
7 the case of Kgatlang District, Botswana. *Journal of Geography and Regional Planning* 1 (1), 12-18.
- 8 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.
9 Cobon, R.A. Cowley, S.J. Crimp, G.W. Fraser, S.M. Howden, P.W. Johnston, J.G. Ryan, C.J. Stokes, K.A.
10 Day, 2009. Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of
11 issues. *The Rangeland Journal* 31, 1-29.
- 12 Mills J. N., K.L. Gage, A.S. Khan, 2010. Potential influence of climate change on vector-borne and zoonotic
13 diseases: a review and proposed research plan. *Environmental Health Perspectives* 118, 1507-1514.
- 14 Molden D., T. Oweis, P. Steduto, P. Bindraban, M.A. Hanjra, J. Kijne, 2010. Improving agricultural water
15 productivity: between optimism and caution. *Agricultural Water Management* 97, 528-535.
- 16 Mortensen C.J., Y.H. Choi, K. Hinrichs, N.H. Ing, D.C. Kraemer, S.G. Vogelsang, M.M. Vogelsang, 2009. Embryo
17 recovery from exercised mare. *Animal Reproduction Science* 110, 237-244.
- 18 Nardone A., B. Ronchi, N. Lacetera, M.S. Ranieri, U. Bernabucci, 2010. Effects of climate changes on animal
19 production and sustainability of livestock systems. *Livestock Science* 130, 57-69.
- 20 Ostfeld R.S., 2009. Climate change and the distribution and intensity of infectious diseases. *Ecology* 90, 903-905.
- 21 Palmer M.A., C.A. Reidy Liermann, C. Nilsson, M. Flörke, J. Alcamo, P.S. Lake, N. Bond, 2008. Climate change
22 and the world's river basins: anticipating management options. *Frontiers in Ecology and the Environment* 6, 81-
23 89. doi:10.1890/060148
- 24 Pfeffer M, G. Dobler, 2010. Emergence of zoonotic arboviruses by animal trade and migration. *Parasites and*
25 *Vectors* 3, 35.
- 26 Rocque S.D.L., J.A. Rioux, J. Slingenbergh, 2008. Climate change: effects on animal disease systems and
27 implications for surveillance and control. *Revue Scientifique et Technique - Office International des Epizooties*
28 27, 339-354.
- 29 Rosegrant M.W., M. Fernandez, A. Sinha, J. Alder, H. Ahammad, C. de Fraiture, B. Eickhout, J. Fonseca, J. Huang,
30 O. Koyama, A.M. Omezzine, P. Pingali, R. Ramirez, C. Ringler, S. Robinson, P. Thornton, D. van Vuuren, H.
31 Yana-Shapiro, 2009. Looking into the future for agriculture and AKST (Agricultural Knowledge Science and
32 Technology). Pp 307-376 in *Agriculture at a Crossroads* (eds. B.D. McIntyre, H.R. Herren, J. Wakhungu, R.T.
33 Watson), Island Press, Washington DC.
- 34 Rosenthal J., 2009. Climate change and the geographic distribution of infectious diseases. *Ecohealth* 6, 489-495.
- 35 Seo S.N., R. Mendelsohn, 2008. Measuring impacts and adaptations to climate change: a structural Ricardian model
36 of African livestock management. *Agricultural Economics* 38, 151–65.
- 37 Soussana J.-F., A-I Graux, F.N. Tubiello, 2010. Improving the use of modelling for projections of climate change
38 impacts on crops and pastures. *Journal of Experimental Botany* 61 (8), 2217-2228.
- 39 Tabachnick W.J., 2010. Challenges in predicting climate and environmental effects on vector-borne disease
40 episystems in a changing world. *Journal of Experimental Biology* 213, 946-954.
- 41 Thornton P.K., P.G. Jones, T. Owiyo, R.L. Kruska, M. Herrero, P. Kristjanson, A. Notenbaert, N. Bekele, A.
42 Omolo, 2008. Climate change and poverty in Africa: mapping hotspots of vulnerability. *African Journal of*
43 *Agricultural and Resource Economics* 2 (1), 24-44.
- 44 Thornton P.K., P.G. Jones, G. Alagarswamy, J. Andresen, M. Herrero, 2010. Adapting to climate change:
45 agricultural system and household impacts in East Africa. *Agricultural Systems* 103, 73-82.
- 46 Thornton P.K., P.G. Jones, P. Ericksen, A.J. Challinor, 2011. Agriculture and food systems in sub-Saharan Africa in
47 a four-plus degree world. *Philosophical Transactions of the Royal Society Series A* 369, 117-136.
- 48 Vitali A., M. Segnalini, L. Bertocchi, U. Bernabucci, A. Nardone, N. Lacetera, 2009. Seasonal pattern of mortality
49 and relationships between mortality and temperature-humidity index in dairy cows. *Journal of Dairy Science* 92,
50 3781-3790.
- 51 Wall E., A. Wreford, K. Topp, D. Moran, 2010. Biological and economic consequences of heat stress due to a
52 changing climate on UK livestock. *Advances in Animal Biosciences* 1, 53.
- 53 Yahdjian L., O.E. Sala, 2008. Climate change impacts on South American rangelands. *Rangelands* 30(3), 34-39.
- 54 Zumbach B., I. Misztal, S. Tsuruta, J.P. Sanchez, M. Azain, W. Herring, J. Holl, T. Long, M. Culbertson, 2008.

- 1 Genetic components of heat stress in finishing pigs: development of a heat load function. *Journal of Animal*
2 *Science* 86, 2082-2088.
- 3 Archambault DJ 2007. Efficacy of herbicides under elevated temperature and CO₂. In: *Agroecosystems in*
4 *a Changing Climate*, (Newton PCD, Carran A, Edwards GR, Niklaus PA, eds.), CRC Press, Boston, MA , pp 262-
5 279.
- 6 Bridges DC. 1992. *Crop Losses Due to Weeds in the United States*. Weed Science Society of America,
7 Champaign, IL, 403 pp.
- 8 Bunce JA, Ziska LH 2000. Crop/Weed Interactions. **In:** *Climate Change and Global Crop Productivity*, (eds. KR
9 Reddy, HF Hodges), CABI International Press, pp 333-348.
- 10 Dukes JS, Mooney HA 2000. Does global change increase the success of biological invaders? *Trends in Ecology*
11 *and Evolution*, 14, 135-139.
- 12 Oerke EC. 2006. Crop losses to pests. *J. Agric. Sci.* **144**:31-43.
- 13 MacDonald AJ, Riha SJ, DiTommaso A, DeGaetano AT. 2009. Climate change and the geography of weed
14 damage: analysis of U.S. maize systems suggests the potential for significant range transformations.
15 *Agric. Ecosyst. Environ.* **130**:131-140.
- 16 Malcolm JR, Markham A, Neilson RP, Garaci M 2002. Estimated migration rates under scenarios of global climate
17 change. *J Biogeo* 29:835-849.
- 18 Manea A, Leishman MR, Downey PO 2011. Exotic C4 Grasses have increased tolerance to glyphosate under
19 elevated carbon dioxide. *Weed Science* 59:28-36.
- 20 Pimentel D, Zuniga R, Morison D 2005. Update on the environmental and economic costs associated with alien-
21 invasive species in the United States. *Ecological Economics* 52:273-288.
- 22 Rejmanek M 1996. A theory of seed plant invasiveness: the first sketch. *Biol Conserv* 78:171-181.
- 23 Taylor CA, Ralphs, MH. 1992. Reducing livestock losses from poisonous plants through grazing management.
24 *Journal of Range Management* 45: 9-12.
- 25 Ziska LH, Faulkner SS, Lydon J. 2004. Changes in biomass and root:shoot ratio of field-grown Canada thistle
26 (*Cirsium arvense*), a noxious, invasive weed, with elevated CO₂: implications for control with glyphosate. *Weed*
27 *Science* 52:584-588.
- 28 Ziska LH, Reeves JB III, Blank R. 2005. The impact of recent increases in atmospheric CO₂ on biomass
29 production and vegetative retention of Cheatgrass (*Bromus tectorum*): implications for fire disturbance.
30 *Global Change Biol.* **11**:1325-1332.
- 31 Ziska LH, Goins EW. 2006. Elevated atmospheric carbon dioxide and weed populations in glyphosate
32 treated soybean. *Crop Sci.* **46**:1354-1359.
- 33 Ziska, L.H., Tomecek, M., and D.R. Gealy 2010. Competitive interactions between cultivated and red rice
34 as a function of recent and projected increases in atmospheric carbon dioxide. *Agronomy J*
35 102:118-123.
- 36 Ziska LH, Blumenthal DM, Runion GB, Hunt Jr. ER, Diaz-Soltero H. 2011a. Invasive species and climate change:
37 an agronomic perspective. *Climatic Change* 105:13-42.
- 38 Ziska LH. 2000. The impact of elevated carbon dioxide on yield loss from a C3 and C4 weed in field grown
39 soybean. *Global Change Biol.* **6**:899-905.
- 40 Ziska LH. 2003. Evaluation of yield loss in field sorghum from a C3 and C4 weed with increasing CO₂.
41 *Weed Sci.* **51**:914-918.

