

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

John R. Porter (Denmark), Liyong Xie (China)

Lead Authors

Andrew Challinor (UK), Keven Cochrane (FAO), Mark Howden (Australia), Muhammad Mohsin Iqbal (Pakistan), David Lobell (USA), Maria Isabel Travasso (Argentina)

Contributing Authors

Netra Chhetri (Australia), Karen Garrett (USA), John Ingram (UK), Leslie Lipper (Italy), Nancy McCarthy (USA), Justin McGrath (USA), Daniel Smith (UK), Philip Thornton (UK), James Watson (UK), Lewis Ziska (USA)

Review Editors

Pramod Aggarwal (India), Kaija Hakala (Finland)

Volunteer Chapter Scientist

Joanne Jordan (UK)

Contents

Executive Summary

7.1. Introduction and Context

7.1.1. Summary from AR4

7.1.2. Food Systems

7.1.3. The Current State of Food Security

7.2. Observed Impacts, with Detection and Attribution

7.2.1. Food Production Systems

7.2.1.1. Crop Production

7.2.1.2. Fisheries Production

7.2.1.3. Livestock Production

7.2.2. Food Security

7.3. Assessing Impacts, Vulnerabilities, and Risks

7.3.1. Methods and Associated Uncertainties

7.3.1.1. Assessing Impacts

7.3.1.2. Treatment of Adaptation in Impacts Studies

7.3.2. Sensitivity of Food Production to Weather and Climate

7.3.2.1. Cereals, Oilseeds, and Legumes

7.3.2.2. Other Crops

7.3.2.3. Pests, Weeds, Diseases

7.3.2.4. Pastures and Livestock

7.3.2.5. Food and Fodder Quality and Human Health

7.3.2.6. Fisheries and Aquaculture

7.3.3. Sensitivity of Food Security to Weather and Climate

7.3.3.1. Non-Production Food Security Elements

7.3.3.2. Accessibility, Utilization, and Stability

7.3.4. Land Use Change and Autonomous Adaptation

7.4. Projected Integrated Climate Change Impacts

7.4.1. Projected Impacts on Cropping Systems

- 1 7.4.2. Projected Impacts on Fisheries and Aquaculture
- 2 7.4.2.1. Capture Fisheries
- 3 7.4.2.2. Aquaculture
- 4 7.4.2.3. National and Regional Vulnerability
- 5 7.4.3. Projected Impacts on Food Prices and Food Security
- 6
- 7 7.5. Adaptation and Managing Risks in Agriculture and Other Food System Activities
- 8 7.5.1. Adaptation Needs and Gaps based on Assessed Impacts and Vulnerabilities
- 9 7.5.1.1. Methods of Treating Impacts in Adaptation Studies – Incremental to Transformational
- 10 7.5.1.2. Practical Regional Experiences of Adaptation, including Lessons Learned
- 11 7.5.2. Food System Case Studies – Examples of Successful and Unsuccessful Adaptation
- 12 7.5.3. Key Findings from Adaptations – Confidence Limits, Agreement, and Level of Evidence
- 13
- 14 7.6. Research and Data Gaps – Food Security as a Cross-Sectoral Activity
- 15

16 Frequently Asked Questions

- 17 7.1: What factors determine food security and does low food production necessarily lead to food
- 18 insecurity?
- 19 7.2: How could adaptation actions enhance food security and nutrition?
- 20 7.3: How could climate change interact with change in fish stocks, ocean acidification?
- 21

22 Cross-Chapter Boxes

- 23 CC-OA. Ocean Acidification
- 24 CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change
- 25

26 References

- 27
- 28

29 Executive Summary

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

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

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

1 levels (*medium evidence, medium agreement*) and competition for water resources as between agriculture, food
2 systems and other sectors of the economy. [7-4, Figure 7-5]
3

4 **Long term climate changes are impacting the abundance and distribution of harvested aquatic species, both**
5 **freshwater and marine, and aquaculture production systems in different parts of the world.** [7.2.1.2, 7.3.2.6,
6 7.4.2] These are expected to continue with negative impacts on nutrition and food security for especially vulnerable
7 people in some regions but with benefits in other regions which become more favourable for aquatic food
8 production (*medium evidence, high agreement*). [7.5.1.1.3]
9

10 **There is new understanding since AR4 of the sensitivity of crops to extreme heat, which reinforces the**
11 **importance of temperature changes for determining impacts of climate change on crop yield at regional scales**
12 **(*medium evidence, medium agreement*).** At scales of individual countries or smaller, differences in precipitation
13 projections continue to be an important source of uncertainty in future impacts (*medium evidence, high agreement*).
14 [7.3]
15

16 **Extreme heat also a negative effect on food quality in terms of nutrition and processing (*robust evidence, high***
17 ***agreement*).** Impacts of increased heat stress and more frequent extreme events will be negative in all regions for
18 livestock (*robust evidence, high agreement*); changes in animal diseases and vectors are less certain (*medium*
19 *evidence, medium agreement*). Extreme climatic events, defined as extremely high and low temperatures and
20 droughts and floods, are important for all food and fodder production, but particularly for annual determinate crops
21 in which yield is harvested as seeds (*medium evidence, medium agreement*). [7.3.2]
22

23 **Evidence since AR4 confirms the positive effects of CO₂ and negative effects of elevated tropospheric ozone**
24 **on crop yields (*high confidence*).** There is emerging experimental and modelling evidence (*medium evidence, high*
25 *agreement*) that interactions between production factors such as CO₂ and ozone, mean temperature, extremes, water
26 and nitrogen can alter primary food production in complex ways. In concert with experimental results, the chapter
27 results take more account of model and other uncertainties than has been the case previously. The large number of
28 studies on mean crop yield impacts of changes in climate and CO₂ allow more robust statements than previously
29 possible, but less confidence is given to simulated increases in yield variability (*medium evidence, medium*
30 *agreement*). [7.3, Figures 7-5/7]
31

32 **Changes in climate and CO₂ levels will enhance the distribution and increase the competitiveness of**
33 **agronomically important and invasive weeds (*robust evidence, high agreement*).** Rising CO₂ reduces the
34 effectiveness of herbicides (*medium evidence, high agreement*). The effects of climate change on disease pressure on
35 food crops is uncertain, with evidence pointing to changed geographical ranges of diseases but less certain changes
36 in disease intensity (*medium evidence, low agreement*). [7.3.2.1.2]
37

38 **Without adaptation, moderate warming of up to 2°C local temperatures are expected to reduce yields on**
39 **average for the major cereals (wheat, rice and maize) in temperate regions, although many individual**
40 **locations may benefit (*medium confidence*).** There is confirmation that even modest warming up to 2°C will
41 decrease yields in low-latitude tropical regions (*robust evidence, medium agreement*). Reductions of more than 5%
42 are *more likely than not* beyond 2050 and *likely* by the end of the century. From the 2070s onwards, all of the
43 positive yield changes are in temperate regions, suggesting that yield reduction in the tropics are very likely by this
44 time and substantial, particularly for wheat (*robust evidence, high agreement*). [7-4, Figures 7-5/6/7]
45

46 **Adaptation possibilities of food systems to climate change show a very wide range in effectiveness, with**
47 ***medium confidence* that adaptation will increase in effectiveness with increasing local mean temperature up to**
48 **ca. 3°C local warming above pre-industrial, after which the net benefits no longer increase (*medium evidence,***
49 ***medium agreement*).** Most studies however, have focussed on food production rather than on adapting food
50 systems. Generally (*medium evidence, high agreement,*) adaptation leads to lower reductions in food production than
51 in its absence with an overall crop yield difference in adaptation cases of about 15-20% over non-adaption cases,
52 with more effective adaption at higher latitudes (*limited evidence, medium agreement,*) but with some adaptation
53 options more effective than others. Thus, benefits of adaptation are greater for wheat, rice and maize in temperate
54 rather than tropical regions. Key adaptations for fisheries are for policy and management to maintain ecosystems in

1 a state that is resilient to change, enabling occupational flexibility, and developing early warning systems for
2 extreme events (*medium evidence, high agreement*). [7.5.1.1.3] Livestock systems' adaptations centre around
3 adjusting management to the available resources, using breeds better adapted to the prevailing climate and removing
4 barriers to adaptation such as improving credit access (*medium evidence, medium agreement*). A range of potential
5 adaptation options exist across all food system activities, not just in the food production, but benefits from potential
6 innovations in food processing, packaging, transport, storage and trade are insufficiently researched. [7.1, 7.5, 7.6,
7 Figures 7-5/9]

8
9 In summary, the key messages from the synthesis and evaluation of the current evidence of the impacts of climate
10 change on food security and food production systems and their adaptation are that:

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

21 22 23 **7.1. Introduction and Context**

24
25 Many definitions of food security exist. Maxwell and Slater (2003) noted over 200 as early as 1992 (Spring, 2009)
26 and more have been formulated (Defra, 2006). While many of the earlier definitions centred on food production, the
27 majority of more recent definitions promote the notion of access to food. The 1996 World Food Summit definition
28 (FAO, 1996), which states that food security is met when “*all people, at all times, have physical and economic*
29 *access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and*
30 *healthy life*”, is still widely adopted. This definition puts the notion of access to food centre stage, also integrating
31 dimensions of food availability, food utilisation and stability over time. The definition has a focus on the
32 under-consumption of food whereas overconsumption and obesity are also relevant as factors in global public
33 health.

34
35 While food security has been on the development agenda for decades, world-wide attention was given considerable
36 impetus by the food ‘price spike’ in 2007-08, triggered by a complex set of long-term and short-term factors (von
37 Braun and Torero, 2009). According to some estimates, the ‘price spike’ increased the number of hungry people by
38 some 40 million (FAO, 2008) but other studies report a lower number (Headey and Fan, 2010). This link between
39 food prices and numbers of food insecure people underscores the importance of the affordability of food in relation
40 to food security. There is strong agreement that more than enough food is currently produced *per capita* to
41 adequately feed the global population, yet about 870 million people remained hungry in 2012 (FAO, 2012), and
42 millions more with insufficient nutrient (Pinstrup-Andersen, 2009). The two overriding questions for this chapter are
43 how far climate change adds to current issues in food production systems and food security and the extent that it will
44 do so in the future.

45 46 47 **7.1.1. Summary from AR4**

48
49 Food systems as integrated activities dealing with the impacts of climate change on the supply and demand for food
50 did not feature strongly in AR4, where the strong emphasis was on food, fibre and forest production. Summary
51 points from AR4 were that, with *medium confidence*, in mid- to high-latitude regions moderate warming will raise
52 crop and pasture yields. However, even slight warming will decrease yields in low-latitude regions. Extreme climate
53 and weather events will, with *high confidence*, reduce food production with or without changes in mean conditions.
54 The benefits of adaptation in crops such as changing varieties and/or planting times and other managements enable

1 avoidance of a 10-15% reduction in yield corresponding to 1-2°C local temperature increase. Adaptive capacity will
2 be exceeded in low-latitude areas with temperature increases of more than 3°C. Local extinctions of particular fish
3 species are expected with *high confidence* at the edges of their ranges and any slowing in the meridional overturning
4 circulation will have serious negative impacts on fisheries with a *medium confidence* level.
5
6

7 **7.1.2. Food Systems**

8

9 A food system includes all processes and infrastructure involved in satisfying a population's food security. It relates
10 to the *Activities* of gathering/catching, growing, harvesting, storing, processing, packaging, transporting, marketing,
11 consuming food, and disposing of food waste and food-related items (the 'food chain'). It also includes the food
12 security *Outcomes* of these *Activities* related to availability and utilization of, and access to, food as well as those
13 related to other socioeconomic and environmental factors. Drawing together the extensive (yet relatively distinct)
14 literatures built up by the food chain and food security communities, respectively, a revised 'food systems' model
15 has been formalised (Ericksen, 2008; Ericksen *et al.*, 2010; Ingram, 2011). This model recognises that food systems
16 operate within, are influenced by, and feed back to social, political, economic and environmental contexts (Figure
17 7-1).
18

19 [INSERT FIGURE 7-1 HERE

20 Figure 7-1: Main global environmental change (GEC) and socioeconomic drivers of food systems, the main food
21 system activities, and the outcomes of these activities. The figure also shows the three main components of food
22 security (circles), all of which need to be stable over time: Availability (with elements of production, distribution
23 and trade); Access (affordability, allocation and preference); and Utilisation (nutritional value, cultural value and
24 safety).]
25

26 There is good agreement that the impacts of climate change on food systems are expected to be widespread,
27 complex, geographically and temporally variable, and profoundly influenced by socio-economic conditions
28 (Vermeulen *et al.*, 2012). Changes in food system activities give rise to changes in food security outcomes, (*medium*
29 *evidence, high agreement*) but often researchers only consider the impacts on the food production element of food
30 security. Food security needs consideration of how any intervention (i.e. a change in the food system activities) will
31 also affect all other components of the food security outcomes; in principle, any intervention, even if only targeted at
32 only one component (e.g. availability) will affect all three components due to the dynamic interactions between
33 them, either directly or mediated via the feedback loops in Figure 7-1. Efforts to increase food production are
34 nevertheless increasingly important as 50% more food will be needed by 2030 given current food consumption
35 trends and assuming no significant reduction in food waste (FAO, 2010a).
36
37

38 **7.1.3. The Current State of Food Security**

39

40 There were an estimated 870 million people undernourished during the period 2010-2012, approximately 12.5% of
41 the global population (FAO *et al.*, 2012); thus, the vast majority of people currently have sufficient food. The vast
42 majority of the undernourished (852 million) live in developing countries (*medium evidence, medium agreement*).
43 Typically this is estimated based on aggregate national calorie availability and assumptions about food distribution
44 and nutritional requirements. More precise estimates are possible with detailed household surveys, which often show
45 higher incidence of food insecurity than estimated by FAO. Smith *et al.*, (2006) estimated average food insecurity
46 rates of 59% for 12 African countries, compared to 39% estimate from FAO for the same period.
47

48 While there is *medium evidence, medium agreement* on absolute numbers, there is *robust evidence, high agreement*
49 that Sub-Saharan Africa has the highest proportion of food insecure people; with up to 60% of people consuming
50 insufficient calories for an active life. The largest numbers of food insecure are found in South Asia, which has
51 roughly 300 million undernourished (FAO *et al.*, 2012). In addition to common measures of calorie availability,
52 food security can be broadened to include nutritional aspects based on the diversity of diet including not only staple
53 foods but also vegetables, fruits, meat, milk, eggs, and fortified foods (FAO, 2011). There is *robust evidence* and

1 *high agreement* that lack of essential micronutrients such as zinc and vitamin A affect hundreds of millions of
2 additional (Lopez *et al.*, 2006; Pinstrup-Andersen, 2009).
3

4 Food insecurity is closely tied to poverty, and more detailed surveys on poverty provide insight into where the food
5 insecure live. Globally, about 25 to 30 percent of poor people – measured using either a \$1 or \$2 per day standard -
6 live in urban areas (Ravallion *et al.*, 2007; IFAD 2010). This is partly because most poor countries have a greater
7 fraction of people living in rural areas, but also because poverty rates tend to be higher in rural settings (by slight
8 margins in South Asia and Africa, and by large margins in China). In Latin America, poverty is more skewed to
9 urban areas, with roughly two-thirds of the poor found in urban areas, a number that has been growing in the past
10 decade (*medium evidence, medium agreement*). The urban share of poverty has also been rising in other regions,
11 although more slowly. It is expected that rural areas will continue to have the majority of poor people for at least the
12 next few decades, even as population growth is higher in urban areas (*medium evidence, medium agreement*)
13 (Ravallion *et al.*, 2007; IFAD 2010).
14

15 For urban poor, who produce relatively small amounts of food, increases in food prices generally reduce food
16 security. Since most rural poor produce some portion of the food they consume, the picture is more complicated.
17 Much of the poor's income is from agricultural activities, which stands to benefit if prices rise. As mentioned,
18 however, the rural poor still tend to be net consumers or marginal net producers. That is, they consume nearly all of
19 what they grow and still need to buy additional food. If prices are rising more quickly for crops they grow, they can
20 sell those and buy cheaper calories, resulting in a net increase in well-being. Rural wage rates may also increase in
21 response to higher prices (for example, if workers are paid with a set amount of grain), with benefits for the many
22 who earn part of their income from working other lands. Thus, the long-term welfare effects of price rises on rural
23 poor are complex, and can vary depending on local factors.
24

25 The effects of price volatility are distinct from the effects of gradual price rises, for two main reasons. First, rapid
26 shifts make it difficult for the poor to adjust their activities to favour producing higher value items. Second,
27 increased volatility leads to greater uncertainty about the future, and can dampen willingness to invest scarce
28 resources into productivity enhancing assets, such as fertilizer purchases in the case of farmers or rural infrastructure
29 in the case of governments. Several factors have been found to contribute to increased price volatility: poorly
30 articulated local markets, increased incidence of adverse weather events and greater reliance on production areas
31 with high exposure to such risks, biofuel mandates, and increased links between energy and agricultural markets
32 (World Bank, 2012). In some cases, trade interventions intended to reduce domestic food price volatility (e.g. export
33 bans) had adverse effects both in local and global markets (HLPE, 2011; World Bank, 2012). Vulnerability to food
34 price volatility depends on the degree to which households and countries are net food purchasers, the level of
35 integration into global, regional and local markets and their relative degree of volatility, which in turn is conditional
36 upon their respective governance (HLPE, 2011; World Bank, 2012) with *robust evidence* and *medium agreement*.
37
38

39 **7.2. Observed Impacts, with Detection and Attribution**

40 **7.2.1. Food Production Systems**

41 Food production systems have changed substantially over the past few decades. These changes were primarily the
42 result of factors other than atmospheric CO₂ or climate, such as cultivar improvement and increased use of synthetic
43 fertilizers, herbicides and irrigation. In many contexts the effects of past changes in weather or CO₂ level are viewed
44 as noise that obscures the effects of agronomic or genetic changes. Yet understanding the effect of past CO₂ and
45 climate shifts are a useful precursor to assessing future impacts and adaptation needs.
46
47
48

49 The number and strength of non-climate drivers of food systems and food security make formal detection and
50 attribution of impacts extremely difficult. Most of these confounding factors, such as fertilizer use or adoption of
51 modern hybrids in the case of crops, are not very well characterized in terms of spatial and temporal distributions,
52 and the relationships between these factors and specific outcomes of interest (e.g., crop production) are often
53 difficult to quantify. Attribution in other food production sectors is equally difficult. No studies to our knowledge
54 simulate historical trends in food-related outcomes with and without changes in anthropogenic emissions of

1 greenhouse gases. A possible exception (Auffhammer *et al.*, 2006) compared rice yield predictions in India using
2 climate model simulations of temperature in the late 20th century with yields using observed temperatures for
3 1930-1960, the latter period used as a surrogate for climate without changes in greenhouse gases after 1960. In their
4 study, they find rice yields would have been significantly higher without greenhouse gas emissions, thus attributing
5 negative impacts to emissions but with *limited evidence*.
6

7 Attributions of crop changes are further complicated by the fact that models linking climate and agriculture must,
8 implicitly or explicitly, make assumptions about farmer behaviour. In most cases, models implicitly assume that
9 farming practices or technologies did not adjust in response to climate over the period of interest. This assumption
10 can be defended in some cases based on ancillary data on practices, or based on small differences between using
11 models with and without adaptation (Schlenker and Roberts, 2009). However, in some instances the relationship
12 between climate conditions and crop production has been shown to change over time because of management
13 changes (Zhang *et al.*, 2008; Liu *et al.*, 2009; Sakurai *et al.*, 2012).
14

15 16 7.2.1.1. Crop Production

17
18 Many studies of cropping systems have estimated impacts of observed changes in climate over the past few decades.
19 Based on these studies, there is *medium confidence (medium evidence, high agreement)* that climate trends have
20 negatively affected wheat and maize production for many regions, as well as *medium confidence (medium evidence,*
21 *high agreement,)* for negative impacts on global aggregate production of these crops (Figure 7-2). There is also
22 medium confidence (*medium evidence, high agreement*) that effects on rice and soybean yields have been small in
23 major production regions and globally (Figure 7-2). There is also *high confidence (robust evidence, high agreement)*
24 that warming has benefitted crop production in some cold regions, such as Northeast China or the United Kingdom
25 (Jaggard *et al.*, 2007; Supit *et al.*, 2010; Chen *et al.*, 2011; Gregory and Marshall, 2012).
26

27 [INSERT FIGURE 7-2 HERE

28 Figure 7-2: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were
29 taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or
30 statistical models), spatial scales (e.g., stations, provinces, countries, or global), and time periods (median length of
31 29 years). Some included effects of positive CO₂ trends (see 7.3.2.1.2) but most did not. (a) shows number of studies
32 with different level of impact (% yield per decade), (b) shows boxplot of studies separated by temperate vs. tropical
33 regions, modelling approach (process-based vs. statistical), whether CO₂ effects were included, and crop. Studies
34 were for China (Tao *et al.*, 2006; Tao *et al.*, 2008; Wang *et al.*, 2008; You *et al.*, 2009; Chen *et al.*, 2010; Tao *et al.*,
35 2012), India (Pathak *et al.*, 2003; Auffhammer *et al.*, 2012), United States (Kucharik and Serbin, 2008), Mexico
36 (Lobell *et al.*, 2005), France (Brisson *et al.*, 2010), Scotland (Gregory and Marshall, 2012) Australia (Ludwig *et al.*,
37 2009), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch *et al.*, 2010;
38 Lobell *et al.*, 2011). Values from all studies were converted to percentage yield change per decade.]
39

40 A sizable fraction of crop modelling studies were concerned with production for individual sites or provinces, scales
41 below which the changes in climate conditions are attributable to anthropogenic activity (IPCC 2013, WG1, Chapter
42 10). Similarly, most crop studies have focused on the past few decades, a time scale shorter than most attribution
43 studies for climate. However, some focused on continental or global scales (Lobell and Field, 2007; You *et al.*,
44 2009; Lobell *et al.*, 2011), at which trends in several climatic variables, including average summer temperatures,
45 have been attributed to anthropogenic activity (IPCC 2013, WG1, Chapter 10). In particular, global temperature
46 trends over the past few decades are attributable to human activity (IPCC, 2013, WG1, Chapter 10), and the studies
47 discussed above indicate that this warming has had significant impacts on global yield trends of some crops.
48

49 Figure 7-3 presents a summary of the detectability of changes in growing season conditions (as measured by total
50 degree-days during summer) and crop yield changes, as well as the ability to attribute changes to climate and CO₂
51 trends (in the case of yield changes) or anthropogenic emissions (in the case of growing season climate changes). As
52 discussed above, attribution of yield impacts relies on multi-step attribution based on process understanding and
53 observed climate trends. Also illustrated in Figure 7-3 is the fact that not all major cropping regions have

1 experienced significant climate trends in the past few decades, with the United States (in the lower, left-hand corner)
2 the most notable example.

3
4 [INSERT FIGURE 7-3 HERE

5 Figure 7-3: Confidence in detection and attribution of observed impacts on crop yields and growing season degree
6 days. Yield impacts include both direct climate effects and effects of elevated CO₂, but do not consider farmer
7 adaptation. Confidence Levels were derived based on expert judgement of the available literature, following the
8 IPCC uncertainty guidance (Mastrandrea *et al.*, 2010). Negative yield impacts: 1= Global maize , 2= Global wheat,
9 3= South Asia wheat; 4 = China maize and wheat; Positive yield impacts: 5 = UK wheat, sugarbeet, and potato.
10 Increase in growing degree days: 6 = South Asia, main crops; 7 = China, main crops; 8 = Europe, main crops; 9 =
11 Latin America, main crops; 10 = North America, maize and soybean. Yield impact confidence based on studies
12 listed in Figure 7-2. Growing degree day confidence based on detection and attribution of trends in growing season
13 temperatures (IPCC 2013, WG1, Chapter 10).]

14
15 In general, little work in food production or food security research has focused on formally attributing observed
16 changes to anthropogenic influence on the climate system. However, as the field of climate detection and attribution
17 proceeds to finer spatial and temporal scales, and as agricultural modelling studies expand to broader scales, there
18 should be many opportunities to link climate and crop studies in the next few years. Importantly, climate attribution
19 is increasingly documented not only for measures of average conditions over growing seasons, but also for
20 extremes. For instance, (Min *et al.*, 2011) attribute changes in rainfall extremes to anthropogenic activity, and these
21 are widely acknowledged as important to cropping systems (Rosenzweig *et al.*, 2002). Frost damage is an important
22 constraint on crop growth in many crops, including for various high-value crops, and significant reductions in frost
23 occurrence have been observed and attributed to greenhouse gas emissions in nearly every region of the world
24 (Alexander *et al.*, 2006; Zwiers *et al.*, 2011; IPCC, 2012). Positive trends in the occurrence of unusually hot nights
25 are also attributable to human activity in most regions (Perring *et al.*, 2010, IPCC 2013, WG1, Chapter 10). These
26 events are damaging to most crops, an effect that has been observed most commonly for rice yields (Peng *et al.*,
27 2004; Wassmann *et al.*, 2009; Welch *et al.*, 2010) as well as rice quality (Okada *et al.* 2011). Extremely high
28 daytime temperatures are also damaging and occasionally lethal to crops (Porter and Gawith, 1999; Schlenker and
29 Roberts, 2009), and trends at the global scale in annual maximum daytime temperatures have been attributed to
30 greenhouse gas emissions (Zwiers *et al.*, 2011). At regional and local scales, however, trends in daytime maximum
31 are harder to attribute to greenhouse gas emissions because of the prominent role of soil moisture and clouds in
32 driving these trends (Christidis *et al.*, 2005; Lobell *et al.*, 2007; Zwiers *et al.*, 2011).

33
34 In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition
35 on crops. It is *virtually certain* that the increase of atmospheric CO₂ by over 100 ppm since pre-industrial times has
36 enhanced water use efficiency and yields, especially for C₃ crops, although these benefits played a minor role in
37 driving overall yield trends (Amthor, 2001; Long *et al.*, 2006; McGrath and Lobell, 2011). As described earlier,
38 increases in carbon dioxide are expected to have had negative impacts on carbon accretion in coral reefs with
39 potential consequences for associated ecosystems and dependent social and economic activities (Hoegh-Guldberg *et al.*, 2007).

40
41
42 Emissions of CO₂ have also been associated with ozone (O₃) precursors that have driven a rise in tropospheric O₃
43 that harms crop yields (Morgan *et al.*, 2006; Mills *et al.*, 2007; *Section 7.3.2.1.2*). It is *very likely* that elevated O₃
44 since pre-industrial times has suppressed global production of major crops compared to what they would have been
45 without O₃ increases, with estimated losses of roughly 10% for wheat and soybean and 3-5% for maize and rice (van
46 Dingenen *et al.*, 2009). Impacts are most severe over India and China, but are also evident for soybean and maize in
47 the United States (Fishman *et al.*, 2010; Boone *et al.* 2013).

48 49 50 7.2.1.2. Fisheries Production

51
52 The detection and attribution of impacts are as confounded in inland and marine fisheries as in terrestrial food
53 production systems. Overfishing, habitat modification, pollution and inter-annual to decadal climate variability can
54 all have impacts that are difficult to separate from those directly attributable to climate change. One of the best

1 studied areas is the North East Atlantic, where the temperature has increased rapidly in recent decades, associated
2 with a poleward shift in distribution of fish (Perry *et al.*, 2005; Brander, 2007; Cheung *et al.*, 2010; *robust evidence*,
3 *high agreement*). In the North Sea, within the NE Atlantic, the average species richness in the region, as indicated by
4 the number of species recorded per year increased by approximately 33% between 1985 and 2006, a period during
5 which North Sea bottom temperatures also rose significantly (Hiddink and Hofstede, 2008); inferring that the
6 increase in richness has been related to the rising water temperature. These trends will have mixed implications for
7 fisheries and aquaculture with some commercial species negatively and others positively affected (Cook and Heath,
8 2005). There is a similar well-documented example in the oceans off SE Australia with large warming trends
9 associated with more southwards incursion of the Eastern Australian Current. This has resulted in southward
10 migration of marine species into the oceans around eastern Tasmania with consequent impacts on ecosystem
11 dynamics (Last *et al.*, 2011; *robust evidence, high agreement*).
12

13 Coral reef ecosystems are important sources of fish for food for local inhabitants. More than 60% of coral reefs are
14 considered to be under immediate threat of damage from a range of local threats, of which overfishing is the most
15 serious followed by coastal development and pollution. The percentage under threat rises to 75% when the effect of
16 rising ocean temperatures is added to these local impacts (Burke *et al.*, 2011). There have been ongoing incidences
17 of coral bleaching from rising sea temperatures since the 1970s which have already caused a global decline in coral
18 reef cover and the trend is expected to continue as temperatures continue to rise (Munday *et al.*, 2008; Chapter
19 30.6.1.1.2). Ocean acidification presents an additional threat by reducing carbon accretion (see Box 5-3 for further
20 information). Wilson *et al.* (Wilson *et al.*, 2006) demonstrated that declines in coral reef cover typically led to
21 declines in abundance of the majority of fish species associated with coral reefs, with species that depended on live
22 coral for food and shelter most impacted while some species that fed on invertebrates, algae or detritus increased.
23

24 There is considerably less information available on climate change impacts on fisheries and fishery resources in
25 freshwater systems. (Xenopoulos *et al.*, 2005) investigated the effect of climate change and water withdrawal on
26 freshwater fish extinctions under the assumptions of two scenarios which they reported were consistent with IPCC
27 SRES scenarios A2 and B2. They forecast that discharge would increase in between 65 and 70% of river basins in
28 the world but it would decrease by as much as 80% in 133 rivers for which fish species data were available. In the
29 rivers experiencing reduced discharge, by 2070 up to 75% of the local fish biodiversity would be 'headed toward
30 extinction' because of changes in climate and water consumption. The areas where the highest rates of fish
31 extinctions were forecast tended to be in tropical and subtropical areas. The authors concluded that climate change,
32 through increased evapotranspiration and reduced precipitation, would be the most important cause of this loss
33 under the two SRES scenarios with water consumption making a considerably smaller contribution. Rates of
34 extinction in fish species cannot be directly related to changes in fishery production but their results indicate that
35 there will be changes in riverine fish communities and productivity which will impact on fisheries, with negative
36 impacts more probable in tropical and sub-tropical systems (*limited evidence; low agreement*).
37

38 Considerable attention has been given to the impacts of climate change in some African lakes but with mixed
39 interpretations (see also Chapter 22.3.3.1.4.). For inland fisheries, there is evidence that increasing temperature has
40 reduced the primary productivity of Lake Tanganyika in East Africa by increasing the stability of the water column
41 and thereby reducing upwelling of nutrients into surface waters. The study by O'Reilly *et al.* (2003) estimated that
42 this would have led to a decrease of approximately 30% in fish yields. However, Sarvala *et al.* (2006) disagreed and
43 concluded that observed decreases in the fish catches could be explained by changed fishery practices. There has
44 been a similar difference of opinion for Lake Kariba where Ndebele-Murisa *et al.*, (2011) argued that a reduction in
45 fisheries productivity had been caused by climate change while Marshall (Marshall, 2012) argues that the declines in
46 fish catches experienced there can only have been caused by fishing. The Sahel region in northern Africa has
47 historically demonstrated high variability. It experienced good rainfall in the 1960s, followed by severe drought over
48 the next 7 years and below average precipitation from then until 2007. This dry period resulted in the area of Lake
49 Chad decreasing from 26,000 km² in the 1960s to 1,425 km² in 2003. The decreasing area was associated with a
50 decline in reported fish catches in Chad from over 100,000t in the late 1960s to under 70,000t in the early 1990s
51 although there is considerable doubt about the accuracy of the reported catch figures, including up to the present
52 (Welcomme, 2011; *medium evidence, low agreement*).
53
54

7.2.1.3. *Livestock Production*

In comparison to crop production, considerably less work has been published on observed impacts for non-crop food production systems, such as livestock and fisheries, and to our knowledge nothing has been published for hunting or collection of wild foods. A study of blue-tongue virus, an important ruminant disease, evaluated the effects of past and future climate trends on transmission risk, and concluded that climate changes have facilitated the recent and rapid spread of the virus into Europe (Guis et al. 2012).

7.2.2. *Food Security*

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

One important aspect of food security is global food prices (Section 7.1.3). Although food prices gradually declined for most of the 20th century, since AR4 there have been several periods of rapid increases in international food prices (Figure 7-4). A major factor in recent price changes has been increased crop demand, notably via increased use in biofuel production related both to energy policy mandates and oil price fluctuations (Roberts and Schlenker, 2010; Wright, 2011; Mueller et al. 2011; Abbot et al. 2011). Yet fluctuations and trends in food production are also widely believed to have played a role in the recent price changes, as illustrated in Figure 7-4. Spikes in prices do not always follow weather induced shortfalls in supply, as illustrated by the lack of response to several events in the 1990's. However, price effects are especially likely in years with low stocks, which can result from sustained periods of low supply growth relative to demand. Domestic policy reactions can also amplify international price responses to weather events, as was the case with export bans announced by several countries since 2007 (FAO, 2008). In a study of global production responses to climate trends, (Lobell *et al.*, 2011) estimated a price increase of 19% due to the impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of increased CO₂ over the study period were considered. Since the price models were developed for a period ending in 2003, these estimates do not account for the policy responses witnessed in recent years which have amplified the price responses to weather.

[INSERT FIGURE 7-4 HERE

Figure 7-4: Since the AR4 report, food prices have reversed historical downward trend. Plot shows history of FAO food and cereal price index, along with events when a top 5 producer of a crop had yields 25% below trend line (indicative of a big weather effect). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years, perhaps reflecting the importance of interactions with global storage levels and rapid growth in crop demand. At the same time, because of increased biofuel demand, food prices are also increasingly linked to the price of crude oil, shown in the blue line (data available at <http://www.eia.gov>). Therefore, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002-2004 averages.]

7.3. *Assessing Impacts, Vulnerabilities, and Risks*

7.3.1. *Methods and Associated Uncertainties*

7.3.1.1. *Assessing Impacts*

Methods developed or extended since AR4 have resulted in more robust statements on climate impacts through:

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

- Greater use of historical empirical evidence of the relationship between climate and food production.

The methods used for field and controlled environment experiments remain similar to those at the time of AR4. There has been a greater interest in the use of Remote Sensing (RS)/Geographic information System (GIS) techniques for assessing temporal and spatial changes in land use particularly in agricultural land use for assessment of food security status (Fishman *et al.*, 2010). There has also been an increase in the number of Free Air Concentration Enrichment (FACE) studies that examine ozone instead of, or in addition to, carbon dioxide. A number of meta-analyses of experimental studies, in particular (FACE) studies have been made since AR4. However, debate continues on the disparities between results from FACE experiments and non-FACE experiments, such as in open-top chambers or greenhouses. As reported in AR4, FACE studies tend to show lower elevated CO₂ responses than non-FACE studies. Although some authors have claimed that the results of the two are statistically indistinct, others have argued that the results are only similar when the FACE experiments are grown under considerably more water stress than non-FACE experiments (Ainsworth *et al.*, 2008). Hence comparisons between different methodologies must take care to control for differences in water levels. Another reason for differences between experiments may be differences in the temporal variance of CO₂ – i.e. whether concentrations are fluctuating or constant (Bunce, 2012). Unfortunately, the number of FACE studies are still quite low, which limits statistical power when evaluating the average yield effects of elevated CO₂ or interactions with temperature and moisture (*Section 7.3.2*).

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

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

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

A considerable body of work since AR4 has used extensive datasets of country-, regional- and farm- level crop yield together with observed and/or simulated weather time series in order to assess the sensitivity of food production to weather and climate. These statistical models offer a complement to more process-based model

1 approaches, some of which require many assumptions about soil and management practices. The regional-scale
2 statistical models that have been developed in recent years can thus produce more widely applicable results than
3 field and controlled environment experiments, whilst avoiding the need for assumptions regarding management and
4 planting dates. Although statistical models forfeit some of the process knowledge embedded in other approaches,
5 they can often reproduce the behavior of other models (Iglesias *et al.*, 2000; Lobell and Burke, 2010) and can
6 leverage within one study a growing availability of crop and weather data (Welch *et al.*, 2010; Lobell *et al.*, 2011).
7 Statistical models usually exclude the direct impact of elevated CO₂, making multi-decadal prediction problematic.
8 Similarly, technological progress and its interaction with climatic variability are not simulated by statistical models.
9 Regional-scale process-based models tend to include at least some of these processes. In determining future trends,
10 crop models of all types can only extrapolate based on historically-determined relationships. Process-based models
11 extrapolate based on measured interactions and mechanisms, whilst statistical models extrapolate based on
12 empirically determined relationships. Agro-climatic indices provide another alternative to process-based crop
13 models that avoid various assumptions by focusing on farmer-relevant metrics, rather than providing yield
14 predictions *per se* (Trnka *et al.*, 2011). However, correlations between climate, or associated indices, and yield are
15 not always statistically significant.

16
17 The robustness of crop model results depends on data quality, model skill prediction and model complexity
18 (Bellocchi *et al.*, 2010). Modelling and experiments are each subject to their own uncertainties. Measurement
19 uncertainty is a feature of field and controlled environment experiments. For example, interactions between CO₂
20 fertilisation, temperature, soil nutrients, ozone, pests and weeds is not well understood (Soussana *et al.*, 2010) and
21 therefore most crop models do not include all these effects, nor broader issues of water availability, such as
22 competition for water between industry and households (Piao *et al.*, 2010). There are also uncertainties associated
23 with generalizing the results of field experiments, since each one has been conducted relatively few times under a
24 relatively small range of environmental and management conditions, and for a limited number of genotypes. This
25 limits breadth of applicability both through limited sample size and limited representation of the diversity of
26 genotypic responses to environment (Craufurd *et al.*, 2013). For example, yield increases normalised by increase in
27 CO₂ have been found to vary between zero and over 30% among crop varieties (Tausz *et al.*, 2011).

28
29 Models have the advantage of exploring a larger number of situations, but with less certainty in the determination of
30 the response variable than in field studies. The uncertainty in climate simulation is generally larger than, or
31 sometimes comparable to, the uncertainty in crop simulation using a single model (Iizumi *et al.*, 2011). There is
32 significant uncertainty in agricultural simulation arising from climate model error, and since AR4 the choice of
33 method for GCM bias correction has been identified as a source of uncertainty, even in the absence of downscaling,
34 which is comparable in some cases to that from scenarios and choice of GCM (Hawkins *et al.*, 2012). There is also a
35 contribution to uncertainty in crop model output from yield measurement error, through the calibration procedure.
36 Yield measurements rarely have associated error bars to give an indication of accuracy. Greater access to accurate
37 regional-scale crop yield data can lead to decreased uncertainty in projected yields

38
39 The use of multiple crop models in impacts studies is relatively rare. Field-scale historical model intercomparisons
40 have shown variations in yield and biomass of more than 100% (Palosuo *et al.*, 2011). Early results from impacts
41 studies with multiple crop models suggest that the crop model uncertainty can be larger than that caused by GCMs,
42 due in particular to high temperature and temperature-by-CO₂ interactions (Asseng *et al.*, 2013). Given these
43 different strengths and weaknesses, and associated dependencies, it is critical that both experimental and modeling
44 lines of evidence, and their uncertainties, are examined carefully when drawing conclusions regarding impacts,
45 vulnerabilities and risks. This approach to assessment is applied to each of the topics described in the rest of the
46 chapter.

