Chapter 11. Climate change impacts on food systems and implications for climate-compatible food policies

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chapter 11

contents

Page

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chapter 11

Climate change impacts on food systems and implications for climate-compatible food policies

Tim Wheeler[1]

main chapter messages

- Climate variability and change will add further stresses on a global food production system that needs to respond to future trends of increasing population, changes in diet and urbanisation.
- The impacts of climate change on food security will vary from one part of the world to another and hinder progress towards a world without hunger.
- The stability of whole food systems may be at risk under climate change, largely due to short term variability and extreme events in agricultural markets.
- Climate change risks to agricultural output, to food systems and for food security will increase over time and so should not be ignored by those making medium- and long-term planning decisions about food security.

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1. Introduction

The overall level of hunger in the world has been steadily falling since the widespread introduction of "green revolution" technologies brought more productive crop varieties and better agricultural technologies to large parts of Asia and elsewhere. The number of hungry people has fallen from an estimated 980 million globally in 1990-1992 to about 850 million in 2010-2012 (FAO, 2012). The boost to production resulting from adoption of green revolution varieties has also contributed to a long-term decline in global food prices. Areas of persistent hunger still remain; many of these are in parts of Africa (von Grebmer *et al.,* 2012). However, recently much attention has been focused on looking ahead to the challenges of the feeding the world now and in the near future. How can the global food system cope over the coming decades with increases in the human population, changes in diet, climate change and greater demands on energy and water resources (Godfray *et al*., 2010), in addition to the challenges of food insecurity that already exist?

Food security is a broad concept, defined by the World Food Summit in 1996: food security "exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO, 1996). Food security means more than just the production of food and encompasses aspects of food availability, access, utilization and stability (Box 1).

The effectiveness of the agricultural sector is only one among many influences that determine whether an individual, community or population is food-secure. However, when considering the potential impacts of climate change on global food security, agriculture is a key sector because it is inherently sensitive to climate variability and change, whether attributable to natural causes or to human activities. Climate change resulting from emissions of greenhouse gases is expected to exert a direct impact on crop production systems for food, feed or fodder, affect livestock health, and alter the patterns and balance of trade of food products. The potential range and extent of indirect impacts on food security are large and will be factors in addition to direct impacts. All of these impacts will vary with the degree of warming and associated changes in rainfall patterns, and from one location to another. It is likely that climate variability and change will add further stresses on food production and food security in the future. This paper takes a broad view of the complex impacts of climate change on food security, with the aim of identifying robust conclusions based on research evidence to date. It also attempts to frame the existing evidence in a way that is accessible to those making policy decisions on climate change and food security, guided by the recognition that, despite

box 1
Food security

The formal definition of food security by the Food and Agricultural Organization of the United Nations (FAO) has the following four components:

1. Availability: availability of sufficient quantities of food of appropriate quality, supplied through domestic production or imports;
2. Access: access by individuals to adequate resources (entitlements) for acquiring appropriate foods for a nutritious diet;
3. Utilization: utilization of food through adequate diet, clean water, sanitation and health care to reach a state of nutritional well-being in which all physiological needs are met;
4. Stability: reliable access to adequate food at all times, for populations, households or individuals.

the complexity and uncertainties of knowledge regarding climate change impacts on food security, it is necessary to make robust policy choices now, to better prepare for the challenges of climate change to food security in the future.

2. Climate change

Multiple observations have provided increasing evidence that the climate is changing. Many pieces of evidence support the conclusion that the Earth has warmed since pre-industrial time – i.e. the middle of the eighteenth century. Evidence ranges from direct measurements of climate (for example, Figure 1) to observations of change in the natural environment that correlate with a warming world (IPCC, 2007a). Global mean temperature has risen by 0.8°C since the 1850s, with warming found in three independent temperature records over land and sea and in the ocean surface water (IPCC, 2007b).

The Berkeley Earth Surface Temperature project (BEST) (Richard, 2012) reassessed existing records of global temperature. The project was independent of any previous organizations that have analysed global warming, and used different methods. BEST analysed temperature measurements dating back to before the 1800s from sources around the world. The interim project findings were almost indistinguishable from previous records of global temperature (Figure 2). The BEST project concluded that “the global warming trend is real”. The project also rejected concerns raised by some climate sceptics that the warming trend is dominated by an urban heat island effect, poor station quality and the risk of data selection bias.