42 43 44 Additional references (AJC) section 7.3

- 45
46 Archambault DJ 2007. Efficacy of herbicides under elevated temperature and CO₂. In: *Agroecosystems in a*
47 *Changing Climate*, (Newton PCD, Carran A, Edwards GR, Niklaus PA, eds.), CRC Press, Boston, MA , pp
48 262-279.
- 49 Bradley BA, Blumenthal DM, Wilcove DS, Ziska LH. 2010. Predicting plant invasions in an era of global change.
50 *TREE* 25:310-318.
- 51 Dukes JS, Mooney HA 2000. Does global change increase the success of biological invaders? *Trends in Ecology*
52 *and Evolution*, 14, 135-139.
- 53 McDonald AJ, Riha SJ, DiTommaso A, DeGaetano AT. 2009. Climate change and the geography of weed damage:
54 analysis of U.S. maize systems suggests the potential for significant range transformations.

- 1 *Agric. Ecosyst. Environ.* **130**:131–140.
- 2 Manea A, Leishman MR, Downey PO 2011. Exotic C4 Grasses have increased tolerance to glyphosate under
3 elevated carbon dioxide. *Weed Science* 59:28-36.
- 4 Oerke EC. 2006. Crop losses to pests. *J. Agric. Sci.* 144:31–43.
- 5 Treharne K. 1989. The implications of the ‘greenhouse effect’ for fertilizers and agrochemicals. In: Bennet RC, Ed.
6 The Greenhouse Effect and UK Agriculture. CAS Paper 19. Ministry of Agriculture, Fisheries and Food, UK, p
7 57-78.
- 8 Rejmanek M 1996. A theory of seed plant invasiveness: the first sketch. *Biol Conserv* 78:171-181.
- 9 Taylor CA, Ralphs, MH. 1992. Reducing livestock losses from poisonous plants through grazing management.
10 *Journal of Range Management* 45: 9-12.
- 11 Ziska, LH. 2010. Global Climate Change and Carbon Dioxide: Assessing Weed Biology and Management. In:
12 *Handbook of climate change and agro-ecosystems: Impacts, adaptation and mitigation.* (eds., Rosenzweig C,
13 Hillel D), World Scientific Publishing, Hackensack, NJ, pages 191-208.
- 14 Ziska LH, Faulkner SS, Lydon J. 2004. Changes in biomass and root:shoot ratio of field-grown Canada thistle
15 (*Cirsium arvense*), a noxious, invasive weed, with elevated CO₂: implications for control with glyphosate. *Weed*
16 *Science* 52:584-588.
- 17 Ziska LH, Knowlton K, Rogers C, et al. 2011. Recent warming by latitude associated with increased
18 length of ragweed pollen season in central North America. *Proc Nat Acad Sci. USA*, 108:4248-4251.
- 19 Challinor et al 2009BAMS,
20 Hawkins et al., 2012 AFM special issue
- 21 Leakey et al, in press. A multi-biome gap in understanding of crop and ecosystem responses to elevated CO₂
22 Andrew DB Leakey^{1,3}, Kristen A Bishop¹ and Elizabeth A Ainsworth^{1,2,3}. *Current opinion in plant biology*.
23 White et al. (2011). *Field Crops Research* Volume 124, Issue 3, 20 December 2011, Pages 357–368 Methodologies
24 for simulating impacts of climate change on crop production Jeffrey W. Whitea, , Gerrit Hoogenboom, 1,
25 Bruce A. Kimballa, Gerard W. Walla
- 26 Craufurd et al, in press. Crop science experiments designed to inform crop modeling Original Research Article
27 In Press, Corrected Proof, Available online 28 September 2011
- 28 Peter Q. Craufurd, Vincent Vadez, S.V. Krishna Jagadish, P.V. Vara Prasad, M. Zaman-Allah
29 Joshi et al. (2011)

30
31

32 Additional references (AJC) section 7.4

33
34
35
36
37
38
39

- Lloyd et al. Climate Change, Crop Yields, and Undernutrition: Development of a Model to Quantify the Impact of
Climate Scenarios on Child Undernutrition. Simon J. Lloyd, R. Sari Kovats, and Zaid Chalabi. *Environmental
Health Perspectives* • volume 119 | number 12 | December 2011 1817. *Environ Health Perspect* 119:1817–1823
(2011). <http://dx.doi.org/10.1289/ehp.1003311> [Online 15 August 2011].

40
41

42 Additional references (KG) section 7.4

- 43 Bearchell SJ, Fraaije BA, Shaw MW, Fitt BD. 2005. Wheat archive links long-term fungal pathogen population
44 dynamics to air pollution. *Proceedings of the National Academy of Sciences of the USA* 102:5438–42.
- 45 Bergot M, Cloppet E, Pérnaud V, Déqué M, Marçais B, Desprez-Loustau M. 2004. Simulation of potential range
46 expansion of oak disease caused by *Phytophthora cinnamomi* under climate change. *Global Change Biology*
10:1539–52.
- 47 Chakraborty, S., J. Luck, G. Hollaway, A. Freeman, R. Norton, K. A. Garrett, K. Percy, A. Hopkins, C. Davis, and
48 D. F. Karnosky. 2008. Impacts of global change on diseases of agricultural crops and forest trees. *CAB
49 Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 3:054.
- 50 Chakraborty, S., and A. C. Newton. 2011. Climate change, plant diseases and food security: an overview. *Plant
51 Pathology* 60:2-14.
- 52 Coakley SM, Scherm H, Chakraborty S, 1999. Climate change and plant disease management. *Annual Review of
53 Phytopathology* 37, 399–426.
- 54 Deutsch CA, Tewksbury JJ, Huey RB, Sheldon KS, Ghalambor CK, Haak DC, Martin PR (2008) Impacts of climate

- 1 warming on terrestrial ectotherms across latitude. Proceedings of the National Academy of Sciences of the
2 United States of America, 105, 6668–6672.
- 3 De Wolf ED, Isard SA, 2007. Disease cycle approach to plant disease prediction. Annual Review of Phytopathology
4 45, 203–20.
- 5 Eastburn, D. M., A. J. McElrone, D. D. Bilgin. 2011. Influence of atmospheric and climatic change on plant-
6 pathogen interactions. Plant Pathology 60:54–69.
- 7 Garrett KA, Dendy SP, Frank EE, Rouse MN, Travers SE, 2006. Climate change effects on plant disease: genomes
8 to ecosystems. Annual Review of Phytopathology 44, 489–509.
- 9 Garrett, K. A., G. A. Forbes, S. Savary, P. Skelsey, A. H. Sparks, C. Valdivia, A. H. C. van Bruggen, L. Willocquet,
10 A. Djurle, E. Duveiller, H. Eckersten, S. Pande, C. Vera Cruz, and J. Yuen. Complexity in climate-change
11 impacts: an analytical framework for effects mediated by plant disease. Plant Pathology 60:15–30.
- 12 Garrett KA, Zuñiga LN, Roncal E et al., 2009b. Intraspecific functional diversity in hosts and its effect on disease
13 risk across a climatic gradient. Ecological Applications 19, 1868–83.
- 14 Ghini R, Hamada E, Pedro MJ, Marengo JA, Gonçalves RRV. 2008. Risk analysis of climate change on coffee
15 nematodes and leaf miner in Brazil. Pesquisa Agropecuária Brasileira 43:187–95.
- 16 Gregory PJ, Johnson SN, Newton AC, Ingram JSI (2009) Integrating pests and pathogens into the climate
17 change/food security debate. Journal of Experimental Botany, 60, 2827–2838.
- 18 Hannukkala AO, Kaukoranta T, Lehtinen A, Rahkonen A. 2007. Late-blight epidemics on potato in Finland, 1933–
19 2002; increased and earlier occurrence of epidemics associated with climate change and lack of rotation. Plant
20 Pathology 56:167–76.
- 21 Juroszek, P., and A. von Tiedemann. 2011. Potential strategies and future requirements for plant disease
22 management under a changing climate. Plant Pathology 60:100–112.
- 23 Luck, J., M. Spackman, A. Freeman, P. Trebicki, W. Griffiths, K. Finlay, and S. Chakraborty. 2011. Climate change
24 and diseases of food crops. Plant Pathology 60:113–121.
- 25 Luedeling, E., K. P. Steinmann, M. Zhang, P. H. Brown, J. Grant, and E. H. Girvetz. 2011. Climate change effects
26 on walnut pests in California. Global Change Biology 17: 228–238.
- 27 Mahmuti M, West JS, Watts J, Gladders P, Fitt BDL, 2009. Controlling crop disease contributes to both food
28 security and climate change mitigation. International Journal of Agricultural Sustainability 7, 189–202.
- 29 Miraglia M, Marvin HJP, Kleter GA et al., 2009. Climate change and food safety: an emerging issue with special
30 focus on Europe. Food and Chemical Toxicology 47, 1009–21.
- 31 Oerke EC, 2006. Crop losses to pests. Journal of Agricultural Science 144, 31–43.
- 32 Paulson MD, Houston AI, McNamara JM, Payne RJH (2009) Seasonal dispersal of pests: one surge or two? Journal
33 of Evolutionary Biology, 22, 1193–1202.
- 34 Pautasso, M., K. Dehnen-Schmutz, O. Holdenrieder, S. Pietravalle, N. Salama, M. J. Jeger, E. Lange, and S. Hehl-
35 Lange. 2010. Plant health and global change – some implications for landscape management. Biological
36 Reviews 85:729–755.
- 37 Pritchard SG, 2011. Soil organisms and global climate change. Plant Pathology 60, 82–99.
- 38 Savary S, Castilla NP, Elazegui FA, Teng PS, 2005. Multiple effects of two drivers of agricultural change, labour
39 shortage and water scarcity, on rice pest profiles in tropical Asia. Field Crops Research 91, 263–71.
- 40 Scherm H, Yang XB. 1995. Interannual variations in wheat rust development in China and the United States in
41 relation to the El Niño/Southern Oscillation. Phytopathology 85:970–6.
- 42 Shaw MW, Bearchell SJ, Fitt BDL, Fraaije BA. 2008. Long-term relationships between environment and abundance
43 in wheat of *Phaeosphaeria nodorum* and *Mycosphaerella graminicola*. New Phytologist 177:229–38.
- 44 Sparks, A. H., G. A. Forbes, R. H. Hijmans, and K. A. Garrett. The global risk of potato late blight under climate
45 change. IN REVIEW.
- 46 Woods A, Coates DK, Hamann A. 2005. Is an unprecedented Dothistroma needle blight epidemic related to climate
47 change? Bioscience 55:761–9.
- 48
49