47 48 49 7.3.1.2. *Treatment of Adaptation in Impacts Studies*

50
51 Adaptation occurs on a range of timescales and by a range of actors. Incremental adaptation, such as a change in
52 crop management, can occur relatively autonomously within farming systems. It is the type of adaptation most
53 commonly assessed in the impacts literature, and it is the only form of adaptation discussed in sections 7.3 and 7.4.
54 Systemic and transformational adaptations are discussed in section 7.5.

7.3.2. Sensitivity of Food Production to Weather and Climate

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

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

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

7.3.2.1. Cereals, Oilseeds, and Legumes

7.3.2.1.1. Mean and extremes of temperature and precipitation

Both statistical and process-based models have widely been used since AR4 to assess the response of crop yield to temperature. Model results confirm the importance of known physiological processes, such as the shortening of the time to maturity of a crop with increasing mean temperature (Iqbal *et al.*, 2009), decline in grain set when high temperatures occur during flowering (Moriondo *et al.*, 2011), and increased water stress at high temperatures throughout the growing cycle (Lobell *et al.*, 2013b). Temperatures responses are generally well-understood for temperatures up to the optimum temperature for development. The impacts of prolonged periods of temperatures beyond the optimum for development are not as well understood (Craufurd and Wheeler, 2009). For example, temperatures above 34 °C after flowering appear to rapidly speed senescence in wheat (Lobell *et al.*, 2013b; Asseng *et al.*, 2013), but many crop models do not represent this process.

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

In cool season legumes, the threshold for heat stress during the reproductive phase is above 25°C (daily maximum temperature) and experimental results with field-pea in North India show that temperatures higher than 25°C at the onset of the reproductive phase led to reductions in pod setting (30%), seeds per pod (41%) and seed weight (36%) and consequently total productivity decreased by 48% (Ali and Gupta, 2012). Also in North India chickpea yields during the last years decreased between 0.53 and 3 q. ha⁻¹ per 1°C increase in seasonal temperature (Kalra *et al.*,

1 2008). Even if chickpea is more heat tolerant than other cool season legumes, high temperatures (above 30°C) during
2 the reproductive phase can affect seed yield (Devasirvatham *et al.*, 2012). Simulation results for short duration
3 pigeon pea in Kenya projected decreases in yields between 7% and 28.7% with 1°C and 5°C increase in temperature
4 respectively (Cooper *et al.*, 2009).

5
6 The relative importance of temperature and water stress for crop productivity can be assessed using models, and can
7 vary according to the criteria used for assessment (Challinor *et al.*, 2010). There are also some cases where the sign
8 of a correlation depends on the direction of the change. For example, (Thornton *et al.*, 2009) found that the response
9 crop yields to climate change in the drylands of East Africa is insensitive to rainfall, since wetter climates are
10 associated with warmer temperatures that act to reduce yields. Variation in crop-climate relationships can also result
11 from the analytical methods used and/or the spatial scale of the analysis e.g. (Challinor and Wheeler, 2008). For
12 example, increases in daily maximum temperature have been found to increase the yield of rice at a number of sites
13 across Asia (Welch *et al.*, 2010), whilst negative responses due to spikelet sterility are a well-known phenomenon in
14 controlled environment experiments. Crop models can be used to quantify abiotic stresses such as these (Challinor *et al.*
15 *et al.*, 2009), although only by hypothesizing that the functional responses to weather derived from experiments are
16 valid at regional scales. Thus, whilst many fundamental bio-physical processes are understood at the plant or field
17 scale, it remains difficult to quantify the extent to which these mechanisms are responsible for the observed
18 regional-scale relationships between crop yield and weather.

19
20 Since precipitation exhibits more spatial variability than temperature, temporal variations in the spatial average of
21 precipitation tend to diminish as the spatial domain widens. As a result, precipitation becomes less important as a
22 predictor of crop yields at broad scales (Lobell and Field, 2007; Li *et al.*, 2010). Similarly, projected changes in
23 precipitation from climate models tend to be more spatially variable than temperature, leading to the greater
24 importance of projected temperatures as the spatial scale of analysis grows wider (Lobell and Burke, 2008). There is
25 also evidence that where irrigation increases over time the influence of temperature on yields starts to dominate over
26 that of precipitation (Hawkins *et al.*, 2012)

27
28 A meta-analysis of yield impact studies for major cereals (Challinor *et al.*, 2013), including both pre- and post- AR4
29 contributions, gave broadly similar results to AR4 and to a more recent meta-analysis using multiple impacts models
30 (Frieler *et al.*, 2013). Challinor *et al.* (2013) reported tropical and temperate regions separately: yields of maize,
31 wheat and rice begin to decline with 1-2°C of local warming in the tropics, with temperate maize yields being less
32 clearly affected at these temperatures and moderately affected for greater warming (Figure 7-5). The new analysis
33 confirms AR4 findings that even slight warming will decrease yields in low-latitude regions (*medium evidence, high*
34 *agreement*). However, whilst AR4 had few indications of yield reductions at less than 2°C of local warming, the new
35 analysis has, in the absence of incremental adaptation, more yield decreases than increases at all temperatures.
36 Hence, whilst AR4 concluded with *medium confidence* that in mid- to high-latitude regions moderate warming will
37 raise crop yields, new knowledge suggests that temperate wheat yield decreases are *about as likely as not* for
38 moderate warming. Quantitative assessments of yield changes can be found in section 7.4. Within both tropical and
39 temperate regions regional variability, which cannot be summarised in meta-analyses, will be important in
40 determining how climate change affects particular agricultural systems.

41
42 [INSERT FIGURE 7-5 HERE

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

48 49 50 7.3.2.1.2. *Impact of carbon dioxide and ozone*

51
52 There is further observational evidence since AR4 that response to a change in CO₂ depends on plant type; C₃ or C₄
53 (DaMatta *et al.*, 2010). The effect of increase in CO₂ concentration tends to be higher in C₃ plants (e.g. wheat, rice,
54 cotton, soybean, sugar beets, and potatoes) than in C₄ plants (e.g. corn, sorghum, sugarcane), because photosynthesis

1 rates in C₄ crops are less responsive to increases in ambient CO₂ (Leakey, 2009). The highest fertilization responses
2 have been observed in tuber crops, which have large capacity to store extra carbohydrates in belowground organs
3 (Fleisher *et al.*, 2008; Högy and Fangmeier, 2009).
4

5 FACE studies have shown that the impact of elevated CO₂ varies according to temperature and availability of water
6 and nutrients; yet there is a strong geographical bias of FACE studies towards temperate zone (Leakey *et al.*, 2013).
7 Water-stressed crops are expected to respond more strongly to elevated CO₂ than well-watered crops, because of
8 CO₂ induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from
9 elevated CO₂ than irrigated systems, and that rain-fed systems in drier regions or years will benefit more than in
10 wetter conditions. This expectation has been cited in TAR and AR4, and new evidence based on historical
11 observations supports this notion by demonstrating that the rate of yield gains in rain-fed systems is higher for dry
12 years than for wet years (McGrath and Lobell, 2011). However, this response is not seen consistently across models
13 and FACE meta-analyses and there is some suggestion that the relationship between water stress and assimilation
14 may vary with spatial scale, with canopy analyses showing a reversal of the expected leaf-level dry vs wet signal
15 (Challinor and Wheeler, 2008).
16

17 Ozone in the stratosphere provides protection from lethal short-wave solar ultraviolet radiation, but in the
18 troposphere it is a phytotoxic air pollutant. Global background concentration of ozone has increased since
19 pre-industrial era due to anthropogenic emission of its precursor, by vehicles, power plants, biomass burning and
20 other sources of combustion. Like CO₂, O₃ is taken up by green leaves through stomata during photosynthesis but
21 unlike CO₂, its concentration is significantly variable depending on geographic location, elevation and extent of
22 anthropogenic sources. Being a powerful oxidant, ozone and its secondary by-products damage vegetation by
23 reducing photosynthesis and other important physiological functions (Mills *et al.*, 2009; Ainsworth and McGrath,
24 2010). This results in stunted crop plants, inferior crop quality and decreased yields (Booker *et al.*, 2009; Fuhrer,
25 2009; Vandermeiren *et al.*, 2009; Pleijel and Uddling, 2012) and posing a growing threat to global food security
26 (*robust evidence, high agreement*).
27

28 The literature published since AR4 further corroborates the negative impacts of increasing concentrations of surface
29 ozone on yield losses on global (Van Dingenen *et al.*, 2009; Teixeira *et al.*, 2011; Avnery *et al.*, 2011a; Avnery *et al.*,
30 2011b) and regional level (Northern Hemisphere: Hollaway *et al.*, 2011); USA: (Emberson *et al.*, 2009; Fuhrer,
31 2009; Fishman *et al.*, 2010); India (Roy *et al.*, 2009; Rai *et al.*, 2010; Sarkar and Agrawal, 2010); China: (Wang *et al.*,
32 2007; Piao *et al.*, 2010); Bangladesh: (Akhtar *et al.*, 2010); Europe: (Hayes *et al.*, 2007; Vandermeiren *et al.*,
33 2009; Fuhrer, 2009). The global yield losses of soybean, wheat and maize in 2000 ranged from 8-15% amounting to
34 production losses of \$11-18 billion (Avnery *et al.*, 2011a). The projected yield losses for the near future (year 2030)
35 would be substantial but less severe under IPCC B2 scenario than A2; yield reduction under A2 would be 9-25%
36 with production losses of \$17-35 billion and under B1 scenario 9-17% with production losses of \$12-21 billion
37 (Avnery *et al.*, 2011b). In separate meta-analyses, some researchers reported even higher losses in wheat yield (Feng
38 *et al.*, 2008) and high losses in rice yield (Ainsworth, 2008) at elevated ozone concentrations. These studies also
39 pointed out the regional hotspots of East and South-east Asia and Eastern US, strong seasonality of O₃ formation
40 (with peaks in pre- and post-monsoon months in India) depending on precursor emission and climate factors and
41 role of crop management practices, such as cropping system, crop species (Teixeira *et al.*, 2013) and crop genotype
42 (Feng *et al.*, 2011), (Biswas *et al.*, 2008; Zhu *et al.*, 2011). The sensitivity of crops to O₃ damage was in the order:
43 soybean ≥ wheat > rice > maize. The irrigated crops suffered highest production losses. Ozone may have direct
44 effect on reproductive process, leading to reduced seed and fruit development and abortion of developing fruit
45 (Royal Society, 2008; *robust evidence, high agreement*).
46

47 The interactive effects of ozone with other environmental factors such as CO₂, temperature, moisture, light, are
48 important but not well understood. Generally, the ambient and increasing concentrations of O₃ and CO₂ individually
49 exert counteractive effects on C₃ plants (Tianhong *et al.*, 2005; Ainsworth, 2008; Gillespie *et al.*, 2012); but their
50 interactive effect may compensate for each other (Ainsworth, 2008; Taub *et al.*, 2008; Gillespie *et al.*, 2012). In
51 some studies, crops grown in both elevated CO₂ and O₃ concentrations showed yield losses which were less than
52 with O₃ alone (Taub *et al.*, 2008; Fuhrer, 2009). The losses might also be greater when elevated O₃ combines with
53 high temperature (Long, 2012) particularly during grain filling of wheat, when elevated ozone causes premature leaf
54 senescence (Feng *et al.*, 2008; Feng *et al.*, 2011). Such interactions may be important for understanding ozone

1 tolerance in C₃ food crops and for exploiting rising CO₂ concentrations for yield enhancement (Ainsworth *et al.*,
2 2008; Mittler and Blumwald, 2010; Ziska *et al.*, 2012). Periods of abundant radiation, high temperature and
3 adequate water supply most favourable for agricultural production are also favourable for the formation of surface
4 ozone; thus the effects of ozone on crops are often not visible in contrast to other yield reducing factors such as
5 insect pests and diseases (Long, 2012).
6
7

8 7.3.2.2. *Other Crops* 9

10 Increases in temperature are already affecting phenology in perennial crops since the accumulation of winter chill
11 hours is decreasing. Observed trends in winter chill range between -50 and -260 chill hours per decade in California
12 and predicted rates of reduced winter chill, for the period between 1950 and 2100, are on the order of -40 h per
13 decade (Baldocchi and Wong, 2008). Averaging over three GCMs annual winter chill loss by 2050 compared to
14 1970 would amount 17.7 % to 22.6 % in Egypt (Farag *et al.*, 2010). The analysis made by (Wolfe *et al.*, 2008) using
15 HadCM3 projections under A1F1 and B1 scenarios indicate that some 400 h could be assured along the century,
16 benefiting species with low chill requirement in the north-eastern USA.
17

18 Earlier flowering and maturity have been observed (*robust evidence, high agreement*) worldwide in grapes
19 (García-Mozo *et al.*, 2010; Duchêne *et al.*, 2010; Jorquera-Fontena and Orrego-Verdugo, 2010; Sadras and Petrie,
20 2011; Webb *et al.*, 2011), apples (Fujisawa and Koyabashi, 2010; Grab and Craparo, 2011) and other perennial
21 horticultural crops (Sugiura *et al.*, 2012; Glenn *et al.*, 2013). Assessing climate change impacts on fruit production
22 in California towards 2050, (Lobell and Field, 2011) found a slightly positive yield trend (*ca.* 5%) for almonds and
23 negative trends for table grapes (5%), berries (10%) and cherries (20%) as compared to 2000. Also in eastern
24 Washington in US under A1F1 and B1 scenarios without the effect of elevated CO₂, future climate change is
25 projected to decrease apple production by 1%, 3%, and 4% for 2020, 2040, and 2080 respectively, but when the
26 effect of CO₂ is added, yields are projected to increase by 6% (2020s), 9% (2040s), and 16% (2080s) (Stöckle *et al.*,
27 2010). Reductions in suitability for grapevine are expected in most of the wine producing regions (Hall and Jones,
28 2009; White *et al.*, 2009; Jones *et al.*, 2010). Grapes/wine production and quality will be affected in Europe, US,
29 Australia
30 (Jones *et al.*, 2005; Wolfe *et al.*, 2008; Cozzolino *et al.*, 2010), Chapter 25 WG2), although it could be a benefit in
31 Portugal (Santos *et al.*, 2011) and British Columbia in Canada (Rayne *et al.*, 2009).
32

33 Important crops in Brazil like sugarcane and coffee are expected to migrate towards more favorable zones in the
34 South (Pinto, 2007; Marin *et al.*, 2009; Pinto *et al.*, 2008; Chapter 27 WG2). Sugarcane fresh stalk mass is generally
35 expected to gain from both warming and elevated CO₂ in Brazil (Marin *et al.*, 2013). The suitability for coffee crops
36 in Costa Rica, Nicaragua and El Salvador will be reduced by 40% (Glenn *et al.*, 2013) while the loss of climatic
37 niches in Colombia will force the migration of coffee crops towards higher altitudes by mid-century
38 (Ramirez-Villegas *et al.*, 2012). In the same way, increases in temperature will affect tea production, in particular at
39 low altitudes (Wijeratne, *et al.*, 2007).
40

41 Cassava is an important source of food for many people in Africa and Latin America and recent studies suggest that
42 future climate could not significantly affect its productivity as this crop is characterized by elevated optimum
43 temperature for photosynthesis and growth, and a positive response to CO₂ increases (Jarvis *et al.*, 2012; Rosenthal
44 and Ort, 2012; El-Sharkawy, 2012).
45

46 The suitability for potato crops is expected to increase in very high latitudes and high tropical altitudes towards 2100
47 (Schaeffleitner *et al.*, 2011). Projections for Europe indicate that by 2030 and 2050 the impacts on potato yields will
48 be mostly positive but towards the end of the century negative impacts are expected in the overall continent except
49 in some northern countries (Supit *et al.*, 2012). In Eastern China yields are expected to increase in the North and to
50 decrease in the South by 2100 (Chavas *et al.*, 2009), also in the Peruvian Altiplano negative impacts are expected
51 under A2 and B2 scenarios by 2100 (Sanabria and Lhomme, 2012) while in eastern Washington in US, potato yields
52 could slightly decrease (-2/-3%) under A1F1 and B1 scenarios (Stöckle *et al.*, 2010).
53
54

1 7.3.2.3. *Pests, Weeds, Diseases*2
3 7.3.2.3.1. *Sensitivity of pests, weeds, and diseases to weather and climate*

4
5 As a world-wide average, current yield loss in major crop species due to animal pests and (non-virus) pathogens, in
6 the absence of any physical, biological or chemical crop protection, is estimated at 18% and 16%, respectively
7 (Oerke, 2006). Although physical changes associated with climate uncertainty are recognized and assessed, (e.g.
8 drought, water, temperature) in the context of agricultural productivity, less attention has focused on biological
9 interactions and climate, even though it is universally recognized that weeds, insects and diseases have limited crop
10 yield potential. A fair question then is to ask whether such limitations will increase or decrease in response to future
11 changes in CO₂/climate?
12

13 The effects of weather on important diseases and pests, including optimal temperature and moisture conditions, have
14 been studied in detail for decades (De Wolf and Isard, 2007). This research forms a base for understanding that
15 climate change will change potential losses to many pests and diseases. Changes in temperature can support range
16 expansions through changes in winter and summer extremes, and thus the potential for overwintering or summer
17 survival. CO₂ and ozone can either increase or decrease plant disease, and can exhibit important interactions in
18 effects, suggesting incorporation of these risk factors in analyses may need to be system specific (Chakraborty *et al.*,
19 2008; Eastburn *et al.*, 2011). It is challenging to estimate the extent to which observed changes in effects may be due
20 to climate change because of the many factors that interact to result in pest and disease risk and management
21 decisions (Chakraborty and Newton, 2011; Garrett *et al.*, 2011). Interactions with landscape effects may be
22 particularly important in such perennial agricultural systems as forests and grasslands (Pautasso *et al.*, 2010).
23

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

37 Changes in climate are expected to affect the range of specific species of insects and diseases for a given crop
38 growing region. For example, Cannon (1998) has suggested that migratory insects could colonize crops over a larger
39 range in response to temperature increases, with subsequent reductions in yield. Guitierrez (2000) has suggested that
40 predator and insect herbivores are will respond differently to increasing temperature, with possible reductions in
41 insect predation (i.e. greater insect numbers). While plant-pathogen interactions are recognised as a factor affecting
42 crop yields, our ability to predict CO₂/climate change impacts on pathogen biology and subsequent changes on yield
43 of rice, soybean, wheat inter alia is tenuous at best, because with few exceptions (Savary *et al.*, 2011), experimental
44 data are not available and analyses focus on individual diseases rather than the complete set of important diseases
45 (*medium evidence, medium agreement*).
46

47 Ostensibly, since many agricultural weeds are C₄, and soybean, wheat and rice, C₃, increasing CO₂ should reduce
48 crop losses due to weedy competition since the C₃ pathway, in general, shows a stronger response to rising carbon
49 dioxide levels. However, the argument that rising CO₂ will reduce weedy competition because the C₄ photosynthetic
50 pathway is over-represented among weed species (Holm, 1977) does not consider the range of available C₃ and C₄
51 weed species present within the agronomic seed bank. For example, in the United States, every crop, on average,
52 competes with an assemblage of 8-10 weed species (Bridges, 1992). In addition, CO₂, and/or climate, can also affect
53 weed demographics. For example, with field grown soybean, elevated CO₂ per se appeared to be a factor in
54 increasing the relative proportion of C₃ to C₄ weedy species with subsequent reductions in soybean yields (Ziska and

1 Goins, 2006). For rice and barnyard grass (C_4), increasing CO_2 favored rice, but if both temperature and CO_2
2 increased simultaneously, the C_4 weed was favored, primarily because higher temperatures resulted in increased
3 seed yield loss for rice (Alberto et al, 1996). Overall, rising atmospheric CO_2 can increase the extent of crop losses
4 due to a greater response of the weed relative to the crop (Ziska, 2000; Ziska, 2003). If weeds are not managed such
5 losses may exceed any observed stimulation in crop yield associated with elevated CO_2 (Ziska, 2000; Ziska, 2003).
6 For weeds that share physiological, morphological, or phenological traits with the crop, including those weeds that
7 are wild relatives of the domesticated crop species, (often among the “worst” weeds in agronomic situations, e.g.
8 rice and red rice) the decrease in seed yield from weeds may, in fact, be greater in response to increasing
9 atmospheric CO_2 (Ziska, 2010). Climate change may be a factor in extending the northward migration of agronomic
10 and invasive weeds (e.g. (Ziska et al., 2011). The projected warming may be exceeding maximum rates of plant
11 migration observed in post-glacial time periods (Malcolm et al., 2002), resulting in preferential selection for the
12 most mobile plant species. A number of characteristics associated with long-distance dispersal are commonly found
13 among weeds (Rejmánek, 1996) suggesting that they will be among the fastest to migrate with increasing
14 temperatures (Dukes and Mooney, 1999). In addition, climate (e.g. precipitation) and/or temperature may change the
15 demographics of C_3 and C_4 weed species in crop production (e.g. (Ziska and Goins, 2006; McDonald et al., 2009).

16
17 Initial studies indicate a potential decline in herbicide efficacy with rising CO_2 and/or temperature for some weeds
18 (Ziska and Goins, 2006; Archambault, 2007; Manea et al., 2011). For Canada thistle, increasing CO_2 appears to
19 have induced greater below-ground growth of roots, diluting the active ingredient of the herbicide and making
20 chemical control less effective (Ziska et al., 2004). To date, studies on physical, cultural or biological weed control
21 are lacking.

22 23 24 7.3.2.3.2. *Effects of climate change on pests, weeds, and diseases*

25
26 Climate change scenario analyses are available for some pests and diseases. For example, range expansion has been
27 predicted for the destructive *Phytophthora cinnamomi* in Europe (Bergot et al., 2004) and for phoma stem canker on
28 oilseed rape in the UK (Evans et al., 2008). Increased generations under climate change for the coffee nematode
29 have been predicted for the coffee nematode in Brazil (Ghini et al., 2008). Walnut pests in California are predicted
30 to experience increased numbers of generations under climate change scenarios (Luedeling et al., 2011). Potato late
31 blight risk increases in some areas of the world, and decreases in others, under climate change scenarios (Sparks et
32 al., 2013). Luck (2011) summarized the mixed results for the qualitative effects of climate change on pathogens that
33 cause disease of four major food crops - wheat, rice, soybean and potato - where some diseases increased in risk
34 while others decreased under climate change scenarios. In syntheses, there is a tendency for risk of insect damage to
35 plants to increase (Deutsch et al., 2008; Paulson et al., 2009). Typical scenario analyses are limited by simplistic
36 assumptions, and work remains to evaluate how conclusions will change as more complete scenarios, such as those
37 including migration and invasion patterns and other types of global change, are considered (Savary et al., 2005;
38 Garrett et al., 2011). Effects on soil communities represent an area that needs more attention (Pritchard, 2011).
39 Mycotoxins and pesticide residues in food are an important concern for food safety in many parts of the world, and
40 identified as an important issue for climate change effects in Europe (Miraglia et al., 2009).

41 42 43 7.3.2.4. *Pastures and Livestock*

44
45 Pastures response to climate change is complex because, in addition to the major climatic drivers (CO_2
46 concentration, temperature, and precipitation), other plant and management factors affect this response (e.g., plant
47 competition, perennial growth habits, seasonal productivity, and plant-animal interactions). Projected increases in
48 temperature and the lengthening of the growing season should extend forage production into late fall and early
49 spring, thereby decreasing the need for accumulation of forage reserves during the winter season in USA. In
50 addition, water availability may play a major role in the response of pasturelands to climate change although there
51 are differences in species response (Izaurre et al., 2011). There is general consensus that increases in CO_2 will
52 benefit C_3 species; however, warmer temperatures and drier conditions will tend to favour C_4 species (Izaurre et
53 al., 2011; Hatfield et al., 2011, WG2 Chapter 4).

1 Projected scenarios for Europe indicate that increased temperatures and CO₂ concentrations have the potential to
2 increase herbage growth and to favour legumes more than grasses, but changes in seasonal precipitation would
3 reduce these benefits particularly in areas with low summer rainfall (Hopkins and Del Prado, 2007). Similarly,
4 legume content of grasslands in most of southern Australia is projected to increase to the 2070s, with larger
5 increases in wetter locations (Moore and Ghahramani, 2013). Further implications for grasslands may arise from
6 increased frequency of droughts, storms and other extreme events (Hopkins and Del Prado, 2007).

7
8 Impacts of climate change on feed crops and grazing systems include changes in herbage growth brought about by
9 changes in atmospheric CO₂ concentrations and rainfall and temperature regimes, and changes in the composition of
10 pastures and in herbage quality. The interactions among climate, plants, livestock grazing and land management
11 practices are complex, and evaluating the impacts of climate change on these elements is difficult (Craine *et al.*,
12 2010). In North American cattle production systems, future increases in precipitation will probably not compensate
13 for the declines in forage quality that accompany projected temperature increases, and cattle will experience greater
14 nutritional stress in the future (Craine *et al.*, 2010) Also in French grasslands (Graux *et al.*, 2013) and in sown
15 pastures in Tasmania (Perring *et al.*, 2010), results from simulations indicate that forage quality will decrease in the
16 future.

17
18 Pastureland species in the USA may experience accelerated metabolism and advanced development with rising
19 temperature, often resulting in changes in length of the growing season, although soil resources will often constrain
20 temperature effects (Izaurrealde *et al.*, 2011). Similar effects are projected for European grasslands, many of which
21 may be mediated via management - sometimes with impacts on mitigation too: ruminants fed tropical legumes
22 produced 20% less methane than those fed C₄ grasses (Archimède *et al.*, 2011).

23
24 While elevated atmospheric CO₂ concentrations reduce sensitivity to lower precipitation in grassland ecosystems
25 and can reduce mortality and increase recovery during severe water stress events, it is still unclear how general this
26 result is (Soussana *et al.*, 2010). Evaluating the differential responses of plant species to elevated CO₂ will require
27 models to include mechanisms of resource capture and use among plant functional types (Lazzarotto *et al.*, 2009;
28 Soussana *et al.*, 2010). Studies on climate change impacts on pastureland that include assessment of the mediating
29 effects of management as well as changes in water, carbon, and nutrient cycling have been undertaken (e.g. (Rütting
30 *et al.*, 2010; Moore and Ghahramani, 2013), but more comprehensive studies are needed (McKeon *et al.*, 2009;
31 Izaurrealde *et al.*, 2011).

32
33 Moreover, IPCC emission scenarios for many cropland regions project elevated ozone concentrations in the
34 atmosphere to the 2050s and beyond. At the same time, crop sensitivity may decline in areas where warming is
35 accompanied by drying, such as in central Europe (Soussana *et al.*, 2010). Parameters in models for ozone risk
36 assessment are uncertain and model improvements will be needed to identify regions most at risk from ozone in
37 future climates (Fuhrer, 2009). At this stage, more experiments using free-air ozone enrichment will be needed
38 across different habitats, climates and productivity levels before generalisations about the sensitivity of pastures to
39 ozone can be made (Fuhrer, 2009).

40
41 As livestock productivity increases, be it increasing milk yield in dairy cattle or higher growth rates and leanness in
42 pigs or poultry, so metabolic heat production increases and the capacity to tolerate elevated temperatures declines
43 (Zumbach *et al.*, 2008; Dikmen and Hansen, 2009). Over the long term, single-trait selection for productivity will
44 tend to result in animals with lower heat tolerance (Hoffmann, 2010). Recent work adds to previous understanding
45 (AR4 Chapter 5) and indicates that heat stress in dairy cows can be responsible for the increase in mortality and
46 economic losses (Vitali *et al.*, 2009); it affects a wide range of parameters in broilers (Feng *et al.*, 2008); it impairs
47 embryonic development and reproductive efficiency in pigs (Barati *et al.*, 2008); and affects ovarian follicle
48 development and ovulation in horses (Mortensen *et al.*, 2009). The impacts of a changing UK climate on dairy cow
49 production were analysed by (Wall *et al.*, 2010), who showed that in some regions, milk yields will be reduced and
50 mortality increased because of heat stress throughout the current century, under a medium-high greenhouse gas
51 emissions scenario, annual production and mortality losses amounting to some £40 million by the 2080s. Given that
52 there is a genotype-by-environment interaction on the impacts of heat stress (Bohmanova *et al.*, 2008), breeding
53 goals that focus on production traits tend to reduce heat tolerance. Breeding goals that aim to reduce greenhouse gas
54 emissions need to take possible future climatic conditions into account (Hoffmann, 2010). Tools to do this in

1 developed country situations are becoming available (e.g. (Hayes *et al.*, 2009). Developing countries may be more
2 reliant on local breeds, most of which are not well characterized, although such breeds may be not only heat tolerant
3 but also tolerant of poor seasonal nutrition and parasites and diseases (Hoffmann, 2010).

4
5 Host and pathogen systems will change their ranges because of climate change. Species diversity of some pathogens
6 may decrease in lowland tropical areas as temperatures increase (Mills *et al.*, 2010). The temperate regions may
7 become more suitable for tropical vector-borne diseases such as Rift Valley fever and malaria, which are highly
8 sensitive to climatic conditions (Rocque *et al.*, 2008). An overall increase in suitable conditions for pathogens and
9 vectors is expected, rather than just a shift in distribution, because minimum temperatures are increasing more than
10 maximum temperatures (Ostfeld, 2009). Vector-borne diseases of livestock such as African horse sickness and
11 bluetongue may expand their range northwards because rising temperatures increase the development rate and
12 winter survival of vectors and pathogens (Cutler *et al.*, 2010). Diseases such as West Nile virus and schistosomiasis
13 are projected to expand into new areas (Rosenthal, 2009). The distribution, composition and migration of wild bird
14 populations that harbour the genetic pool of Avian Influenza viruses will all be affected by climate change, although
15 in ways that are somewhat unpredictable (Gilbert *et al.*, 2008). The changing frequency of extreme weather events,
16 particularly flooding, will affect diseases too. For example, outbreaks of Rift Valley fever in East Africa are
17 associated with increased rainfall and flooding due to El Niño-Southern Oscillation events (Gummow, 2010; Pfeffer
18 and Dobler, 2010). In general, the impacts of climate change on livestock diseases remain difficult to predict and
19 highly uncertain (Mills *et al.*, 2010; Tabachnick, 2010).

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

35 36 37 7.3.2.5. *Food and Fodder Quality and Human Health*

38
39 Climate change is will have some adverse impacts food quality through both biotic and abiotic stresses (Ceccarelli *et*
40 *al.*, 2010). These changes may affect crop quality by altering carbon and nutrient uptake and biochemical processes
41 that produce secondary compounds or redistribute and store compounds during grain development and maturation
42 which in turn could impact human and livestock health by altering nutritional intake. They also affect economic
43 value by altering traits valuable to processors or the consumers. Food quality is any characteristic other than yield
44 that is valuable to the producer or consumer, and includes properties such as protein and starch concentrations,
45 which affect dough quality, dough strength, and loaf volume of wheat flour; chalkiness, amylose content and
46 gelatinization temperature in rice, which affect taste; and mineral concentrations, which affect nutrient intake of
47 consumers.

48
49 Change in N concentration, a proxy for protein concentration, is the most examined quality trait, and since AR4,
50 studies have been extended to almost all the major food crops. Meta-analysis of 228 experimental observations finds
51 decreases between 10 to 14 % in edible portions of wheat, rice, barley and potato, but only 1.5 % in soybeans, a
52 nitrogen-fixing legume, when grown in elevated (540 - 958 ppm CO₂) compared to current (315 - 400 ppm CO₂)
53 concentrations (Taub *et al.*, 2008). The decrease in protein content of cereals grown in elevated CO₂ concentrations

1 was reported by many other workers (Piikki *et al.*, 2007; Hogy *et al.*, 2009; Erbs *et al.*, 2010; Ainsworth and
2 McGrath, 2010; DaMatta *et al.*, 2010; Erda *et al.*, 2010; Fernando *et al.*, 2012).

3
4 Mineral concentration of edible plant tissues are affected by growth in elevated CO₂ in a similar manner as N.
5 Although there are numerous studies measuring mineral concentration, there are many minerals relevant to human
6 health. Therefore, there are relatively few measurements for any given mineral. Although there were several studies
7 published before the release of AR4, this topic was not covered in any depth in AR4. Meta-analysis of studies prior
8 to 2002 finds that P, Ca, S, Mg, Fe, Zn, Mn and Cu decline by 2.5 - 20 % in wheat grain and leaves of numerous
9 species in elevated CO₂, but K increases insignificantly in wheat grain (Loladze, 2002; Hogy *et al.*, 2009; Fernando
10 *et al.*, 2012). Since 2002, studies generally find decreases in Zn, S, P, Mg and Fe in wheat and barley grain, but
11 results are mixed for Ca and K, whereas limited evidence shows an increase in Cu, Mo and Pb (Hogy *et al.*, 2009;
12 Erbs *et al.*, 2010; Fernando *et al.*, 2012). The magnitude of such decreases is likely to be affected by several factors
13 including crop species, soil type, tissue (e.g. tuber, leaves or grain) and water status. In addition to effects of climate
14 on plants directly, climate change-mediated soil degradation may affect nutrient composition by altering mineral
15 availability (Lal, 2009).

16
17 The primary reason for the decline in protein concentration, and by extension mineral concentrations, is that
18 enhanced production of carbohydrates in elevated CO₂ decreases the concentrations of all non-carbonaceous
19 compounds because the increase in canopy carbon uptake increases without a concomitant increase in nutrient
20 uptake. Thus, the increased amount of carbon dilutes the concentrations of other nutrients (Poorter *et al.*, 1997). The
21 declines in nitrogen concentration are usually larger than expected from carbon dilution alone though (Taub *et al.*,
22 2008; Pleijel and Uddling, 2012) which indicates that nutrient uptake per unit biomass is lower under elevated CO₂
23 concentration. The reasons for this are unclear but altered root architecture, reduced root uptake activity and reduced
24 flow of nutrients to the roots (Taub and Wang, 2008). Understanding the basis for these declines is imperative as it
25 would allow for prediction of nutrient decline in various environments, and give some insight into nutrient change in
26 relation to change in other environmental factors in the future climate.

27
28 Elevated O₃ concentrations appear to have the opposite effect as elevated CO₂. Meta-analysis of about 50 wheat
29 experiments found that elevated O₃ increased grain protein concentration by decreasing yield (Pleijel and Uddling,
30 2012). For other species, studies find both increases and decreases of N and several minerals (Taub *et al.*, 2008), and
31 as such no firm conclusions can be drawn, but they likely response similarly. Similarly, experiments examining the
32 effect of drought on mineral concentrations find both decreases and increases in mineral concentrations (Ghorbanian
33 *et al.*, 2011; Sun *et al.*, 2011).

34
35 Elevated CO₂ can lower the nutritional quality of flour produced from grain cereals (Hogy *et al.*, 2009; Erbs *et al.*,
36 2010) and of cassava (Gleadow *et al.*, 2009). When coupled with increased crop and pathogen biomass, elevated
37 CO₂ can result in increased severity of the *Fusarium pseudograminearum* pathogen, leading to shriveled grains with
38 low market value (Melloy *et al.*, 2010). High and low temperature even for a short time during reproductive growth
39 can cause pollen sterility and shriveling of grain in wheat with consequent reduction in yield and market value.
40 Extreme temperatures and elevated CO₂ concentrations reduce milling quality of rice by increasing chalkiness,
41 which causes breakage during milling, leading to reduced head yield (the percentage of unbroken kernels) but
42 increased consumer -valued traits, such as reduced amylase concentration, increased mass viscosity and increased
43 breakdown, all of which correlate with taste, are increased (Yang *et al.*, 2007). The cultivars, however, vary in their
44 susceptibility (Ambardekar *et al.*, 2011; Lanning *et al.*, 2011). Rice is sensitive to daytime extreme temperature and
45 humidity during flowering and also to high night-time temperature causing a decrease in rice eating quality and
46 assimilates accumulation, and yield (Okada *et al.*, 2009; Wassmann *et al.*, 2009).

47
48 There is robust evidence and high agreement that elevated CO₂ on its own likely results in decreased N
49 concentrations. Combining knowledge of N and mineral studies, there is *medium evidence* and *medium agreement*
50 that mineral concentrations will decline. The majority of these data are from wheat, with comparatively little
51 information from key crops such as maize, rice, potato and cassava; thus magnitudes are uncertain for the species.
52 Increases in CO₂ concentration are global and uniform, thus this effect will have global impacts, but confidence in
53 this effect does not imply confidence in changes regarding human health for several reasons. First, elevated CO₂ can
54 increase yield of minerals (g mineral per m² land area) even though concentrations are decreased (Duval *et al.*,

1 2011). Therefore, for any group for which increased crop yields allows for greater consumption (e.g., because they
2 produce and consume the food directly, or through effects of prices) intake of calories and minerals could increase,
3 despite lower mineral concentrations. Furthermore, since calorie intake is the primary concern in many food
4 insecure populations, even if intake of minerals is decreased, those negative effects could be outweighed by
5 increased calorie intake. Second, altered temperature, precipitation and ozone concentrations affect nutrient
6 concentrations and their effects are globally variable. Third, changes in mineral concentrations do not directly relate
7 to changes in consumption since many foods are processed in ways that affect nutrient concentrations, e.g., the
8 nutrient-rich outer layers of rice are removed, leaving the starch dense endosperm. Lastly, impacts on health must
9 take into account current diets. Decreased mineral intake will matter for those who currently do not meet, or just
10 barely meet, requirements, but will not affect those who already exceed requirements. Little is known about
11 combined effects of climate change factors on food quality or the economic and behavioral changes that will occur.
12 Thus, there is little to no confidence regarding effects of climate change on human health through changes in
13 nutrient composition. Hence, a complete understanding of how climate-induced changes in food quality will impact
14 human health in different environments and how this information will be used to make predictions about impacts on
15 health is needed.

18 7.3.2.6. Fisheries and Aquaculture

20 The fisheries and aquaculture sector differs from mainstream agriculture and is characterized by distinct interactions
21 and needs in relation to climate change. Capture fisheries in particular, comprising the largest remaining example of
22 harvesting natural, wild resources, are strongly influenced by global ecosystem processes. The social, economic and
23 nutritional requirements of the growing human population are already driving heavy exploitation of capture fisheries
24 and rapid development of aquaculture. This demand will increase over the next 20 to 30 years at least: (Merino *et*
25 *al.*, 2012) forecast that in addition to a predicted small increase in marine fisheries production, between 71 and 117
26 MT of fish will need to be produced by aquaculture to maintain current average *per capita* consumption of fish.
27 Climate change is an additional threat to the sustainability of capture fisheries and aquaculture development, adding
28 to the threats of over-fishing and other environmental impacts (FAO, 2009). Expected changes in the intensity,
29 frequency and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification
30 and changes in precipitation with associated changes in groundwater and river flows are expected to result in
31 significant changes across a wide range of aquatic ecosystem types and regions. There is no conclusive evidence at
32 this stage, but the potential risks of climate change enabling the spread of pathogenic species has been raised and
33 there are some concerns that, for example, poleward increases in temperature could lead to the spread of pathogens
34 with impacts on wild and cultured aquatic resources (De Silva and Soto, 2009).