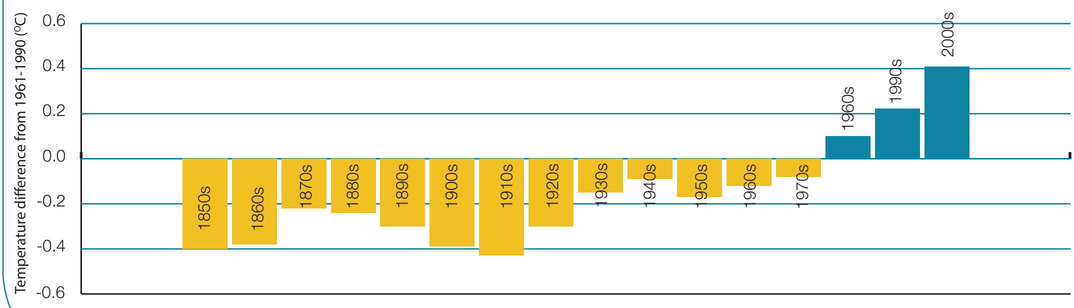
Climate change can result from natural causes, from human activities, through the emission of greenhouse gases, such as carbon dioxide (CO_2), methane and nitrous oxides, and from changes in land use. CO_2 levels in the atmosphere have gone up from about 284 ppm in 1832 to 395 ppm in 2013 (Tans and Keeling, 2013; www.esrl.noaa.gov/gmd/ccgg/trends/global.html). Fundamental physics indicates a clear theoretical link between more greenhouse gases in the atmosphere and increased global warming. The key question for scientists is whether or not the warming observed since pre-industrial times can be largely attributed to human activities.

Three independent reviews since 2007 have found strong evidence for human causes of climate change. The headline findings are:

- “Most of observed increase in globally averaged temperature since the mid-20th

figure 1

Decadal changes in global mean temperature from 1850 to 2009 (from Pope *et al*., 2010)



century is very likely (more than a 90% chance) due to observed increase in anthropogenic greenhouse gas concentrations", *Intergovernmental Panel on Climate Change* (IPCC, 2007, WG1).

- "There is strong evidence that the warming of the Earth over the last half-century has been caused largely by human activity, such as the burning of fossil fuels and changes in land use", *The Royal Society* (2010).
- "A strong, credible body of scientific evidence shows that climate change is occurring, is caused largely by human activities, and poses significant risks for a broad range of human and natural systems", *United States National Science Academy* (2010).

A recent study by Huber and Knutti (2012) reported that at least three-quarters of the temperature rise observed in the past 60 years is due to human activity and that natural climate variability is extremely unlikely to have contributed more than one-quarter of the observed global warming. The study findings reinforce previous reports that greenhouse gases, in particular CO_2, are the main cause of recent global warming. It calculated a net warming value of 0.5°C (since the 1950s), which is very close to the actual observed temperature rise of 0.55°C. The study was also able to model the contribution of solar radiation, commonly cited by climate sceptics as the cause of global warming. Solar radiation only contributed around 0.07°C of the recent warming. This study produces even higher confidence that human-induced causes dominate the observed global warming.

Finally, the IPCC 5th Assessment Report, published recently, concluded that "there is a clear human influence on the climate" and that "it is *extremely likely* that human influence has been the dominant cause of observed warming since 1950" (IPCC, 2013a).

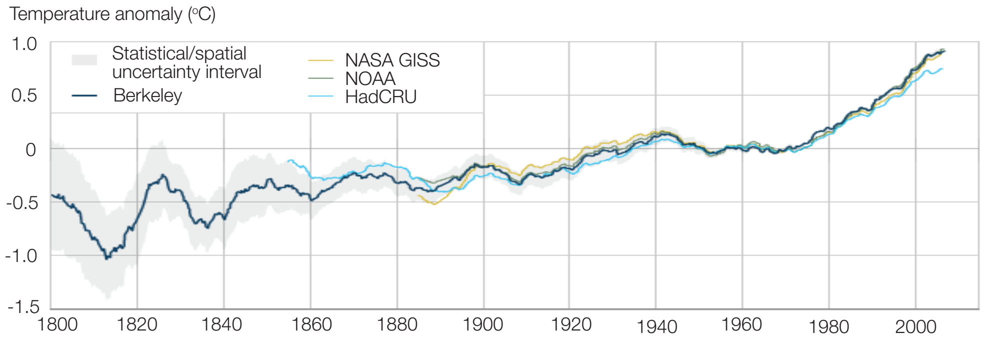
3. Climate variability and agriculture

Agriculture is sensitive to variability in weather and climate (principally rainfall and temperature) at a range of time and spatial scales, as evidenced from observations of crop plants, the behaviour of soft commodity prices and the productivity of the entire agricultural sector.