50 Additional references (MT) section 7.3.2.1

- 51
52 Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht,
53 M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud, 2011: Bioenergy. In IPCC Special Report
54 on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona,

1 K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow
2 (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
3
4

5 Additional references (DL) section 7.2
6

- 7 Abbott, P.C., Hurt, C. and Tyner, W.E., 2008. What's driving food prices?, Farm Foundation.
8 Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A., Haylock, M., Collins, D.,
9 Trewin, B. and Rahimzadeh, F., 2006. Global observed changes in daily climate extremes of temperature and
10 precipitation. *J. Geophys. Res.*, 111: D05109, doi:10.1029/2005JD006290.
11 Amthor, J.S., 2001. Effects of atmospheric co2 concentration on wheat yield: Review of results from experiments
12 using various approaches to control co2 concentration. *Field Crops Research*, 73(1): 1-34.
13 Auffhammer, M., Ramanathan, V. and Vincent, J.R., 2006. Integrated model shows that atmospheric brown clouds
14 and greenhouse gases have reduced rice harvests in india. *Proceedings of the National Academy of Sciences*,
15 103(52): 19668-19672.
16 Auffhammer, M., Ramanathan, V. and Vincent, J.R., 2012. Climate change, the monsoon, and rice yield in india.
17 *Climatic Change*: 1-14.
18 Bell, M.A. and Fischer, R.A., 1994. Using yield prediction models to assess yield gains - a case study for wheat.
19 *Field Crops Research*, 36(2): 161-166.
20 Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.-X. and Huard, F., 2010. Why are wheat yields stagnating
21 in europe? A comprehensive data analysis for france. *Field Crops Research*, 119(1): 201-212.
22 Chen, C., Lei, C., Deng, A., Qian, C., Hoogmoed, W. and Zhang, W., 2011. Will higher minimum temperatures
23 increase corn production in northeast china? An analysis of historical data over 1965–2008. *Agricultural and*
24 *Forest Meteorology*, 151(12): 1580-1588.
25 Chen, C., Wang, E., Yu, Q. and Zhang, Y., 2010. Quantifying the effects of climate trends in the past 43 years
26 (1961–2003) on crop growth and water demand in the north china plain. *Climatic Change*, 100(3): 559-578.
27 Christidis, N., Stott, P.A., Brown, S., Hegerl, G.C. and Caesar, J., 2005. Detection of changes in temperature
28 extremes during the second half of the 20th century. *Geophys. Res. Lett.*, 32.
29 FAO, 2008. Policy measures taken by government to reduce the impact of soaring prices. *Global Information and*
30 *Early Warning System*.
31 Fishman, J., Creilson, J.K., Parker, P.A., Ainsworth, E.A., Vining, G.G., Szarka, J., Booker, F.L. and Xu, X., 2010.
32 An investigation of widespread ozone damage to the soybean crop in the upper midwest determined from
33 ground-based and satellite measurements. *Atmospheric Environment*, 44(18): 2248-2256.
34 Garcia, P., Irwin, S.H., Leuthold, R.M. and Yang, L., 1997. The value of public information in commodity futures
35 markets. *Journal of Economic Behavior & Organization*, 32(4): 559-570.
36 Jaggard, K., Qi, A. and Semenov, M., 2007. The impact of climate change on sugarbeet yield in the uk: 1976–2004.
37 *The Journal of Agricultural Science*, 145(04): 367-375.
38 Kucharik, C.J. and Serbin, S.P., 2008. Impacts of recent climate change on wisconsin corn and soybean yield trends.
39 *Environmental Research Letters*, 3: 034003.
40 Liu, Y., Wang, E., Yang, X. and Wang, J., 2009. Contributions of climatic and crop varietal changes to crop
41 production in the north china plain, since 1980s. *Global Change Biology*, 9999(999A).
42 Lobell, D.B., Bonfils, C. and Duffy, P.B., 2007. Climate change uncertainty for daily minimum and maximum
43 temperatures: A model inter-comparison. *Geophysical Research Letters*, 34: L05715,
44 doi:10.1029/2006GL028726.
45 Lobell, D.B. and Field, C.B., 2007. Global scale climate-crop yield relationships and the impacts of recent warming.
46 *Environmental Research Letters*, 2: 004000 (7pp).
47 Lobell, D.B., Ortiz-Monasterio, J.I., Asner, G.P., Matson, P.A., Naylor, R.L. and Falcon, W.P., 2005. Analysis of
48 wheat yield and climatic trends in mexico. *Field Crops Research*, 94(2-3): 250-256.
49 Lobell, D.B., Schlenker, W.S. and Costa-Roberts, J., 2011. Climate trends and global crop production since 1980.
50 *Science*, 333(6042): 616-620.
51 Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nosberger, J. and Ort, D.R., 2006. Food for thought: Lower-than-
52 expected crop yield stimulation with rising co2 concentrations. *Science*, 312(5782): 1918-1921.
53 Ludwig, F., Milroy, S. and Asseng, S., 2009. Impacts of recent climate change on wheat production systems in
54 western australia. *Climatic Change*, 92(3): 495-517.

- 1 McGrath, J. and Lobell, D.B., 2011. An independent method of deriving the carbon dioxide fertilization effect in dry
2 conditions using historical yield data from wet and dry years. *Global Change Biology*, in press.
- 3 Mills, G., Buse, A., Gimeno, B., Bermejo, V., Holland, M., Emberson, L. and Pleijel, H., 2007. A synthesis of
4 aot40-based response functions and critical levels of ozone for agricultural and horticultural crops. *Atmospheric*
5 *Environment*, 41(12): 2630-2643.
- 6 Min, S.-K., Zhang, X., Zwiers, F.W. and Hegerl, G.C., 2011. Human contribution to more-intense precipitation
7 extremes. *Nature*, 470(7334): 378-381.
- 8 Morgan, P.B., Mies, T.A., Bollero, G.A., Nelson, R.L. and Long, S.P., 2006. Season long elevation of ozone
9 concentration to projected 2050 levels under fully open air conditions substantially decreases the growth and
10 production of soybean. *New Phytologist*, 170(2): 333-343.
- 11 Naylor, R.L. and Falcon, W.P., 2010. Food security in an era of economic volatility. *Population and Development*
12 *Review*, 36(4): 693-723.
- 13 Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A.,
14 Aggarwal, H.P., Das, D.K. and Gupta, R.K., 2003. Trends of climatic potential and on-farm yields of rice and
15 wheat in the indo-gangetic plains. *Field Crops Research*, 80(3): 223-234.
- 16 Peng, S., Huang, J., Sheehy, J., Laza, R., Visperas, R., Zhong, X., Centeno, G., Khush, G. and Cassman, K., 2004.
17 Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy*
18 *of Sciences of the United States of America*, 101(27): 9971-9975.
- 19 Porter, J.R. and Gawith, M., 1999. Temperatures and the growth and development of wheat: A review. *European*
20 *Journal of Agronomy*, 10(1): 23-36.
- 21 Roberts, M. and Schlenker, W., 2010. Identifying supply and demand elasticities of agricultural commodities:
22 Implications for the us ethanol mandate, NBER Working Paper No. 15921.
- 23 Rosenzweig, C., Tubiello, F.N., Goldberg, R., Mills, E. and Bloomfield, J., 2002. Increased crop damage in the us
24 from excess precipitation under climate change. *Global Environmental Change-Human and Policy Dimensions*,
25 12(3): 197-202.
- 26 Schlenker, W. and Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to u.S. Crop yields
27 under climate change. *Proceedings of the National Academy of Sciences*, 106(37): 15594-15598
- 28 Tao, F., Yokozawa, M., Liu, J. and Zhang, Z., 2008. Climate-crop yield relationships at provincial scales in china
29 and the impacts of recent climate trends. *Clim Res*, 38(1): 83-94.
- 30 Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y. and Zhang, Z., 2006. Climate changes and trends in phenology and
31 yields of field crops in china, 1981-2000. *Agricultural and Forest Meteorology*, 138(1-4): 82-92.
- 32 Van Dingenen, R., Dentener, F.J., Raes, F., Krol, M.C., Emberson, L. and Cofala, J., 2009. The global impact of
33 ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment*,
34 43(3): 604-618.
- 35 Wang, H.L., Gan, Y.T., Wang, R.Y., Niu, J.Y., Zhao, H., Yang, Q.G. and Li, G.C., 2008. Phenological trends in
36 winter wheat and spring cotton in response to climate changes in northwest china. *Agricultural and Forest*
37 *Meteorology*, 148(8-9): 1242-1251.
- 38 Wassmann, R., Jagadish, S.V.K., Heuer, S., Ismail, A., Redona, E., Serraj, R., Singh, R.K., Howell, G., Pathak, H.
39 and Sumfleth, K., 2009. Climate change affecting rice production: The physiological and agronomic basis for
40 possible adaptation strategies. *Advances in Agronomy*.
- 41 Welch, J.R., Vincent, J.R., Auffhammer, M., Moya, P.F., Dobermann, A. and Dawe, D., 2010. Rice yields in
42 tropical/subtropical asia exhibit large but opposing sensitivities to minimum and maximum temperatures.
43 *Proceedings of the National Academy of Sciences*, 107(33): 14562.
- 44 Wright, B.D., 2011. The economics of grain price volatility. *Applied Economic Perspectives and Policy*, 33(1): 32.
- 45 You, L., Rosegrant, M., Wood, S. and Sun, D., 2009. Impact of growing season temperature on wheat productivity
46 in china. *Agricultural and Forest Meteorology*, 149(6-7): 1009-1014.
- 47 Zhang, T., Zhu, J., Yang, X. and Zhang, X., 2008. Correlation changes between rice yields in north and northwest
48 china and enso from 1960 to 2004. *Agricultural and Forest Meteorology*, 148(6-7): 1021-1033.
- 49 Zwiers, F.W., Zhang, X. and Feng, Y., 2011. Changes in the extremes of the climate simulated by ccc gcm2 under
50 co2 doubling. *Journal of Climate*: in press.