37 7.3.2.6.1. Mean and extremes of temperature and precipitation

39 There is widespread agreement that, under most emission scenarios, increasing mean temperatures will lead to
40 changes in the distribution of marine fish and invertebrate species. In general, the distribution of species will shift
41 towards the poles as has already been observed in, for example, the North Sea (Brander, 2007) and Australia
42 (Hobday, 2010) JP: I have highlighted the following in red for you to decide if it needs to be deleted, Chapter 6 of
43 this volume). These shifts will result in positive and negative impacts on fisheries production with the direction of
44 change varying from locality to locality and species to species. Overall, increased temperatures are expected to
45 reduce ecosystem productivity in most tropical and subtropical oceans, seas and lakes and to increase productivity in
46 high latitudes. Projections based on a dynamic bioclimate envelope model under the SRES A1B scenario suggested
47 that climate change could lead to an average 30–70% increase in fisheries yield from high-latitude regions (>50° N
48 in the northern hemisphere), but a decrease of up to 40% in the tropics by 2055 compared to yields obtained in 2005
49 (Cheung *et al.*, 2010). A recent study using a suite of models linking physical, ecological, fisheries, and
50 bioeconomic processes projected that, under the A1B scenario, the global yield from ‘large’ fish could increase by
51 6% and that of the ‘small fish’ used in fishmeal production by 3.5%. This forecast was predicated on the assumption
52 that marine fisheries and fish resources would be managed sustainably (Merino *et al.*, 2012). A study on the effects
53 of climate warming on marine fish along the Portuguese coast forecast, under the A2 and B2 emission scenarios,
54 that fish species richness would increase, potentially creating opportunities for the development of new commercial

1 fisheries (Vinagre *et al.*, 2011). Fulton (2011) used available end-to-end models to forecast the impacts of climate
2 change under the A2 scenario across approximately two-thirds of Australia's EEZ. The results indicated that by
3 2060 the large-scale commercial fisheries in all of the regions that were covered by the models would experience an
4 overall increase of 90% in their economic returns, although differing across sectors. The change in returns for the
5 small-scale sector varied between the regions from a decrease of 30-51% in some regions to an increase of 9-14% in
6 another. The difference between the sectors was because the large-scale fisheries had greater flexibility to adapt to
7 changes in distribution, composition and abundance of their target species (Fulton, 2011). These and other available
8 forecasts demonstrate substantial differences in the direction and magnitude of impacts of climate change on
9 fisheries production around the world, driven by different physical and biological attributes and the ability of
10 fisheries operations and management to adapt to the changes that do occur.

11
12 The changes in marine yields projected by (Cheung *et al.*, 2010) result from changes in distribution of important fish
13 stocks. In the case of freshwater fisheries, natural boundaries will frequently restrict the ability of species to change
14 distribution. Endemic species, those in fragmented habitats and those in aquatic systems with a predominantly
15 east-west orientation will be particularly restricted (Ficke *et al.*, 2007), as will food production systems dependent
16 on them.

17
18 Many aquatic species are routinely subjected to large daily and seasonal fluctuations in temperature and are able to
19 cope with them. For example, temperatures in shallow coastal habitats in the tropical Pacific can vary by more than
20 14°C diurnally (Pratchett *et al.*, 2011). Nevertheless, changes in temperature extremes are expected to have impacts
21 in some cases. For example, a study on salmon populations in Washington State, USA by (Mantua *et al.*, 2010)
22 demonstrated the important impacts of seasonal variations and extremes, as opposed to means, on population
23 responses to climate change. The study concluded that warming in winter and spring would have some positive
24 impacts while increased summertime stream temperatures, seasonal low flows and changes in the peak and base
25 flows would have negative impacts. Coral reefs are particularly susceptible to extremes in temperature: temperatures
26 1 or 2°C in excess of normal maximums for 3 to 4 weeks are sufficient to disrupt the essential relationship between
27 endosymbiotic dino-flagellates and their coral hosts leading to coral bleaching. Large scale bleaching of coral reefs
28 has increased in recent decades both in intensity and frequency (Hoegh-Guldberg *et al.*, 2007); Box 5-3).

29
30 Reliable fine scale projections are not available at present because of the ecological complexity of the responses as
31 well as the potential role of human adaptation in minimising risks and taking advantage of new opportunities.

32 33 34 7.3.2.6.2. *Impact of ocean acidification*

35
36 The impact of increasing CO₂ concentrations on coral reefs as a result of higher concentrations of carbonic acid in
37 the ocean reducing the availability of carbonate to the reef building organisms is addressed in the Cross-chapter
38 ocean acidification box (IPCC 2014, WG2). It is reported there, citing the original references, that the annual
39 economic cost of ocean-acidification-induced coral reef loss by 2100 has been estimated to be 870 and 500 billion
40 USD respectively for A1 and B2 SRES emission scenarios and that the global cost of loss of production of molluscs
41 could be over 100 billion USD by 2100.

42 43 44 7.3.2.6.3. *Combined impacts on fish and seafood production*

45
46 Climate change is modifying the distribution of marine and freshwater species with a general displacement towards
47 the poles and is leading to changes in the size and productivity of suitable aquatic habitats. This will have a mixture
48 of negative and potentially positive impacts which will vary from locality to locality. The ability to take advantage
49 of new opportunities brought about by these changes will depend on the adaptive capacity of countries and local
50 communities.

51
52 Where these ecological changes are significant, countries and communities will need to adapt through, for example,
53 changes in fishing and aquaculture practices and operations. Given the proximity of fishing and aquaculture sites to
54 oceans, seas and riparian environments, extreme events can be expected to have impacts on the associated

1 infrastructure and to affect safety at sea and for communities, with those living in low-lying areas at particular risk.
2 In areas that experience water stress and competition for water resources, aquaculture operations and inland fisheries
3 production will be at risk. The impacts of climate change on the fisheries and aquaculture sector will have
4 implications for the four dimensions of food security i.e. availability of aquatic foods, stability of supply, access to
5 aquatic foods, and utilization of aquatic products (FAO, 2009).
6
7

8 **7.3.3. Sensitivity of Food Security to Weather and Climate**

9

10 *7.3.3.1. Non-Production Food Security Elements*

11

12 As indicated in the discussion in 7.1.1 and Figure 7-1, food security is dependent on access and consumption
13 patterns, food utilization and nutrition, and overall stability of the system as much as food production and
14 availability. The overall impact of climate change on food security is considerably more complex and potentially
15 greater than projected impacts on agricultural productivity alone. Figure 7-1 indicates the main components of food
16 security and their key elements. All of these will be affected by climate change to some extent. For example, climate
17 change effects on water, sanitation and energy availability have major implications for food access and utilization as
18 well as availability. Likewise, changes in the frequency and severity of climate extremes can affect stability of food
19 availability and prices, with consequent impacts on access to food.
20

22 *7.3.3.2. Accessibility, Utilization, and Stability*

23

24 *7.3.2.2.1. Climate change impacts on access*

25

26 As noted in the discussion in section 7.1.3, change in the levels and volatility of food prices is a key determinant of
27 food access. Given the hypothesis that climate change will be a contributing factor to food price increases, and
28 hence its affordability, the vulnerability of households to reduced food access depends on their channel of food
29 access (*medium evidence; medium agreement*). Table 7-1 divides households into five main categories of food
30 access, indicating their relative impacts of food price increases.
31

32 [INSERT TABLE 7-1 HERE

33 Table 7-1: Households divided into five categories of food access, indicating the impacts for them of food price
34 increases.]
35

36 Concern about the impact of increased food prices on poverty and food security arises due to the high share of
37 income that poor consumers spend on food, thus generating a disproportionately negative effect of price increases on
38 this group (FAO, 2011). A recent study by the World Bank estimated a net increase of 44 million people in extreme
39 poverty in low and middle income countries as a result of food price increases since June 2010 (Ivanic *et al.*, 2011).
40

41 Recent studies have indicated that the distribution of net food buyers and net food sellers varies considerably across
42 countries and can be expected to change with the process of economic development (Zezza *et al.*, 2008; Aksoy *et*
43 *al.*, 2010; FAO, 2011). Changing consumption patterns associated with dietary transitions that accompany income
44 growth, urbanization, market development, and trade liberalization determines the rate and nature of food demand
45 growth and nutritional levels, and thus is a key determinant of global and local food security (Kearney, 2010).
46 However the evidence base on potential climate change impacts on consumption patterns, or on other
47 non-production elements of food security is thin (*limited evidence, low agreement*), particularly when compared
48 with the literature on climate change impacts on food production and availability.
49

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

1 low income agricultural dependent economies that are net food importers, which are those that already have high
2 rates of food insecurity, could experience significant losses in food access through a double negative effect on
3 reduced domestic agricultural production and increased food prices on global markets.

6 7.3.2.2.2. *Climate change impacts on stability*

8 There is increasing evidence and confidence in the effect of climate change on increasing the incidence and
9 frequency of some types of climate extreme events (IPCC, 2012), and this will have significant impacts on food
10 security (*medium evidence; medium agreement*) Recent experience with global climate pattern impacts on food
11 security indicate the potential nature and magnitude of increased climate extremes. An impact assessment of the
12 2010 Pakistan floods surveyed 1800 households 6 months after the floods and found that 88% of the households
13 reported income losses of up to 50%, with significantly higher rates in rural than urban areas (Kirsch *et al.*, 2012).
14 The same study indicated that loss of key services such as electricity, sanitation and clean water resulted in lower
15 standards of living even in the wake of significant relief attempts, again with significantly heavier effects on rural
16 populations (Kirsch *et al.*, 2012). The Russian heat wave of 2010 and subsequent export ban contributed to the more
17 than doubling of global wheat prices by the end of the year. The degree to which these price increases affected
18 domestic consumers and poverty depended on national responses in importing countries, although a significant net
19 negative effect on poverty was found (Ivanic *et al.*, 2011).

20
21 Increased incidence of climate extremes increases uncertainty, which mitigates incentives to invest in agricultural
22 production, potentially offsetting positive impacts from increasing food price trends. This is particularly true for
23 poor smallholders with limited or no access to credit and insurance. Greater exposure to climate risk, in the absence
24 of well-functioning insurance markets, leads to: 1) greater emphasis on low-return but low-risk subsistence crops
25 (Roe and Graham-Tomasi, 1986; Fafchamps, 1992; Heltberg and Tarp, 2002), 2) a lower likelihood of applying
26 purchased inputs such as fertilizer (Kassie *et al.*, 2008; Dercon and Christiansen, 2011), 3) a lower likelihood of
27 adopting new technologies (Feder *et al.*, 1985; Antle and Crissman., 1990), and 4) lower investments (Skees *et al.*,
28 1999). All of these responses generally lead to both lower current and future farm profits (*robust evidence, high*
29 *agreement*) (Rosenzweig and Binswanger, 1993; Hurley, 2010).

30
31 It is also well documented that in many rural areas, smallholders in particular do not have the capacity to smooth
32 consumption in the face of climate shocks, particularly generalized shocks that affect a majority of households in the
33 same location (Dercon, 2004; Skoufias and Quisumbing, 2005; Dercon *et al.*, 2006; Fafchamps, 2009; Prakash,
34 2011). Any increases in climate extremes will exacerbate the vulnerability of all food insecure people, including
35 smallholders (*robust evidence, high agreement*). Currently, smallholders rely to a large extent on increasing labor
36 off-farm where possible (Fafchamps, 1999; McPeak, 2004; Kazianga and Udry, 2006), but also by decreasing both
37 food consumption and non-food expenditures, such as those on education and healthcare (Frankenberg, 1999;
38 Skoufias and Quisumbing, 2005) (*medium evidence, high agreement*). Furthermore, some evidence also suggests
39 that poorer households are more likely to reduce consumption, while wealthier households liquidate assets to cover
40 current deficits (*limited evidence, medium agreement*) (Kazianga and Udry, 2006; Carter and Lybbert, 2012).
41 Reductions in food consumption, sales of productive assets, education and healthcare can lead to long-term losses in
42 terms of income-generation and thus to future food security (*limited evidence, medium agreement*) (Hoddinot and
43 Maluccio, 2002; Skoufias and Quisumbing, 2005). Increased uncertainty of future climate conditions and increases
44 in climate extremes will increase food insecurity unless these significant barriers to consumption and asset
45 smoothing can be addressed (*medium evidence, medium agreement*).

46 47 48 7.3.2.2.3. *Climate change impacts on utilization*

49
50 Climate change impacts on utilization may come about through changes in consumption patterns in response to
51 shocks, as well as changes in nutrient content of food as well as food safety (*medium evidence; medium agreement*).
52 Rationing consumption to prioritize calorie-rich, but nutrient poor foods is another common response (Bloem *et al.*,
53 2010). The effects are a decrease in dietary quality as well as quantity, which are magnified by pre-existing
54 vulnerabilities – and lead to long term loss of health, productivity capacity and low incomes (*medium evidence;*

1 *medium agreement*) (Bloem *et al.*, 2010; Alderman, 2010; Brinkman *et al.*, 2010; Campbell *et al.*, 2010; Sari *et al.*,
2 2010). The biological effects of climate change on nutrient content of foods is one of main pathways for effects on
3 utilization. A summary of recent literature on the impacts of climate change on the composition of nutrients in food
4 items is given in HLPE (2012). Research on grains generally shows lowering of protein content with elevated
5 temperature and CO₂ levels (Ainsworth and McGrath, 2010; Erda *et al.*, 2005; Hatfield *et al.*, 2011). There is good
6 agreement that for plant-derived foods, mycotoxins are considered the key issue for food safety under climate
7 change (Miraglia *et al.*, 2009). The impacts of climate change on mycotoxins in the longer term are complex and
8 region-specific; temperatures may increase sufficiently to eliminate certain mycotoxin-producing species from parts
9 of the tropics, but in colder tropical regions and temperate zones, infections may increase (Cotty and Jaime-Garcia,
10 2007).

11 12 13 **7.3.4. Land Use Change and Autonomous Adaptation** 14

15 As noted in the AR4, changes in land use, for example adjusting the location of crop production, are a potential
16 adaptation response to climate change. Studies since the AR4 have confirmed that high latitude locations are likely
17 to become more suitable as the total time regions (Iqbal *et al.*, 2009). Trnka *et al.* (2011), for example, examined
18 projections of eleven agro-climatic indices across Europe, and found that declines in frost occurrence will lead to
19 longer growing seasons, although temperature and moisture stress will likely lead to greater inter-annual variability
20 in crop suitability. The potential influence of pests and diseases is commonly beyond the scope of such studies
21 (Gregory *et al.*, 2009).

22
23 For tropical systems where moisture availability or extreme heat rather than frost limits the length of the growing
24 season, there is a likelihood that the length of the growing season and overall suitability for crops will decline
25 (*medium evidence, medium agreement*) (Jones and Thornton, 2009; Zhang and Cai, 2011). For example, half of the
26 wheat-growing area of the Indo-Gangetic Plains could become significantly heat stressed by the 2050s, whilst
27 temperate wheat environments are likely to expand northwards as climate changes (Ortiz *et al.*, 2008). Similarly, by
28 2050, the majority of African countries will experience climates over at least half of their current crop area that lie
29 outside the range currently experienced within the country (Burke *et al.*, 2009). The majority of these novel climates
30 have analogues in other African countries. In mountainous regions, where temperature varies significantly across
31 topography, changes in crop suitability can be inferred from the variation of temperature across topography. The
32 resulting vertical zones of increasing, decreasing and unchanging suitability can be relatively robust in the face of
33 uncertainty in future climate (Schroth *et al.*, 2009).

34
35 The interaction between water resources and agriculture is likely to be increasingly important as climate changes.
36 For example, whilst projected changes in crop productivity in China are uncertain, even within a single emissions
37 scenario, irrigation has significant adaptation potential (Piao *et al.*, 2010). However, limitations to availability of
38 water will affect this potential (Frieler *et al.*, 2013). Changes in water use, including increased water diversion and
39 development to meet increasing water demand, and increased dam building will also have implications for inland
40 fisheries and aquaculture, and therefore for the people dependent on them (Ficke *et al.*, 2007; FAO, 2009). In the
41 case of the Mekong River basin, a large proportion of the 60 million inhabitants are dependent in some way on
42 fisheries and aquaculture which will be seriously impacted by human population growth, flood mitigation, increased
43 offtake of water, changes in land use and overfishing, as well as by climate change (Brander, 2007). Ficke *et al.*
44 (2007) reported that at that time there were 46 large dams planned or already under construction in the Yangtze
45 River basin, the completion of which would have detrimental effects on those dependent on fish for subsistence and
46 recreation.

47
48 The models used in projections of land suitability and cropland expansion discussed above rely on assumptions
49 about non-climatic constraints on crop productivity, such as soil quality and access to markets. These assumptions
50 are increasingly amenable to testing as the climate system shifts, by comparing observed changes in cropland area
51 with model predictions. The location of the margin between cropping land and extensive grazing in southern
52 Australia has varied with decadal climate conditions and is projected to shift towards the coast with hotter and drier
53 conditions, notwithstanding the positive impacts of elevated CO₂ (Nidumolu *et al.*, 2011). Recent trends in climate
54 have seen reductions in cropping activity consistent with these projections (Nidumolu *et al.*, 2011).

1
2 The application of first-generation biofuel conversion technologies have expanded the uses for traditional
3 commodities such as maize, oil seeds, and sugarcane, enabling farmers to market their crops beyond the traditional
4 food, feed or industrial food-processing uses. Such changes in land use have potentially adverse consequences for
5 food security. There are a number of developing countries that are relatively food secure, and have a higher demand
6 for fossil-based fuels – Brazil, Malaysia, Peru, Argentina, and Thailand–. A number of these countries which are
7 export-oriented and have relatively large areas of land available are currently expanding biofuel production in order
8 to meet both domestic and international demand (Ewing and Msangi, 2009). However, the expansion of biofuel
9 production has created new linkages, trade-offs, and competition between the agricultural and energy sectors. It has
10 also introduced new food-security risks and new challenges for the poor, particularly when natural-resource
11 constraints have led to trade-offs between food and biofuel production and also to rising food prices (FAO, 2008;
12 von Braun and Torero, 2009; Chum et al., 2011). The current food crop based biofuels are of concern as their
13 development will also exacerbate food insecurity particularly in many of developing countries. Biofuels targets
14 imply that an additional 140 and 150 million people may be at risk of hunger by 2020. Africa and South Asia will
15 account for over two-thirds of those people most affected (Fischer *et al.*, 2009).
16
17

18 7.4. Projected Integrated Climate Change Impacts

19 7.4.1. Projected Impacts on Cropping Systems

20
21
22 Crop productivity remains the most well studied aspect of food security impacts from climate change, with many
23 projections published since AR4. These newer studies confirm many of the patterns identified in AR4, namely that
24 tropical areas fare worse than temperate areas for small amounts of warming, and all areas are projected to have
25 negative yield impacts past 3°C of local warming without adaptation, even with benefits of higher CO₂ and rainfall
26 (Challinor *et al.*, 2013). One exception is that more recent studies often show negative impacts for temperate wheat
27 for 1-3 °C local warming, whereas AR4 showed primarily positive responses at these temperatures.
28

29 Figure 7-6 shows the changes in mean crop yield in twenty-year bins, from a meta-analysis of over 1800 projections
30 (Challinor *et al.*, 2013), including cases with no adaptation and a range of incremental adaptations. Taking the data
31 as an indication of risk of crop yield reduction shows that reductions in mean yield become *more likely than not*
32 from the 2030s. Reductions of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the
33 century. Some important regional differences are masked in the figure. From the 2070s onwards, all of the positive
34 yield changes are in temperate regions, suggesting that yield reduction in the tropics are *very likely* by this time. This
35 is consistent with the analysis of Knox *et al.* (2012). A recent model intercomparison of global gridded crop models
36 (Rosenzweig *et al.*, 2013) presents a similar pattern for projections from site-based crop models.
37

38 [INSERT FIGURE 7-6 HERE

39 Figure 7-6: Projected changes in crop yield as a function of time. The y-axis indicates degree of consensus and the
40 colours denote percentage change in crop yield. Data are plotted according to the 20-year period in which the centre
41 point of the projection period falls. Taken from (Challinor *et al.*, 2013).]
42

43 Fewer studies have explicitly compared projections for different regions or crops to identify areas at most risk.
44 (Lobell *et al.*, 2008) used a statistical crop model with 20 GCMs and identified South Asia and Southern Africa as
45 two regions that, in the absence of adaptation, would likely suffer negative impacts on several important crops.
46 Yields changes have also been assessed by regional meta-analyses: Knox *et al.* (2012) found yield reductions of up
47 to 50% in the second half of the century for Sub-Saharan Africa and South Asia, with wheat, maize, sorghum, and
48 millets more affected than rice, cassava, and sugarcane.
49

50 Changes in the interannual variability of yields are likely to be important in determining future stability of food
51 availability and access. Figure 7-7 shows projected changes in the coefficient of variation of yield from some of the
52 few studies that publish this information. The data shown are consistent with reports of CV elsewhere: Müller *et al.*
53 (2013) conducted gridded simulations across the globe and reported an increase of more than 5% in CV in 64% grid
54 cells, and a decrease of more than 5% in 29% of cases. Increases in CV can be due to reductions in mean yields

1 and/or increases in standard deviation of yields, and often simulated changes are a combination of the two.
2 However, many studies reported increases in standard deviation, for example (Challinor *et al.*, 2010) projected
3 increasing occurrence of extremely low crop yields due to heat and water stress. Teixeira *et al.* (2013) report that
4 under SRES A1B for 2070–2100 high temperature stress is likely to affect many parts of the globe, including
5 temperate regions. Semenov and Shewry (2011) also find evidence from models that temperate heat stress will be an
6 important determinant of yield from the 2050s. Thus temperature extremes due to changes in the distribution of
7 climate are likely to increase yield variability. Overall, there is *medium confidence* that climate change will increase
8 variability in crop yield in many regions (*medium evidence, medium agreement*).
9

10 [INSERT FIGURE 7-7 HERE

11 Figure 7-7: Projected percentage change in coefficient of variation (CV) for wheat (gold), maize (green), rice (blue)
12 and C4 crops (red) taken from C2010 (Challinor *et al.*, 2010), B2012 (Berg *et al.*, 2012), T2009 (Tao *et al.*, 2009),
13 TZ2013 (Tao and Zhang, 2010), TZ2012 (Tao and Zhang, 2011) and U2012 (Urban *et al.*, 2012). U2012 and C2012
14 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage
15 changes in CV. For C2012 paired CV changes were not available, so the box shows changes in the mean CV, the
16 mean CV plus one standard deviation, and the mean CV minus one standard deviation. The studies used a range of
17 scenarios (SRES A1B, A2, A1F1 and B1). B2012 is a global study, U2012 is for the US, and the remaining studies
18 are for China.]
19

20 Given an increasing likelihood that mean global warming will be in excess of 2°C (New *et al.* 2011) and perhaps up
21 to 4°C by 2100, studies have examined the effects of such warming on two very different regions; sub-Saharan
22 Africa and northern Europe (Finland). With *medium evidence* and *high agreement*, the studies (Rötter *et al.*, 2011;
23 Thornton *et al.*, 2011) conclude that positive effects of modest warming and increased CO₂ levels on crop yields are
24 likely to be reversed at minimum temperatures increases of 4°C, leading to grain yield decreases in excess of 20% in
25 relation to current conditions (Rötter *et al.* 2011). An analysis for sub-Saharan Africa predicted overall decreases of
26 19% for maize yields, 68% decrease for bean yields and a small increase for fodder grass (*Brachiaria descumbens*)
27 given 5°C global average warming (Thornton *et al.*, 2011).
28

29 Weed populations and demographics are expected to change, with an overall poleward migration in response to
30 warming (Ziska *et al.*, 2011). An overview of crop and weed competitive studies indicate that weeds could limit
31 crop yields to a greater extent with rising levels of carbon dioxide per se (Ziska, 2010). This may be related to the
32 greater degree of phenotypic and genotypic plasticity associated with weedy species relative to the uniformity
33 inherent in large cropping systems (Treharne, 1989); such plasticity, in turn, would be advantageous in a rapidly
34 changing climate. Finally, chemical control of weeds, which is the preferred management method for large-scale
35 farms, may become less effective (*medium evidence, medium agreement*), with increasing economic and
36 environmental costs.
37

38 Climate change effects on productivity of food systems will alter land use patterns, both in terms of total area sown
39 to crops and the geographic distribution of that area. Given expected trends in population, incomes, bioenergy
40 demand, and agricultural technology, global arable area is likely to increase from 2007 to 2050 (medium evidence,
41 high agreement), with projected increases over this period of +9% (Bruinsma, 2009), +8% (Fischer *et al.*, 2009),
42 +10–20% (Smith *et al.*, 2010), and +5–25% (Schmitz *et al.*, 2013) (medium evidence, medium agreement). Not all
43 such studies included the effects of global warming. Where this is the case, estimates range from a 20% increase in
44 cropping area (Schmitz *et al.*, 2013) to a decline of 9% (Zhang and Cai, 2011), but with large regional differences
45 (limited evidence, low agreement). Countries at northern latitudes and under the current constraint of low
46 temperature may increase cultivated area (limited evidence, low agreement). The generally lower nutrient quality of
47 soils and the lack of available and necessary infrastructure required to convert virgin land into productive arable
48 land, make estimates of any actual increase in harvested cropping areas highly uncertain, with this uncertainty
49 increasing even more after 2050.
50
51
52

7.4.2. Projected Impacts on Fisheries and Aquaculture

7.4.2.1. Capture Fisheries

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

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

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

In a broad-based modelling study (Brown *et al.*, 2010) forecast that, under the A2 emissions scenario, primary production in the ocean around Australia will increase over the 50-year period from 2000-2050 as a result of small increases in nutrient availability from changes in ocean stratification and temperature, although the authors acknowledge considerable model uncertainty. This increase is forecast, in general, to benefit fisheries catch and value. As another example, described in Section 2.1, impacts on fish and fisheries in the North Sea are widely expected to vary from area to area and species to species.

7.4.2.2. Aquaculture

Complementing the study by Mantua *et al.* (2010) on the impacts of climate change on salmon populations in Washington State, USA, (Huppert *et al.*, 2009) considered the impacts on the coast of that state. They concluded that there would be a number of physical and chemical consequences including inundation of low-lying coastal areas from sea level rise, coastal flooding from major storm events and increased ocean temperatures and acidification. These physical and chemical drivers are forecast to create a number of problems for the important shellfish aquaculture industry in the state arising from reduced growth and reproductive rates as a result of increased

1 temperatures, inundation of existing shellfish habitats from sea level rise, increased incidence of harmful algal
2 blooms and higher rates of mortality as a result of greater acidity of sea water and resulting decreased calcification
3 rates in skeleton and shell formation. The authors report that the socio-economic impacts cannot be quantified at this
4 stage but are considered to be substantial.

5
6 Aquaculture is considered to be under-developed in the island states and territories of the tropical Pacific. At present
7 just over 20 000 people are estimated to be employed in aquaculture enterprises throughout the region, including the
8 culture of black pearls in French Caledonia. Starting from this low base, pond aquaculture is seen as an important
9 contributor to meeting the shortage of fish required for food security in the region. Using a structured vulnerability
10 framework which uses the B1 and A2 emission scenarios to make forecasts to 2035 and 2100 (Bell *et al.*, 2011b), it
11 was concluded that production of freshwater species such as tilapia, carp and milkfish will probably benefit from the
12 expected climate changes, while coastal enterprises are expected to encounter problems in the same time horizons,
13 varying according to species. The drivers of these trends include changes to temperature, rainfall and sea-level rise
14 (Pickering *et al.*, 2011).

15 16 17 *7.4.2.3. National and Regional Vulnerability*

18
19 The consequences of the many and diverse impacts on capture fisheries and aquaculture, both positive and negative,
20 on food security are more difficult to estimate than the biological and ecological consequences. A preliminary but
21 informative study by (Allison *et al.*, 2009) attempted to estimate the vulnerability of the economies of 132 countries
22 to climate change impacts on fisheries in 2050 under the A1FI and B2 scenarios (also discussed in Chapter
23 6.4.1.1.2). They estimated vulnerability as a composite of three components: exposure to the physical effects of
24 climate change, the sensitivity of the country to impacts on fisheries (measured by total fisheries production,
25 contribution of fisheries to national employment, export income and dietary protein) and adaptive capacity within
26 the country (a composite index derived from life expectancy, indicators of education levels, various indicators of
27 governance effectiveness and size of economy). This analysis suggested that under both scenarios several of the
28 least developed countries were also amongst the most vulnerable. They included countries in central and western
29 Africa, Peru and Columbia in South America and four tropical Asian countries. Food security will be a major
30 consideration in these vulnerable countries.

31 32 33 *7.4.3. Projected Impacts on Food Prices and Food Security*

34
35 AR4 presented a summary of food price projections based on five studies that used projected yield impacts as inputs
36 to general or partial equilibrium models of commodity trade. Many additional projections of this type have been
37 made since AR4, expanding the number of trade models used, the diversity of yield projections considered, and the
38 disaggregation of prices by commodity (Hertel *et al.*, 2010; Baldos and Hertel, 2013; Lobell *et al.*, 2013; Nelson *et al.*,
39 2013). Many of the studies did not include CO₂ effects, which is sometimes justified on the grounds that studies
40 are concerned with “worst-case” scenarios, or that the bias from omitting positive CO₂ effects balances the known
41 bias from omitting negative effects of elevated O₃ and increased weed and pest damage.

42
43 Based on these studies, it is *very likely* that changes in temperature and precipitation, without considering effects of
44 CO₂, will lead to increased food prices by 2050, with estimated increases ranging from 3-84%. The combined effect
45 of climate and CO₂ change (but ignoring O₃ and pest and disease impacts) appears *about as likely as not* to increase
46 prices, with a range of projected impacts from -30% to +45% by 2050. One lesson from recent model
47 intercomparison experiments (Nelson *et al.*, 2013) is that the choice of economic model matters at least as much as
48 the climate or crop model for determining price response to climate change, indicating the critical role of economic
49 uncertainties for projecting the magnitude of price impacts.

50
51 The AR4 concluded that climate change was likely to result in higher real prices for food past 2050. This conclusion
52 remains intact with *medium confidence*, albeit with a relative lack of new studies exploring price changes to 2100 or
53 beyond. The pathways by which price changes can affect food security are outlined in section 7.3. A limited number
54 of studies have estimated the effects of price changes on food security and related health outcomes. Nelson *et al.*

1 (2009) project that, without accelerated investment in planned adaptations, climate change by 2050 would increase
2 the number of undernourished children under the age of 5 by 20-25 million (or 17-22%), with the range including
3 projections with and without CO₂ fertilization. Lloyd et al. (2011) used the projected changes in undernourishment
4 from Nelson (2009) to project the impact of climate change on human nutrition, estimating a relative increase in
5 moderate stunting of 1–29% in 2050 compared with a future without climate change. Severe stunting was projected
6 to increase by 23% (central SSA) to 62% (South Asia). Baldos and Hertel (2013) estimate that climate change
7 results in an increase in global malnourished population by 49 million (11%) in 2050, but that the combined effects
8 of climate change and CO₂, which results in yield increases in their study, reduces the number by 66 million (15%).
9

10 In summary, there is *medium confidence (limited evidence, high agreement)* that if global yields are negatively
11 impacted by climate change, there would be a resulting increase in both food prices and the global headcount of
12 food insecure people. However, it is only *about as likely as not* that such global yield effects will be experienced by
13 2050 as the net effect of climate and CO₂ changes, but *likely* that such changes will occur later in the 21st century. At
14 the same time, it is *likely* that overall growth and development will remain a relatively stronger driver of food
15 security over the next few decades, particularly when accompanied by changes in institutions and policies (Goklany,
16 2007; Parry *et al.*, 2009). Importantly, all of the studies that project price impacts assume some level of on-farm
17 agronomic adaptation, often by optimizing agronomic practices within the model. Most, but not all, also prescribe
18 income growth rates as exogenous factors, despite the fact that incomes are heavily dependent on agriculture in
19 many poor countries. One study that accounted for income effects found that, in countries such as Indonesia that had
20 both a large share of poverty in agriculturally dependent households and yield impacts that were small relative to
21 other regions, poverty was reduced by the effects of climate change (Hertel *et al.*, 2010). However, in most countries
22 the positive income effects of higher prices could not outweigh the costs of reduced productivity and higher food
23 prices.
24

25 Recent work has also highlighted that productivity in many sectors besides agriculture are significantly influenced
26 by warming, with generally negative effects of warming on economic output in tropical countries (Hsiang, 2010;
27 Dell *et al.*, 2012). Given the importance of incomes to food access, incorporating these effects into future estimates
28 of food security impacts will be important. Conflict is also known to be an important factor in food security (FAO,
29 2010a), and evidence of climate variability effects on conflict risk (Hsiang *et al.*, 2011) indicates a need to also
30 consider this dimension in future work.
31

32 The impacts of climate change on food production and food security will depend on interactions between the
33 multiple drivers outlined above. The timing of extreme events, which are expected to become more frequent (IPCC,
34 2012), is one such driver. Extremes contribute to variability in productivity (Figure 7-7) and can form part of
35 compound events that are driven by common external forcing (e.g. El Niño), climate system feedbacks, or causally
36 unrelated events (IPCC, 2012). Such compound events, where extremes have simultaneous impacts in different
37 regions, may have negative impacts on food security, particularly against the backdrop of high food price volatility
38 (Figure 7-4). There are very few projections of compound extreme events (IPCC, 2012), and interactions between
39 multiple drivers are difficult to predict. Thus nonlinear interactions in food systems may mean that thresholds are
40 reached through non-predicted mechanisms. Effective monitoring and prediction, and building resilience into food
41 systems, are likely to be two key tools in avoiding the negative impacts resulting from these interactions (Misselhorn
42 *et al.*, 2010).
43

44 The impacts of climate change on food production and food security will depend on interactions between the
45 multiple drivers outlined above. The timing of extreme events, which are expected to become more frequent (IPCC,
46 2012), is one such driver. Extremes contribute to variability in productivity (Figure 7-6) and can form part of
47 compound events that are driven by common external forcing (e.g. El Niño), climate system feedbacks, or causally
48 unrelated events (IPCC, 2012). Such compound events, where extremes have simultaneous impacts in different
49 regions, may have negative impacts on food security, particularly against the backdrop of high food price volatility.
50 There are very few projections of compound extreme events (IPCC, 2012), and interactions between multiple drivers
51 are difficult to predict. Thus nonlinear interactions in food systems may mean that thresholds are reached through
52 non-predicted mechanisms. Effective monitoring and prediction, and building resilience into food systems, are likely
53 to be two key tools in avoiding the negative impacts resulting from these interactions (Misselhorn *et al.*, 2010).
54

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

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

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

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

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

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

7.5.1.1.1. Cropping

Effective adaptation of cropping could be critical in enhancing food security and sustainable livelihoods, especially in developing countries (Chapter 5 AR4). There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times and crop cultivars and species (e.g. Olesen *et al.* (2011) and marketing arrangements (WG II Box 9-4, Fujisawa and Koyabashi 2011) although this response is not ubiquitous (Bryan *et al.* 2009). There are a large number of potential adaptations for cropping systems and for the food systems of which they are part, many of them enhancements of existing climate risk management and all of which need to be embedded in the wider farm systems and community contexts.

The possibility of extended growing seasons because of higher temperatures increasing growth in cooler months means that changing planting dates is a frequently identified option for cereals and oilseeds (Krishnan *et al.* 2007; Magrin *et al.*, 2009; Travasso *et al.*, 2009; Laux *et al.*, 2010; Stockle *et al.*, 2010; Shimono *et al.*, 2010, Deressa *et al.* 2009. Van de Giesen *et al.* 2008, Mary and Majule 2009, Meza and Silva 2009, Olesen *et al.* 2011, Tao and Zhang 2010, Tingem and Rivington 2010, Cho *et al.* 2012). Aggregated across studies, changing planting dates may increase yields by a mean of 13% but with substantial variation (Figure 7-8). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura 2010), seedling transplanting and seed priming and these adaptations can be integrated with varieties with greater thermal time

1 requirements so as to maximize production benefits and to avoid late season frosts (e.g. Tingem and Rivington 2010,
2 Crimp et al. 2012, Cho et al. 2012). In some situations early sowing may allow double cropping where currently
3 only a single crop is feasible. For example, this could occur for irrigated maize in central Chile (Meza et al., 2008)
4 and the double crop wheat/soybean in the southern pampas of Argentina (Monzon et al, 2007), increasing
5 productivity per unit land although increasing nitrogen and water demand at the same time. However, in
6 Mediterranean climates, early sowing of cereals is dependent on adequate planting rains in autumn and climate
7 projections indicate that this may decrease in many regions (WG I cross-reference), limiting the effectiveness of this
8 adaptation (Figure 7-8) and possibly resulting in later sowings than are currently practiced. In such circumstances,
9 use of short duration cultivars could be desirable so as to reduce exposure to end of season droughts and high
10 temperature events (Orlandini et al. 2008; Walter et al. 2010). There is *medium confidence (high agreement, medium
11 evidence)* that optimisation of crop varieties appears to be an effective adaptation, increasing yields by around 50%
12 compared with the use of current varieties and planting schedules when aggregated across studies (Figure 7-8).
13 Flexibility in planting dates and varieties according to seasonal conditions could be increasingly important with
14 ongoing climate change (Meza and Silva 2009, Deressa et al. 2009). Approaches that integrate climate forecasts at a
15 range of scales in some cases are able to better inform crop risk (e.g. Cooper et al. 2008; Challinor *et al.*, 2009;
16 Baethgen 2010, Li et al. 2010) although care is needed to ensure that the provision of forecasts does not increase
17 existing inequities in farming or fishing communities.

18
19 [INSERT FIGURE 7-8 HERE

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

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

32
33 Improving cultivar tolerance to high temperature is a frequently identified adaptation for almost all crops and
34 environments worldwide as high temperatures are known to reduce grain number, fill and quality (Challinor *et al.*,
35 2009; Wassmann *et al.*, 2009; Krishnan et al. 2007; Luo et al. 2009; Shimono et al. 2010; Stockle et al. 2010;
36 Wassman et al. 2008) noting that a new cultivar usually takes between 8 and 20 years to deliver. Improving gene
37 conservation and access to gene banks could facilitate the development of cultivars with appropriate thermal time
38 and thermal tolerance characteristics (e.g. Mercer et al. 2008, Wassman et al. 2008) as well as to take advantage of
39 increasing atmospheric CO₂ concentrations (Ziska *et al.*, 2012) and respond to changing pest, disease and weed
40 threats with these developments needing to be integrated with *in situ* conservation of local varieties (IAASTD
41 2009).