51
52
53
54

1 Additional references (LL) for 7.3.3.1

- 2
- 3 Ainsworth, E. and J.M. McGrath. 2010. Direct effects of rising atmospheric carbon dioxide and ozone on crop
4 yields. *Global Change Research* 37: 109-130.
- 5 Aksoy, A. and A. Isik-Dikmelik. 2008. Are Low Food Prices Pro-Poor? Net Food Buyers and Sellers in Low-
6 Income Countries. *World Bank Policy Research Working Paper No. 4642*.
- 7 Alderman, H. 2010. Safety nets can help address the risks to nutrition from increasing climate variability. *The*
8 *Journal of Nutrition* 140: 143-7.
- 9 Antle, J.M. and C.C. Crissman. 1990. Risk, Efficiency, and the Adoption of Modern Crop Varieties: Evidence from
10 the Philippines. *Economic Development and Cultural Change*, 38(3): 517-537.
- 11 Battisti, D. S. and R.L. Naylor. 2009. Historical Warnings of Future Food Insecurity with Unprecedented Seasonal
12 Heat. *Science* 323: 240-44.
- 13 Brinkman H.J., De Pee S. Aanogao I. Subran L., Bloem MW 2010. High food prices and the global financial crisis
14 have reduced access to nutritious food and worsened nutritional status and health. *Journal of Nutrition* 140: 153-
15 161.
- 16 Bloem, M.W., R. Semba and K. Kraemer. 2010. Caster Gandolfo Workshop: An Introduction to the Impact of
17 Climate Change, the Economic Crisis and the Increases in the Food Prices on Malnutrition. *Journal of Nutrition*
18 140: 132s-135s.
- 19 Brinkman, H.J., S. de Pee, I. Aanogao, L. Subran and M.W. Bloem. 2010. High food prices and the global financial
20 crisis have reduced access to nutritious food and worsened nutritional status and health. *Journal of Nutrition*
21 140: 153-161.
- 22 Brown, M., B. Hinterman and N. Higgins. 2009. Markets, Climate Change, and Food Security in West Africa.
23 *Environmental Science and Technology* 43: 8016-8020.
- 24 Caldazilla, A., K. Rehdanz, R. Betts, P. Falloon, A. Wiltshire and R.S.J. Tol. 2010. Climate Change Impacts on
25 Global Agriculture. Kiel Institute for the World Economy.
- 26 Campbell, A.A., S. de Pee, K. Sun, K. Kraemer, A. Thorne-Olyman, R. Moench-Pfanner, M. Sari, N. Akhter, M.W.
27 Bloem and R.D. Semba. 2010. Household rice expenditure and maternal and child nutritional status in
28 Bangladesh. *Journal of Nutrition* 140: 189-194.
- 29 Carter, M.R. and C.B. Barrett. 2006. The economics of poverty traps and persistent poverty: An asset-based
30 approach. *Journal of Development Studies*, 42:178-199.
- 31 Dercon, S. 2004. Growth and shocks: evidence from rural Ethiopia. *Journal of Development Economics* 74(2): 309-
32 329.
- 33 Dercon, S. and L. Christiaensen. 2011. Consumption risk technology adoption and poverty traps: evidence from
34 Ethiopia. *Journal of Development Economics* 96(2): 159-173.
- 35 Erda, L., X. Wei, J. Hui, X. Yinlong, L. Yue, B. Liping and X. Liyong. 2005. Climate change impacts on crop yield
36 and quality with CO₂ fertilization in China. *Philosophical Transactions of the Royal Society London B*
37 *Biological Sciences* 360: 2149-2154.
- 38 Fafchamps, M. 1992. Solidarity Networks in Pre-Industrial Societies: Rational Peasants with a Moral Economy.
39 *Economic Development and Cultural Change*, 41(1): 147-174.
- 40 Fafchamps, M. 1999, "Rural Poverty, Risk and Development", *Economic and Social Development Paper*, no. 144.
41 Rome: Food and Agriculture Organization.
- 42 Fafchamps, M. 2009. Vulnerability, Risk Management, and Agricultural Development. *Agriculture for*
43 *Development*, Center of Evaluation for Global Action, Working Paper Series No. AfD-0904 July. UC Berkeley.
- 44 FAO 2006. Food Security. Policy Brief, Issue 2 June. Food and Agriculture Organization of the United Nations,
45 Rome. ftp://ftp.fao.org/es/esa/policybriefs/pb_02.pdf
- 46 FAO 2008. Challenges for Sustainable Land management (SLM) for Food Security in Africa. Twenty-fifth Regional
47 Conference for Africa. Nairobi, Kenya, 16-20 June 2008. Food and Agriculture Organization of the United
48 Nations (FAO), Rome.
- 49 FAO 2011. The state of food insecurity in the world: How does international price volatility affect domestic
50 economies and food security? Food and Agriculture Organization of the United Nations, Rome.
- 51 FAO 2012 Stability of Food Security in a Green Economy Environment. FAO GEA Working Paper 3. February
52 2012 FAO Rome. Available at:..
- 53 Feder, G., R. Just, and D. Zilberman. 1985. Adoption of Agricultural Innovations in Developing Countries: A
54 Survey. *Economic Development and Cultural Change*, 33(2): 255-298.

- 1 Frankenger et al. 1999
- 2 Hatfield, J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson and D. Wolfe. 2011.
- 3 Climate impacts on agriculture: Implications for crop production. *Agronomy Journal* 103:351-370.
- 4 Heltberg, R. and F. Tarp. 2002. Agricultural Supply Response and Poverty in Mozambique. *Food Policy*, 27: 103-
- 5 124.
- 6 Hertl, T.W., M.B. Burke and D.B. Lobell. 2010. The poverty implications of climate-induced crop yield changes by
- 7 2030. *Global Environment Change* 20: 577-585.
- 8 Hill, R.V. and A. Viceisza. 2010. An experiment on the impact of weather shocks and insurance on risky
- 9 investment. IFPRI discussion papers 974. International Food Policy Research Institute (IFPRI).
- 10 HLPE 2012. Food Security and Climate Change: A zero draft consultation paper. Committee on World Food
- 11 Security. High-level Panel of Experts (HLPE) on Food Security and Nutrition. www.fao.org/cfs/cfs-hlpe
- 12 Hoddinott, J.
- 13 Hoddinott and Maluccio 2002
- 14 Hurley, T. 2010. A Review of Agricultural Production Risk in the Developing World. Harvest Choice Working
- 15 Paper 11. Washington, DC: International Food Policy Research Institute.
- 16 Karfakis, P., M. Knowles, M. Smulders and J. Capaldo. 2011. Effects of Global Warming on Vulnerability to Food
- 17 Insecurity in Rural Nicaragua. ESA-FAO WP series No. 11-18.
- 18 Kurosaki, T. and M. Fafchamps. 2002. Insurance Market Efficiency and Crop Choices in Pakistan. *Journal of*
- 19 *Development Economics*, 67: 419-453.
- 20 M.A. Aksoy and A. Isid-Dikmelik. 2008. Are low food prices pro-poor? Net food buyers and sellers in low-income
- 21 countries. Policy Research Working Paper 4642. Washington, DC, World Bank.
- 22 Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, et al. 2010. Food
- 23 Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options. International Food Policy
- 24 Research Institute (IFPRI), Washington, D.C.
- 25 Prakash, A. 2011. Why volatility matters In: A. Prakash (ed.) Safeguarding food security in volatile global markets.
- 26 Food and Agriculture Organization of the United Nations (FAO), Rome.
- 27 Roe, T. and T. Graham-Tomasi. 1986 "Yield risk in a dynamic model of the agricultural household," in Singh, I. L,
- 28 Squire and J. Strauss, *Agricultural Household Models: Extension, Applications and Policy*, Johns Hopkins
- 29 University Press, Baltimore, MD.
- 30 Roson, R. and D. van der Mensbrugge, 2010. Climate Change and Economic Growth: Impacts and Interactions.
- 31 University Ca' Foscari of Venice, Department of Economics Research Paper Series No. 07_10.
- 32 Rosenzweig, M.R. and H.P. Binswanger. 1993. Wealth, Weather Risk and the Composition and Profitability of
- 33 Agricultural Investments. *Economic Journal*, 103(416) : 56-78.
- 34 Sadoulet, E. and A. de Janvry. 1995. "Behavior and Welfare Under Risk". Chapter 5, In: *Quantitative Development*
- 35 *Policy Analysis*. Baltimore, MD: Johns Hopkins University Press.
- 36 Sari M., de Pee S., Bloem M.W., Sun K., Thorne-Lymeane A., Moench-Pfanner R., Akhter N., Kraemer K., Semba
- 37 R.D., 2010 Higher household expenditure on Animal Source and nongrain foods lowers the risk of stunting
- 38 among children 0-59 month old in Indonesia: implications of rising food prices. *J Nutr* 140: 195-200.
- 39 Schmidhuber, J. and F.N. Tubiello. 2007. Global food security under climate change. *Proceedings of the National*
- 40 *Academy of Sciences of the United States of America (PNAS)* 104, 19703-19708.
- 41 Skees, J. and A. Enkh-Amgalan. 2002. Examining the Feasibility of Livestock Insurance in Mongolia. World Bank
- 42 Policy Research Working Paper 2886. Washington, DC: World Bank.
- 43 Skees, J., P. Hazell, and M. Miranda. 1999. New Approaches to Crop Yield Insurance in Developing Countries.
- 44 EPTD Discussion Paper No. 55. Washington, DC: International Food Policy Research Institute.
- 45 Skoufias and Quisumbing 2005
- 46 SREX 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX).
- 47 Special Report of the Intergovernmental Panel on Climate Change (IPCC).
- 48 World Bank 2008. World Development Report 2008: Agriculture for Development. The International Bank for
- 49 Reconstruction and Development/The World Bank. Washington, D.C.
- 50
- 51 Alessa, L., Kliskey, A., Williams, P., Barton, M. 2008. Perception of change in freshwater in remote resource-
- 52 dependent Arctic communities. *Global Environ Chang*, Vol. 18, pp. 153-164.

- 1 Biazin, B., G. Sterk, M. Temesgen, A. Abdulkedir, L. Stroosnijder. 2011. Rainwater harvesting and management in
2 rainfed agricultural systems in sub-Saharan Africa – A review. *Physics and Chemistry of the Earth* xxx (2011)
3 xxx–xxx
- 4 Ford, D.J. 2009. Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: a case
5 study from Igloodik, Nunavut. *Reg Environ Change* (2009) 9:83–100
- 6 Green, D., J. Billy, A. Tapim. 2010. Indigenous Australians’ knowledge of weather and climate. *Climatic Change*
7 (2010) 100:337–354. DOI 10.1007/s10584-010-9803-z
- 8
- 9 Goodman-Elgar, M. 2008. Evaluating soil resilience in long-term cultivation: a study of pre-Columbian terraces
10 from the Paca Valley, Peru. *Journal of Archaeological Science* 35 (2008) 3072–3086
- 11 Kalanda-Joshua, M., C. Ngongondo, L. Chipeta, F. Mpembeka. 2011. Integrating indigenous knowledge with
12 conventional science: Enhancing localised climate and weather forecasts in Nessa, Mulanje, Malawi. *Physics*
13 *and Chemistry of the Earth* 36 (2011) 996–1003
- 14 Marin, A. 2010. Riders under storms: Contributions of nomadic herders’ observations to analyzing climate change
15 in Mongolia. *Global Environmental Change* 20 (2010) 162–176
- 16 Nakashima, D.J., Galloway McLean, K., Thulstrup, H.D., Ramos Castillo, A. and Rubis, J.T. 2011. *Indigenous*
17 *Knowledge, Marginalized Peoples and Climate Change: Foundations for Assessment and Adaptation*.
18 Technical Report prepared for the Intergovernmental Panel on Climate Change – Working Group II.
19 UNESCO/UNU: Paris/Darwin.
- 20 Nyong A, F. Adesina, B. Osman Elasha, 2007. The value of indigenous knowledge in climate change mitigation and
21 adaptation strategies in the African Sahel. *Mitig Adapt Strat Glob Change* (2007) 12:787–797 DOI
22 10.1007/s11027-007-9099-0
- 23 Renard, D., J. Iriarte, J.J. Birk, S. Rostain, B. Glaser, D. McKey. 2011. Ecological engineers ahead of their time: The
24 functioning of pre-Columbian raised-field agriculture and its potential contributions to sustainability today.
25 *Ecological Engineering* xxx (2011) xxx–xxx
- 26 Rengalakshmi, R., 2007. Localized climate forecasting system: seasonal climate and weather prediction for farm-
27 level decision-making. In: Sivakumar, M.V.K., Hansen, J. (Eds.), *Climate Prediction and Agriculture: Advances*
28 *and Challenges*. World Meteorological Organization. Springer-Verlag, Berlin Heidelberg
- 29
- 30
- 31 Additional references (MH) for 7.5.3
- 32
- 33 Salick, J; N., Ross, 2009. Introduction .Traditional peoples and climate change *Global Environmental Change* 19
34 (2009) 137–139
- 35 Speranza, Ch.I, B. Kiteme, P. Ambenje, U. Wiesmann, S. Makali, 2010. Indigenous knowledge related to climate
36 variability and change: insights from droughts in semi-arid areas of former Makeni District, Kenya. *Climatic*
37 *Change* (2010) 100:295–315. DOI 10.1007/s10584-009-9713-0
- 38 Alcamo, J., N. Dronin, M. Endejan, G. Golubev, A. Kirilenko. A new assessment of climate change impacts on food
39 production shortfalls and water availability in Russia. *Global Environmental Change* 17 (2007) 429–444
- 40 Bindi, M, J.E. Olesen. 2011. The responses of agriculture in Europe to climate change. *Reg Environ Change* (2011)
41 11 (Suppl 1):S151–S158
- 42 Chen, Ch., Ch. Qian, Ch., A. Deng, W. Zhang. 2011. Progressive and active adaptations of cropping system to
43 climate change in Northeast China. *Eur. J. Agron.* (2011), doi:10.1016/j.eja.2011.07.003
- 44 Dronin, N., A. Kirilenko. 2011. Climate change, food stress, and security in Russia. *Reg Environ Change* (2011) 11
45 (Suppl 1):S167–S178
- 46 Kulshreshtha, S. N. 2011. Climate Change, Prairie Agriculture, and Prairie
47 Economy: The New Normal. *Canadian Journal of Agricultural Economics* 59 (2011) 19–44
- 48 Kvalvik, I, Sigridur Dalmannsdottir, Halvor Dannevig, Grete Hovelsrud, Lars Rønning & Eivind Uleberg (2011):
49 Climate change vulnerability and adaptive capacity in the agricultural sector in Northern Norway, *Acta*
50 *Agriculturae Scandinavica*, Section B - Soil & Plant Science, 61:sup1, 27-37
- 51 Odgaard, M.V., P. K. Bøcher, T. Dalgaard, J-Ch. Svenning. 2011. Climatic and non-climatic drivers of
52 spatiotemporal maize-area dynamics across the northern limit for maize production— A case study from
53 Denmark. *Agriculture, Ecosystems and Environment* 142 (2011) 291– 302

- 1 Tchebakova, N.M., E. I. Parfenova, G I Lysanova and A J Soja. 2011. Agroclimatic potential across central Siberia
2 in an altered twenty-first century Environ. Res. Lett. 6 (2011) 045207
- 3 Cochrane, K.L., W. Emerson and R. Willmann. 2009. Sustainable Fisheries: The Importance of the Bigger Picture.
4 In Eds W. W. Taylor, A. J. Lynch and M. G. Schechter, *Sustainable Fisheries: Multi-Level Approaches to a*
5 *Global Problem*. Herndon, VA, American Fisheries Society. pp 3–19
- 6 Rosenberg1, A.A. and K. L. McLeod. 2005. Implementing ecosystem-based approaches to management for the
7 conservation of ecosystem services. *Mar. Ecol. Prog. Ser.* 300: 270-274.
- 8 Welcomme, Robin, L., Ian G. Cowx, David Coates, Christophe Béné, Simon Funge-Smith, Ashley Halls and Kai
9 Lorenzen. 2010. Inland capture fisheries . *Phil. Trans. R. Soc. B.* 365, 2881-2896.
- 10 Park, S.E., Marshall, N., Jakku, E., Dowd, A.M., Howden, S.M., Mendham, E., Fleming, A. (2012) Informing
11 adaptation responses to climate change through theories of transformation. *Global Environmental Change*,
12 22(1):115-126
- 13 Rickards, L., Howden, S.M. (2011) Transformational Adaptation to climate change. *Crop and Pasture Science* (in
14 press)
- 15 Nidumolu, U.B., Hayman, P.T., Howden, S.M., & Alexander, B.M. (2012) Re-evaluating the margin of the South
16 Australia grain belt in a changing climate. *Climate Research* 51: 249-260. DOI: 10.3354/cr01075.
- 17 Nelson, R., Howden, S.M. and Stafford Smith M., 2008. Using adaptive governance to rethink the way science
18 supports Australian drought policy. *Environmental Science & Policy* 11: 588-601.
- 19 Howden, S.M., Crimp, S.J. and Stokes, C.J. (2008) Climate change and its effect on Australian livestock systems.
20 *Aust. J. Experimental Agriculture*, 40:780-788.
- 21 Howden, S.M., Soussana, J.F., Tubiello, F.N., Chhetri, N., Dunlop, M., and Meinke, H.M. (2007) Adapting
22 agriculture to climate change. *Proceedings of the National Academy of Sciences*, 104:19691-19696.
- 23 Howden SM, Crimp SJ and Nelson RN (2010) Australian agriculture in a climate of change. In Jubb I, Holper P and
24 Cai W (Eds) *Managing Climate Change: Papers from the GREENHOUSE 2009 Conference*. CSIRO
25 Publishing, Melbourne. pp 101-111
- 26 Battaglini A, Barbeau G., Bindi M., Badeck FW (2009) European winegrowers' perceptions of climate change
27 impact and options for adaptation. *Regional Environmental Change* 9:61–73.
- 28 McCrum G, Blackstock K, Matthews K, Rivington M, Miller D, Buchan K (2009) Adapting to Climate Change in
29 Land Management: the Role of Deliberative Workshops in Enhancing Social Learning. *Environmental Policy*
30 and Governance, 19, 413–426.
- 31