42
43 Similarly, the prospect of increasing drought conditions in many cropping regions of the world (e.g. Olesen et al.
44 2011) raises the need for breeding additional drought-tolerant crop varieties (Tao and Zhang, 2011; Mutekwa 2009,
45 Naylor et al. 2007), for enhanced storage and access to irrigation water, more efficient delivery systems, improved
46 irrigation technologies such as deficit irrigation, more effective water harvesting, agronomy that increases soil water
47 retention through practices such as minimum tillage and canopy management, increase in soil carbon and more
48 effective decision support (Olesen et al 2011, Thomas, 2008, Falloon and Betts 2010, Luo et al. 2009, Lioubimtseva
49 et al. 2009; Piao *et al.*, 2010) amongst many other possible adaptations (e.g. WG II 22.4.3.7.1). Increasing soil
50 organic carbon levels plays an important role for improved water retention and absorption capacity of soils (El-Hage
51 et al. 2010; Smith and Olesen 2010). Several agricultural practices support increased soil carbon levels, such as use
52 of organic fertilizers (compost, farm yard manure), crop rotations with deep rooting forage legumes or mulching of
53 crop residues (e.g. Diacono and Montemurro 2010; Smith and Olesen 2010). Increasing soil carbon levels can also
54 contribute to climate change mitigation (AR5 WG III). There is *medium confidence (high agreement, limited*

1 *evidence*) that crop adaptations can lead to moderate yield benefits under persistently drier conditions (about 10%
2 from aggregation of studies (Challinor et al. 2013) and that irrigation optimisation for changed climate can increase
3 yields by about 4% (Figure 7-8).

4
5 Diversification of activities is another climate adaptation option for cropping systems (Thornton *et al.*, 2010;
6 Lioubimtseva et al 2009). For example, Reidsma and Ewert (2009) found that regional farm diversity reduces the
7 risk that is currently associated with unfavourable climate conditions in Europe. Diversification of activities often
8 seeks to incorporate higher value activities or those that increase efficiency of a limited resource such as through
9 increased water use efficiency (Thomas, 2008). For future conditions, Seo (2010) assessed that under climate
10 predictions for 2060, integrated crop-livestock farms could increase in number in Africa at the expense of
11 specialized crop or livestock systems. The analysis indicated that the net revenue of the specialized farms could
12 decrease by up to 75% compared with only 10% for the mixed farm but the nature and degree of change will in part
13 depend on the specific climate changes. In some cases, increased diversification outside of agriculture may be
14 favoured (e.g. Coulthard 2008, Mary and Majule 2009; Mertz *et al.*, 2009a).

15
16 The above adaptations, either singly or in combination, could significantly reduce negative impacts of climate
17 change and increase the benefit of positive changes as found in AR4 (*high confidence: high agreement, medium
18 evidence*). To quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been
19 undertaken for wheat, rice and maize (see Section 7.5.2). This meta-analysis adds more recent studies to that
20 undertaken in the AR4 (Chapter 5). It indicates that the average benefit (the yield difference between the adapted
21 and non-adapted cases) of adapting crop management increases approximately linearly with increasing temperature
22 change being equivalent to about 15% of current yields for a temperature increase of 5°C (Figure 7-9). This response
23 is, however, extremely variable, ranging from negligible benefit from adaptation (even potential dis-benefit) to very
24 substantial. The responses are dissimilar between wheat, maize and rice (Figure 7-5) and differ markedly between
25 adaptation management options (Figure 7-8). For example, cultivar adaptation is assessed by several studies as
26 providing substantially more benefit (mean of over 50%) than changing planting dates (13%) or optimizing
27 irrigation to the new climatic conditions (4%).

28
29 [INSERT FIGURE 7-9 HERE

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

33
34 Potential increased variability of crop production means there is *high confidence (high agreement, medium evidence)*
35 that other aspects of food systems such as food reserve, storage and distribution policies and systems may need to be
36 enhanced (IAASTD 2009) along with a range of broader issues such as provision of effective insurance markets,
37 clarity in property rights, building adaptive capacity and developing effective participatory research cultures that
38 apply to more than just farming systems (Chapter 9, AR4 Chapter 5).

39
40 It is notable that most of the above adaptations raised above and used in this analysis are essentially either
41 incremental changes to existing agricultural systems or are systemic changes which integrate new aspects into
42 current systems. Few could be considered to be transformative changes. Consequently, the potential adaptation
43 benefits could be understated and a considerable opportunity cost may emerge (*low confidence: medium agreement,
44 limited evidence*) (Challinor et al. 2013).

45 46 47 7.5.1.1.2. Livestock

48
49 Extensive livestock systems occur over a huge range of biophysical and socio-ecological systems, with a consequent
50 large range of potential adaptations. In many cases, these livestock systems are highly adapted to past climate risk,
51 and there is *high confidence* that this provides a sound starting point for climate change adaptation (*high agreement,
52 medium evidence*). These adaptations include matching stocking rates with pasture production, adjusting herd and
53 water point management to altered seasonal and spatial patterns of forage production, managing diet quality (using
54 diet supplements, legumes, choice of introduced pasture species and pasture fertility management), more effective

1 use of silage, pasture spelling and rotation, fire management to control woody thickening, using more suitable
2 livestock breeds or species, migratory pastoralist activities and a wide range of biosecurity activities to monitor and
3 manage the spread of pests, weeds and diseases (Fitzgerald et al. 2008, Howden et al. 2008, Nardone et al. 2010,
4 Ghahramani and Moore 2013, Moore and Ghahramani 2013). Combining adaptations can result in substantial
5 increases in benefits in terms of production and profit when compared with single adaptations (Ghahramani and
6 Moore 2013, Moore and Ghahramani 2013). In some regions, these activities can in part be informed by climate
7 forecasts at differing time-scales to enhance opportunities and reduce risks including soil degradation (e.g. McKeon
8 et al. 2009). Many livestock systems are integrated with or compete for land with cropping systems and one climate
9 adaptation may be to change these relationships. For example, with increased precipitation, farmers in Africa may
10 need to reduce their livestock holdings in favour of crops, but with rising temperatures, they may need to substitute
11 small ruminants in place of cattle with small temperature increases or reduce stocking rates with larger temperature
12 rises (Kabubo-Mariara 2009, Seo 2010, Thornton et al. 2010). As with other food systems there is a range of barriers
13 to adaptation which could be addressed on-farm and off-farm by changes in infrastructure, establishment of
14 functioning markets, improved access to credit, improved access to water and water management technologies,
15 enhanced animal health services and enhanced knowledge adoption and information systems (Howden et al. 2008,
16 Kabubo-Mariara 2009, Mertz et al. 2009).

17
18 Heat stress is an existing issue for livestock in some regions (*high confidence: high agreement, robust evidence*),
19 especially in higher productivity systems (7.3.2.6). For example, some graziers in Africa are already making
20 changes to stock holdings in response to shorter term variations in temperatures (Seo et al. 2008). Breeding livestock
21 with increased heat stress resistance is an adaptation often identified but there are usually trade-offs with
22 productivity (Nardone et al. 2010) and so this option needs careful evaluation. Increased shade provision through
23 trees or cost-effective structures can substantially reduce the incidence of high heat stress days (Nidumolu et al.
24 2011). In cooler climates, with warming there might be lesser need for winter housing and feed stocks.

25 26 27 7.5.1.1.3. Fisheries

28
29 The resources for capture fisheries are largely already fully or overexploited with an estimated 32 percent of stocks
30 being overexploited and 53% being fully exploited (FAO 2010). Comparable global statistics are not available for
31 inland fisheries but the status of those stocks may not be any better. Overfishing is widely regarded as the primary
32 pressure on marine fishery resources but other human activities including coastal and offshore mining, oil and gas
33 extraction, coastal zone development, land-based pollution and other activities are also negatively impacting status
34 and production (WG II 30.6.7, Rosenberg and MacLeod 2005, Cochrane et al. 2009). For inland fisheries,
35 overfishing is also widespread but the majority of impacts on the integrity of freshwater ecosystems and their
36 resources originate from outside the sector (Welcomme et al. 2010). Climate change adds another compounding
37 influence in both cases.

38
39 The vulnerability of fisheries and fishing communities to climate change will depend on their exposure to its
40 physical and ecological effects, their dependence on the fishery and their sensitivity to physical effects, and their
41 adaptive capacity (Allison et al. 2009). Adaptive responses to climate change in fisheries could include:
42 management approaches and policies that strengthen the livelihood asset base, improved understanding of the
43 existing response mechanisms to climate variability to assist in planning adaptation, recognising and responding to
44 new opportunities brought about by climate change, monitoring biophysical, social and economic indicators linked
45 to management and policy responses and adoption of multi-sector adaptive strategies to minimise negative impacts
46 (WG II 6.4.2.1, Allison et al. 2009, Badjeck et al. 2010, MacNeil et al. 2010). A wide range of management tools
47 and strategies have been developed to manage fisheries. However, Grafton (2010) points out that this array of tools
48 is necessary but not sufficient for adaptation to climate change in fisheries. He argues that the standard tools for
49 fisheries management were developed to control fishing mortality and to maintain adequate levels of recruitment to
50 fishery stocks but without necessarily addressing the needs for resilience to change or to be able to function under
51 changing climates. He therefore proposes that these conventional management tools must be used within processes
52 that i) have a core objective to encourage ecosystems that are resilient to change and ii) that explicitly take into
53 account uncertainties about future conditions and the effect of adaptation, and make use of models to explore the
54 implications of these (Grafton 2010). There are also opportunities for fisheries to contribute to mitigation efforts

1 (Grafton 2010). Complementary adaptive responses include occupational flexibility, changing target species and
2 fishing operations, protecting key functional groups, developing early warning systems for extreme events and the
3 establishment of insurance schemes (Coulthard 2008, FAO 2009a, Daw et al. 2009, MacNeil et al. 2010, Koehn et
4 al., 2011). Governance and management of fisheries will need to follow an ecosystem approach to maximise
5 resilience of the ecosystem, and to be adaptive and flexible to allow for rapid responses to climate induced change
6 (FAO 2009a, Daw et al. 2009). Some adaptation options for tropical industrial tuna fisheries and coral reef fisheries
7 are presented in Chapter 30, Section 30.6.1.1.
8

9 In contrast to capture fisheries, aquaculture is estimated to be the fastest-growing animal-food-producing sector and
10 is outpacing human population growth. Per capita supply from aquaculture increased at an average annual growth
11 rate of 6.6 percent from 1970 to 2008 (FAO, 2010). Adaptive responses in aquaculture include use of improved
12 feeds and selective breeding for higher temperature tolerance strains to cope with increasing temperatures (De Silva
13 and Soto 2009) and shifting to more tolerant strains of molluscs to cope with increased acidification (Huppert et al.
14 2009). Better planning and improved site selection to take into account expected changes in water availability and
15 quality; integrated water use planning that recognises and takes into account the water requirements and social and
16 economic importance of fisheries and aquaculture in addition to other sectors; and improving the efficiency of water
17 use in aquaculture operations are other adaptation options (De Silva and Soto 2009). Integrated water use planning
18 will require making trade-offs between different land and water uses in the watershed (e.g. Mantua et al. 2010). De
19 Silva and Soto (2009) also describe the need for insurance schemes accessible to small-scale producers so as to
20 increase their resilience. In some near-shore locations there may be a need to shift property lines as the mean high
21 water mark is displaced landwards by rising sea level (Huppert et al. 2009).
22

23 There are no simple, generic recipes for fisheries adaptation. Bell et al. (2011) suggest a list of 24 separate, but
24 inter-related, actions that could be taken to adapt fisheries and aquaculture in the tropical Pacific to climate change.
25 They break these management steps into three categories according to the primary objective: economic development
26 and government revenue; maintaining the contribution of fish to food security; and maximising sustainable
27 livelihoods. These authors also point out that actions and policies for adaptation in fisheries and aquaculture must
28 complement those for other sectors. They suggest that the greater the number of different production systems to
29 which communities have access, the greater the chance that some systems available to them will not be negatively
30 impacted and that some may even benefit from climate change. Similar case-by-case, integrated planning will be
31 required in all other regions and at scales from community to regional to achieve clearly defined adaptation goals.
32
33

34 7.5.1.1.4. *Indigenous knowledge* 35

36 Indigenous Knowledge (IK) has developed to cope with climate hazards contributing to food security in many parts
37 of the world. Examples in the Americas include Alaska, where the Inuit knowledge of climate variability assured the
38 source of food to hunters and reduced various risks (Ford 2009, Alessa 2008, Weatherhead et al. 2010), down to the
39 southern Andes where the Inca traditions of crop diversification, genetic diversity, raised bed cultivation,
40 agroforestry, weather forecasting and water harvesting are still used in agriculture (Goodman-Elgar 2008, Renard et
41 al., 2011; McDowell and Hess 2012). In Africa, weather forecasting, diversity of crops and agropastoralism
42 strategies have been useful in the Sahel (Nyong et al. 2007). Rainwater harvesting has been a common practice in
43 Sub-Saharan Africa (Biazin et al. 2011) to cope with dry spells and improve crop productivity, while strategies from
44 agropastoralists in Kenya are related to drought forecasting based on the fauna, flora, moon, winds and other factors
45 (Speranza et al. 2010). In South Africa, farmer's early warning indicators of wet or dry periods in Namibia based on
46 animals, plants and climate observations contributed to deal with climatic variability (Newsham and Thomas 2011).
47 In the same way, in Asia and Australia IK plays an important role to assure food security of certain groups (Marin,
48 2010, Speranza et al. 2010; Biazin et al. 2012, Salick and Ross 2009, Kalanda et al. 2011; Green et al. 2010; Pareek
49 and Trivedi 2011), although IK and the opportunities to implement it can differ according to gender and age in some
50 communities (WG II 9.3.5.2.9, Rengalakshmi 2007; Turner and Clifton 2009, Kalanda et al. 2011) leading to
51 distinct adaptive capacities and options.
52

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

1 Speranza et al. 2009, McDowell & Hess 2012) affecting the adaptive capacity of a number of peoples globally
2 (*medium agreement, medium evidence*). Moreover, there is *medium confidence* that some policies and regulations
3 leading to limit the access to territories, promoting sedentarization, the substitution of traditional livelihoods,
4 reduced genetic diversity and harvesting opportunities as well as loss of transmission of IK, may contribute to limit
5 the adaptation to climate change in many regions (Nakashima et al. 2012) (*medium agreement, medium evidence*).
6
7

8 7.5.1.2. *Practical Regional Experiences of Adaptation, including Lessons Learned*

9

10 Given the early stages of climate change, there are relatively few unequivocal examples of adaptation (see Section
11 7.5.2) additional to existing climate risk management. Where there have been management changes these have often
12 been in response to several driving variables of which climate is only one (Smit and Wandel 2006, Mertz et al. 2009,
13 Chen et al. 2011, Odgaard et al. 2011). More farmers express an intention to change rather than having implemented
14 adaptive actions (Battaglini et al. 2009) although in some regions there appears to be adaptation to climate change
15 that is happening now (Olesen et al. 2011, Fujisawa and Kobayashi 2010, Bohensky et al. 2012). Activities to build
16 adaptive capacity to better manage climate change are more widespread (Twomlow et al. 2008) but there remain
17 questions as to how this capacity will evolve and be maintained (Nelson et al. 2009). Crucial in this will be
18 devolution of the decision-making process so as to integrate local, contextual information into adaptation
19 decision-making (Nelson et al. 2008).
20
21

22 7.5.1.2.1. *Observed and expected barriers and limits to adaptation*

23

24 Adaptation is strongly influenced by factors including institutional, technological, informational and economic (WG
25 II 14, WG II 15) and there can be barriers (restrictions that can be addressed) and limits in all these factors (WG II
26 16: *very high confidence: high agreement, robust evidence*). Several barriers to adaptation of food systems have
27 been raised including inadequate information on the climate, climate impacts and on the risks and benefits of the
28 adaptation options, lack of adaptive capacity, inadequate extension, institutional inertia, cultural acceptability,
29 financial constraints including access to credit, insufficient fertile land, infrastructure, lack of functioning markets
30 and insurance systems (WG II 16, Bryan et al. 2009, de Bruin and de Link 2011, Deressa et al. 2009,
31 Kabubo-Mariara 2009). Limits to adaptation can occur for example where crop yields drop below the level required
32 to sustain critical infrastructure such as sugar or rice mills (Park et al. 2012). In some cases, these can be effectively
33 irreversible. Some studies have shown that access to climate information is not the principal limitation to improving
34 decision making and it can result in perverse outcomes, increasing inequities and widening gender gaps (Coles and
35 Scott 2009). Incomplete adoption of adaptations may also occur.
36

37 Lack of technical options can also be a barrier to adaptation. New varieties of crops or breeds of livestock are
38 assessed with *high confidence* as providing possible core adaptations of production systems (*high agreement,*
39 *medium evidence*) (Mercer et al. 2008, Tingem and Rivington 2010) however, there is substantial investment needed
40 to develop these along with delays before they are available, both of which can act as adaptation barriers. This may
41 be addressed in part by investments to improve local crop varieties or livestock breeds that are easily adopted
42 (IAASTD, 2009). There also can be physiological limits to performance such as upper temperature limits for heat
43 tolerance (AR4 WGII 5.2.1).
44
45

46 7.5.1.2.2. *Facilitating adaptation and avoiding maladaptation*

47

48 Adaptation actions would usually be expected to provide benefits to farmers, the food industry along the value chain
49 or perhaps to a broader community. However, there are possible maladaptations that arise from adapting too early or
50 too late, by changing the incorrect elements of the food system or changing them by the incorrect amount. A key
51 maladaptation would be one which increased emissions of greenhouse gases, this making the underlying problem
52 worse (Smith and Olesen 2010; AR5 WGIII Chapter 11, *high agreement, robust evidence*). A recent review of
53 agricultural adaptations however, has found that most categories of climate change adaptation options tend to reduce
54 greenhouse gas emissions (Smith and Olesen 2010, Falloon and Betts 2010) (*medium confidence: medium*

1 *agreement, medium evidence*). These adaptations include measures that reduce soil erosion or reduce leaching of
2 nitrogen and phosphorus, for increasing soil carbon, measures for conserving soil moisture and reducing temperature
3 extremes by increasing vegetative cover.
4

5 There is a strong focus on incremental adaptation of existing food systems in the literature since AR4 (see above)
6 however, and there is *medium confidence* that this may result in large opportunity costs that could arise from not
7 considering more systemic adaptation or more transformative change (Kates et al. 2012; Howden et al. 2010) (*high*
8 *agreement, limited evidence*). For example, in the USA, changes in farming systems (i.e. the combination of crops)
9 have been assessed as providing significant adaptation benefit in terms of net farm income (Prato et al. 2010). There
10 is a need to also engage farmers, policymakers and other stakeholders in evaluating transformative, pro-active,
11 planned adaptations such as structural changes (Mäder, 2006; McCrum et al. 2009, Olesen et al. 2011). This could
12 involve changes in land allocation and farming systems, breeding of functionally-different crop varieties, new land
13 management techniques and new classes of service from lands such as ecosystem services (Howden et al. 2010). In
14 Australia, industries including the wine, rice and peanut industries are already adopting transformative changes such
15 as change in location so as to be early adopters of what are perceived as opportunities arising from change (Park et
16 al. 2012).
17

18 There is substantial commonality in adaptation actions within different agricultural systems. For example, changing
19 varieties and planting times are incremental adaptations found in studies of many different cropping systems as
20 evidenced by the sample size in the meta-analysis. Collating information on the array of adaptation options available
21 for farmers, their relative cost and benefit and their broad applicability could be a way of initiating engagement with
22 decision-makers. In the climate mitigation domain, this has been attempted using marginal abatement cost curves
23 which identify mitigation options, their relative cost and the potential size of emission-reductions (IPCC WG3).
24 These curves can be used in setting investment priorities and informing policy discussions. The local nature of many
25 adaptation decisions, their interactions with other highly contextual driving factors and the time and climate
26 change-sensitive nature of adaptation decisions means however, that global, time-independent curves are not
27 feasible. The studies in Figure 7-8 indicate that there some options which may be more relevant and useful to
28 consider than others. These results however, illustrate the potential scope and benefit of developing effective crop
29 adaptation options if implemented in an adaptive management approach.
30
31

32 **7.5.2. Food System Case Studies – Examples of Successful and Unsuccessful Adaptation**

33

34 Incremental, systemic and transformational adaptation to climate change is beginning to be documented, though the
35 peer-reviewed literature largely covers vulnerability assessments and intentions to act, not adaptation actions
36 (Berang-Ford et al. 2010).
37

38 *Case 1: Incremental adaptation in the Sahel*

39 Much of the literature covers incremental, reactive adaptation, but given actors are constantly adapting to changing
40 social and economic conditions, incremental adaptation to climate change is difficult to distinguish from other
41 actions (Berrang-Ford et al. 2010, Speranza 2010), and in fact is usually a response to a complex of factors. This
42 case, of the zaï soil management practice in the Sahel region, is an example where a complex of factors drives local
43 actions, and factors such as growing land scarcity and new market opportunities, rather than climate, may be the
44 primary factors (Barbier et al. 2009, Mertz et al. 2010). Inherent poor soil quality and human activities have resulted
45 in soil degradation – crusting, sealing, erosion by water and wind, and hardpan formation (Zougmore et al. 2010,
46 Fatondji et al. 2009). Zaï, a traditional integrated soil and water management practice, can combat land degradation
47 and improve yield and decrease yield variability by concentrating runoff water and organic matter in small pits
48 (20-40 cm in diameter and 10-15 cm deep) dug manually during the dry season and combined with contour stone
49 bunds to slow runoff. A handful of animal manure or compost is placed in each pit. . By breaking the soil crust, the
50 pits facilitate greater water infiltration, while the applied organic matter improves soil nutrient status and attracts
51 termites, which have a positive effect on soil structure. The zaï technique is very labour intensive requiring some 60
52 days of labour per hectare. Innovations to the system, involving animal-drawn implements, can reduce labour
53 substantially.
54

1 *Case 2: Mixed farming systems in Tanzania*

2 In Morogoro, Tanzania, farming households have adapted in many ways to climatic and other stresses (Paavola
3 2008). They have extended cultivation through forest clearance or reducing the length of the fallow period.
4 Intensification is under way, through change in crop choices, increased fertiliser use and irrigation, and especially
5 greater labour inputs. Livelihood diversification has been the main adaptation strategy – this has involved more
6 non-farm income-generating activities, tapping into natural resources for subsistence and cash income (e.g. charcoal
7 production), and has included artisanal gold and gemstone mining. Households have also altered their cropping
8 systems, for example, by changing planting times. Migration is another frequently used strategy – with farmers
9 moving to gain land, access markets or get employment. Parents also send children to cities to work for upkeep and
10 cash income to reduce the household numbers that need to be supported by uncertain agricultural income. While
11 many of these strategies help in terms of the short-term needs, in the longer term they may be reducing the capacity
12 of households to cope. For instance, land cover change has negative impacts on future water supplies for irrigation,
13 and deforestation and forest degradation means faltering forest-based income sources. This will be particularly
14 problematic to the more vulnerable groups in the community, including women and children.
15

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

17 Anticipatory and planned adaptation has been initiated in many places, but it has been poorly documented in the
18 peer-reviewed literature. In many cases these adaptation actions are the basis of externally-funded projects. For
19 example, the humanitarian organization CARE is piloting an approach to increase the capacity of vulnerable
20 communities to adapt to adverse climate change (Patt et al. 2009). In their project in Bangladesh they work directly
21 with households to implement practical strategies to support adaptation to climate risk, as well as with local
22 organisations to build their capacity to support communities to adapt. The initial stage in their work involves
23 participatory assessments of vulnerability and adaptive capacity and perceived climate risk. In Bangladesh flooding,
24 salinity, waterlogging and cyclones were the key challenges to be addressed. Given that vulnerability and adaptive
25 capacity is gendered, the assessments were undertaken separately with men's and women's groups. The results of
26 the assessments were then used to identify strategies to increase capacity to cope with the challenges, both present
27 and those predicted under climate change. At the household level an example of an adaptation strategy that was
28 taken up by households was the shift from raising chickens to raising ducks in light of increased flood risks. The
29 work highlighted the difference in family responsibilities between men and women and differing vulnerability, and
30 how this translates to differing priorities when planning for adaptation. Lack of mobility of women means that
31 women have less access to information regarding potential hazards and possible adaptation strategies.
32

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

34 Many of the cases identified in chapter 7 are examples of incremental adaptation; in many circumstances climate
35 change may call for transformational changes in the agricultural sector, as incremental change will be insufficient
36 (Howden et al. 2010). The primary industries in Australia are highly sensitive to the impacts of climate change and
37 transformational adaptation is being considered and planned for (Park et al. 2012; Rickards and Howden 2012).
38 Examples of transformational adaptations being implemented now include 1) relocation of parts of the rice and
39 peanut industries to regions where future rainfall and irrigation water availability are anticipated to be more
40 favourable causing major change in transport chains, inputs and management and, 2) the relocation of parts of the
41 wine industry to cooler regions to offset risks of warming and forcing changes in supply chains through changes in
42 grower contracts to increase the proportion of grape supplies from cooler regions with lower risk from high
43 temperatures (Park et al. 2012). Researchers are working with those transforming to understand the processes
44 needed so as to generalize and communicate them.
45
46

47 **7.5.3. Key Findings from Adaptations – Confidence Limits, Agreement, and Level of Evidence**

48
49 There have been many studies of crop adaptation since the AR4. In aggregate these show that adaptations to
50 changed temperature and precipitation will bring substantial benefit, (*high confidence: high agreement, robust
51 evidence*) with some adaptations (e.g. cultivar adaptation) being more effective than others (e.g. irrigation
52 optimisation) (7.5.1.1.1). Most studies have assessed key farm-level adaptations such as changing planting dates and
53 associated decisions to match evolving growing seasons and improving cultivar tolerance to high temperature,
54 drought conditions and elevated CO₂ levels. There is *medium confidence (medium agreement, limited evidence)* that

1 limits to adaptation will increasingly emerge for such incremental adaptations beyond temperature changes of around
2 2°C raising the need for more systemic or transformational changes (7.5.1, 7.5.1.2.2). An example of
3 transformational change is latitudinal expansion of cold-climate cropping zones polewards but this may be largely
4 offset by reductions in cropping production in the mid-latitudes due to rainfall reduction and temperature increase
5 (*medium confidence: high agreement, limited evidence*) (7.5.1.1.1). Adaptations to food systems additional to the
6 production phase have been identified and sometimes implemented but the benefits of these have largely not been
7 quantified.

8
9 Livestock and fisheries systems also have available a large range of possible adaptations often tailored to local
10 conditions but there is not adequate information to aggregate the possible value of these adaptations although there
11 is *high confidence (high agreement, medium evidence)* that they will bring substantial benefit, particularly if
12 implemented in combination (7.5.1.1.2, 7.5.1.1.3). Key livestock adaptations include matching stocking rates with
13 pasture availability, water management, monitoring and managing the spread of pests, weeds and diseases, livestock
14 breeding and adjusting to changed frequencies of heat stress and cold conditions (7.5.1.1.2). Fishery adaptations
15 include management approaches and policies that strengthen the livelihood asset base, take an ecosystem approach
16 to managing the resource and adoption of multi-sector adaptive strategies to minimise negative impacts.
17 Importantly, there is an emerging recognition that existing fishery management tools and strategies are necessary but
18 not sufficient for adaptation to climate (7.5.1.1.3).

19
20 Indigenous knowledge is an important resource in climate risk management and is important for food security in
21 many parts of the world. There is *medium confidence (medium agreement, medium evidence)* that climate changes
22 are reducing reliance on indigenous knowledge in some locations but also that some policies and regulation are
23 limiting the contribution that indigenous knowledge can make to effective climate adaptation (7.5.1.1.4).

24
25 The focus on incremental adaptations and few studies on more systemic and transformational adaptation or
26 adaptation across the food system mean that there is *medium confidence (high agreement, limited evidence)* that
27 there may be underestimation of adaptation opportunities and benefits (7.5.1.2.2). In addition to this, there is a range
28 of limits and barriers to adaptation and many of these could be addressed by devolution of the decision-making
29 process so as to integrate local, contextual information into adaptation decision-making (7.5.1.2.2).

30 31 32 **7.6. Research and Data Gaps – Food Security as a Cross-Sectoral Activity**

33
34 Research and data gaps are seen mainly in the fact that most work since AR4 has concentrated on food production
35 and not included other aspects of the food system that connects climate change to food security. Features such as
36 food processing, distribution, access and consumption have recently become areas of research interest in their own
37 right but only tangentially attached to climate change.

38
39 Other areas of neglect include food quality and nutritional aspects of climate change, the need to update and revise
40 food production impact models, the need to create reliable, integrated food systems models at the regional and
41 global scales geared to including climate change effects on the global food system.

42
43 In terms of crop production, important research questions are the extent to which CO₂ acts as a stimulant to crop
44 growth, particularly in combination with other trace gases such as ozone. More attention needs to be given to the
45 interaction between crop physiological thresholds in terms of high and low temperatures and drought and flooding.
46 To date crop-climate models have not adequately included such thresholds and need to include them and examine
47 their effects on crop yields and their quality under low and high levels of global warming. Excluding such features
48 from models means that currently they may underestimate the impacts of global warming.

49
50 One of our conclusions from attempts to synthesise information on yield variation is that many studies either do not
51 examine yield variability or do not report it. We recommend that closer attention is paid to yield variability, both for
52 quantity and quality of food production, especially given observed price fluctuations associated with climate events.
53 Within the context of yield variability, we expect environmental thresholds and tipping points, such as high
54 temperatures, droughts and floods, to become more important in the future. Specific recommendations are food

1 production experiments in which changes in variability reflect predicted changes for given warming scenarios.
2 Including such thresholds in models for high levels of global warming (i.e. 4-5 °C above pre-industrial) will very
3 likely lead to reduced predictions of yield given changes in climate variability and increasing mean temperature.
4 Research has also demonstrated that accurate crop productivity data would significantly improve future projections
5 of yield. Important gaps in knowledge continue to be studies of weeds, pests, and diseases, including animal
6 diseases, in response to climate change and how related adaptation activities can be robustly incorporated into food
7 security assessments.

8
9 Current forecasts of changes in distribution and productivity of marine fish species and communities are typically at
10 a global or regional scale only and include adaptations to a limited extent. Increasing the resolution to forecast
11 impacts and changes at the national and local ecosystem scale would provide valuable information to governments
12 and stakeholders and enable them to prepare more effectively for expected impacts on food production and security.
13

14 The real contribution of inland fisheries and small-scale aquaculture to food security and nutrition is still poorly
15 understood in many developing countries and regions and is probably frequently under-estimated. Research is
16 required to determine the true contributions from these sectors and their vulnerability to climate variability and
17 change to ensure that planning and implementation of adaptation gives due consideration to them and does not result
18 in undesirable negative impacts on food security.
19

20 Currently, approximate estimates of the vulnerability of countries to climate change impacts on fisheries are
21 available. Building on this start, further research is required to improve the accuracy of these estimates and to
22 increase the resolution of the study to identify the most vulnerable zones and communities within countries for
23 priority action in adaptation. There is considerable general information available on what adaptive strategies will be
24 required where fisheries and aquaculture are expected to be impacted by climate change but there are very few case
25 studies of actual adaptation or preparation for adaptation in practice. Implementation of case studies in a range of
26 different social and ecological contexts would enable the existing theories to be tested and revised according to
27 lessons learned.
28

29 Possibilities for agronomic and breeding adaptations of food production to global warming are possible up to *ca.* 5°C
30 above pre-industrial but that the relative effectiveness of these often plateaus after about 3°C. However, food
31 security studies are urgently required to estimate the actual range of adaptations open to farmers and other actors in
32 the food system especially when possible changes in climate variability are included .

33 From this chapter it is evident that since AR4, the production aspects of food production have continued to be
34 studied much more comprehensively than the non-production elements of food security. Further studies require
35 impacts and adaptation of global food security and systems in relation to global warming to be studied under a full
36 range of radiative forcing scenarios and that these studies should be quantitative as possible. Such research should
37 include climate impacts and adaptations of crops, livestock, fisheries, fruits and vegetables as production elements
38 and processing, distribution and retailing and consumption patterns as the non-production but equally important
39 elements of food security.
40

41 42 **Frequently Asked Questions**

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

44 Observed data and many studies indicate that a warming climate has a negative effect to crop production, generally
45 reduce yields of staple cereals such as wheat, rice and maize, which, however, differs between regions and latitudes.
46 Elevated CO₂ could benefit crops yields in short term by increasing photosynthesis rates, however, there is big
47 uncertainty in the magnitude of the CO₂ effect and that interactions with other factors. Climate change will affect
48 fisheries and aquaculture through gradual warming, ocean acidification and through changes in the frequency,
49 intensity and location of extreme events. Other aspects of the food chain are also sensitive to climate but such
50 impacts are much less well known. Climate-related disasters are among the main drivers of food insecurity, both in
51 the aftermath of a disaster and in the long run. Drought is a major driver of food insecurity, and contributes to a
52 negative impact on nutrition. Floods and tropical storms also affect food security by destroying livelihood assets.
53 The relationship between climate change and food production depends to a large degree on when and which
54

1 adaptation actions are taken. Other links in the food chain from production to consumption are sensitive to climate
2 but such impacts are much less well known.

3
4 **FAQ 7.2: How could adaptation actions enhance food security and nutrition?**

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

18
19 **FAQ 7.3: How could climate change interact with change in fish stocks, ocean acidification?**

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

28
29
30 **Cross-Chapter Boxes**

31
32 **Box CC-OA. Ocean Acidification**

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

35
36 **Introduction**

37 Anthropogenic ocean acidification and climate change share the same primary cause at the global level, the increase
38 of atmospheric carbon dioxide (WGI, 2.2.1). Eutrophication and upwelling contribute to local ocean acidification
39 (5.3.3.6, 30.5.4). Past and futures changes in chemistry are well known in the surface open ocean (WGI, 3.8.2 and
40 6.4.4) but are more difficult to project in the more complex coastal systems (5.3.3.6 and 30.5.2).

41
42 **Chemistry and Projections**

43 The fundamental chemistry of ocean acidification has long been understood: the uptake of CO₂ into mildly alkaline
44 ocean results in an increase in dissolved CO₂ and reductions in pH, dissolved carbonate ion, and the capacity of
45 seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of surface seawater can
46 be projected at the global scale with high accuracy from projections of atmospheric CO₂ levels. Time series
47 observations of changing upper ocean CO₂ chemistry support this linkage (WGI Table 3.2 and Figure 3.17; WGII
48 Figure 30.5). Projections of regional changes, especially in coastal waters (5.3.3.6), and at depth are more difficult;
49 observations and models show with high certainty that fossil fuel CO₂ has penetrated at depths of 1 km and more.
50 Importantly, the natural buffering of increased CO₂ is less in deep than in surface water and thus a greater chemical
51 impact is projected. Additional significant CO₂ increases and pH decreases at mid-depths are expected to result from
52 increases in microbial respiration induced by warming. Projected changes in open ocean, surface water chemistry for
53 year 2100 based on representative concentration pathways (WGII, Figure 6.28) compared to preindustrial values
54 range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO₂, +1 °C, 22% reduction of carbonate ion

1 concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO₂, +3.7 °C, 56% reduction of carbonate ion
2 concentration).

4 ***Biological, Ecological, and Biogeochemical Impacts***

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

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

16 Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*) and
17 harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may
18 significantly stimulate nitrogen fixation in the oceans (*limited evidence, low agreement*; 6.2.3, 6.3.4). There are few
19 known direct effects on early stages of fish and adult fish remain relatively undisturbed by elevated CO₂. Serious
20 behavioral disturbances were reported, mostly on larval and juvenile coral reef fishes (6.2.4).

21 Projections of ocean acidification effects at the ecosystem level are limited by the diversity of species-level
22 responses. Natural analogues at CO₂ vents indicate decreased species diversity, biomass and trophic complexity of
23 communities living on the sea-floor. Shifts in community structure have been documented in rocky shore
24 environments (e.g., Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012).
25 Differential sensitivities and associated shifts in performance and distribution will change predator-prey
26 relationships and competitive interactions (6.2-3), which could impact food webs and higher trophic levels (*limited
27 evidence, high agreement*).

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

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

38 ***Risks***

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

51 ***Socioeconomic Impacts and Costs***

52 The biological, ecological and biogeochemical changes driven by ocean acidification will affect several key
53 ecosystem services. The oceans will become less efficient at absorbing CO₂, hence less efficient at moderating
54 climate change, as their CO₂ content will increase (*very high confidence*). The impacts of ocean acidification on

1 coral reefs, together with those of bleaching and sea level rise, will in turn diminish their role of shoreline protection
2 in atolls and small island nations as well as their direct and indirect benefits on the tourism industry (*limited*
3 *evidence, high agreement*; Box CC-CR).

4 There is no global estimate of the observed or projected economic costs of ocean acidification. The production
5 of commercially-exploited shelled mollusks may decrease (Barton et al., 2012) resulting in an up to 13% reduction
6 of US production (*limited evidence, low agreement*; Cooley and Doney, 2009). The global cost of production loss of
7 mollusks could be over 100 billion USD by 2100 (Narita et al., 2012). The largest uncertainty is how the impacts on
8 prey will propagate through the marine food webs and to top predators. Models suggest that ocean acidification will
9 generally reduce fish biomass and catch (*limited evidence, high agreement*) and that complex additive, antagonistic
10 and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management)
11 factors (Branch et al., 2012; Griffith et al., 2012). The annual economic damage of ocean-acidification-induced coral
12 reef loss by 2100 has been estimated, in 2009, to be 870 and 500 billion USD, respectively for A1 and B2 SRES
13 emission scenarios (Brander et al. 2012). Although this number is small compared to global GDP, it represents a
14 large proportion of the GDP of some regions or small island states which rely economically on coral reefs.
15

16 *Adaptation and Mitigation*

17 The management of ocean acidification comes down to mitigation of the source of the problem and adaptation to the
18 consequences (Rau et al., 2012; Billé et al., sbm). Mitigation of ocean acidification through reduction of atmospheric
19 CO₂ is the most effective and the least risky method to limit ocean acidification and its impacts. Climate
20 geoengineering techniques based on solar radiation management would have no direct effect on ocean acidification
21 because atmospheric CO₂ would continue to rise (6.4.2). Techniques based on carbon dioxide removal could directly
22 address the problem but their effectiveness at the scale required to ameliorate ocean acidification has yet to be
23 demonstrated. Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean
24 acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels
25 (Williamson and Turley, 2012; 6.4.2; 30.3.2.3 and 30.5.7). Mitigation of ocean acidification at the local level could
26 involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Specific
27 activities, such as aquaculture, could adapt to ocean acidification within limits, for example by altering the
28 production process, selecting less sensitive species or strains, or relocating elsewhere. A low-regret approach is to
29 limit the number and the magnitude of drivers other than CO₂. There is evidence, for example, that reducing a
30 locally determined driver (i.e. nutrient pollution) may substantially reduce its synergistic effects with a globally
31 determined driver such as ocean acidification (Falkenberg et al., 2013).
32

33 [INSERT FIGURE OA-1 HERE

34 Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy
35 options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface
36 pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for
37 emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the
38 distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution
39 using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global
40 carbon cycle while being driven by prescribed atmospheric CO₂ concentrations. The number of CMIP5 models to
41 calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C:
42 Effect of near future acidification on major response variables estimated using weighted random effects
43 meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size
44 indicates which process is most uniformly affected by ocean acidification but large variability exists between
45 species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number
46 of experiments used in the analyses is shown in parentheses. * denotes a significant effect.]
47
48

49 **CC-OA References**

- 51 **Barton** A., Hales B., Waldbusser G. G., Langdon C. & Feely R. A., 2012. The Pacific oyster, *Crassostrea gigas*, shows negative correlation to
52 naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnology and Oceanography* 57:698-710.
53 **Branch** T. A., DeJoseph B. M., Ray L. J. & Wagner C. A., in press. Impacts of ocean acidification on marine seafood. *Trends in Ecology &*
54 *Evolution*.

- 1 **Brander** L. M., Rehdanz K., Tol R. S. J. & Van Beukering P. J. H., 2012. The economic impact of ocean acidification on coral reefs. *Climate*
2 *Change Economics* 3, 1250002. doi:10.1142/S2010007812500029.
- 3 **Cooley** S. R. & Doney S. C., 2009. Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research*
4 *Letters* 4:1-8.
- 5 **Falkenberg** L. J., Connell S. D. & Russell B. D., 2013. Disrupting the effects of synergies between stressors: improved water quality dampens
6 the effects of future CO₂ on a marine habitat. *Journal of Applied Ecology* 50:51-58.
- 7 **Gazeau** F., Parker L. M., Comeau S., Gattuso J.-P., O'Connor W., Martin S., Pörtner H.-O. & Ross P., in press. Impacts of ocean acidification on
8 marine shelled molluscs. *Marine Biology* .
- 9 **Griffith** G. P., Fulton E. A., Gorton R. & Richardson A. J., 2012. Predicting interactions among fishing, ocean warming, and ocean acidification
10 in a marine system with whole-ecosystem models. *Conservation Biology* 26:1145-1152.
- 11 **Kroeker** K., Kordas R. C., Ryan, Hendriks I., Ramajo L., Singh G., Duarte C. & Gattuso J.-P., in press. Impacts of ocean acidification on marine
12 biota: Quantifying variation in sensitivity among organisms and life stages and at elevated temperature. *Global Change Biology*.
- 13 **Narita** D., Rehdanz K. & Tol R. S. J., 2012. Economic costs of ocean acidification: a look into the impacts on shellfish production. *Climatic*
14 *Change* 113:1049-1063.
- 15 **Raven** J. A., 2011. Effects on marine algae of changed seawater chemistry with increasing CO₂. *Biology and Environment: Proceedings of the*
16 *Royal Irish Academy* 111B:1-17.
- 17 **Rau** G. H., McLeod E. L. & Hoegh-Guldberg O., 2012. The need for new ocean conservation strategies in a high-carbon dioxide world. *Nature*
18 *Climate Change* 2:720-724.
- 19 **Williamson** P. & Turley C., 2012. Ocean acidification in a geoengineering context. *Philosophical Transactions of the Royal Society A*
20 *A370:4317-4342*.
- 21 **Wootton** J. T., Pfister C. A. & Forester J. D., 2008. Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution
22 multi-year dataset. *Proceedings of the National Academy of Science U.S.A.* 105:18848-18853.
- 23 **Wootton** J. T. & Pfister C. A., 2012. Carbon system measurements and potential climatic drivers at a site of rapidly declining ocean pH. *PLoS*
24 *ONE* 7, e53396. doi:10.1371/journal.pone.0053396.

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

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

30
31 Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as
32 depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and
33 production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels
34 and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops)
35 require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a,
36 Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per
37 unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and
38 Hajra 2009, Gerten et al. 2011). While food production and transport require large amounts of energy (Pelletier et al
39 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food
40 production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

41
42 [INSERT FIGURE WE-1 HERE

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

44
45 Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy
46 sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2
47 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue
48 disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who
49 computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the
50 IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase
51 from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on
52 freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges
53 from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water
54 requirements will depend on electric demand growth, the portfolio of generation technologies and water

1 management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will
2 change due to climate change (Chapter 3.5.2.2).

3
4 Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination.
5 Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per
6 m³ of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater
7 vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global
8 water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy
9 intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping
10 from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use
11 (kWhr/m³) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of
12 water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or
13 water supply gaps.

14
15 Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem
16 services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and
17 energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can
18 compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among
19 energy, food, land, and water (McCornick *et al.*, 2008, Bazilian *et al.*, 2011, Bierbaum and Matson, 2013),
20 addressing the issues from a security standpoint and describing early integrated modeling approaches. The
21 interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand,
22 bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of
23 supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the
24 implications for health and economic impacts as described throughout this Assessment Report.

25 26 27 CC-WE References

- 28
29 **Bazilian**, M. Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S.J., Yumkella, K., ;
30 Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, Volume 39, Issue 12, December
31 2011, Pages 7896-7906
- 32 **Bierbaum**, R., and P. Matson, “Energy in the Context of Sustainability”, Daedalus, The Alternative Energy Future, Vol.2, 90-97, 2013.
- 33 **Döll**, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., Scanlon, B. (2012): Impact of water
34 withdrawals from groundwater and surface water on continental water storage variations. *J. Geodyn.* 59-60, 143-156,
35 doi:10.1016/j.jog.2011.05.001.
- 36 **Davies**, E., Page, K. and Edmonds, J. A., 2013. "[An Integrated Assessment of Global and Regional Water Demands for Electricity Generation to 2095.](#)" *Advances in Water Resources* 52:296–313.[10.1016/j.advwatres.2012.11.020.](#)
- 37
38 **Diffenbaugh**, N., Hertel, T., M. Scherer & M. Verma, “Response of corn markets to climate volatility under alternative energy futures”, *Nature*
39 *Climate Change* 2, 514–518 (2012)
- 40 **Gerten** D., Heinke H., Hoff H., Biemans H., Fader M., Waha K. (2011): Global water availability and requirements for future food production,
41 *Journal of Hydrometeorology*, doi: 10.1175/2011JHM1328.1.
- 42 **Khan**, S., Hanjra, M. A. 2009. Footprints of water and energy inputs in food production - Global perspectives. *Food Policy*, 34, 130-140.
- 43 **King**, C. and Webber, M. E., Water intensity of transportation, *Environmental Science and Technology*, 2008, 42 (21), 7866-7872.
- 44 **Macknick**, J.; Newmark, R.; Heath, G.; Hallett, K. C.; Meldrum, J.; Nettles-Anderson, S. (2012). Operational Water Consumption and
45 Withdrawal Factors for Electricity Generating Technologies: A Review of Existing Literature”, *Environmental Research Letters*. Vol. 7(4),
46 2012a
- 47 **Macknick**, J.; Sattler, S.; Averyt, K.; Clemmer, S.; Rogers, J. (2012). Water Implications of Generating Electricity: Water Use Across the United
48 States Based on Different Electricity Pathways through 2050.” *Environmental Research Letters*. Vol. 7(4), 2012b
- 49 **McCornick** P.G., Awulachew S.B. and Abebe M. (2008): Water-food-energy-environment synergies and tradeoffs: major issues and case
50 studies. *Water Policy*, 10: 23-36.
- 51 **Plappally**, A.K., and J.H. Lienhard V; Energy requirements for water production, treatment, end use, reclamation, and disposal; *Renewable and*
52 *Sustainable Energy Reviews*, Volume 16, Issue 7, September 2012, Pages 4818-4848
- 53 **Pelletier**, N., Audsley, E. , Brodt, S. , Garnett, T., Henriksson, P., Kendall, A., Kramer, K.J. , Murphy, D., Nemeck, T. and M. Troell, “Energy
54 Intensity of Agriculture and Food Systems”, *Annual Review of Environment and Resources*, 36: 223-246, 2011.

- 1 **Sattler, S.**; Macknick, J.; Yates, D.; Flores-Lopez, F.; Lopez, A.; Rogers, J. (2012). Linking Electricity and Water Models to Assess Electricity
2 Choices at Water-Relevant Scales. *Environmental Research Letters*. Vol. 7(4), October-December 2012
- 3 **Shah T.** (2007): Groundwater, a global assessment of scale and significance, in: Molden (ed) *Comprehensive Assessment of Water Management*
4 in Agriculture, Earthscan, Colombo, International Water Management Institute.
- 5 **Skaggs, R.**, Janetos, TC, Hibbard, KA , Rice, JS, Climate and Energy-Water-Land System Interactions; Technical Report to the U.S. Department
6 of Energy in Support of the National Climate Assessment, PNNL report 21185, March 2012
- 7 **van Vliet, M.T.H.**, , J.R., Ludwig, F., Vögele, S., Lettenmaier, D. P., and Kabat, P. , Vulnerability of US and European electricity supply to
8 climate change. *Nature Climate Change*, 2, 676–681(2012).
- 9 **Wise, M.**, Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A, Edmonds, J. 2009. Implications of limiting
10 CO2 concentrations for land use and energy. *Science* 324, 1183-1186.
- 11 **World Energy Council**; Water for Energy; 2010.
- 12
13

14 References

- 15
16 Abbott, P., C. Hurt, and W. Tyner, 2011: What’s Driving Food Prices in 2011? *Farm Foundation*.
- 17 Adger, W., S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D. Nelson, L. Naess, J. Wolf, and A. Wreford, 2009:
18 Are there Social Limits to Adaptation to Climate Change? *Climate Change*, 93, 335-354.
- 19 Ainsworth, E.A., 2008: Rice production in a changing climate: a meta-analysis of responses to carbon dioxide and
20 elevated ozone concentrations. *Global Change Biology*, 14(7), 1642-1650.
- 21 Ainsworth, E.A., A. Leakey, D.R. Ort, and S.P. Long, 2008: FACE-ing the facts: inconsistencies and
22 interdependence among field, chamber and modeling studies of elevated [CO2] impacts on crop yield and food
23 supply. *New Phytologist*, 179(1), 5-9.
- 24 Ainsworth, E.A. and J.M. McGrath, 2010: Direct effects of rising atmospheric carbon dioxide and ozone on crop
25 yields. In: *Climate Change and Food Security: adapting agriculture to a warmer world*. [Lobell, D. and M.
26 Burke (eds.)]. Springer, pp. 109-130.
- 27 Akhtar, N., M. Yamaguchi, H. Inada, D. Hoshino, T. Kondo, M. Fukami, R. Funada, and T. Izuta, 2010: Effects of
28 ozone on growth, yield and leaf gas exchange rates of four Bangladeshi cultivars of rice (*Oryza sativa* L.).
29 *Environmental Pollution*, 158(9), 2970-2976.
- 30 Aksoy and Sid-Dimelik, 2008: Are Low Food Prices Pro-Poor? Net Food Buyers and Sellers in Low-Income
31 Countries. World Bank Policy Research Working Paper No. 4642. **
- 32 Aksoy, A., J. Beverinotti, K. Covarrubias, and A. Zezza, 2010: Household Income Structures in Low-income
33 Countries. In: *Food Prices and Rural Poverty*. [Aksoy, M. and B. Hoekstra(eds.)]. World Bank, Washington
34 D.C.
- 35 Alberto, A.M.P et al, 1996: The influence of increasing carbon dioxide and temperature on competitive interactions
36 between a C3 crop, rice (*Oryza sativa*) and a C4 weed (*Echinochloa glabrescens*). *Australian Journal of Plant*
37 *Physiology*, 23, 795-802. **
- 38 Alcamo, J., N. Dronin, M. Endejan, G. Golubev, and A. Kirilenko, 2007: A new Assesment of Climate Change
39 Impacts on Food Production Shortfalls and Water Availability in Russia. *Global Environmental Change*, 17,
40 429-444.
- 41 Alderman, H., 2010: Safety nets can help address the risks to nutrition from increasing climate variability. *Journal*
42 *of Nutrition*, 140(1), 148S-152S.
- 43 Alexander, L.V., X. Zhang, T.C. Peterson, J. Caesar, B. Gleason, A. Klein Tank, M. Haylock, D. Collins, B. Trewin,
44 and F. Rahimzadeh, 2006: Global observed changes in daily climate extremes of temperature and precipitation.
45 *J. Geophys. Res*, 111.
- 46 Alessa, L., Kliskey, A., Williams, P., Barton, M. 2008. Perception of change in freshwater in remote resource
47 dependent Arctic communities. *Global Environ Chang*, 18, 153–164. **
- 48 Ali, M. and S. Gupta, 2012: Carrying capacity of Indian agriculture: pulse crops. *Current Science*, 102, 874-881.
- 49 Allison, E.H., A.L. Perry, M. Badjeck, W. Neil Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D.
50 Reynolds, N.L. Andrew, and N.K. Dulvy, 2009: Vulnerability of national economies to the impacts of climate
51 change on fisheries. *Fish and Fisheries*, 10(2), 173-196.
- 52 Ambardekar, A.A., T.J. Siebenmorgen, P.A. Counce, S.B. Lanning, and A. Mauromoustakos, 2011: Impact of
53 field-scale nighttime air temperatures during kernel development on rice milling quality *Field Crops Research*,
54 122, 179-185.

- 1 Amthor, J.S., 2001: Effects of atmospheric CO₂ concentration on wheat yield: review of results from experiments
2 using various approaches to control CO₂ concentration. *Field Crops Research*, 73(1), 1-34.
- 3 Antle, J.M. and C.C. Crissman., 1990: Risk, Efficiency, and the Adoption of Modern Crop Varieties: Evidence from
4 the Philippines. *Economic Development and Cultural Change*, 38(3), 517-537.
- 5 Archambault, D.J., 2007: Efficacy of herbicides under elevated temperature and CO₂. *Agroecosystems in a*
6 *Changing Climate*, 262-279.
- 7 Archimède, H., M. Eugène, C.M. Magdeleine, M. Boval, C. Martin, D.P. Morgavi, P. Lecomte, and M. Doreau,
8 2011: *Comparison of methane production between C3 and C4 grasses and legumes* pp. 59-64.
- 9 Asseng, S., F. Ewert, C. Rosenzweig, J.W. Jones, J.L. Hatfield, A. Ruane, K.J. Boote, P. Thorburn, R.P. Rötter, D.
10 Cammarano, N. Brisson, B. Basso, P. Martre, P.K. Aggarwal, C. Angulo, P. Bertuzzi, C. Biernath, A.J.
11 Challinor, J. Doltra, S. Gayler, R. Goldberg, R. Grant, L. Heng, J. Hooker, L.A. Hunt, J. Ingwersen, R.C.
12 Izaurralde, K.C. Kersebaum, C. Müller, S.N. Kumar, C. Nendel, G. O'Leary, J.E. Olesen, T.M. Osborne, T.
13 Palosuo, E. Priesack, D. Ripoche, M.A. Semenov, I. Shcherbak, P. Steduto, C. Stöckle, P. Stratonovitch, T.
14 Streck, I. Supit, F. Tao, M. Travasso, K. Waha, D. Wallach, J.W. White, J.R. Williams, and J. Wolf, 2013, In
15 review: Quantifying uncertainties in simulating wheat yields under climate change. *Nature Climate Change*. In
16 review.
- 17 Auffhammer, M., V. Ramanathan, and V.R. Jeffrey, 2006: Integrated model shows that atmospheric brown clouds
18 and greenhouse gases have reduced rice harvests in India. *Proceedings of the National Academy of Sciences*,
19 103(52), 19668-19672.
- 20 Auffhammer, M., V. Ramanathan, and J.R. Vincent, 2012: Climate Change, the Monsoon, and Rice Yield in India.
21 *Climate Change*, 1(14).
- 22 Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz, 2011a: Global Crop Yield Reductions due to Surface Ozone
23 Exposure: 1. Year 2000 Crop Production losses and Economic damage. *Atmospheric Environment*, 45,
24 2264-2296.
- 25 Avnery, S., D.L. Mauzerall, J. Liu, and L.W. Horowitz., 2011b: Global crop yield reductions due to surface ozone
26 exposure: 2. Year 2030 potential crop production losses and economic damage under two scenarios of O₃
27 pollution. *Atmospheric Environment*, 45, 2296-2309.
- 28 Badjeck, M.-C., Allison, E. H., Halls, A.S. and Dulvey, N.K. (2010). Impacts of climate variability and change on
29 fishery-based livelihoods. *Marine Policy* 34, 375–383. **
- 30 Baethgen, W.E. 2010: Climate Risk Management for Adaptation to Climate Variability and Change. *Crop Science*,
31 50, S70-S76. **
- 32 Baldocchi, D. and S. Wong, 2008: *Accumulated winter chill is decreasing in the fruit growing regions of California*
33 Springer Netherlands, The Netherlands, pp. 153-166.
- 34 Baldos, U.L.C. and T.W. Hertel, 2013: Global food security in 2050: The role of agricultural productivity and
35 climate change. *Australian Journal of Agricultural and Resource Economics*, In review.
- 36 Barati, F., B. Agung, P. Wongsrikeao, M. Taniguchi, T. Nagai, and T. Otoi, 2008: *Meiotic competence and DNA*
37 *damage of porcine oocytes exposed to an elevated temperature* Elsevier, pp. 767-772.
- 38 Barbier B, Yacouba H, Karambiri H, Zorome M, Some B. 2009. Human Vulnerability to Climate Variability in the
39 Sahel: Farmers' Adaptation Strategies in Northern Burkina Faso. *Environmental Management* 43:790-803. **
- 40 Battaglini, A. et al., 2009: European winegrowers' perceptions of climate change impact and options for adaptation
41 *Reg Environ Change*, 9, 61-73. **
- 42 Bearchell, S.J., B.A. Fraaije, M.W. Shaw, and B.D. Fitt, 2005: Wheat archive links long-term fungal pathogen
43 population dynamics to air pollution. *Proceedings of the National Academy of Sciences*, 102(15), 5438-5442.
- 44 Bell, J., M. Batty, A. Ganachaud, P. Gehr, A. Hobday, O. Hoegh-Guldberg, R.L.B. Johnson, P. Lehody, and J.
45 Lough, 2011: Preliminary Assessment of the Effects of Climate Change on Fisheries to the Economies of
46 Pacific Island Countries and Territories. *Pacific Studies Series*.
- 47 Bell, J., T.J.H. Adams, J.E. Johnson, A.J. Hobday, and A.S. Gupta, 2011b: Pacific communities, fisheries,
48 aquaculture and climate change: an introduction. In: *Vulnerability of tropical Pacific fisheries and aquaculture*
49 *to climate change*. [Bell, J.D., J.E. Johnson, and A.J. Hobday(eds.)]. Secretariat of the Pacific Community,
50 Noumea, New Caledonia, pp. 1-47.
- 51 Bellocchi, G., M. Rivington, M. Donatelli, and K. Matthews, 2010: Validation of biophysical models: issues and
52 methodologies. A review. *Agron.Sustain.Dev.*, 30(1), 109-130.
- 53 Berg A. et al., 2012 Projections of climate change impacts on potential C4 crop productivity over tropical regions,
54 *Agricultural and Forest Meteorology*, 170, 89-102.

- 1 Bergot, M., E. Cloppet, V. Pérnaud, M. Déqué, B. Marçais, and M. Desprez-Loustau, 2004: Simulation of potential
2 range expansion of oak disease caused by *Phytophthora cinnamomi* under climate change. *Global Change*
3 *Biology*, 10(9), 1539-1552.
- 4 Berrang-Ford, L., J. Ford, and J. Paterson, 2010: Are we adapting to climate change? *Global Environmental*
5 *Change*, 21(1), 25-33.
- 6 Biazin, B., G. Sterk, M. Temesgen, A. Abdulkedir, L. Stroosnijder. 2012: Rainwater harvesting and management in
7 rainfed agricultural systems in sub-Saharan Africa – A review. *Physics and Chemistry of the Earth*, 47,
8 139-151.**
- 9 Bindi, M. and Olesen, J., 2011: The responses of agriculture in Europe to climate change. *Reg Environ Change*, 11,
10 (Suppl 1):S151–S158.
- 11 Biswas, D.K., H. Xu, Y.G. Li, J.Z. Sun, X.Z. Wang, X.G. Han, and G.M. Jiang, 2008: Genotypic differences in leaf
12 biochemical, physiological and growth responses to ozone in 20 winter wheat cultivars released over the past 60
13 years. *Global Change Biology*, 14, 46-59.
- 14 Bloem, M.W., R. Semba, and K. Kraemer, 2010: Caster Gandolfo Workshop: An Introduction to the Impact of
15 Climate Change, the Economic Crisis and the Increases in the Food Prices on Malnutrition. *Journal of*
16 *Nutrition*, 140(1), 132s-135s.
- 17 Bohensky, E., A. Smaigl, and T. Brewer, 2012: Patterns in household-level engagement with climate change in
18 Indonesia. *Nature Climate Change*,
- 19 Bohmanova, J., I. Misztal, S. Tsuruta, H.D. Norman, and T.J. Lawlor, 2008: *Short Communication: Genotype by*
20 *Environment Interaction Due to Heat Stress* American Dairy Science Association, pp. 840-846.
- 21 Bondeau, A., P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller,
22 M. Reichstein, and B. Smith, 2007: Modelling the Role of Agriculture for the 20th Century Global Terrestrial
23 Carbon Balance. *Global Change Biology*, 13(3), 679-706.
- 24 Booker, F., R. Muntifering, M. McGrath, K. Burkey, D. Decoteau, E. Fiscus, W. Manning, S. Krupa, A. Chappelka,
25 and D. Grantz, 2009: The Ozone Component of Global Change: Potential Effects on Agricultural and
26 Horticultural Plant Yield, Product Quality and Interactions with Invasive Species. *Journal of Integrative Plant*
27 *Biology*, 51(4), 337-351.
- 28 Boone et al., 2013: In press. **
- 29 Brander, K.M., 2007: Global Fish Production and Climate Change. *Proceedings of the National Academy of*
30 *Sciences*, 104, 19709-19714.
- 31 Bridges, D., C., 1992: Crop Losses Due to Weeds in the United States. *Weed Science Society of America*, 403pp.
32 ISBN 0911733159.
- 33 Brinkman, H.J., S. de Pee, I. Aanogao, L. Subran, and M.W. Bloem, 2010: High food prices and the global financial
34 crisis have reduced access to nutritious food and worsened nutritional status and health *Journal of Nutrition*,
35 140(1), 153S-161S.
- 36 Brisson, N., P. Gate, D. Gouache, G. Charmet, F. Oury, and F. Huard, 2010: Why are Wheat Yields Stagnating in
37 Europe? A Comprehensive Data Analysis for France. *Field Crops Research*, 119(1), 201-212.
- 38 Brown, C.J., E.A. Fulton, A.J. Hobday, R.J. Matear, H.P. Possingham, C. Bulman, V. Christensen, R.E. Forrest,
39 P.C. Gehrke, N.A. Gribble, S.P. Griffiths, H. Lozano-Montes, J.M. Martin, S. Metcalf, T.A. Okey, R. Watson,
40 and A.J. Richardson, 2010: Effects of Climate-driven Primary Production Change on Marine Food Webs:
41 Implications for Fisheries and Conservation. *Global Change Biology*, 16(4), 1194-1212.
- 42 Bruinsma, J. 2009: Bruinsma, J. (2009), The resource outlook to 2050: By how much do land, water and crop yields
43 need to increase by 2050? Expert Meeting on How to Feed the World in 2050. FAO Publications. 33 pp. **
- 44 Bryan, E., T. Deressa, G. Gbetibouo, and C. Ringler, 2009: Adaptation to Climate Change in Ethiopia and South
45 Africa: Options and Constraints. *Environmental Science and Policy*, , 413-426.
- 46 Bunce, J.L., 2012: Responses of cotton and wheat photosynthesis and growth to cyclic variation in carbon dioxide
47 concentration. *Photosynthetica*, 50(3), 395-400.
- 48 Burke, L., K. Reytar, M. Spalding, and A. Perry, 2011: Reefs at Risk Revisited. *Executive Summary. World*
49 *Resources Institute, Washington DC*.
- 50 Campbell, A.A., S. de Pee, K. Sun, K. Kraemer, A. Thorne-Lyman, and R. Moench-Pfanner, 2010: Household rice
51 expenditure and maternal and child nutritional status in Bangladesh. *Journal of Nutrition Journal of Nutrition*,
52 140(1), 189S-194S.
- 53 Cannon, R.J.C., 1998: The implications of predicted climate change for insect pests in the UK, with emphasis on
54 non-indigenous species. *Global Change Biology*, 4(7), 785-796.

- 1 Carter, M.R. and T.J. Lybbert, 2012: Consumption versus asset smoothing: testing the implications of poverty trap
2 theory in Burkina Faso. *Journal of Development Economics*, 99(2), 255-264.
- 3 Ceccarelli, S., S. Grando, M. Maatougui, M. Michael, M. Slash, R. Haghparast, M. Rahmanian, A. Taheri, A.
4 Al-Yassin, A. Benbelkacem, M. Labdi, H. Mimoun, and M. Nachit, 2010: Plant Breeding and Climate Changes.
5 *The Journal of Agricultural Science*, 148(06), 627-637.
- 6 Chakraborty, S., J. Luck, A. Freeman, R.M. Norton, K.A. Garrett, K.E. Percy, A.A. Hopkin, C. Davis, and D.F.
7 Karnosky, 2008: Impacts of global change on diseases of agricultural crops and forest types. *CAB Reviews:*
8 *Perspectives in Agriculture, Veterinary Science, Nutrition, and Natural Resources*, 3(054), 1-15.
- 9 Chakraborty, S. and A.C. Newton, 2011: Climate change, plant diseases and food security: an overview *Plant*
10 *Pathology*, 60(1), 2-14.
- 11 Challinor, A.J. and T.R. Wheeler, 2008: Use of a Crop Model Ensemble to Quantify CO2 Stimulation of
12 Water-Stressed and Well-Watered Crops. *Agricultural and Forest Meteorology*, 148(6-7), 1062-1077.
- 13 Challinor, A.J., T.R. Wheeler, D. Hemming, and H.D. Upadhyaya, 2009: Ensemble Yield Simulations: Crop and
14 Climate Uncertainties, Sensitivity to Temperature and Genotypic Adaptation to Climate Change. *Climate*
15 *Research*, 38, 117-127.
- 16 Challinor, A.J., E.S. Simelton, E.G. Fraser, D. Hemming, and M. Collins, 2010: Increased Crop Failure due to
17 Climate Change: Assessing Adaptation Options using Models and Socio-Economic Data for Wheat in China.
18 *Environmental Research Letters*, 5(3).
- 19 Challinor, A.J., J. Watson, D. Lobell, M. Howden, D. Smith, and N. Chhetri, 2013, In review: A meta-analysis of
20 crop yield under climate change and adaptation. *Nature Climate Change*,
- 21 Chavas, D.R., R.C. Izaurralde, A.M. Thomson, and X. Gao, 2009: Long-term Climate Change Impacts on
22 Agricultural Productivity in Eastern China. *Agricultural and Forest Meteorology*, 149(6-7), 1118-1128.
- 23 Chen, C., E. Wang, Q. Yu, and Y. Zhang, 2010: Quantifying the Effects of Climate Trends in the past 43 years
24 (1961-2003) on Crop Growth and Water Demand in the North China Plain. *Climatic Change*, 100(3), 559-578.
- 25 Chen, C., C. Lei, A. Deng, C. Qian, W. Hoogmoed, and W. Zhang, 2011: Will Higher Minimum Temperatures
26 Increase Corn Production in Northeast China? An Analysis of Historical data over 1965-2008. *Agricultural and*
27 *Forest Meteorology*, 151(12), 1580-1588.
- 28 Cheung, W., V. Lam, J. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly, 2010: Large Scale
29 Redistribution of Maximum Fisheries Catch in the Global Ocean under Climate Change. *Global Change*
30 *Biology*, 16, 24-35.
- 31 Cho, K., P. Falloon, J. Gornall, R. Betts, and R. Clark, 2012: Winter Wheat Yields in the UK: Uncertainties in
32 Climate and Management Impacts. *Climate Research*, 54(1), 49-68.
- 33 Christidis, N., P.A. Stott, S. Brown, G.C. Hegerl, and J. Caesar, 2005: Detection of Changes in Temperature
34 Extremes during the Second half of the 20th Century. *Geophys. Res. Lett.*, 32.
- 35 Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht,
36 M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud, 2011: Bioenergy. In IPCC Special Report
37 on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona,
38 K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow
39 (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. **
- 40 Coakley, S.M., H. Scherm, and S. Chakraborty, 1999: Climate change and plant disease management. *Annual*
41 *Review of Phytopathology*, 37, 399-426.
- 42 Cochrane, K.L., W. Emerson and R. Willmann. 2009: Sustainable Fisheries: The Importance of the Bigger Picture.
43 In Eds W. W. Taylor, A. J. Lynch and M. G. Schechter, *Sustainable Fisheries: Multi-Level Approaches to a*
44 *Global Problem*. Herndon, VA, American Fisheries Society. pp 3-19. **
- 45 Coles, A. and C. Scott, 2009: Vulnerability and adaptation to climate change and variability in semi-arid rural
46 southeastern Arizona, USA. *Natural Resources Forum*, 33(297), 309.
- 47 Cook, R.M. and M.R. Heath, 2005: The Implications of Warming Climate for the Management of North Sea
48 Demersal Fisheries. *ICES Journal of Marine Science*, 62, 1322-1326.
- 49 Cooper, P., K.P.C. Rao, P. Singh, J. Dimes, P.S. Traore, K. Rao, P. Dixit, and S.J. Twomlow, 2009: Farming with
50 current and future climate risk: Advancing a "Hypothesis of Hope" for rainfed agriculture in semi-arid tropics.
51 *Journal of SAT Agricultural Research*, 7.
- 52 Cotty, J.L. and R. Jaime-Garcia, 2007: Influences of Climate on Aflatoxin Producing Fungi and Aflatoxin
53 Contamination. *International Journal of Food Microbiology*, (119), 109-115.

- 1 Coulthard, S., 2008: Adapting to environmental change in artisanal fisheries – Insights from a South Indian Lagoon. *Global Environmental Change*, 18, 479-489.
- 2
- 3 Cozzolino, D., W.U. Cynkar, R.G. Damberg, M. Gishen, and P. Smith, 2010: Grape (*Vitis vinifera*) compositional
4 data spanning ten successive vintages in the context of abiotic growing parameters. *Agriculture, Ecosystems &*
5 *Environment*, 139(4), 565-570.
- 6 Craine, J.M., A.J. Elmore, K.C. Olson, and D. Tolleson, 2010: Climate Change and Cattle Nutritional Stress. *Global*
7 *Change Biology*, 16(10), 2901-2911.
- 8 Craufurd, P.Q. and T.R. Wheeler, 2009: Climate Change and the Flowering time of Annual Crops. *Journal of*
9 *Experimental Botany*, 60(9), 2529-2539.
- 10 Craufurd, P.Q., V. Vadez, S.V.K. Jagadish, P.V.V. Prasad, and M. Zaman-Allah, 2013: Crop science experiments
11 designed to inform crop modeling. *Agricultural and Forest Meteorology*, 170(0), 8-18.
- 12 Crimp, S.J., Laing, A., Alexander, B., Anwar, M., Bridle, K., Brown, P., Cox, H., Crean, J., deVoil, P., Hayman, P.,
13 Kokic, P., Lu, D., Lisson, S., Lorimer-Ward, K., Masters, L., McLeod, N., Mudge, B., Parsons, D., Power, B.,
14 Robertson, M., Rodriguez, D., Smith, J., M., van Rees, H., van Wensveen, M., Wurst, M. 2012: Developing
15 climate change resilient cropping and mixed cropping/grazing businesses in Australia. A report prepared for
16 DAFF as part of the Australia's Farming Future Program, 173pp.
- 17 Cutler, S.J., A.R. Fooks, and van der Poel, W. H., 2010: Public Health Threat of new, reemerging, and neglected
18 Zoonoses in the Industrialized World. *Emerging Infectious Diseases*, 16(1), 1-7.
- 19 DaMatta, F.M., A. Grandis, B.C. Arenque, and M.S. Buckeridge, 2010: Impacts of climate changes on crop
20 physiology and food quality. *Food Research International*, 43(7), 1814-1823.
- 21 De Bruin, K.C. and R. Dellink, 2011: How harmful are restrictions on adapting to climate change? *Global*
22 *Environmental Change*, 21, 34-45.
- 23 de Fraiture, C., D. Molden, and D. Wichelns, 2010: Investing in Water for Food, Ecosystems, and Livelihoods: An
24 overview of the comprehensive Assessment of Water Management in Agriculture. *Agricultural Water*
25 *Management*, 97(4), 495-501.
- 26 de Fraiture, C. and D. Wichelns, 2010: Satisfying future water demands for agriculture. *Agricultural Water*
27 *Management*, 97(4), 502-511.
- 28 De Silva, S.S. and D. Soto, 2009: Climate Change and Aquaculture: Potential Impacts, Adaptation and Mitigation.
29 Climate Change Implications for Fisheries and Aquaculture. Overview of Current Scientific Knowledge. *FAO*
30 *Fisheries and Aquaculture Technical Paper 530. Rome.*
- 31 De Wolf, E.D. and S.A. Isard, 2007: Disease cycle approach to plant disease prediction. *Annual Review of*
32 *Phytopathology*, 45, 203-220.
- 33 DEFRA, 2006: Food security and the UK: An Evidence and Analysis Paper. *Food Chain Analysis Group*, .
- 34 Dell, M., B.F. Jones, and B.A. Olken, 2012: Temperature Shocks and Economic Growth: Evidence from the Last
35 Half Century. *American Economic Journal: Macroeconomics*, 4, 66-95.
- 36 Dercon S et al., 2006: Dercon, Stephen 2006 Economic reform, growth and the poor: Evidence from rural Ethiopia
37 *Journal of Development Economics*, 81, 1–24. **
- 38 Dercon, S., 2004: Growth and shocks: evidence from rural Ethiopia. *Journal of Development Economics*, 74(2),
39 309-329.
- 40 Dercon, S. and L. Christiansen, 2011: Consumption risk, technology adoption and poverty traps: Evidence from
41 Ethiopia. *Journal of Development Economics*, 96(2), 159-173.
- 42 Deressa, T., R. Hassan, C. Ringler, T. Alemu, and M. Yesuf, 2009: Determinants of Farmers' Choice of Adaptation
43 Methods to Climate Change in the Nile Basin of Ethiopia. . *Global Environmental Change*, 19, 248-255.
- 44 Descheemaeker, K., T. Amede, and A. Hailelassie, 2010: Improving Water Productivity in mixed Crop–Livestock
45 Farming Systems of sub-Saharan Africa. *Agricultural Water Management*, 97(5), 579-586.
- 46 Deutsch, C.A., J.J. Tewksbury, R.B. Huey, K.S. Sheldon, C.K. Ghalambor, D.C. Haak, and P.R. Martin, 2008:
47 Impacts of climate warming on terrestrial ectotherms across latitude. of the United States of America.
48 *Proceedings of the National Academy of Sciences*, 105, 6668-6672.
- 49 Devasirvatham, V., D.K.Y. Tan, P.M. Gaur, T.N. Raju, and R.M. Trethowan, 2012: High temperature tolerance in
50 chickpea and its implications for plant improvement. *Crop and Pasture Science*, 63(5), 419-428.
- 51 Diacono, M., and F. Montemurro (2010) Long-term effects of organic amendments on soil fertility. A review.
52 *Agronomic Sustainable Development* 30 401-422. **
- 53 Dikmen, S. and P.J. Hansen, 2009: *Is the Temperature-humidity index the best indicator of heat stress in Lactating*
54 *Dairy Cows in a subtropical Environment?* American Dairy Science Association, pp. 109-116.

- 1 Drinkwater, K.F., 2005: The response of Atlantic cod (*Gadus morhua*) to future climate change. *ICES Journal of*
2 *Marine Science*, 62, 1327-1337.
- 3 Dronin, N. and A. Kirilenko, 2011: Climate Change, Food Stress, and Security in Russia. *Regional Environmental*
4 *Change*, 11, 167-178.
- 5 Duchêne, E., F. Huard, V. Dumas, C. Schneider, and D. Merdinoglu, 2010: The challenge of adapting grapevine
6 varieties to climate change. *Climate Research*, 41, 193-204.
- 7 Dukes, J.S. and H.A. Mooney, 1999: Does Global Change increase the success of Biological Invaders? *Trends in*
8 *Ecology & Evolution*, 14(4), 135-139.
- 9 Duval, B.D., P. Dijkstra, S.M. Natali, J.P. Megonigal, M.E. Ketterer, B.G. Drake, M.T. Lerdau, G. Gordon, A.D.
10 Anbar, and B.A. Hungate, 2011: Plant-Soil Distribution of Potentially Toxic Elements in Response to Elevated
11 Atmospheric CO². *Environmental Science and Technology*, 45(7), 2570-2574.
- 12 Eastburn, D.M., A.J. McElrone, and D.D. Bilgin, 2011: Influence of atmospheric and climatic change on
13 plant-pathogen interactions. *Plant Pathology*, 60(1), 54-69.
- 14 El-Hage Scialabba, N. and M. Müller-Lindenlauf, 2010: Organic agriculture and climate change. *Renewable*
15 *Agriculture and Food Systems*, 25(11).
- 16 El-Sharkawy, M.A., 2012: Stress-tolerant cassava: the role of integrative ecophysiology-breeding research in crop
17 improvement. *Open Journal of Soil Science*, 2, 162-186.
- 18 Emberson, L.D., P. Büker, M.R. Ashmore, G. Mills, L.S. Jackson, M. Agrawal, M.D. Atikuzzaman, S. Cinderby, M.
19 Engardt, C. Jamir, K. Kobayashi, N.T.K. Oanh, Q.F. Quadir, and A. Wahid, 2009: A comparison of North
20 American and Asian Exposure–Response data for Ozone effects on Crop Yields. *Atmospheric Environment*,
21 43(12), 1945-1953.
- 22 Erbs, M., R. Manderscheid, G. Jansen, S. Seddig, A. Pacholski, and H. Weigel, 2010: Effects of free-air CO₂
23 enrichment and nitrogen supply on grain quality parameters and elemental composition of wheat and barley
24 grown in a crop rotation. *Agriculture, Ecosystem and Environment*, 136(1-2), 59-68.
- 25 Erda, L., X. Wei, J. Hui, X. Yinlong, L. Yue, B. Liping and X. Liyong. 2005. Climate change impacts on crop yield
26 and quality with CO₂ fertilization in China. *Philosophical Transactions of the Royal Society London B*
27 *Biological Sciences* 360: 2149-2154. **
- 28 Ericksen, P., 2008: Conceptualizing Food Systems for Global Environmental Change Research. *Global*
29 *Environmental Change*, 18(1), 234-245.
- 30 Ericksen, P.J., B. Stewart, J. Dixon, D. Barling, P. Loring, and Anderson, M., Ingram, J., 2010: The Value of a Food
31 System Approach. In: *Food Security and Global Environmental Change*. [Ingram, J., P. Ericksen, and D.
32 Liverman(eds.)]. Earthscan, London, U.K., pp. 25-45.
- 33 Evans, N., A. Baierl, M.A. Szmenov, P. Gladders, and B.D.L. Fitt, 2008: Range and severity of a plant disease
34 increased by global warming. *Journal of the Royal Society Interface*, 5(22), 525-531.
- 35 Ewing, M. and S. Msangi, 2009: Biofuels Production in Developing Countries: Assessing tradeoffs in Welfare and
36 Food Security. *Environmental Science & Policy*, 12(4), 520-528.
- 37 Fafchamps, M., 1992: Solidarity Networks in Pre-Industrial Societies: Rational Peasants with a Moral Economy.
38 *Economic Development and Cultural Change*, 41(1), 147-174.
- 39 Fafchamps, M., 1999: In: Economic and Social Development Paper, no. 144. FAO, Rome, Italy, pp. 1-147.
- 40 Fafchamps, M., 2009: *Vulnerability, Risk Management, and Agricultural Development*. In: Working Paper Series
41 No. AfD-0904. Agriculture for Development, Center for Effective Global Action, University of California,
42 Berkeley, pp. 1-29.
- 43 Falloon, B. and R. Betts, 2010: Climate impacts on European agriculture and water management in the context of
44 adaptation and mitigation – The importance of an integrated approach. *Science of the Total Environment*, 408,
45 5667-5687.
- 46 FAO, 1996: *Rome Declaration and World Food Summit Plan of Action*. FAO, Rome, Italy.
- 47 FAO, 2008: *Policy Measures taken by Government to Reduce the Impact of Soaring Prices*. Global Information and
48 Early Warning System, .
- 49 FAO, 2009: Introduction. In: *Climate change implications or fisheries and aquaculture. Overview of current*
50 *scientific knowledge. Technical Paper 530*. [Cochrane, K., C. De Young, D. Soto, and T. Bahri(eds.)]. FAO,
51 Rome.
- 52 FAO, 2010: *Food and Agriculture Organization of the United Nations (FAO), FAO Statistical Databases*.
- 53 FAO, 2010a: *The State of Food Insecurity in the World: Addressing food insecurity in protracted crises*. FAO,
54 Rome, Italy, pp. 1-59.