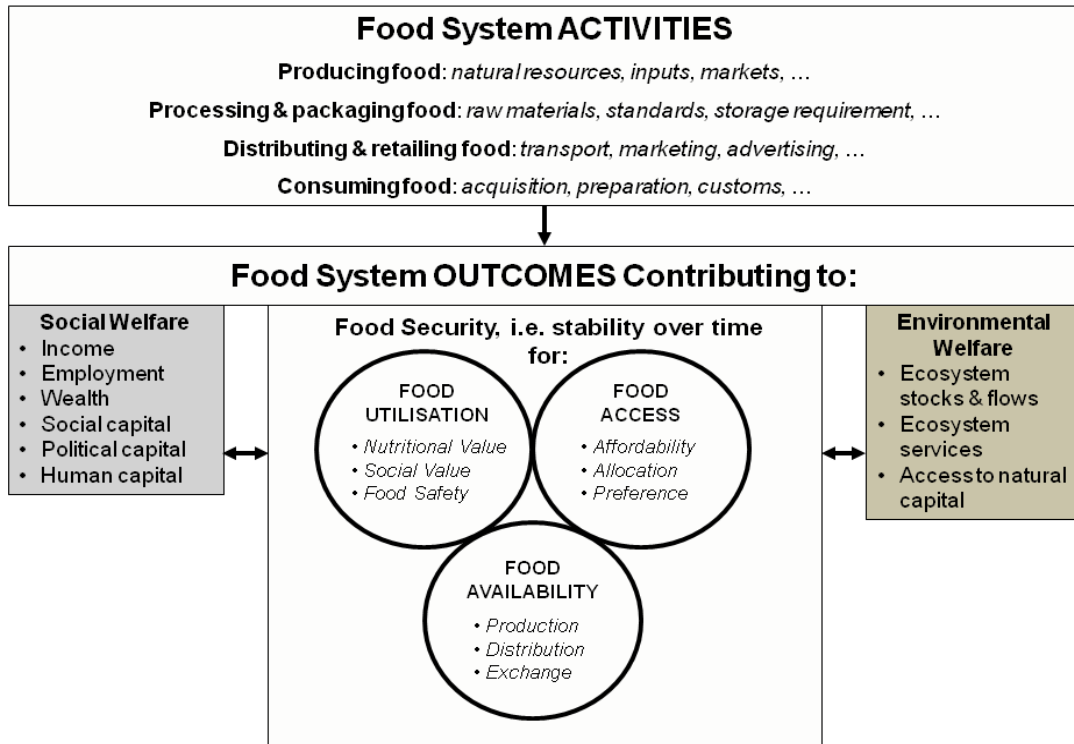


Figure 7-1: The components of food systems in terms of activities and outcomes for food security and environmental and social welfare (GECAFS, 2009).

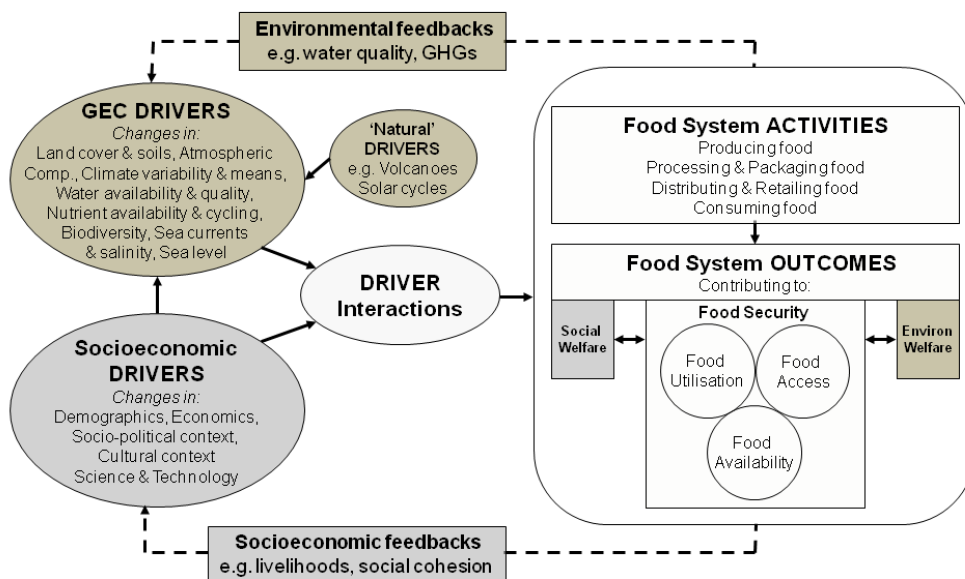


Figure 7-2: Main drivers of food systems. (MAY BE REMOVED DUE TO OVERLAP WITH FIGURE 7-1)

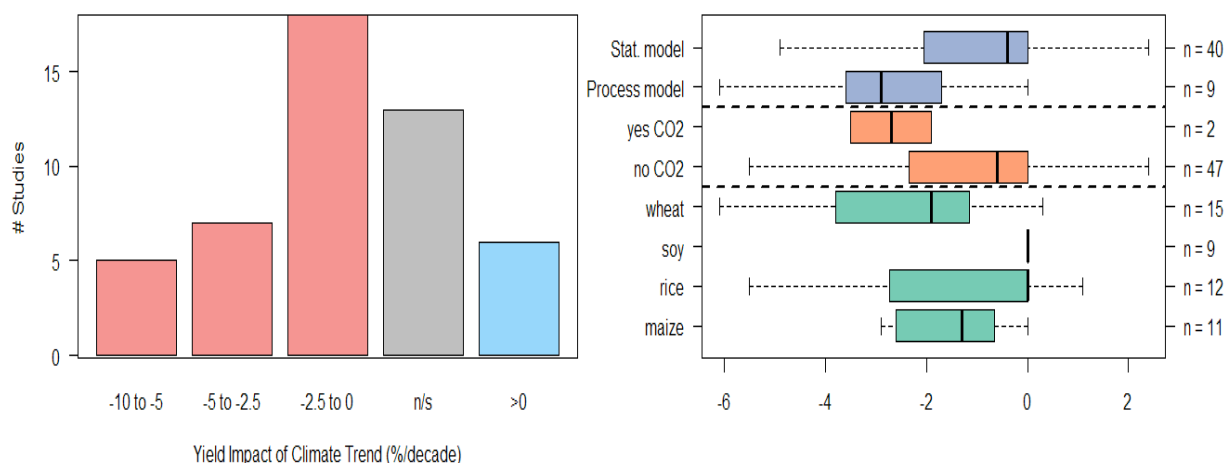


Figure 7-3: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological crop models or statistical models), spatial scales (e.g., stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO₂ trends but most did not. (a) shows number of studies with different level of impact (% yield per decade), (b) shows boxplot of studies separated by modelling approach, whether CO₂ effects were included, and crop. Studies were for China (Tao et al., 2006; Tao et al., 2008; Wang et al., 2008; You et al., 2009; Chen et al., 2010), India (Pathak et al., 2003; Auffhammer et al., 2012), United States (Kucharik and Serbin, 2008), Mexico (Lobell et al., 2005), France (Brisson et al., 2010), Australia (Ludwig et al., 2009), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch et al., 2010; Lobell et al., 2011).

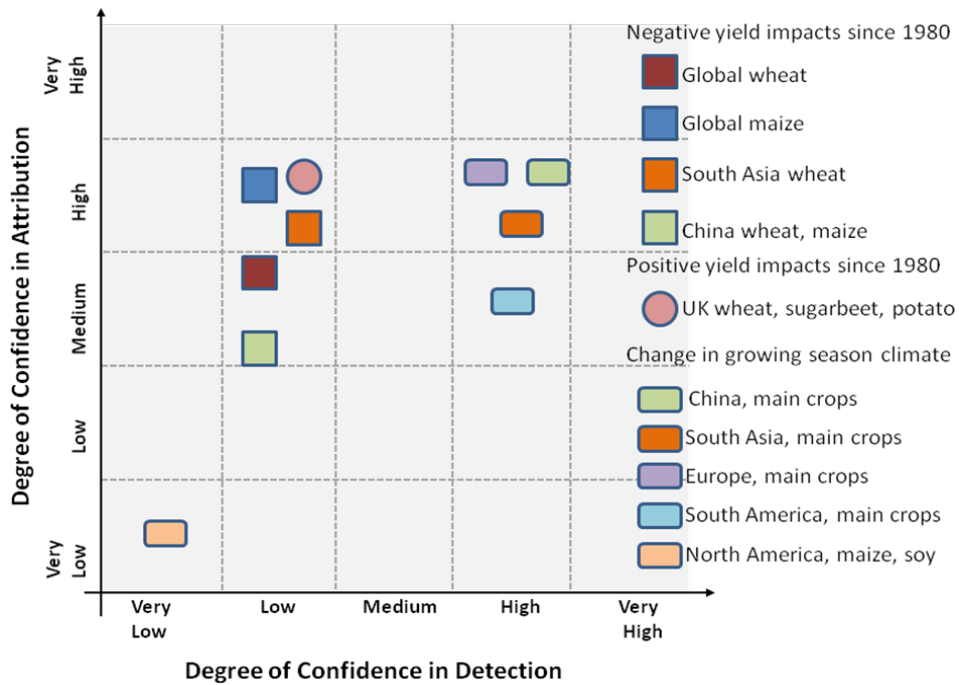


Figure 7-4: Confidence in Detection and Attribution of Observed Impacts on crop yields and growing season agroclimatic conditions. Yield impacts include both direct climate effects and effects of elevated CO₂, but do not consider farmer adaptation. Confidence Levels were derived based on expert judgement of the available literature, following the IPCC uncertainty guidance (Mastrandrea et al., 2010). References: to fill in when complete, many of the same from Figure 7-3.

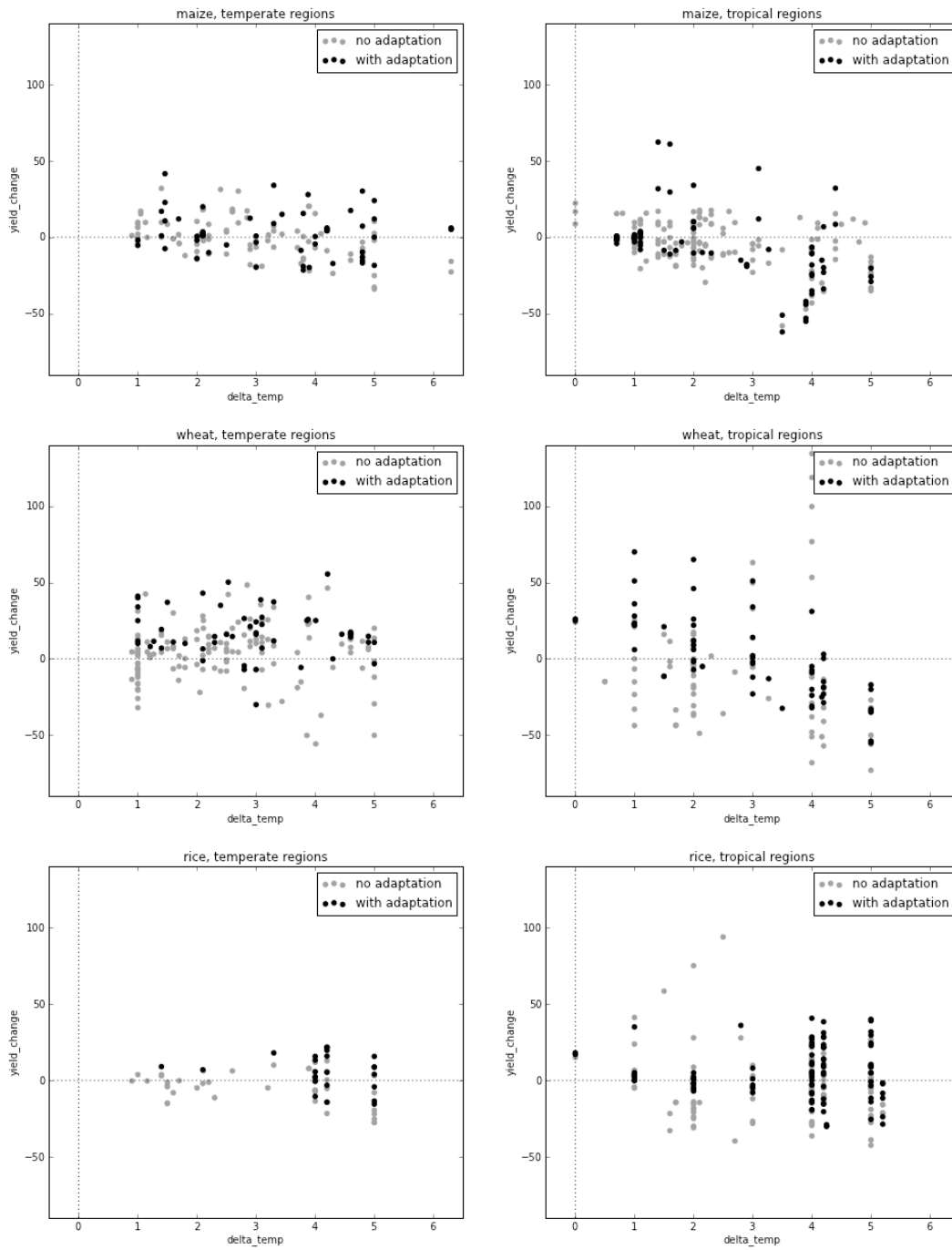


Figure 7-5: Reproduction of AR4 (Figure 5.2, WG II, p. 286) temperature (delta_temp) vs yield change with more up-to-date database (number of data points ca. doubled from AR4). All available data points used (cf Figure 7-7 which is where adaptation is dealt with more fully). Boxplots may be used for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

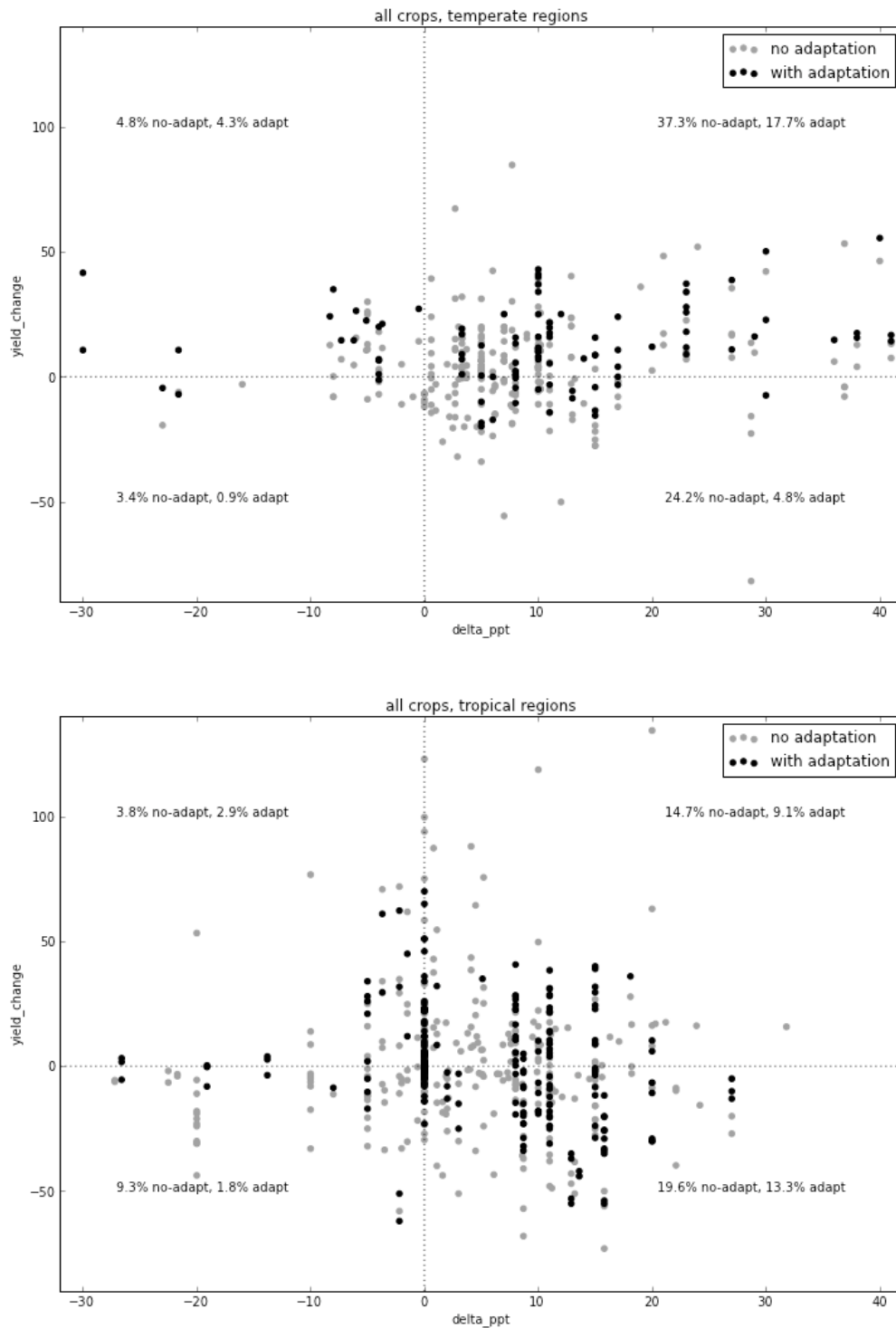


Figure 7-6: Yield change vs precipitation (delta_ppt), showing a contrast between tropical and temperature regions. Redrawn from (Chettri, Lobell, Challinor, Watson – in prep). Figure contains a subset of the total envisaged final data; any conclusions are preliminary.