- 1 FAO, 2011: *State of Food Insecurity in the World. How does International Price Volatility affect Domestic*
2 *Economies and Food?*. FAO, Rome.
- 3 FAO, WFP, and IFAD, 2012: *The State of Food Insecurity in the World 2012. Economic Growth is necessary but*
4 *not Sufficient to Accelerate Reduction of Hunger and Malnutrition*. FAO, Rome, Italy, pp. 1-61.
- 5 Farag, A.A., A.A. Khalil, and M.K. Hassanein, 2010: Chilling requirement for deciduous fruit under Climate Change
6 in Egypt. *Research Journal of Agriculture and Biological Sciences*, 6(6), 815-822.
- 7 Fatondji, D., C. Martius, R. Zougmore, P. Vlek, C. Biielders, and S. Koala, 2009: *Decomposition of Organic*
8 *Amendment and Nutrient Release under the Zai technique in the Sahel* Springer Netherlands, pp. 225-239.
- 9 Feder, G., R. Just, and D. Zilberman, 1985: Adoption of Agricultural Innovations in Developing Countries: A
10 Survey. *Economic Development and Cultural Change*, 33(2), 255-298.
- 11 Feng, J., M. Zhang, S. Zheng, P. Xie, and A. Ma, 2008: Effects of high temperature on multiple parameters of
12 broilers in vitro and in vivo. *Poultry Science*, 87(10), 2133-2139.
- 13 Feng, Z., J. Pang, K. Kobayashi, J. Zhu, and D.R. Ort, 2011: Differential responses in two varieties of winter wheat
14 to elevated ozone concentration under fully open-air field conditions. *Global Change Biology*, 17(1), 580-591.
- 15 Fernando, N., J. Panozzo, M. Tausz, R. Norton, G. Fitzgerald, and S. Seneweera, 2012: Rising atmospheric CO₂
16 concentration affects mineral content and protein concentration of wheat grain. *Food Chemistry*, 133(4),
17 1307-1311.
- 18 Ficke, A.D., C.A. Myrick, and L.J. Hansen, 2007: Potential impacts of global climate change on freshwater
19 fisheries. *Review in Fish Biology and Fisheries*, 17(4), 581-613.
- 20 Fischer, G., E. Hitznyik, S. Prieler, M. Shah, and H.v. Velthuisen, 2009: Biofuels and Food Security. *Final Report*
21 *to Sponsor: The OPEC Fund for International Development (OFID)*,
- 22 Fishman, J., J.K. Creilson, P.A. Parker, E.A. Ainsworth, G.G. Vining, J. Szarka, F.L. Booker, and X. Xu, 2010: An
23 Investigation of Widespread Ozone Damage to the Soybean Crop in the upper Midwest Determined from
24 Ground-based and Satellite Measurements. *Atmospheric Environment*, 44(18), 2248-2256.
- 25 Fitzgerald, et al., 2008: Assessment of the adaptation potential of grass-based dairy systems to climate change in
26 Ireland – The maximised production scenario. *Agricultural and Forest Meteorology*, 149 244-255.
- 27 Fleisher, D.H., D.J. Timlin, and V.R. Reddy, 2008: Interactive Effects of Carbon Dioxide and Water Stress on
28 Potato Canopy Growth and Development. *Agronomy Journal*, 100(3), 711-719.
- 29 Fraser, E.D.G., M. Termansen, N. Sun, D. Guan, E. Simelton, P. Dodds, K. Feng, and Y. Yu, 2008: Quantifying
30 Socioeconomic Characteristics of Drought-Sensitive Regions: Evidence from Chinese Provincial Agricultural
31 Data. *Comptes Rendus Geoscience*, 340(9–10), 679-688.
- 32 Frieler, K., C. Müller, J. Elliott, J. Heinke, A. Arneth, M.F.P. Bierkens, P. Ciais, D.B. Clark, D. Deryng, P. Döll, P.
33 Falloon, B. Fekete, C. Folberth, A.D. Friend, C. Gellhorn, S.N. Gosling, I. Haddeland, N. Khabarov, M. Lomas,
34 Y. Masaki, K. Nishina, K. Neumann, T. Oki, R. Pavlick, A.C. Ruane, E. Schmid, and C. Schmitz, 2013, In
35 review: Impact cascades of climate change. *Proceedings of the National Academy of Sciences*, .
- 36 Fuhrer, J., 2009: *Ozone Risk for Crops and Pastures in Present and Future Climates* Springer Berlin / Heidelberg,
37 pp. 173-194.
- 38 Fujisawa, M. and K. Koyabashi, 2010: Apple (*Malus pumila* var. *domestica*) phenology is advancing due to rising
39 air temperature in northern Japan. *Global Change Biology*, 16, 2651-2660.
- 40 Fulton, E.A., 2011: Interesting times: winners, losers, and system shifts under climate change around Australia.
41 *ICES Journal of Marine Science*, 68(6), 1329-1342.
- 42 García-Mozo, H., A. Mestre, and C. Galán, 2010: Phenological trends in southern Spain: A response to climate
43 change. *Agricultural and Forest Meteorology*, 150(4), 575-580.
- 44 Garrett KA, Zuñiga LN, Roncal E et al., 2009b. Intraspecific functional diversity in hosts and its effect on disease
45 risk across a climatic gradient. *Ecological Applications* 19, 1868–83. **
- 46 Garrett, K.A., G.A. Forbes, S. Savary, P. Skelsey, A.H. Sparks, C. Valdivia, van Bruggen, A. H. C., L. Willocquet,
47 A. Djurle, E. Duveiller, H. Eckersten, S. Pande, C. Vera Cruz, and J. Yuen, 2011: Complexity in
48 climate-change impacts: an analytical framework for effects mediated by plant disease *Plant Pathology*, 60,
49 15-30.
- 50 Ghahramani, A. and A. Moore, 2013: *Climate change and broadacre livestock production across southern*
51 *Australia. 2. Adaptation options via grassland management*. Crop and Pasture Science, .
- 52 Ghini, R., E. Hamada, M.J. Pedro, J.A. Marengo, and R.R.V. Gonçalves, 2008: Risk analysis of climate change on
53 coffee nematodes and leaf miner in Brazil. *Pesquisa Agropecuária Brasileira*, 43(2), 187-195.

- 1 Ghorbanian, D., S. Harutyunyan, D. Mazaheri, and F. Rejali, 2011: Effects of mycorrhizal symbiosis and different
2 levels of phosphorus on yield, macro and micro elements of *Zea mays* L. under water stress condition. *Journal*
3 *of Agricultural Research*, 6, 5481-5489.
- 4 Gilbert, M., J. Slingenbergh, and X. Xiao, 2008: Climate Change and Avian Influenza. *Revue Scientifique Et*
5 *Technique - Office International Des Epizooties*, 27, 459-466.
- 6 Gillespie, K.M., F. Xu, K.T. Richter, J.M. Mcgrath, R.J.C. Markelz, D.R. Ort, and A.D.B. Leakey, 2012: reater
7 anti-oxidant and respiratory metabolism in field grown soybean exposed to elevated O₃ under both ambient and
8 elevated CO₂. *Plant, Cell and Environment*, 35, 169-184.
- 9 Gleadow, R.M., J.R. Evans, S. McCaffrey, and T.R. Cavagnara, 2009: Growth and nutritive value of cassava
10 (*Manihot esculenta* Cranz.) are reduced when grown in elevated CO₂. *Plant Biology*, 11, 76-82.
- 11 Glenn, M., S.Y. Kim, J. Ramirez-Villegas, and P. Laderach, 2013: Response of perennial horticultural crops to
12 climate change. *Horticultural Reviews*, Accepted for publication.
- 13 Goklany, I.M., 2007: Integrated Strategies to Reduce Vulnerability and Advance Adaptation, Mitigation and
14 Sustainable Development. *Mitigation and Adaptation Strategies for Global Change*, (12), 755-786.
- 15 Goodman-Elgar, 2008: Evaluating soil resilience in long-term cultivation: a study of pre-Columbian terraces from
16 the Paca Valley, Peru. *Journal of Archaeological Science* 35 (2008) 3072-3086
- 17 Grab, S. and A. Craparo, 2011: Advance of apple and pear tree full bloom dates in response to climate change in the
18 southwestern Cape, South Africa: 1973-2009. *Agricultural and Forest Meteorology*, 151(3), 406-413.
- 19 Grafton, R.Q., 2010: Adaptation to climate change in marine capture fisheries. *Marine Policy*, 34(606), 615.
- 20 Graux, A.-., G. Bellocchi, R. Lardy, and J.-. Soussana, 2013: Ensemble modelling of climate change risks and
21 opportunities for managed grasslands in France. *Agricultural and Forest Meteorology*, 170, 114-131.
- 22 Green D. et al., 2010: Indigenous Australians' knowledge of weather and climate. *Climatic Change* 100, 337-354.**
- 23 Gregory P.J. et al., 2009: Integrating pests and pathogens into the climate change/food security debate. *Journal of*
24 *Experimental Botany*, 60, 2827-2838. **
- 25 Gregory, P.J. and B.E. Marshall, 2012: Attribution of Climate Change: a Methodology to Estimate the potential
26 Contribution to Increases in Potato Yield in Scotland since 1960. *Global Change Biology*, 18, 1372-1388.
- 27 Guis, H.; Caminade, C.; Calvete, C.; Morse, A. P.; Tran, A.; Baylis, B. (2012) Modelling the effects of past and
28 future climate on the risk of bluetongue emergence in Europe. *Journal of the Royal Society Interface*, 9(67),
29 339-350.
- 30 Guitierrez, 2000: TO COME FROM KG. **
- 31 Gummow, B., 2010: Challenges Posed by New and Re-emerging Infectious Diseases in Livestock Production,
32 Wildlife and Humans. *Livestock Science*, 130(1-3), 41-46.
- 33 Hall, A. and G.V. Jones, 2009: Effect of potential atmospheric warming on temperature-based indices describing
34 Australian winegrape growing conditions. *Australian Journal of Grape and Wine Research*, 15, 97-119.
- 35 Hannukkala, A.O., T. Kaukoranta, A. Lehtinen, and A. Rahkonen, 2007: Late-blight epidemics on potato in Finland,
36 1933-2002; increased and earlier occurrence of epidemics associated with climate change and lack of rotation. .
37 *Plant Pathology*, 56(1), 167-176.
- 38 Hatfield, J.L., K.J. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, and D. Wolfe, 2011:
39 Climate Impacts on Agriculture: Implications for Crop Production. *Agronomy Journal*, (103), 351-370.
- 40 Hawkins, E., T.M. Osborne, C.K. Hoa, and A.C. Challinor, 2012: Calibration and bias correction of climate
41 projections for crop modelling: An idealised case study over Europe. *Agricultural and Forest Meteorology*, .
- 42 Hayes, B.J., P.J. Bowman, A.J. Chamberlain, K. Savin, C.P. van Tassell, T.S. Sonstegard, and M.E. Goddard, 2009:
43 A Validated Genome Wide Association Study to Breed Cattle Adapted to an Environment Altered by Climate
44 Change. *Plos One*, 4(8), 6676.
- 45 Hayes, F., G. Mills, H. Harmens, and D. Norris, 2007: *Evidence of widespread ozone damage to vegetation in*
46 *Europe (1990-2006)*. Centre for Ecology and Hydrology, Natural Environment Research Council, Bangor,
47 Wales, UK, pp. 1-58.
- 48 Headey, D. and S. Fan, 2010: *Reflections on the Global Food Crisis: How did it happen? How has it hurt? And how*
49 *can we prevent the next one?*. International Food Policy Research Institute, Washington D.C.
- 50 Heltberg, R. and F. Tarp, 2002: Agricultural supply response and poverty in Mozambique. *Food Policy*, 27(2),
51 103-124.
- 52 Hertel, T.W., M.B. Burke, and D.B. Lobell, 2010: The poverty implications of climate-induced crop yield changes
53 by 2030. *Global Environmental Change*, 20(4), 577-585.

- 1 Hiddink, J.G. and R.t. Hofstede, 2008: Climate Induced Increases in Species Richness of Marine Fishes. *Global*
2 *Change Biology*, 14, 453-460.
- 3 HLPE, 2011: *Price Volatility and Food Security. A Report by the High Level Panel of Experts on Food Security and*
4 *Nutrition of the Committee on World Food Security*. HLPE, Rome, Italy.
- 5 Hobday, A.J., 2010: Ensemble analysis of the future distribution of large pelagic fishes off Australia. *Progress in*
6 *Oceanography*. 86(1-2), 291-301.
- 7 Hoddinott, J., J. Maluccio, J. R. Behrman, R. Flores, and R. Martorell. 2008. "Effect of a Nutrition Intervention
8 during Early Childhood on Economic Productivity in Guatemalan Adults." *The Lancet* 371 (9610): 411–416. **
- 9 Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J.
10 Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, and
11 M.E. Hatzitolos, 2007: Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science*, (318),
12 1737-1742.
- 13 Hoffmann, I., 2010: Climate Change and the Characterization, Breeding and Conservation of Animal Genetic
14 Resources. *Animal Genetics*, 41, 32-46.
- 15 Högy, P. and A. Fangmeier, 2009: Atmospheric CO2 Enrichment Affects Potatoes: 1. Aboveground Biomass
16 Production and Tuber Yield. *European Journal of Agronomy*, 30(2), 78-84.
- 17 Hollaway, M.J., S.R. Arnold, A.J. Challinor, and L.D. Emberson, 2011: Intercontinental trans-boundary contribution
18 to ozone-induced crop yield losses in Northern Hemisphere. *Biogeosciences Discussion*, 8, 8645-8691.
- 19 Holm, L., 1977: Weeds and water in World Food-production. *Weed Science*, 25(4), 338-342.
- 20 Hopkins, A. and A. Del Prado, 2007: Implications of Climate Change for Grassland in Europe: Impacts, Adaptations
21 and Mitigation Options: a Review. *Grass and Forage Science*, 62(2), 118-126.
- 22 Howden, S.M., S.J. Crimp, and C.J. Stokes, 2008: Climate change and Australian livestock systems: impacts,
23 research and policy issues. *Australian Journal of Experimental Agriculture*, 48(7), 780-788.
- 24 Hsiang, S.M., 2010: Temperatures and cyclones strongly associated with economic production in the Caribbean and
25 Central America. *Proceedings of the National Academy of Sciences*, 107(35), 15367-15372.
- 26 Hsiang, S.M., K.C. Meng, and M.A. Cane, 2011: Civil conflicts are associated with the global climate. *Nature*, 476,
27 438-441.
- 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, D.D., A. Moore, and K. Dyson, 2009: Impacts of climate change on the coasts of Washington State. *Ch. 8*
31 *in the Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing*
32 *Climate, Climate Impacts Group*,
- 33 Hurley, T., 2010: *A Review of Agricultural Production Risk in the Developing World*. In: Harvest Choice Working
34 Paper 11. International Food Policy Research Institute, Washington, DC, pp. 1-56.
- 35 IFAD, 2010: *The Rural Poverty Report. New realities, new challenges: new opportunities for tomorrow's*
36 *generation*. IFAD, Rome, Italy, pp. 1-317.
- 37 Iglesias, A., C. Rosenzweig, and D. Pereira, 2000: Agricultural impacts of climate change in Spain: developing tools
38 for a spatial analysis. *Global Environmental Change*, 10(1), 69-80.
- 39 IAASTD 2009: International Assessment of Agricultural Knowledge, Science and Technology for Development. **
- 40 Iizumi, T., M. Yokozawa, and M. Nishimori, 2009: Parameter Estimation and Uncertainty Analysis of a Large-Scale
41 Crop Model for Paddy Rice: Application of a Bayesian Approach. *Agricultural and Forest Meteorology*,
42 149(2), 333-348.
- 43 Ingram, J., 2011: A Food Systems Approach to Researching Interactions between Food Security and Global
44 Environmental Change. *Food Security*, 3, 417-431.
- 45 IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A*
46 *Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B.,
47 Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-., Allen,
48 S.K., Tignor, M. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, UK, and New York,
49 USA, pp. 1-582.
- 50 IPCC, 2013: Reference Pending, WG1, Ch10.,
- 51 Iqbal, M.M., M.A. Goheer, and A.M. Khan, 2009: Climate-change Aspersions on Food Security of Pakistan.
52 *Science Vision*, 15, 15-23.
- 53 Ivanic, M. and W. Martin, 2008: Implications of Higher Global Food Prices for Poverty in Low-Income Countries.
54 *Agricultural Economics*, (39), 405-416.

- 1 Ivanic, M., W. Martin, and H. Zaman, 2011: *Estimating the Short-Run Poverty Impacts of the 2010-11 Surge in*
2 *Food Prices*. In: Policy Research Working Paper 5633. World Bank, Washington, D. C., USA.
- 3 Izaurrealde, R.C., A.M. Thomson, J.A. Morgan, P.B. Fay, H.W. Polley, and J.L. Hatfield, 2011: Climate Impacts on
4 Agriculture: Implications for Forage and Rangeland Production. *Agronomy Journal*, (103), 371-381.
- 5 Jadadish SVK et al., 2007: High temperature stress and spikelet fertility in rice (*Oryza sativa* L.) *J. Exp. Bot.*, 58,
6 1627-1635. **
- 7 Jaggard, K., A. Qi, and M.A. Semenov, 2007: The Impact of Climate Change on Sugarbeet Yield in the UK:
8 1976–2004 . *The Journal of Agricultural Science*, 145(04), 367-375.
- 9 Jarvis, A., J. Ramirez-Villegas, B. Herrera Campo, and C. Navarro-Racines, 2012: Is cassava the answer to African
10 climate change adaptation? *Tropical Plant Biology*, 51, 9-29.
- 11 Jones , P.G. and P.K. Thornton, 2009: Croppers to Livestock Keepers: Livelihood Transitions to 2050 in Africa due
12 to Climate Change. *Environmental Science & Policy*, 12(4), 427-437.
- 13 Jones, G.V., M.A. White, O.R. Cooper, and K. Storchmann, 2005: Climate change and global wine quality. *Climatic*
14 *Change*, 73, 319-343.
- 15 Jones, G.V., A.A. Duff, A. Hall, and J.W. Myers, 2010: Spatial analysis of climate winegrape growing regions in the
16 Western United States *American Journal of Enology and Viticulture*, 61, 313-326.
- 17 Jorquera-Fontena, E. and R. Orrego-Verdugo, 2010: Impact of global warming on the phenology of a variety of
18 grapevine grown in southern Chile. *Agrociencia*, 44, 427-435.
- 19 Joshi, M., R. Sutton, J. Lowe, and D. Frame, 2011: Projections of when temperature change will exceed 2 °C above
20 pre-industrial levels. *Nature Climate Change*, 1(8), 407-412.
- 21 Juroszek, P. and A. von Tiedemann, 2011: Potential strategies and future requirements for plant disease management
22 under a changing climate. *Plant Pathology*, 60(1), 100-112.
- 23 Kabubo-Mariara, J., 2009: Global warming and livestock husbandry in Kenya: Impacts and adaptations. . *Ecological*
24 *Economics*, 68, 1915-1924.
- 25 Kalanda J. et al., 2011: Integrating indigenous knowledge with conventional science: Enhancing localised climate
26 and weather forecasts in Nessa, Mulanje, Malawi. *Physics and Chemistry of the Earth*, 36, 996–1003. **
- 27 Kalra, N., D. Chakraborty, A. Sharma, H.K. Rai, M. Jolly, S. Chander, P.R. Kumar, S. Bhadraray, D. Barman, R.B.
28 Mittal, M. Lal, and M. Sehgal, 2008: Effect of increasing temperature on yield of some winter crops in
29 northwest India. *Current Science*, 94, 82-88.
- 30 Kang, Y., S. Khan, and X. Ma, 2009: Climate Change Impacts on Crop Yield, Crop Water Productivity and Food
31 Security – A Review. *Progress in Natural Science*, 19(12), 1665-1674.
- 32 Kassie M. et al., 2008: Estimating returns to soil conservation adoption in the northern Ethiopian highlands.
33 *Agricultural Economics*, 38, 213-232. **
- 34 Kates, R., W. Travis, and T. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate
35 change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*,
36 109(9), 7156-7161.
- 37 Kazianga, H. and C. Udry, 2006: Consumption smoothing? Livestock, insurance and drought in rural Burkina Faso
38 *Journal of Development Economics*, 79(2), 413-446.
- 39 Kearney, J., 2010: Food consumption trends and drivers. *Philosophical Transactions of the Royal Society Biological*
40 *Sciences*, 365(1554), 2793-2807.
- 41 Kirsch, T., C. Wadhvani, L. Sauer, S. Doocy, and C. Catlett, 2012: Impact of the 2010 Pakistan Floods on Rural and
42 Urban Populations at Six Months. *PLoS Currents Published Online*.
- 43 Knox, J., T. Hess, A. Daccache, and T. Wheeler, 2012: Climate change impacts on crop productivity in Africa and
44 South Asia. *Environmental Research Letters*, 7(3).
- 45 Koehn J., A. Hobday, M. Pratchett, and B. Gillanders, 2011: Climate change and Australian marine and freshwater
46 environments, fishes and fisheries: synthesis and options for adaptation. *Marine and Freshwater Research*, 62,
47 1148-1164.
- 48 Krishnan, P., D. Swain, B. Bhaskar, S. Nayak, and R. Dash, 2007: Impact of elevated CO₂ and Temperature on Rice
49 Yield and Methods of Adaptation as Evaluated by Crop Simulation Studies. *Agricultural Ecosystems and*
50 *Environment*, 122(2), 233-242.
- 51 Kucharik, C.J. and S.P. Serbin, 2008: Impacts of Recent Climate Change on Wisconsin Corn and Soybean Yield
52 Trends. *Environmental Research Letters*, 3, 034003.

- 1 Kulshreshtha, S.N., 2011: . 2011.Climate Change, Prairie Agriculture, and Prairie Economy: The New Normal.
2 *Canadian Journal of Agricultural Economics* 59 (2011) 19–44. *Canadian Journal of Agricultural Economics*,
3 59, 19-44.
- 4 Kvalvik, I., S. Dalmannsdottir, H. Dannevig, G. Hovelsrud, L. Rønning, and E. Uleberg, 2011: Climate Change
5 Vulnerability and Adaptive Capacity in the Agricultural Sector in Northern Norway . *Acta Agriculturae*
6 *Scandinavica, Section B - Soil & Plant Science*, 61, 27-37.
- 7 Lal, R., 2009: *Soil Degradation as a Reason for Inadequate Human Nutrition* Springer Netherlands, pp. 45-57.
- 8 Lanning, S.B., T.J. Siebenmorgen, P.A. Counce, A.A. Ambardekar, and A. Mauromoustakos, 2011: Extreme
9 nighttime air temperatures in 2010 impact rice chalkiness and milling quality. *Field Crops Research*, 124,
10 132-136.
- 11 Last, P., W. White, D. Gledhill, A. Hobday, R. Brown, G. Edgar, and G. Pecl, 2011: Long Term Shifts in
12 Abundance and Distribution of a Temperate Fish Fauna: A Response to Climate Change and Fishing Practices.
13 *Global Ecology and Biogeography*, 20, 58-72.
- 14 Laux, P., G. Jacket, R. Tingem, and H. Kunstmann, 2010: Impact of Climate Change on Agricultural Productivity
15 under Rainfed Conditions in Cameroon - A Method to Improve Attainable Crop Yields by Planting Date
16 Adaptations. *Agricultural and Forest Meteorology*, 150(9), 1258-1271.
- 17 Lazzarotto, P., P. Calanca, and J. Fuhrer, 2009: Dynamics of Grass-Clover-Mixture: An Analysis of the Response
18 to Management with the PROductive GRASSland Simulator (PROGRASS). *Ecological Modelling*, 220(703),
19 703-724.
- 20 Leakey et al., 2013, In press. **
- 21 Leakey, A.D.B., 2009: Rising Atmospheric Carbon Dioxide Concentration and the Future of C4 Crops for Food and
22 Fuel. *Proceedings of the Royal Society B: Biological Sciences*, .
- 23 Lehodey, P., I. Senina, J. Sibert, L. Bopp, B. Calmettes, J. Hampton, and R. Murtugudde, 2010: Preliminary
24 Forecasts of Pacific Bigeye Tuna Population Trends under the A2 IPCC Scenario. *Progress in Oceanography*,
25 86(1–2), 302-315.
- 26 Lenz-Wiedemann, V.I.S., C.W. Klar, and K. Schneider, 2010: Development and Test of a Crop Growth Model for
27 Application within a Global Change Decision Support System. *Ecological Modelling*, 221(2), 314-329.
- 28 Li, S., T. Wheeler, A. Challinor, E. Lin, H. Ju, and Y. Xu, 2010: The observed relationships between wheat and
29 climate in China. *Agricultural and Forest Meteorology*, 150(11), 1412-1419.
- 30 Lioubimtseva E. et al., 2009: Climate and environmental change in arid Central Asia: Impacts, vulnerability, and
31 adaptations *Journal of Arid Environments*, 73, 963-977. **
- 32 Liu, Y., E. Wang, X. Yang, and J. Wang, 2009: Contributions of Climatic and Crop Varietal Changes to Crop
33 Production in the North China Plain, since 1980s. *Global Change Biology*,
- 34 Lloyd, S.J., R.S. Kovats, and Z. Chalabi, 2011: Climate Change, Crop Yields, and Undernutrition: Development of a
35 Model to Quantify the Impact of Climate Scenarios on Child Undernutrition . *Environmental Health*
36 *Perspectives*, 119(2), 1817-1823.
- 37 Lobell, D. and M.B. Burke, 2008: Why are Agricultural Impacts of Climate Change so uncertain? The Importance
38 of Temperature Relative to Precipitation. *Environmental Research Letters*, 3(3), 034007.
- 39 Lobell, D.B. and C.B. Field, 2007: Global Scale Climate-Crop Yield Relationships and the Impacts of Recent
40 Warming. *Environmental Research Letters*, 2.
- 41 Lobell, D.B. and M.B. Burke, 2010: On the use of statistical models to predict crop yield responses to climate
42 change. *Agricultural and Forest Meteorology*, 150(11), 1443-1452.
- 43 Lobell, D.B., U.L.C. Baldos, and T.W. Hertel, 2013: Climate adaptation as mitigation: the case of agricultural
44 investments. *Environmental Research Letters*, 8.
- 45 Lobell, D.B., G.L. Hammer, G. McLean, C. Messina, M.J. Roberts, and W. Schlenke, 2013b: The critical role of
46 extreme heat for maize production in the United States. *Nature Climate Change*, .
- 47 Lobell, D.B., J.I. Ortiz-Monasterio, G.P. Asner, P.A. Matson, R.L. Naylor, and W.P. Falcon, 2005: Analysis of
48 wheat yield and climatic trends in Mexico. *Field Crops Research*, 94(2-3), 250-256.
- 49 Lobell, D.B., W.S. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global food production since 1980.
- 50 Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor, 2008: Prioritizing Climate
51 Change Adaptation Needs for Food Security in 2030. *Science*, 319(5863), 607-610.
- 52 Loladze, I., 2002: Rising atmospheric CO2 and human nutrition: toward globally imbalanced plant stoichiometry?
53 *Trends in Ecology and Evolution*, 17(10), 457-461.

- 1 Long, S.P., 2012: Virtual Special Issue on food security – greater than anticipated impacts of near-term global
2 atmospheric change on rice and wheat. *Global Change Biology*, 18, 1489-1490.
- 3 Long, S.P., E.A. Ainsworth, A.D.B. Leakey, J. Nosberger, and D.R. Ort, 2006: Food for Thought:
4 Lower-Than-Expected Crop Yield Stimulation with Rising CO₂ Concentrations. *Science*, 312(5782),
5 1918-1921.
- 6 Lopez, A.D., C.D. Mathers, M. Ezzati, D.T. Jamison, and C.J. Murray, 2006: Global and Regional Burden of
7 Disease and Risk Factors, 2001: Systematic Analysis of Population Health Data. *The Lancet*, 367(9524),
8 1747-1757.
- 9 Loukos, H., P. Monfray, L. Bopp, and P. Lehodey, 2003: Potential changes in skipjack tuna (*Katsuwonus pelamis*)
10 habitat from a global warming scenario: modelling approach and preliminary results. *Fisheries Oceanography*,
11 12(4-5), 474-482.
- 12 Luck, J., M. Spackman, A. Freeman, P. Trebicki, W. Griffiths, K. Finlay, and S. Chakraborty, 2011: Climate change
13 and diseases of food crops. *Plant Pathology*, 60(1), 113-121.
- 14 Ludwig, F., S. Milroy, and S. Asseng, 2009: Impacts of Recent Climate Change on Wheat Production Systems in
15 Western Australia. *Climate Change*, 92(3), 495-517.
- 16 Luedeling, E., K.P. Steinmann, M. Zhang, P.H. Brown, J. Grant, and E.H. Girvetz, 2011: Climate change effects on
17 walnut pests in California. *Global Change Biology*, 17(1), 228-238.
- 18 Luo, Q., W. Bellotti, M. Williams, and E. Wang, 2009: Adaptation to climate change of wheat growing in South
19 Australia: Analysis of management and breeding strategies. *Agriculture Ecosystems and Environment*, 129(1-3),
20 261-267.
- 21 Macneil, M., N. Graham, J. Cinner, N. Dulvy, P. Loring, S. Jennings, N. Polunin, A. Fisk, and T. McClanahan,
22 2010: Transitional states in marine fisheries: adapting to predicted global change. *Philosophical Transactions of*
23 *the Royal Society of Biological Sciences*, 365, 3753-3763.
- 24 Mäder, P., Fließbach, A., D, D., L, G., Jossi, W., Widmer, F., Oberson, A., Frossard, E., Oehl, F., Wiemken, A.,
25 Gattinger, A., Niggli, U., 2006. The DOK experiment (Switzerland). In: Raupp, J., Pekrun, C., Oltmanns, M.,
26 Köpke, U. (Eds.), ISOFAR Scientific Series. University of Bonn, Germany.
- 27 Magrin, G., M. Travasso, G. Rodríguez, S. Solman, and M. Núñez, 2009: Climate Change and Wheat Production in
28 Argentina. *International Journal of Global Warming*, 1(1), 214-226.
- 29 Malcolm, J.R., A. Markham, R.P. Neilson, and M. Garaci, 2002: Estimated migration rates under scenarios of global
30 climate change. *Journal of Biogeography*, 29(7), 835-849.
- 31 Manea, A., M.R. Leishman, and P.O. Downey, 2011: Exotic C4 Grasses Have Increased Tolerance to Glyphosate
32 under Elevated Carbon Dioxide. *Weed Science*, 59(1), 28-36.
- 33 Mantua, N., I.M. Tohver, and A.F. Hamlet, 2010: Climate change impacts on streamflow extremes and summertime
34 stream temperature and their possible consequences for freshwater salmon habitat in Washington State.
35 *Climatic Change*, 102(1-2), 187-223.
- 36 Marin, F., G.Q. Pellegrino, Assad, E.D., Nassif, D. S. P., M.S. Viana, A. Soares, and Cabral, L. L., Guiatto, D.,
37 2009: Future Scenarios for Sugarcane in the state of Sao Paulo based on regionized Climate Change
38 Projections XVI Congresso Brasileiro de Agrometeorologia - Belo Horizonte - MG - Brazil.
- 39 Marin, A. 2010: Riders under storms: Contributions of nomadic herders' observations to analyzing climate change
40 in Mongolia. *Global Environmental Change* 20, 162–176. **
- 41 Marin, F.R., J.W. Jones, A. Singels, F. Royce, E.D. Assad, G.Q. Pellegrino, and F. Justino, 2013: Climate change
42 impacts on sugarcane attainable yield in southern Brazil. *Climatic Change*, 117, 227-239.
- 43 Marshall, B.E., 2012: Does climate change really explain changes in the fisheries productivity of Lake Kariba
44 (Zambia-Zimbabwe)? *Transactions of the Royal Society of South Africa*, 67(1), 45-51.
- 45 Mary, A. and A. Majule, 2009: Impacts of climate change, variability and adaptation strategies on agriculture in
46 semi arid areas of Tanzania: The case of Manyoni District in Singida Region, Tanzania. . *African Journal of*
47 *Environmental Science and Technology*, 3(8), 206-218.
- 48 Masike, S. and P. Urich, 2008: Vulnerability of traditional beef sector to drought and the challenges of climate
49 change: The case of Kgatleng District, Botswana. *Journal of Geography and Regional Planning*, 1(1), 12-18.
- 50 Mastrandrea, M., C. Field, T. Stocker, O. Edenhofer, K. Ebi, D. Frame, H. Held, E. Kriegler, and K. Mach, 2010:
51 *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of*
52 *Uncertainties*. Intergovernmental Panel on Climate Change (IPCC).
- 53 Maxwell S and Slater R. 2003: Food Policy Old and New. *Development Policy Review*, 21, 531-553. **

- 1 McCrum, et al., 2009: Adapting to Climate Change in Land Management: the Role of Deliberative Workshops in
2 Enhancing Social Learning. *Environmental Policy and Governance*, 19, 413–426. **
- 3 McDonald, A., S. Riha, A. DiTommaso, and A. DeGaetano, 2009: Climate change and the geography of weed
4 damage: Analysis of U.S. maize systems suggests the potential for significant range transformations.
5 *Agriculture, Ecosystems & Environment*, 130(3–4), 131-140.
- 6 McDowell, J and Hess, JJ 2012: Accessing adaptation: Multiple stressors on livelihoods in the Bolivian highlands
7 under a changing climate. *Global Environmental Change*, 22, 342-352. **
- 8 McGrath, J. and D.B. Lobell, 2011: An independent method of deriving the carbon dioxide fertilization effect in dry
9 conditions using historical yield data from wet and dry years. *Global Change Biology*, in press.
- 10 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.
11 Cobon, R.A. Cowley, S.J. Crimp, G.W. Fraser, S.M. Howden, P.W. Johnston, J.G. Ryan, C.J. Stokes, and K.A.
12 Day, 2009: Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of
13 issues. *The Rangeland Journal*, 31(1), 1-29.
- 14 Melloy, P., G. Hollaway, J. Luck, R. Norton, E. Aitken, and S. Chakraborty, 2010: Production and fitness of
15 *Fusarium pseudograminearum* inoculum at elevated carbon dioxide in FACE. *Global Change Biology*, 16(12),
16 3363-3373.
- 17 Mercer, K., A. Martinez-Vasquez, and H. Perales, 2008: Asymmetrical local adaptation of maize landraces along an
18 altitudinal gradient. *Evolutionary Applications*, 1, 489-500.
- 19 Merino, G., M. Barange, J.L. Blanchard, J. Harle, R. Holmes, I. Allen, E.H. Allison, M.C. Badjeck, N.K. Dulvy, J.
20 Holt, S. Jennings, C. Mullon, and L.D. Rodwell, 2012: Can marine fisheries and aquaculture meet fish demand
21 from a growing human population in a changing climate? *Global Environmental Change*, 22(4), 795-806.
- 22 Mertz, O., K. Halsnaes, J. Olesen, and K. Rasmussen, 2009a: Adaptation to climate change in developing countries.
23 *Environmental Management*, 43(5), 743-752.
- 24 Mertz, O., C. Mbow, A. Reenberg, and A. Diouf, 2009: Farmers' perceptions of climate change and agricultural
25 adaptation strategies in rural Sahel. *Environmental Management*, 43(5), 804-816.
- 26 Meza, F., D. Silva, and H. Vigil, 2008: Climate change impacts on irrigated maize in mediterranean climates:
27 Evaluation of double cropping as an emerging adaptation alternative. *Agricultural Systems*, 98(1), 21-30.
- 28 Meza, F. and D. Silva, 2009: Dynamic Adaptation of Maize and Wheat Production to Climate Change. . *Climate*
29 *Change*, 94(1-2), 143-156.
- 30 Mills, G., A. Buse, B. Gimeno, V. Bermejo, M. Holland, L. Emberson, and H. Pleijel, 2007: A synthesis of
31 AOT40-based response functions and critical levels of ozone for agricultural and horticultural crops.
32 *Atmospheric Environment*, 41(12), 2630-2643.
- 33 Mills, G., F. Hayes, S. Wilkinson, and W.J. Davies, 2009: Chronic exposure to increasing background ozone impairs
34 stomatal functioning in grassland species. *Global Change Biology*, 15(6), 1522-1533.
- 35 Mills, J.N., K.L. Gage, and A.S. Khan, 2010: Potential Influence of Climate Change on Vector-Borne and Zoonotic
36 Diseases: A Review and Proposed Research Plan. *Environ Health Perspect*, 118(11).
- 37 Min, S., X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense precipitation
38 extremes. *Nature*, 470(7334), 378-381.
- 39 Miraglia, M., H.J.P. Marvin, G.A. Kleter, P. Battilani, C. Brera, and et al., 2009: Climate Change and Food safety:
40 an Emerging Issue with Special Focus on Europe. *Food and Chemical Toxicology*, (47), 1009-1021.
- 41 Misselhorn, A., A. Challinor, P. Thornton, J.W. Jones, R. Schaldach, and V. Plocq-Fichelet, 2010: Surprises and
42 Possibilities. In: *Food Security and Global Environmental Change*. [Ingram, J., P. Ericksen, and D.
43 Liverman(eds.)]. Earthscan, pp. Chapter 20.
- 44 Mittler, R. and E. Blumwald, 2010: Genetic engineering for modern agriculture: Challenges and perspectives.
45 *Annual Review of Plant Biology*, 61, 443-462.
- 46 Mo, X., S. Liu, Z. Lin, and R. Guo, 2009: Regional crop yield, water consumption and water use efficiency and their
47 responses to climate change in the North China Plain. *Agriculture, Ecosystems & Environment*, 134(1–2),
48 67-78.
- 49 Molden, D., T. Oweis, P. Steduto, P. Bindraban, M.A. Hanjra, and J. Kijne, 2010: Improving agricultural water
50 productivity: Between optimism and caution. *Agricultural Water Management*, 97(4), 528-535.
- 51 Monzon et al., 2007: Modelling management strategies for wheat–soybean double crops in the south-eastern
52 Pampas. *Field Crops Research*, 101: 44-52. **