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

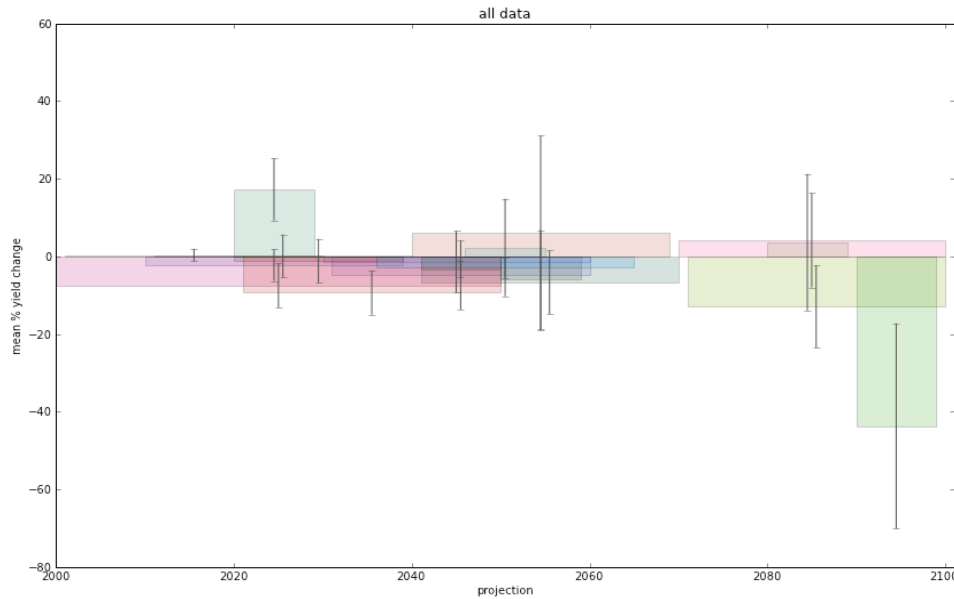


Figure 7-7: Summary of yield projections, demonstrating when decreases in mean yields of e.g. 40% are likely. Redrawn from (Chettri, Lobell, Challinor, Watson – in prep). Figure contains a subset of the total envisaged final data; any conclusions are preliminary. The widths of the boxes indicate the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

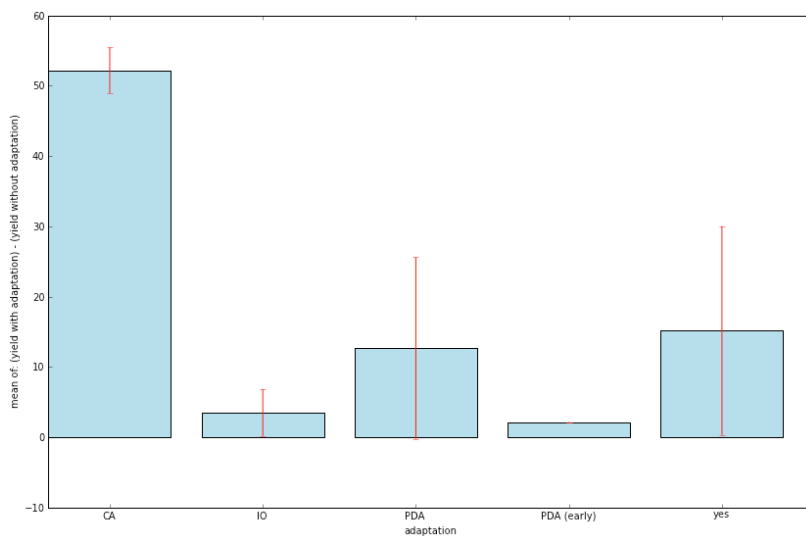


Figure 7-8: The benefit (% difference from baseline) for different crop management adaptations (CA – cultivar adjustment; IO – irrigation optimisation; PDA – planting date adjustment; PDA early – adjusting planting date earlier; yes – other treatments). The bars indicate \pm SE.

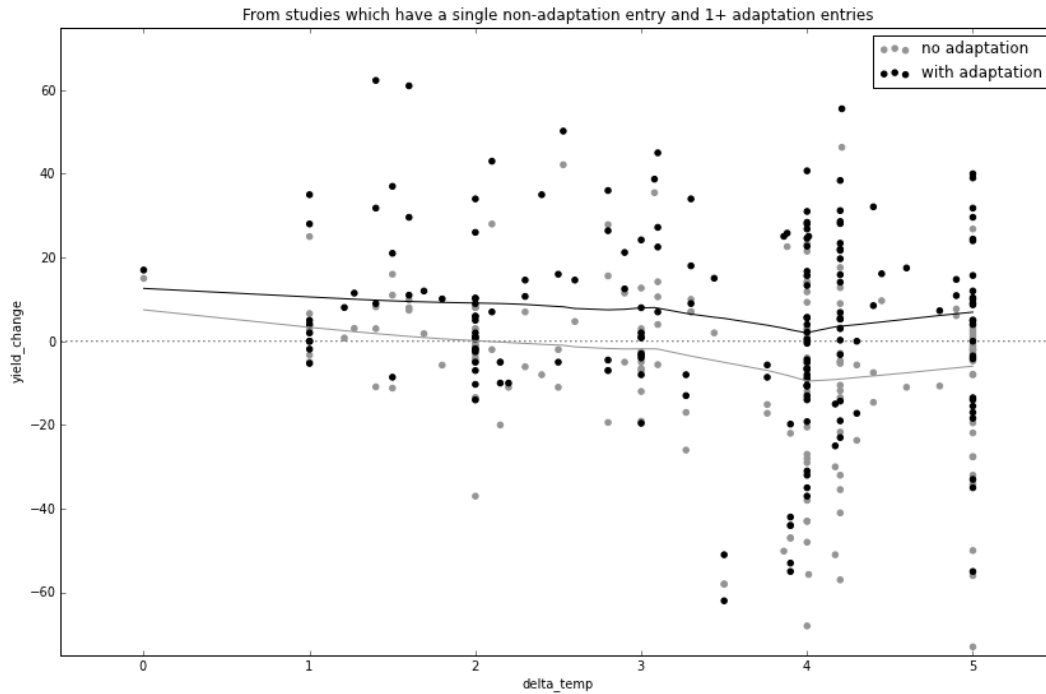


Figure 7-9: Yield change (% difference from baseline) as affected by temperature aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a ‘no adaptation’ and an ‘adaptation’ scenario are used (this is a subset of the data points in fig 7.5). For the final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

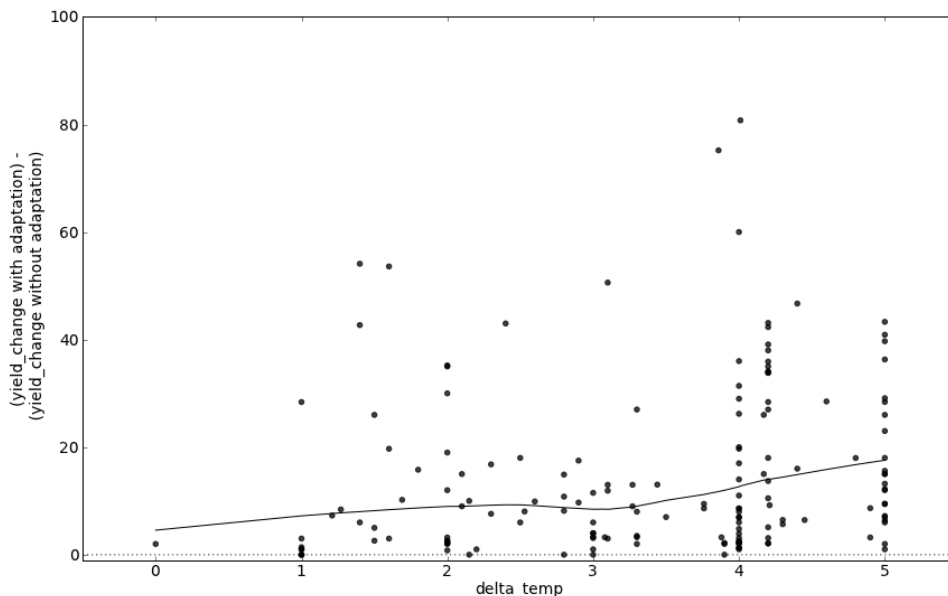


Figure 7-10: The benefit of crop management adaptations as a function of global temperature change expressed as the difference between yield change between the adapted and non-adapted cases aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a ‘no adaptation’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