- 1 Moore, A.D. and A. Ghahramani, 2013: Estimated effects of climate change on grassland production and legume
2 content across southern Australia. *In: Proceedings of the 22nd International Grassland Congress Proceedings*
3 *of Revitalising grasslands to sustain our communities*, .
- 4 Morgan, P.B., T.A. Mies, G.A. Bollero, R.L. Nelson, and S.P. Long, 2006: Season long elevation of ozone
5 concentration to projected 2050 levels under fully open air conditions substantially decreases the growth and
6 production of soybean. *New Phytologist*, 170(2), 333-343.
- 7 Moriondo, M., C. Giannakopoulos, and M. Bindi, 2011: *Climate change impact assessment: the role of climate*
8 *extremes in crop yield simulation* Springer Netherlands, pp. 679-701.
- 9 Mortensen, C.J., Y.H. Choi, K. Hinrichs, N.H. Ing, D.C. Kraemer, S.G. Vogelsang, and M.M. Vogelsang, 2009:
10 *Embryo recovery from exercised mares* Elsevier Scientific Pub. Co, pp. 237-244.
- 11 Mueller, S., J. Anderson, and T. Wallington, 2011: Impact of Biofuel Production and other Supply and Demand
12 Factors on Food Price Increases in 2008. *Biomass and Bioenergy*, 35, 1623-1632.
- 13 Müller et al., 2013, In review. **
- 14 Munday, P.L., G.P. Jones, M.S. Pratchett, and A.J. William, 2008: Climate Change and the Future for Coral Reef
15 Fishes *Fish and Fisheries*, (9), 261-285.
- 16 Mutekwa, V., 2009: Climate change impacts and adaptation in the agricultural sector: The case of smallholder
17 farmers in Zimbabwe. *Journal of Sustainable Development in Africa*, 11(2), 237-256.
- 18 Nakashina, D., K. Galloway McLean, H. Thulstrup, A. Ramos Castillo, and J. Rubis, 2012: *Weathering uncertainty:*
19 *traditional knowledge for climate change assessment and adaptation*. . UNESCO; UNU, Paris; Darwin.
- 20 Nardone, A., B. Ronchi, N. Lacetera, M.S. Ranieri, and U. Bernabucci, 2010: *Effects of climate changes on animal*
21 *production and sustainability of livestock systems* pp. 57-69.
- 22 Naylor, R., D. Battisti, D. Vimont, W. Falcon, and Burke M., 2007: Assessing risks of climate variability and
23 climate change for Indonesian rice agriculture. *Proceedings of the National Academy of Sciences of the United*
24 *States of America*, 104(19), 7752-7757.
- 25 Ndebele-Murisa, M., E. Mashonjowa, and T. Hill, 2011: The implications of a changing climate on the Kapenta fish
26 stocks of Lake Kariba, Zimbabwe. *Transactions of the Royal Society of South Africa*, 66(2), 105-119.
- 27 Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M.
28 Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee, 2009: *Impact on Agriculture and Costs of*
29 *Adaptation*. Food Policy Report. International Food Policy Research Institute, Washington D. C.
- 30 Nelson, G.C., D. van der Mensbrugge, T. Hasegawa, K. Takahashi, R.D. Sands, and Kyle, P. (other author details
31 pending), In review: Agriculture and Climate Change in Global Scenarios: Why Don't the Models Agree.
32 *Proceedings of the National Academy of Sciences*.
- 33 Nelson R et al., 2008: Using adaptive governance to rethink the way science supports Australian drought policy.
34 *Environmental Science & Policy* 11: 588-601. **
- 35 Newsham A.J. and Thomas DSG, 2011: Knowing, farming and climate change adaptation in North-Central
36 Namibia. *Global Environmental Change-Human and Policy Dimensions*, 21, 761-770. **
- 37 Nidumolu, U., S. Crimp, D. Gobbett, A. Laing, M. Howden, and S. Little, 2011: *Heat stress in dairy cattle in*
38 *northern Victoria: responses to a changing climate*. . In: Climate Adaptation Flagship Working Paper No.10.
39 CSIRO Publishing, Collingwood, Australia.
- 40 Nyong et al., 2007: The value of indigenous knowledge in climate change mitigation and adaptation strategies in the
41 African Sahel. *Mitig Adapt Strat Glob Change*, 12, 787-797. **
- 42 Odgaard et al., 2011: Climatic and non-climatic drivers of spatiotemporal maize-area dynamics across the northern
43 limit for maize production—A case study from Denmark. *Agriculture, Ecosystems and Environment* 142, 291-
44 302. **
- 45 Oerke, E., 2006: Crop losses to pests. *The Journal of Agricultural Science*, 144(01), 31-43.
- 46 Okada, M., T. Iizumi, Y. Hayashi, and M. Yokozawa, 2009: A climatological analysis on the recent declining trend
47 of rice quality in Japan. *Journal of Agricultural Meteorology*, 65(4), 327-337.
- 48 Okada, M., T. Lizumi, Y. Hayashi, and M. Yokozawa, 2011: Modeling the Multiple Effects of Temperature and
49 Radiation on Rice Quality. *Environmental Research Letters*, 6, 034031.
- 50 Olesen, J., M. Trnka, K. Kersebaum, A. Skjelvag, B. Seguin, P. Peltonen-Sainio, F. Rossi, J. Kozyra, and F.
51 Micale, 2011: Impacts and Adaptation of European Crop Production Systems to Climate Change. . *European*
52 *Journal of Agronomy*, 34, 96-112.
- 53 O'Reilly, C.M., S.R. Alin, P.D. Plisnier, A.S. Cohen, and B.A. McKee, 2003: Climate Change Decreases Aquatic
54 Ecosystem Productivity of Lake Tanganyika, Africa. *Nature*, 424, 766-768.

- 1 Orlandini, S., M. Bindi, and S. Howden, 2008: *Plant biometeorology and adaptation*. In: Biometeorology for
2 adaptation to climate variability and change: research frontiers and perspectives [Ebi, K., Burton, I. and
3 McGregor, G. (eds.)]. International Society of Biometeorology, pp. 107-129.
- 4 Ortiz, R., K.D. Sayre, B. Govaerts, R. Gupta, G.V. Subbarao, T. Ban, D. Hodson, J.M. Dixon, J. Iván
5 Ortiz-Monasterio, and M. Reynolds, 2008: Climate change: Can wheat beat the heat? *Agriculture, Ecosystems
6 & Environment*, 126(1-2), 46-58.
- 7 Osborne, T.M., D.M. Lawrence, A.J. Challinor, J.M. Slingo, and T.R. Wheeler, 2007: Development and assessment
8 of a coupled crop?climate model. *Global Change Biology*, 13(1), 169-183.
- 9 Ostfeld, R.S., 2009: Climate change and the distribution and intensity of infectious diseases. *Ecology*, 90(4),
10 903-905.
- 11 Paavola, J 2008: Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental
12 Science & Policy* 2008,11:642-654. **
- 13 Palmer, M.A., C. Reidy Liermann A., C. Nilsson, M. Flarke, J. Alcamo, P.S. Lake, and N. Bond, 2008: Climate
14 change and the world's river basins: anticipating management options. *Frontiers in Ecology and the
15 Environment*, 6(2), 81-89.
- 16 Palosuo et al., 2011: Simulation of winter wheat yield and its variability in different climates of Europe: A
17 comparison of eight crop growth models. *European Journal of Agronomy*, 35, 103-114. **
- 18 Pareek, A. and P. Trivedi, 2011: Cultural values and indigenous knowledge of climate change and disaster
19 prediction in Rajasthan India. *Indian Journal of Traditional Knowledge*, 10(1), 183-189.
- 20 Park, S. et al., 2012: Informing adaptation responses to climate change through theories of ransformation. *Global
21 Environmental Change*, 22(1):115-126. **
- 22 Parry, M., A. Evans, M.W. Rosegrant, and T. Wheeler, 2009: *Climate Change and Hunger: Responding to the
23 challenge*. World Food Programme, Rome, Italy, pp. 1-104.
- 24 Passioura, J. and J. Angus, 2010: Improving Productivity of Crops in Water-Limited Environments. *Advances in
25 Agronomy*, 106, 37-75.
- 26 Pathak, H., J.K. Ladha, P.K. Aggarwal, S. Peng, S. Das, Y. Singh, B. Singh, S.K. Kamra, B. Mishra, A. Sastri, H.P.
27 Aggarwal, D.K. Das, and R.K. Gupta, 2003: Trends of climatic potential and on-farm yields of rice and wheat
28 in the Indo-Gangetic Plains. *Field Crops Research*, 80(3), 223-234.
- 29 Patt, A.G., A. Dazé, and P. Suarez, 2009: Gender and climate change vulnerability: What's the problem, what's the
30 solution? In: *Distributional Impacts of Climate Change and Disasters: Concepts and Cases*. [Ruth, M. and M.E.
31 Ibarraran(eds.)]. Edward Elgar Publishing Limited, Cheltenham, UK., .
- 32 Paulson, M.D., A.I. Houston, J.M. McNamara, and R.J.H. Payne, 2009: Seasonal dispersal of pests: one surge or
33 two? *Journal of Evolutionary Biology*, 22(6), 1193-1202.
- 34 Pautasso, M., K. Dehnen-Schmutz, O. Holdenrieder, S. Pietravalle, N. Salama, M.J. Jeger, E. Lange, and S.
35 Hehl-Lange, 2010: Plant health and global change – some implications for landscape management. *Biological
36 Reviews of the Cambridge Philosophical Society*, 85(4), 729-755.
- 37 Peng, S., J. Huang, J. Sheehy, R. Laza, R. Visperas, X. Zhong, G. Centeno, G. Khush, and K. Cassman, 2004: Rice
38 yields decline with higher night temperature from global warming. *Proceedings of the National Academy of
39 Sciences of the United States of America*, 101(27), 9971-9975.
- 40 Perring, M.P., B.R. Cullen, I.R. Johnson, and M.J. Hovenden, 2010: Modelled effects of rising CO2 concentration
41 and climate change on native perennial grass and sown grass-legume pastures. *Climate Research*, 42, 65-78.
- 42 Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds, 2005: Climate Change and Distribution Shifts in Marine Fishes.
43 *Science*, 308(5730), 1912-1915.
- 44 Pfeffer, M. and G. Dobler, 2010: Emergence of zoonotic arboviruses by animal trade and migration. *Parasites &
45 Vectors*, 3(1), 35.
- 46 Piao, S., P. Ciais, Y. Huang, Z. Shen, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, Y. Ding, P. Friedlingstein, C. Liu, K.
47 Tan, Y. Yu, T. Zhang, and J. Fang, 2010: The impacts of climate change on water resources and agriculture in
48 China. *Nature*, 467(7311), 43-51.
- 49 Pickering, T.D., B. Ponia, C.A. Hair, P.C. Southgate, and E.S. Poloczanska, 2011: Vulnerability of aquaculture in
50 the tropical Pacific to climate change. In: *Vulnerability of Tropical Pacific Fisheries*. [Bell, J.D., J.E. Johnson,
51 and A.J. Hobday(eds.)]. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 647-731.
- 52 Piikki, K., V. Vorne, K. Ojanperä, and H. Pleijel, 2007: Impact of elevated O3 and CO2 exposure on potato
53 (*Solanum tuberosum* L. cv. Bintje) tuber macronutrients (N, P, K, Mg, Ca). *Agriculture, Ecosystems &
54 Environment*, 118(1-4), 55-64.

- 1 Pinstrup-Andersen, P., 2009: Food Security: Definition and Measurement. *Food Security*, 1, 5-7.
- 2 Pinto, H.e.a., 2007: O aquecimento global e a cafeicultura brasileira. *Boletim Da Sociedade Brasileira De*
3 *eterologia*, 30, 65-72.
- 4 Pinto, H.S., E.D. Assad, J.Z. Junior, S.R.M. Evangelista, A.F. Otavian, A.M.H. Ávila, B. Evangelista, F.R. Marin,
5 C.M. Junior, G.Q. Pellegrino, P.P. Coltri, and G. Coral, 2008: *Global warming and the new geography of*
6 *agricultural production in Brazil*. Embrapa, São Paulo.
- 7 Pleijel, H. and J. Uddling, 2012: Yield vs. Quality trade-offs for wheat in response to carbon dioxide and ozone.
8 *Global Change Biology*, 18(2), 596-605.
- 9 Poorter, H., Y. Van Berkel, R. Baxter, J. Den Hertog, P. Dijkstra, R.M. Gifford, K.L. Griffin, C. Roumet, J. Roy,
10 and S.C. Wong, 1997: The effect of elevated CO₂ on the chemical composition and construction costs of leaves
11 of 27 C³ species. *Plant Cell and Environment*, 20(4), 472-482.
- 12 Porter, J.R. and M. Gawith, 1999: Temperatures and the growth and development of wheat: a review. *European*
13 *Journal of Agronomy*, 10(1), 23-36.
- 14 Prakash, A., 2011: *Why volatility matters*. In: Safeguarding food security in volatile global markets [Prakash, A.
15 (ed.)]. FAO, Rome, Italy, pp. 3-26.
- 16 Pratchett, M.S., P.L. Munday, N.A.J. Graham, M. Kronen, S. Pinca, K. Friedman, T.D. Brewer, J.D. Bell, S.K.
17 Wilson, J.E. Cinner, J.P. Kinch, R.J. Lawton, A.J. Williams, L. Chapman, F. Magron, and A. Webb, 2011:
18 Vulnerability of coastal fisheries in the tropical Pacific to climate change. In: *Vulnerability of tropical Pacific*
19 *fisheries and aquaculture to climate change*. [Bell, J.D., J.E. Johnson, and A.J. Hobday(eds.)]. Secretariat of the
20 Pacific Community, Noumea, New Caledonia, pp. 493-573.
- 21 Prato, T., Q. Zeyuan, G. Pederson, D. Fagre, L. Bengtson, and J. Williams, 2010: Potential economic benefits of
22 adapting agricultural production systems to future climate change. *. Environmental Management*, 45(3), 577-589.
- 23 Pritchard, S.G., 2011: Soil organisms and global climate change. *Plant Pathology*, 60(1), 82-99.
- 24 Rai, R., M. Aggarwal, and S.B. Aggarwal, 2010: Threat to food security under current levels of ground level ozone:
25 A case study for Indian cultivars of rice. *Atmospheric Environment*, 44(34), 4272-4282.
- 26 Ramirez-Villegas, J.M., A. Salazar, C. Jarvis, and E. Navarro-Racines, 2012: A way forward on adaptation to
27 climate change in Colombian agriculture: perspectives towards 2050. *Climatic Change*, 115(3-4), 611-628.
- 28 Ravallion, M., S. Chen, and P. Sangraula, 2007: New Evidence on the Urbanization of Global Poverty. *Population*
29 *and Development Review*, 33(4), 667-701.
- 30 Rayne, S., K. Forest, and K. Friesen, 2009: Projected Climate Change Impacts on Grape Growing in the Okanagan
31 Valley, British Columbia, Canada. *Nature Precedings*, , 1-46.
- 32 Reidsma, P., F. Ewert, L. Oude A., and R. Leemans, 2009: Vulberability and adaptation of European farmers: a
33 multi-level analysis of yield and income responses to climate variability. *Regional Environmental Change*, 9,
34 25-40.
- 35 Rejmánek, M., 1996: A theory of seed plant invasiveness: The first sketch. *Biological Conservation*, 78; Vol.78(1;
36 1), 171; 171-181; 181.
- 37 Renard, et al., 2011: Ecological engineers ahead of their time: The functioning of pre-Columbian raised-field
38 agriculture and its potential contributions to sustainability today. *Ecological Engineering*, 45, 30-44. **
- 39 Rengalakshmi, R., 2007. Localized climate forecasting system: seasonal climate and weather prediction for
40 farm-level decision-making. In: Sivakumar, M.V.K., Hansen, J. (Eds.), *Climate Prediciton and Agriculture:*
41 *Advances and Challenges*. World Meteorological Organization. Springer-Verlag, Berlin Heidelberg. **
- 42 Rickards and Howden, 2012: Transformational adaptation: agriculture and climate change. *Crop and Pasture*
43 *Science*, 63, 240-250. **
- 44 Roberts, M. and W. Schlenker, 2010: Identifying Supply and Demand Elasticities of Agricultural Commodities:
45 Implications for the US Ethanol Mandate. *NBER Working Paper no. 15921*, .
- 46 Rocque, S.D.L., J.A. Rioux, and J. Singenbergh, 2008: Climate Change: Effects on animal disease systems and
47 implications for surveillance and control. *Revue Scientifique Et Technique - Office International Des Epizooties*,
48 (27), 339-354.
- 49 Roe, T. and T. Graham-Tomasi, 1986: Yield risk in a dynamic model of the agricultural household. In: *Agricultural*
50 *Household Models: Extension, Applications and Policy*. [Singh, I., L. Squire, and J. Strauss(eds.)]. Johns
51 Hopkins University Press, Baltimore, MD, .
- 52 Rosenberg and Macleod, 2005: Implementing ecosystem-based approaches to management for the conservation of
53 ecosystem services. *Mar. Ecol. Prog. Ser.*, 300, 270-274. **

- 1 Rosenthal, D. and D.R. Ort, 2012: Examining Cassava's Potential to Enhance Food Security Under Climate Change.
2 *Tropical Plant Biology*, 5, 30-38.
- 3 Rosenthal, J., 2009: Climate change and the geographic distribution of infectious diseases. *Ecohealth*, 6(4), 489-495.
- 4 Rosenzweig, M.R. and H.P. Binswanger, 1993: Wealth, Weather Risk and the Composition and Profitability of
5 Agricultural Investments. *Economic Journal*, 103(416), 56-78.
- 6 Rosenzweig, C., F.N. Tubiello, R. Goldberg, E. Mills, and J. Bloomfield, 2002: Increased crop damage in the US
7 from excess precipitation under climate change. *Global Environmental Change-Human and Policy Dimensions*,
8 12(3), 197-202.
- 9 Rosenzweig, C., J.W. Jones, J.L. Hatfield, A.C. Ruane, K.J. Boote, P. Thorburn, J.M. Antle, G.C. Nelson, C. Porter,
10 S. Janssen, S. Asseng, B. Basso, F. Ewert, D. Wallach, G. Baigorria, and J.M. Winter, 2013: The Agricultural
11 Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural and Forest
12 Meteorology*, 170(0), 166-182.
- 13 Rötter RP, Palosuo T, Pirttioja NK, Dubrovsky M, Salo T, Fronzek S, Aikasalo R, Trnka M, Ristolainen, Carter TR.
14 2011 What would happen to barley production in Finland if global warming exceeded 4°C? A model-based
15 assessment. *European Journal of Agronomy*, 35, 205-214.
- 16 Roy, S., G. Beig, and S. Ghude, 2009: *Exposure-plant response of ambient ozone over the tropical Indian region -*
17 *Copernicus Publications*, pp. - 4141.
- 18 Royal Society, 2008: *Ground level ozone in the 21st century: Future trends, impacts and policy implications*. In:
19 Royal Society Policy Document 15/08. The Royal Society, London, UK.
- 20 Ruane, A.C., L.D. Cecil, R.M. Horton, R. Gordón, R. McCollum, B. Brown, B. Killough, R. Goldberg, A.P.
21 Greeley, and C. Rosenzweig, 2013: Climate change impact uncertainties for maize in Panama: Farm
22 information, climate projections, and yield sensitivities. *Agricultural and Forest Meteorology*, In review.
- 23 Rütting, T., T.J. Clough, C. Müller, M. Lieffering, and P.C.D. Newton, 2010: Ten years of elevated atmospheric
24 CO₂ alters soil N transformations in a sheep-grazed pasture. *Global Change Biology*, 16, 2530-2542.
- 25 Sadras, V.O. and P.R. Petrie, 2011: Climate shifts in south-eastern Australia: early maturity of Chardonnay, Shiraz
26 and Cabernet Sauvignon is associated with early onset rather than faster ripening. *Australian Journal of Grape
27 and Wine Research*, 17, 199-205.
- 28 Sakurai, G., T. Lizumi, and M. Yokozawa, 2012: Varying Temporal and Spatial Effects of Climate on Maize and
29 Soybean affect Yield Prediction. *Climate Research*, 49(143).
- 30 Sanabria, J. and J.P. Lhomme, 2012: Climate change and potato cropping in the Peruvian Altiplano. *Theoretical and
31 Applied Climatology*, DOI 10.1007/s00704-012-07.
- 32 Santos, J.A., A.C. Malheiro, M.K. Karremann, and J.G. Pinto, 2011: Statistical modelling of grapevine yield in the
33 Port Wine region under present and future climate conditions. *International Journal of Biometeorology*, 55,
34 119-131.
- 35 Sari, M., S. de Pee, M.W. Bloem, K. Sun, A. Thorne-Lymean, R. Moench-Pfanner, N. Akhter, K. Kraemer, and
36 R.D. Semba, 2010: Higher household expenditure on Animal Source and nongrain foods lowers the risk of
37 stunting among children 0-59 month old in Indonesia: implications of rising food prices. *The Journal of
38 Nutrition*, 140(1), 195-200.
- 39 Sarkar, A. and S.B. Agrawal, 2010: Elevated ozone and two modern wheat cultivars: An assessment of dose
40 dependent sensitivity with respect to growth, reproductive and yield parameters. *Environmental and
41 Experimental Botany*, 69(3), 328-337.
- 42 Sarvala, J., V.T. Langenberg, K. Salonen, D. Chitamwebwa, G.W. Coulter, T. Huttula, R. Kanyaru, P. Kotilainen, S.
43 Makasa, N. Mulimbwa, and H. Molsa, 2006: Fish catches from Lake Tanganyika mainly reflect changes in
44 fishery practices, not climate. *Verhandlungen Internationale Vereinigung Für Theoretische Und Angewandte
45 Limnologie*, 29, 1182-1188.
- 46 Savary, S., N.P. Castilla, F.A. Elazegui, and P.S. Teng, 2005: Multiple effects of two drivers of agricultural change,
47 labour shortage and water scarcity, on rice pest profiles in tropical Asia. *Field Crops Research*, 91(2-3),
48 263-271.
- 49 Savary, S., A. Mila, L. Willocquet, P.D. Esker, O. Carisse, and N. McRoberts, 2011: Risk Factors for Crop Health
50 Under Global Change and Agricultural Shifts: A Framework of Analyses Using Rice in Tropical and
51 Subtropical Asia as a Model. *Phytopathology*, 101(6), 696-709.
- 52 Schaeffleitner, R., J. Ramirez, A. Jarvis, D. Evers, R. Gutierrez, and M. Scurrah, 2011: Adaptation of the Potato Crop
53 to Changing Climates. In: *Crop Adaptation to Climate Change*. [Yadav, S., Redden, B. Hattfield, J.L., and
54 Lotze-Campen, H. (ed.)]. Wiley-Blackwell, Oxford, UK, pp. 287-297.

- 1 Scherm, H. and X.B. Yang, 1995: Interannual variations in wheat rust development in China and the United States
2 in relation to the El Niño/Southern Oscillation. *Phytopathology*, 85(9), 970-976.
- 3 Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields
4 under climate change. *Proceedings of the National Academy of Sciences*, 106(37), 15594-15598.
- 5 Schlenker, S. and David, B.L., 2010: Robust negative impacts of climate change on African agriculture.
6 *Environmental Research Letters*, 5(1), 014010.
- 7 Schmitz, C., H. van Meijl, P. Kyle, S. Fujimori, and P. Havlík, 2013: How Much Cropland Is Needed?
8 Insights from a Global Agro-economic Model Comparison. *Proceedings of the National Academy of Sciences*.
9 In review.
- 10 Schroth, G., P. Laderach, J. Dempewolf, S. Philpott, J. Hagggar, H. Eakin, T. Castillejos, J. Garcia Moreno, L. Soto
11 Pinto, R. Hernandez, A. Eitzinger, and J. Ramirez - Villegas, 2009: Towards a climate change adaptation
12 strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico.(Report). *Mitigation
13 and Adaptation Strategies for Global Change*, Oct, 2009, 14; Vol.14(7; 7), 605; 605(21).
- 14 Semenov et al., 2012: Shortcomings in wheat yield predictions, *Nature Climate Change*, 2, 380-382. **
- 15 Semenov, M.A. and P.R. Shewry, 2011: Modelling predicts that heat stress, not drought, will increase vulnerability
16 of wheat in Europe *Science Scientific Reports*, 1(66).
- 17 Seo, S., 2010: Is an integrated farm more resilient against climate change? A micro-econometric analysis of portfolio
18 diversification in African agriculture. *Food Policy*, 35, 32-40.
- 19 Shaw, M.W., S.J. Bearchell, B.D.L. Fitt, and B.A. Fraaije, 2008: Long-term relationships between environment and
20 abundance in wheat of *Phaeosphaeria nodorum* and *Mycosphaerella graminicola*. *New Phytologist*, 177,
21 229-238.
- 22 Shimono, H., H. Kanno, and S. Sawano, 2010: Can the Cropping Schedule of Rice be Adapted to Changing
23 Climate? A Case Study in Cool Areas of Northern Japan. . *Field Crops Research*, 118(2), 126-134.
- 24 Skees, J., P. Hazell, and M. Miranda, 1999: *New Approaches to Crop Yield Insurance in Developing Countries*
25 In: EPTD Discussion Paper No. 55. International Food Policy Research Institute, Washington, DC.
- 26 Skoufias, E. and A.R. Quisumbing, 2005: Consumption insurance and vulnerability to poverty: A synthesis of the
27 evidence from Bangladesh, Ethiopia, Mali, Mexico and Russia. *European Journal of Development Research*,
28 17(1), 24-58.
- 29 Smit, B. and J. Wandel, 2006: Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, 16,
30 282-292.
- 31 Smith, L., H. Alderman, and D. Aduayom, 2006: *Food Insecurity in sub-Saharan Africa: New Estimates from*
32 *Household Expenditure Survey*. IFPRI Research Report no. 146. IFPRI, Washington D.C.
- 33 Smith, P., P.J. Gregory, D. van Vuren, M. Obersteiner, P. Havlik, M. Rounsevell, J. Woods, E. Stehfest, and J.
34 Bellarby, 2010: Competition for land. *Philosophical Transactions of the Royal Society*, 365, 2941-2957.
- 35 Smith, P. and J. Olesen, 2010: Synergies between the mitigation of, and adaptation to, climate change in agriculture.
36 *Journal of Agricultural Science*, 148(543), 552.
- 37 Soltani, A. and G. Hoogenboom, 2007: Assessing crop management options with crop simulation models based on
38 generated weather data. *Field Crops Research*, 103(3), 198-207.
- 39 Soussana, J., A. Graux, and F.N. Tubiello, 2010: Improving the use of modelling for projections of climate change
40 impacts on crops and pastures. *Journal of Experimental Botany*, 61(8), 2217-2228.
- 41 Sparks, A.H., G.A. Forbes, R.H. Hijmans, and K.A. Garrett, 2013, In review: The global risk of potato late blight
42 under climate change.
- 43 Speranza, Ch.I, B. Kiteme, P. Ambenje, U. Wiesmann, S. Makali, 2009. Indigenous knowledge related to climate
44 variability and change: insights from droughts in semi-arid areas of former Makueni District, Kenya. *Climatic
45 Change*, 100, 295-315. **
- 46 Speranza, C.I., Drought Coping and Adaptation Strategies: Understanding Adaptations to Climate Change in
47 Agro-pastoral Livestock Production in Makueni District, Kenya 2010: *European Journal of Development
48 Research*, 22, 623-642. **
- 49 Spring, Ú.O., 2009: Food as a New Human and Livelihood Security Challenge. In: *Facing Global Environmental
50 Change. Hexagon Series on Human and Environmental Security and Peace*. [Brauch, H.G. and et al.(eds.)].
51 Springer Berlin Heidelberg, .
- 52 Stöckle, C.O., R.L. Nelson, S. Higgins, J. Brunner, G. Grove, R. Boydston, M. Whiting, and C. Kruger, 2010:
53 Assessment of climate change impact on Eastern Washington agriculture. *Climatic Change*, 102(1-2), 77-102.

- 1 Sugiura, T., H. Sumida, S. Yokoyama, and H. Ono, 2012: Overview of Recent Effects of Global Warming on
2 Agricultural Production in Japan . *Jarq*, 46(1), 7-13.
- 3 Sun, C., H. Cao, H. Shao, X. Lei, and Y. Xiao, 2011: Growth and physiological responses to water and nutrient
4 stress in oil palm. *Journal of Biotechnology*, 10, 10465-10471.
- 5 Supit, I et al., 2010: Recent changes in the climatic yield potential of various crops in Europe, *Agricultural Systems*,
6 103, 683-694. **
- 7 Supit, I., C.A. van Diepen, A.J.W. de Wit, J. Wolf, P. Kabat, B. Baruth, and F. Ludwig, 2012: Assessing climate
8 change effects on European crop yields using the Crop Growth Monitoring System and a weather generator.
9 *Agricultural and Forest Meteorology*, 164, 96-111.
- 10 Tabachnick, W.J., 2010: Challenges in predicting climate and environmental effects on vector-borne disease
11 episystems in a changing world. *Journal of Experimental Biology*, (213), 946-954.
- 12 Tao F. et al., 2009: Modelling the impacts of weather and climate variability on crop productivity over a large area:
13 A new process-based model development, optimization, and uncertainties analysis. *Agricultural and Forest*
14 *Meteorology* 149, 831-850. **
- 15 Tao, F. and Z. Zhang, 2010: Adaptation of Maize Production to Climate Change in North China Plain: Quantify the
16 Relative Contributions of Adaptation Options. *European Journal of Agronomy*, 33, 103-116.
- 17 Tao, F. and Z. Zhang, 2011: Climate change, wheat productivity and water use in the North China Plain: A new
18 super-ensemble-based probabilistic projection. *Agricultural and Forest Meteorology*, In press.
- 19 Tao, F., Z. Zhang, S. Zhang, Z. Zhu, and W. Shi, 2012: Response of Crop Yields to Climate Trends Since 1980 in
20 China. *Climate Research*, 54, 233-247.
- 21 Tao, F., M. Yokozawa, J. Liu, and Z. Zhang, 2008: Climate–crop yield relationships at provincial scales in China
22 and the impacts of recent climate trends. *Clim Res*, 38(1), 83-94.
- 23 Tao, F., M. Yokozawa, Y. Xu, Y. Hayashi, and Z. Zhang, 2006: Climate changes and trends in phenology and yields
24 of field crops in China, 1981-2000. *Agricultural and Forest Meteorology*, 138(1-4), 82-92.
- 25 Tao, F., Z. Zhang, J. Liu, and M. Yokozawa, 2009a: Modelling the impacts of weather and climate variability on
26 crop productivity over a large area: A new super-ensemble-based probabilistic projection. *Agricultural and*
27 *Forest Meteorology*, 149(8), 1266-1278.
- 28 Tao, F., M. Yokozawa, J. Liu, and Z. Zhang, 2009b: *Climate change, land use change, and China's food security in*
29 *the twenty-first century: an integrated perspective* Springer Netherlands, pp. 433-445.
- 30 Taub, D.R., B. Miller, and H. Allen, 2008: Effect of elevated CO₂ on the protein concentration of food crops: a
31 meta-analysis. *Global Change Biology*, 14(3), 565-575.
- 32 Taub, D.R. and X. Wang, 2008: Why are nitrogen concentrations in plant tissues lower under elevated CO₂? A
33 critical examination of the hypotheses. *Journal of Integrative Plant Biology*, 50(11), 1365-1374.
- 34 Tausz, M., S. Tausz-Posch, R.M. Norton, G.J. Fitzgerald, M.E. Nicolas, and S. Seneweera, 2011: Understanding
35 crop physiology to select breeding targets and improve crop management under increasing atmospheric CO₂
36 concentrations. *Environmental and Experimental Botany*, 88, 71-80.
- 37 Tchebakova, N., E. Parfenova, G. Lysanova, and A. Soja, 2011: Agroclimatic Potential across Central Siberia in an
38 Altered Twenty-First Century . *Environmental Research Letters*, 6.
- 39 Teixeira, E.I., G. Fischer, H. van Velthuizen, C. Walter, and F. Ewert, 2013: Global hot-spots of heat stress on
40 agricultural crops due to climate change. *Agricultural and Forest Meteorology*, 170, 206-215.
- 41 Teixeira, E., G. Fischer, H. van Velthuisen, R. van Dingenen, F. Dentener, G. Mills, C. Walter, and F. Ewert, 2011:
42 Limited potential of crop management for mitigating surface ozone impacts on global food supply. *Atmospheric*
43 *Environment*, 45(15), 2569-2576.
- 44 Thornton, P.K., P.G. Jones, G. Alagarswamy, and J. Andresen, 2009: Spatial variation of crop yield response to
45 climate change in East Africa. *Global Environmental Change*, 19(1), 54-65.
- 46 Thornton, P.K., P.G. Jones, G. Alagarswamy, J. Andresen, and M. Herrero, 2010: Adapting to climate change:
47 Agricultural system and household impacts in East Africa. *Agricultural Systems*, 103(2), 73-82.
- 48 Thornton PK, Jones PG, Ericksen PJ, Challinor AJ. 2011. Agriculture and food systems in Sub-Saharan Africa in a
49 4°C+ world. *Philosophical Transactions of the Royal Society, London, A*, 369, 117-136.
- 50 Tianhong, Z., S. Yi, H. Guohong, W. Yan, and S. Bei, 2005: Respective and interactive effects of doubled CO₂ and
51 O₃ concentration on membrane lipid peroxidation and anti-oxidative ability of soybean. *Science in China Series*
52 *C: Life Sciences*, 48(1), 136-141.
- 53 Tingem, M. and M. Rivington, 2009: Adaptation for crop agriculture to climate change in Cameroon: Turning on the
54 heat. *Mitigation and Adaptation Strategies for Global Change*, 14, 153-168.

- 1 Travasso, M., G. Magrin, G. Rodríguez, S. Solman, and M. Núñez, 2009: Climate Change Impacts on Regional
2 Maize Yields and Possible Adaptation Measures in Argentina. *International Journal of Global Warming*,
3 1(1-3), 201-213.
- 4 Treharne, K., 1989: The implications of the ‘greenhouse effect’ for fertilizers and agrochemicals
5 In: *The Greenhouse Effect and UK Agriculture. CAS Paper 19*. [Bennet, R.C. (ed.)]. Ministry of Agriculture,
6 Fisheries and Food, UK, pp. 57-78.
- 7 Trnka, M., J.E. Olesen, K.C. Kersebaum, A.O. Skjelvåg, J. Eitzinger, B. Seguin, P. Peltonen-Sainio, R. Rötter, A.
8 Iglesias, S. Orlandini, M. Dubrovský, P. Hlavinka, J. Balek, H. Eckersten, E. Cloppet, P. Calanca, A. Gobin, V.
9 VuEti, P. Nejedlik, S. Kumar, B. Lalic, A. Mestre, F. Rossi, J. Kozyra, V. Alexandrov, D. Semerádová, and Z.
10 Alud, 2011: Agroclimatic conditions in Europe under climate change. *Global Change Biology*, 17(7),
11 2298-2318.
- 12 Turner, N. and H. Clifton, 2009: ‘It’s so different today’: Climate change and indigenous lifeways in British
13 Columbia, Canada. *Global Environmental Change*, 19, 180-190.
- 14 Twomlow, S., F. Mugabe, M. Mwale, R. Delve, D. Nanja, P. Carberry, and M. Howden, 2008: Building adaptive
15 capacity to cope with increasing vulnerability due to climatic change in Africa – A new approach. . *Physics and*
16 *Chemistry of the Earth*, 33(780), 787.
- 17 Urban D et al., 2012: Projected temperature changes indicate significant increase in interannual variability of U.S.
18 maize yields. *Climatic Change*, 112, 525-533.
- 19 Van de Geisen, N., J. Liebe, and G. Jung, 2010: Adapting to Climate Change in the Volta Basin, West Africa. .
20 *Current Science*, 98(8), 1033-1037.
- 21 Van Dingenen, R., F.J. Dentener, F. Raes, M.C. Krol, L. Emberson, and J. Cofala, 2009: The global impact of ozone
22 on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment*, 43(3),
23 604-618.
- 24 Vandermeiren, K., H. Harmens, G. Mills, and L. De Temmerman, 2009: Impacts of ground-level ozone on crop
25 production in changing climate. In: *Climate Change and Crops*. [Singh, S.N. (ed.)]. Springer Berlin Heidelberg,
26 Berlin, Germany, pp. 213-243.
- 27 Vermeulen, S.J., B. Campbell, and J. Ingram, 2012: Climate Change and Food Systems. *Annual Review of*
28 *Environment and Resources*, 37, 195-222.
- 29 Vinagre, C., F.D. Santos, H. Cabral, and M.J. Costa, 2011: Impact of climate warming upon the fish assemblages of
30 the Portuguese coast under different scenarios. *Regional Environmental Change*, 11, 779-789.
- 31 Vitali, A., M. Segnalini, L. Bertocchi, U. Bernabucci, A. Nardone, and N. Lacetera, 2009: Seasonal pattern of
32 mortality and relationships between mortality and temperature-humidity index in dairy cows. *Journal of Dairy*
33 *Science*, 92(8), 3781-3790.
- 34 Von Braun, J. and M. Torero, 2009: Exploring the Price Spike. *Choices*, 24, 16-21.
- 35 Wall, E., A. Wreford, K. Topp, and D. Moran, 2010: Biological and economic consequences heat stress due to a
36 changing climate on UK livestock. *Advances in Animal Biosciences*, 1(01), 53-53.
- 37 Walter, L., T. Streck, H. Rosa, and C. Kruger, 2010: Climate change and its effects on rice. *Ciencia Rural*, 40(11),
38 2411-2418.
- 39 Wang, H.L., Y.T. Gan, R.Y. Wang, J.Y. Niu, H. Zhao, Q.G. Yang, and G.C. Li, 2008: Phenological trends in winter
40 wheat and spring cotton in response to climate changes in northwest China. *Agricultural and Forest*
41 *Meteorology*, 148(8-9), 1242-1251.
- 42 Wang, X., W. Manning, Z. Feng, and Y. Zhu, 2007: Ground-level ozone in China: Distribution and effects on crop
43 yields. *Environmental Pollution*, 147(2), 394-400.
- 44 Wassmann, R., S. Jagadish, S. Heuer, A. Ismail, E. Redona, R. Serraj, R. Singh, G. Howell, H. Pathak, and K.
45 Sumfleth, 2009: Climate change affecting rice production: the physiological and agronomic basis for possible
46 adaptation strategies. *Advances in Agronomy*, 101, 59-122.
- 47 Weatherhead, E., S. Gearheard, and R. Barry, 2010: Changes in weather persistence: Insight from Inuit knowledge.
48 *Global Environmental Change*, 20, 523-528.
- 49 Webb, L.B., P.H. Whetton, and E.W.R. Barlow, 2011: Observed trends in winegrape maturity in Australia. *Global*
50 *Change Biol*, 17(8), 2707-2719.
- 51 Welch, J.R., J.R. Vincent, M. Auffhammer, P.F. Moya, A. Dobermann, and D. Dawe, 2010: Rice yields in
52 tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures.
53 *Proceedings of the National Academy of Sciences*, 107(33), 14562.

- 1 Welcomme, R., 2011: Review of the State of the World Fishery Resources: Inland Fisheries. *FAO Fisheries and*
2 *Aquaculture Circular*, 2(942), 97.
- 3 White, A., P. Whalen, and G.V. Jones, 2009: Land and wine. *Nature Geoscience*, 2, 82-84.
- 4 White, J.W., G. Hoogenboom, B.A. Kimball, and G.W. Wall, 2011: Methodologies for simulating impacts of
5 climate change on crop production. *Field Crops Research*, 124(3), 357-368.
- 6 Wijeratne, M.A, et al. 2007.: Assessment of impact of climate change on productivity of tea (*Camellia sinensis* L.)
7 plantations in Sri Lanka. *Natn.Sci,Foundation Sri Lanka*, 35, 119-126.
- 8 Wilson, S.K., N.J. Graham, M.S. Pratchett, G.P. Jones, and V.C. Polunin, 2006: Multiple Disturbances and the
9 Global Degradation of Coral Reefs: Are Reef Fishes at Risk or Resilient? *Global Change Biology*, , 2220-2234.
- 10 Wolfe, D.W., L. Ziska, C. Petzoldt, A. Seaman, L. Chase, and K. Hayhoe, 2008: Projected change in climate
11 thresholds in the Northeastern U.S.: implications for crops, pests, livestock, and farmers. *Mitigation and*
12 *Adaptation Strategies for Global Change*, 13, 555-575.
- 13 World Bank, 2012: *Global Monitoring Report 2012: Food Prices, Nutrition, and the Millenium Development Goals*.
14 World Bank 2012 Global Monitoring Report. World Bank, Washington D.C.
- 15 Wright, B.D., 2011: The Economics of Grain Price Volatility. *Applied Economic Perspectives and Policy*, 33(1), 32.
- 16 Xenopoulos, M.A., D.M. Lodge, J. Alcamo, Märker, M., Schulze, K., and D.P. Van Vuuren, 2005: Scenarios of
17 Freshwater Fish Extinctions from Climate Change and Water Withdrawal . *Global Change Biology*, 11(10),
18 1557-1564.
- 19 Yang, L., Y. Wang, G. Dong, H. Gu, J. Huang, J. Zhu, H. Yang, G. Liu, and Y. Han, 2007: The impact of free-air
20 CO₂ enrichment (FACE) and nitrogen supply on grain quality of rice. *Field Crops Research*, 102(2), 128-140.
- 21 You, L., M. Rosegrant, S. Wood, and D. Sun, 2009: Impact of growing season temperature on wheat productivity in
22 China. *Agricultural and Forest Meteorology*, 149(6-7), 1009-1014.
- 23 Zezza, A., B. Davis, C. Azzarri, K. Covarrubias, L. Tasciotti, and G. Angriquez, 2008: *The Impact of Rising Food*
24 *Prices on the Poor*. In: ESA Working Paper 08-07. FAO, Rome.
- 25 Zhang, X. and X. Cai, 2011: Climate change impacts on global land availability. *Environmental Research Letters*, 6,
26 1-18.
- 27 Zhang, T., J. Zhu, X. Yang, and X. Zhang, 2008: Correlation changes between rice yields in North and Northwest
28 China and ENSO from 1960 to 2004. *Agricultural and Forest Meteorology*, 148(6-7), 1021-1033.
- 29 Zhu, X.K., Z.Z. Feng, T.F. Sun, X.C. Liu, H.Y. Tang, J.G. Zhu, W.S. Guo, and K. Kobayashi, 2011: Effect of
30 elevated ozone concentration on yield of four Chinese varieties of winter wheat under fully open-air field
31 conditions. *Global Change Biology*, 17, 2697-2706.
- 32 Ziska LH, Blumenthal DM, Runion GB, Hunt Jr. ER, Diaz-Soltero H. 2011a. Invasive species and climate change:
33 an agronomic perspective. *Climatic Change* 105:13-42.
- 34 Ziska, L.H., 2010: Global Climate Change and Carbon Dioxide: Assessing Weed Biology and Management. In:
35 *Handbook of climate change and agro-ecosystems: Impacts, adaptation and mitigation*. [Rosenzweig, C. and D.
36 Hillel(eds.)]. World Scientific Publishing, Hackensack, NJ, pp. 191-208.
- 37 Ziska, L.H., J.A. Bunce, H. Shimono, D.R. Gealy, J.T. Baker, P.C.D. Newton, M.P. Reynolds, K.S.V. Jagadish, C.
38 Zhu, M. Howden, and L.T. Wilson, 2012: Food security and climate change: on the potential to adapt global
39 crop production by active selection to rising atmospheric carbon dioxide. *Proceedings of the Royal Society*
40 *Biological Sciences*, 279(1745), 4097-4105.
- 41 Ziska, L.H., 2003: Evaluation of yield loss in field sorghum from a C3 and C4 weed with increasing CO₂. *Weed*
42 *Science*, 51(6), 914-918.
- 43 Ziska, L.H., 2000: The impact of elevated CO₂ on yield loss from a C3 and C4 weed in field-grown soybean. *Global*
44 *Change Biology*, 6(8), 899-905.
- 45 Ziska, L.H., S. Faulkner, and J. Lydon, 2004: Changes in biomass and root:shoot ratio of field-grown Canada thistle
46 (*Cirsium arvense*), a noxious, invasive weed, with elevated CO₂: implications for control with glyphosate.
47 *Weed Science*, 52(4), 584-588.
- 48 Ziska, L.H. and E.W. Goins, 2006: Elevated Atmospheric Carbon Dioxide and Weed Populations in Glyphosate
49 Treated Soybean. *Crop Sci.*, 46(3), 1354-1359.
- 50 Zougmore, R., A. Mando, and L. Stroosnijder, 2010: *Benefits of integrated soil fertility and water management in*
51 *semi-arid West Africa: an example study in Burkina Faso* Springer Netherlands, pp. 17-27.
- 52 Zumbach, B., I. Misztal, S. Tsuruta, J.P. Sanchez, M. Azain, W. Herring, J. Holl, T. Long, and M. Culbertson, 2008:
53 Genetic components of heat stress in finishing pigs: Development of a heat load function. *Journal of Animal*
54 *Science*, 86(9), 2082-2088.

- 1 Zwiers, F.W., X. Zhang, and Y. Feng, 2011: Changes in the extremes of the climate simulated by CCC GCM2 under
2 CO2 doubling. *Journal of Climate*, In press.

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

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

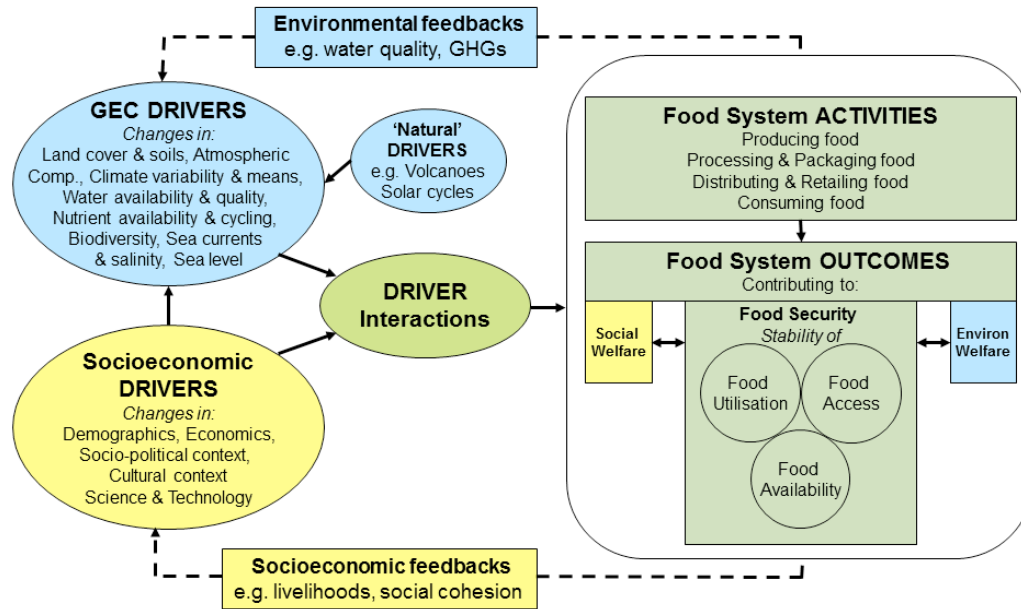


Figure 7-1: Main global environmental change (GEC) and socioeconomic drivers of food systems, the main food system activities, and the outcomes of these activities. The figure also shows the three main components of food security (circles), all of which need to be stable over time: Availability (with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

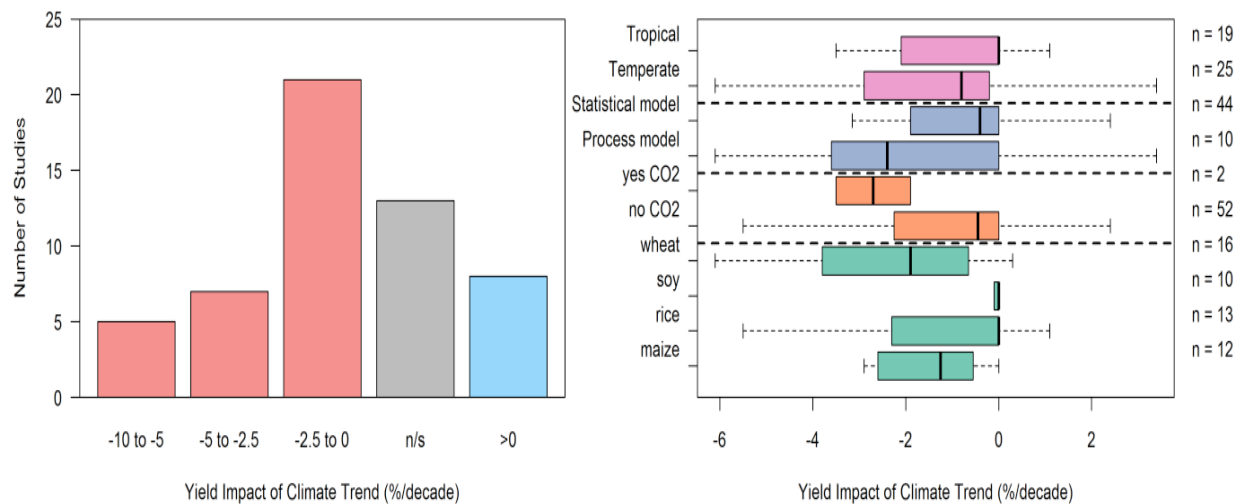


Figure 7-2: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (e.g., stations, provinces, countries,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

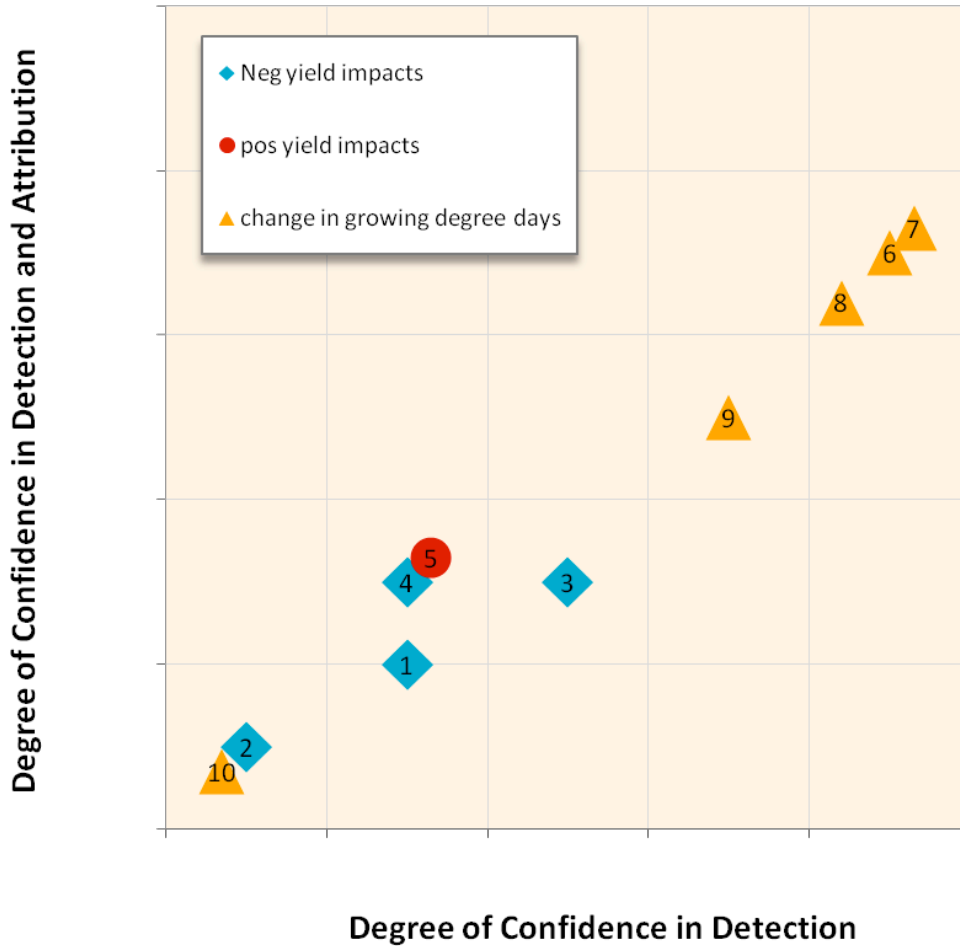


Figure 7-3: Confidence in detection and attribution of observed impacts on crop yields and growing season degree days. Yield impacts include both direct climate effects and effects of elevated CO₂, but do not consider farmer adaptation. Confidence Levels were derived based on expert judgement of the available literature, following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010). Negative yield impacts: 1= Global maize , 2= Global wheat, 3= South Asia wheat; 4 = China maize and wheat; Positive yield impacts: 5 = UK wheat, sugarbeet, and potato. Increase in growing degree days: 6 = South Asia, main crops; 7 = China, main crops; 8 = Europe, main crops; 9 = Latin America, main crops; 10 = North America, maize and soybean. Yield impact confidence based on studies listed in Figure 7-2. Growing degree day confidence based on detection and attribution of trends in growing season temperatures (IPCC 2013, WG1, Chapter 10).

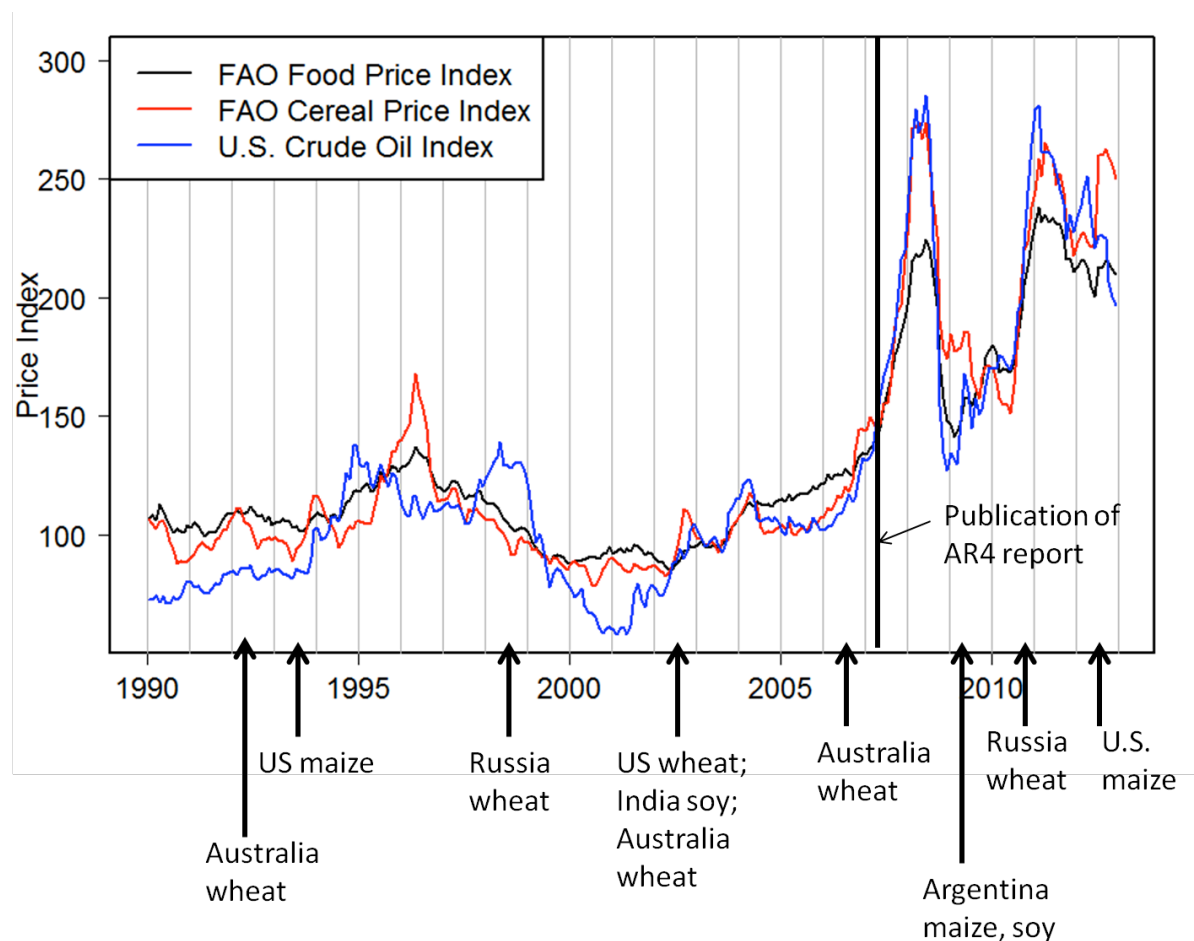


Figure 7-4: Since the AR4 report, food prices have reversed historical downward trend. Plot shows history of FAO food and cereal price index, along with events when a top 5 producer of a crop had yields 25% below trend line (indicative of a big weather effect). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years, perhaps reflecting the importance of interactions with global storage levels and rapid growth in crop demand. At the same time, because of increased biofuel demand, food prices are also increasingly linked to the price of crude oil, shown in the blue line (data available at <http://www.eia.gov>). Therefore, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002-2004 averages.

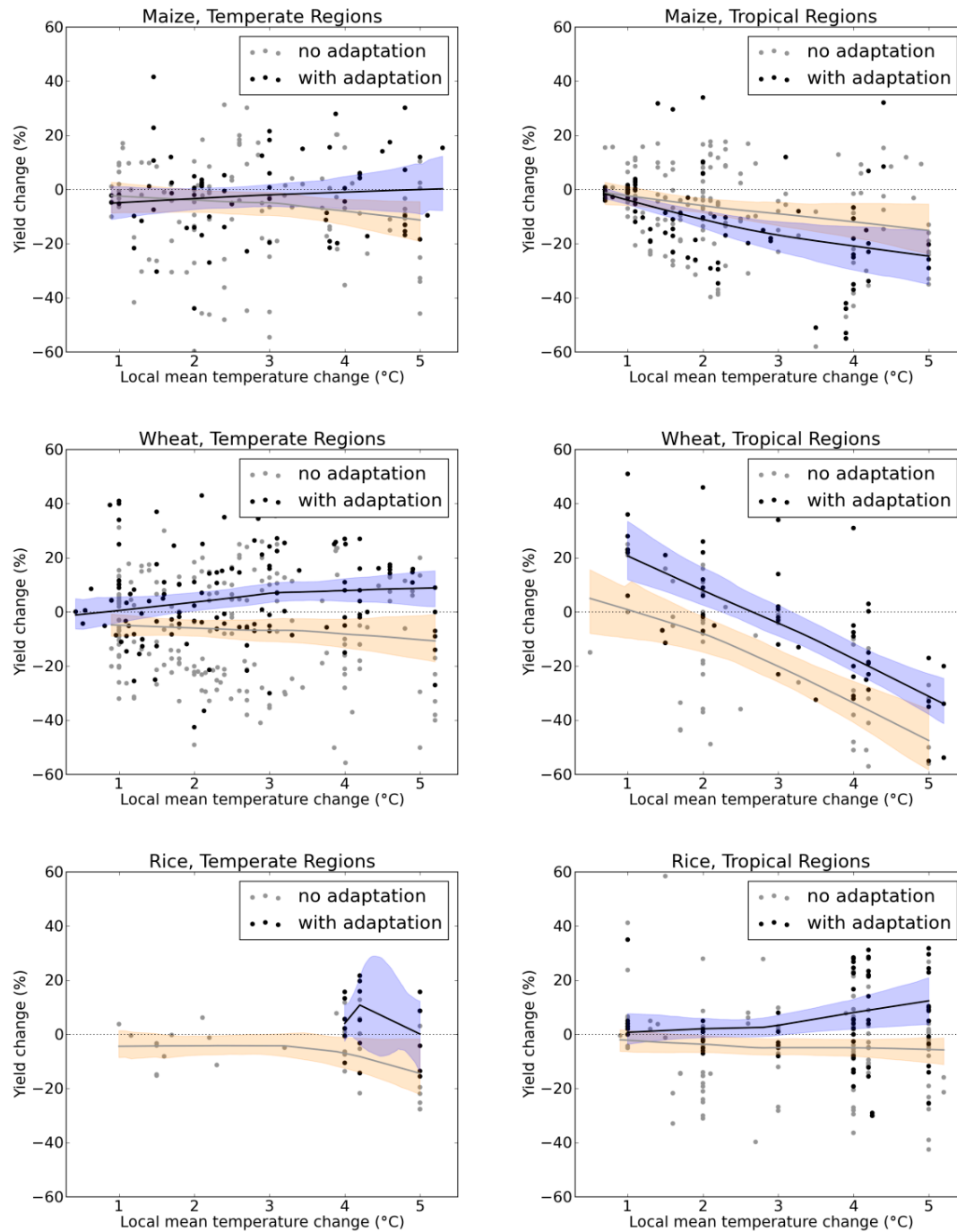


Figure 7-5: Percentage simulated yield change as a function of local temperature change temperature for the three major crops and for temperate and tropical regions. Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, which are separated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

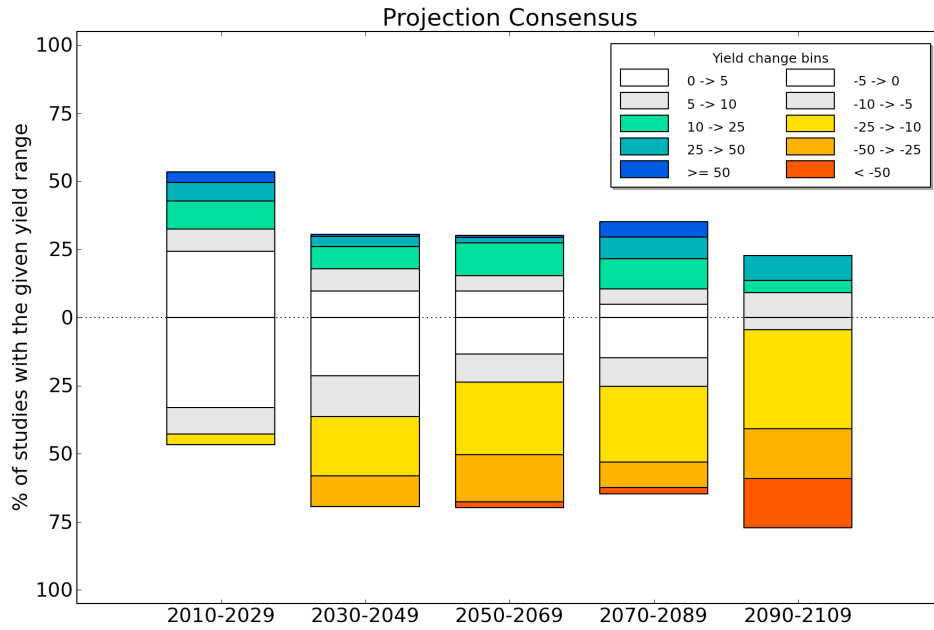


Figure 7-6: Projected changes in crop yield as a function of time. The y-axis indicates degree of consensus and the colours denote percentage change in crop yield. Data are plotted according to the 20-year period in which the centre point of the projection period falls. Taken from (Challinor *et al.*,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

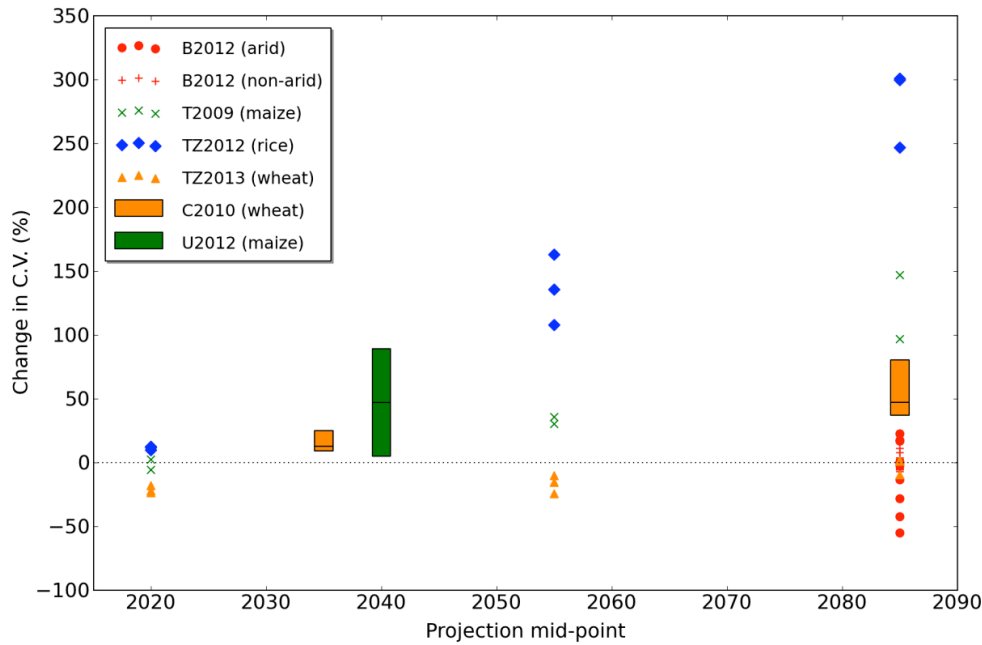


Figure 7-7: Projected percentage change in coefficient of variation (CV) for wheat (gold), maize (green), rice (blue) and C4 crops (red) taken from C2010 (Challinor *et al.*, 2010), B2012 (Berg *et al.*, 2012), T2009 (Tao *et al.*, 2009), TZ2013 (Tao and Zhang, 2010), TZ2012 (Tao and Zhang, 2011) and U2012 (Urban *et al.*, 2012). U2012 and C2012 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in CV. For C2012 paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. The studies used a range of scenarios (SRES A1B, A2, A1F1 and B1). B2012 is a global study, U2012 is for the US, and the remaining studies are for China.

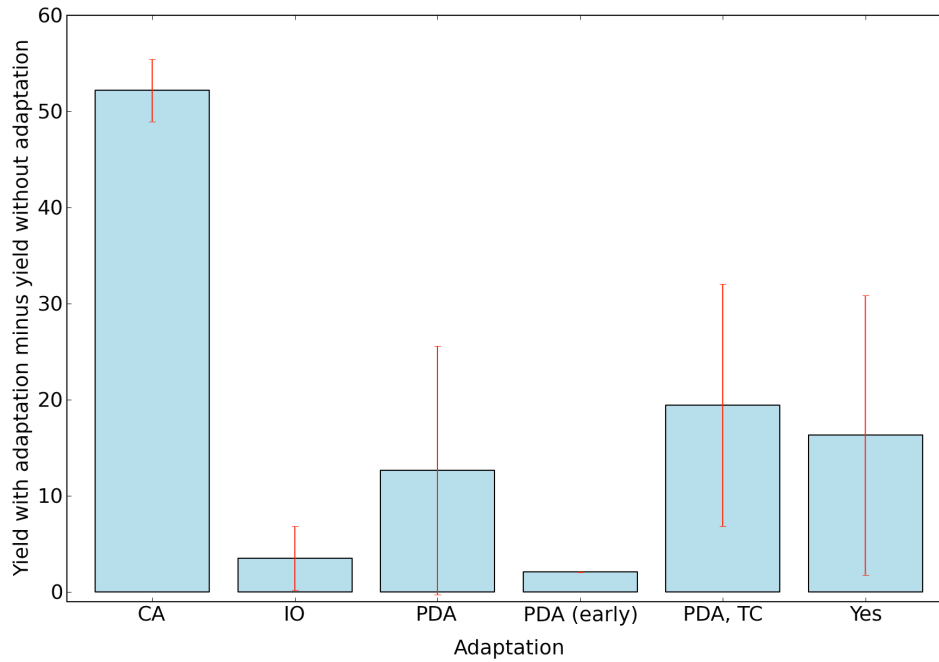


Figure 7-8: The benefit (% difference from baseline) for different crop management adaptations (CA – cultivar adjustment; IO – irrigation optimisation; PDA – planting date adjustment; PDA early – adjusting planting date earlier; yes – other treatments). The bars indicate \pm SE.

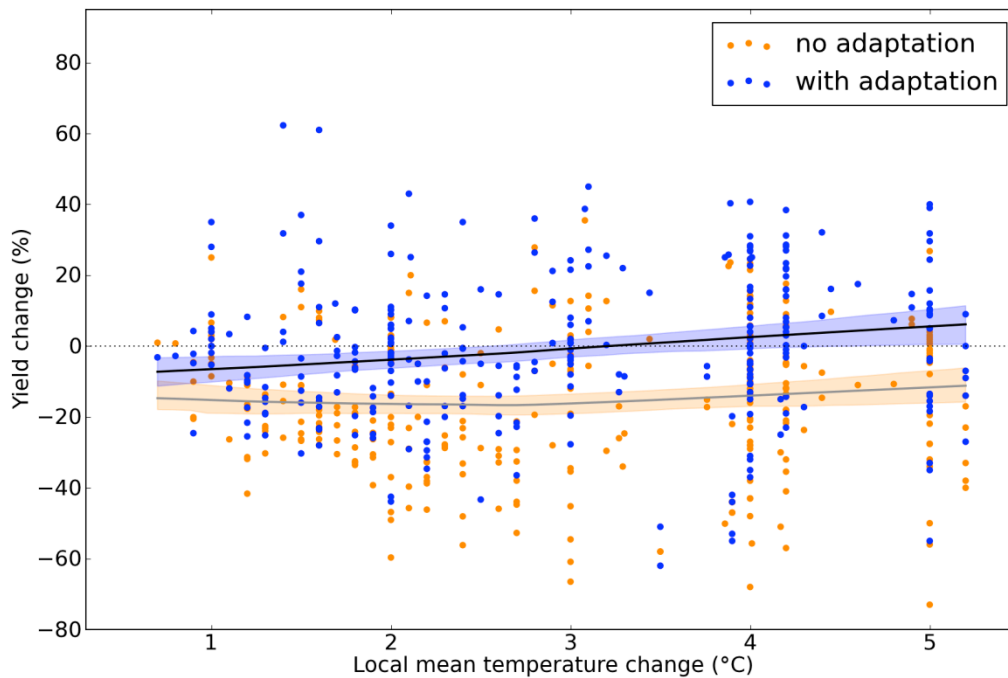
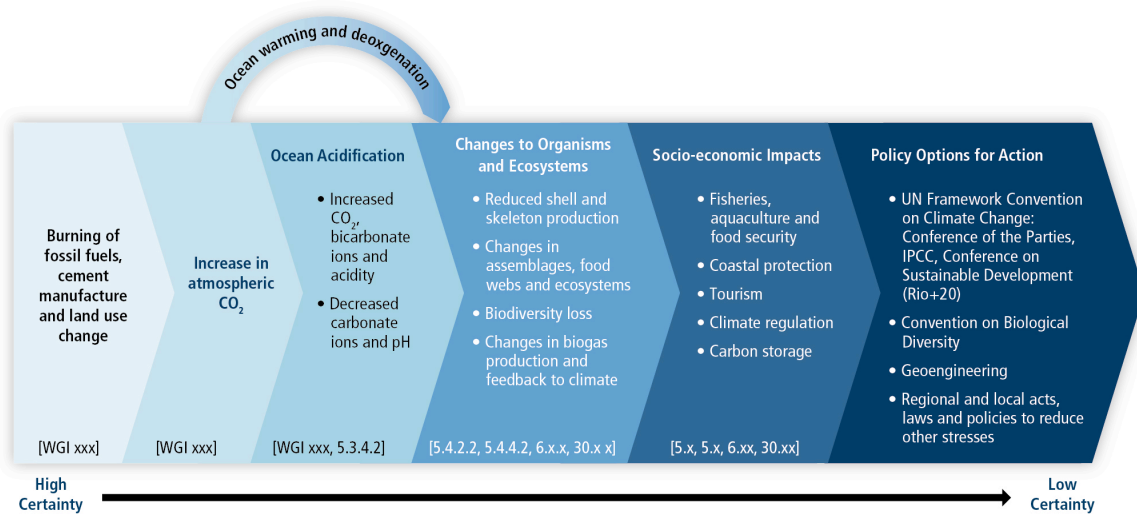
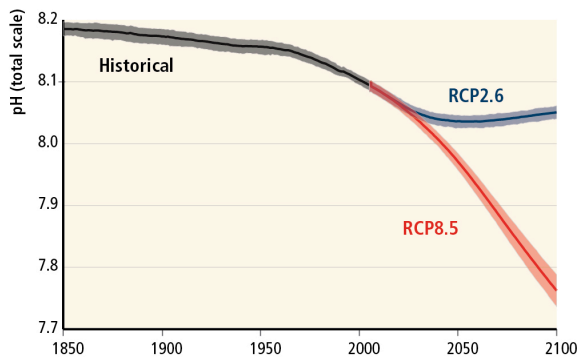


Figure 7-9: Yield change (% difference from baseline) as affected by temperature aggregated across all crops for paired non-adapted and adapted cases. Only studies that examine both a ‘no adaptation’ and an ‘adaptation’ scenario are used.

A.



B.



C.

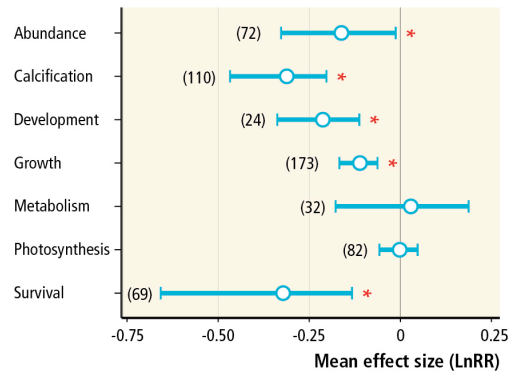


Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley & Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO₂ concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (IPCC AR5 WG1 report, Figure 6.28). C: Effect of near future acidification on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., in press). The effect size indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a significant effect.

The global-scale water – energy – food – climate change nexus

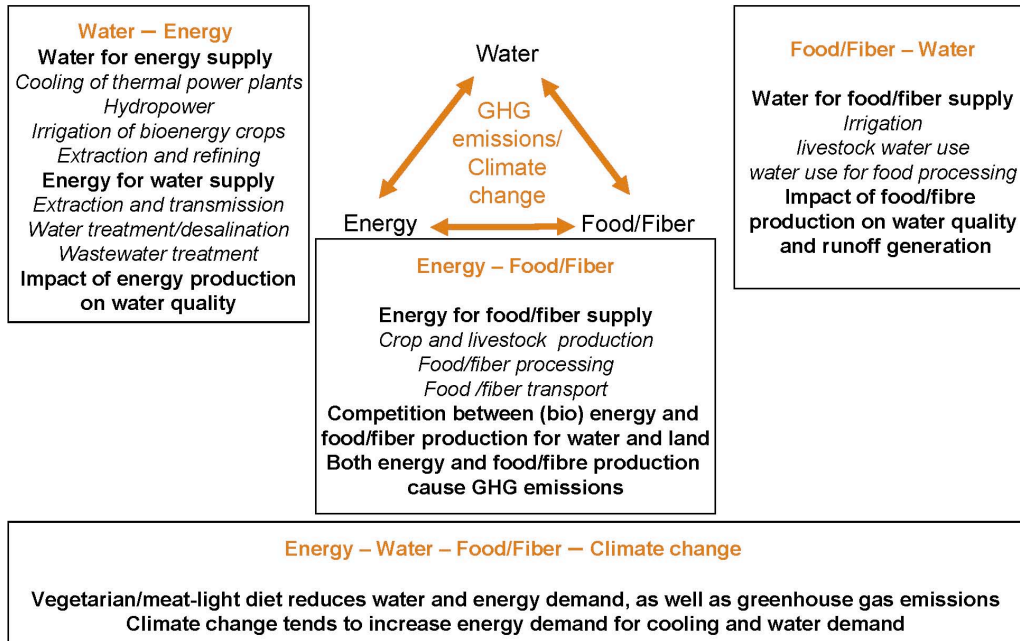


Figure WE-1: The water-energy-food nexus as related to climate change.