In many monsoon-affected regions of the world, clear, large-scale correlations are seen between seasonal rainfall and national crop yields and even gross national products (GNPs). For example, between 1966 and 1990, the total

figure 2

Decadal land-surface average temperature (from Richard, 2012; Figure at http://www.bbc.co.uk/news/science-environment-15373071



Source: Berkeley Earth Project

average annual monsoon rain over all of India varied from about 450 mm to over 1200 mm. Over the same period, the yield of groundnut, an oilseed crop, varied from 600 kg/ha to over 1200 kg/ha as a country average. Within these country averages considerable variation in rainfall and yield existed, from state to state and from one district to another. Challinor *et al*. (2004) analysed these spatial and temporal patterns and found that just over half (52%) the variation in crop yield over this time period and from one district to another in India could be attributed to variability in the total monsoon rains alone (Figure 3). There is a simple, large-scale, coherent correlation between variability in rainfall and crop yield in India, demonstrating the importance of that simple metric of climate in India for rainfed crop production. Such large-scale patterns can even be found between rainfall and GDP growth in countries where the agricultural sector represents a large share of national income. For example, de Jong (2005) found an association between rainfall variability and GDP growth over an 18-year period in Ethiopia (Figure 4). Given such examples of the sensitivity of agriculture to natural variability in climate, it is not surprising that there are many potential ways in which climate change due to human influences could also have an impact on agriculture and food security.

4. Impacts of climate change on food availability

Much of the early literature on the impacts of climate change on food availability focused on direct effects on crop plants. Increasing the concentration of CO_2, one of the main greenhouse gases, enhances the productivity of most crops, due to enhanced rates of photosynthesis (Drake *et al*., 1997). This boost to productivity is apparent for all crops that use the C3 photosynthetic pathway[2], such as wheat, barley, rice and soybean. Reviews of hundreds of plant studies found an average yield gain of 33 percent for these crops (Kimball *et al*., 1983). Although there is some disagreement about whether the full extent of these benefits to crops can always be found under field conditions (Long *et al*., 2006), we can expect increasing CO_2 to benefit the productivity of most food crops, pasture grasses and feed crops.

There are, however, a number of important crops that have a different response to elevated CO_2. Maize, sorghum, millet and sugar cane use the C4 photosynthetic pathway. The leaf photosynthetic rates of C4 plants are not substantially enhanced by elevated concentrations

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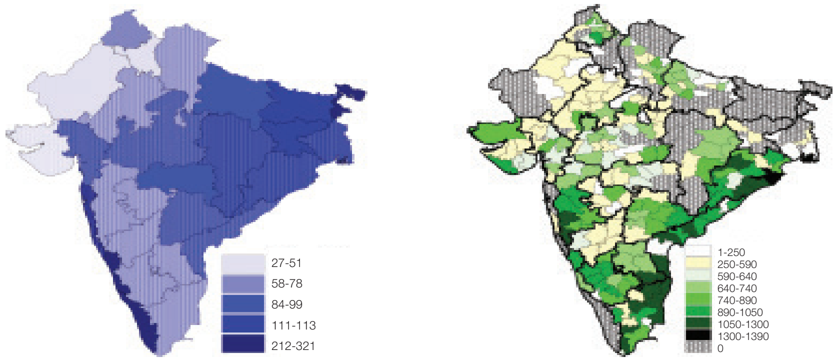
[2] See chapter, section 2.3 for a detailed definition of C3 and C4 pathways.

figure 3

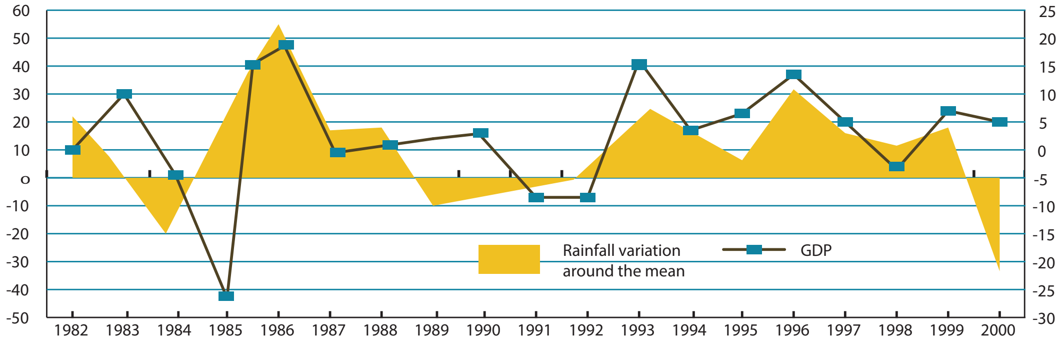
Patterns of seasonal rainfall (left, cm) and yield of groundnut (right, kg ha-1) in India from 1966 to 1990



Source: Challinor *et al*., 2004)

figure 4

Variation in GDP growth with total seasonal rainfall variation in Ethiopia



Source: de Jong (2005), World Bank (2005)

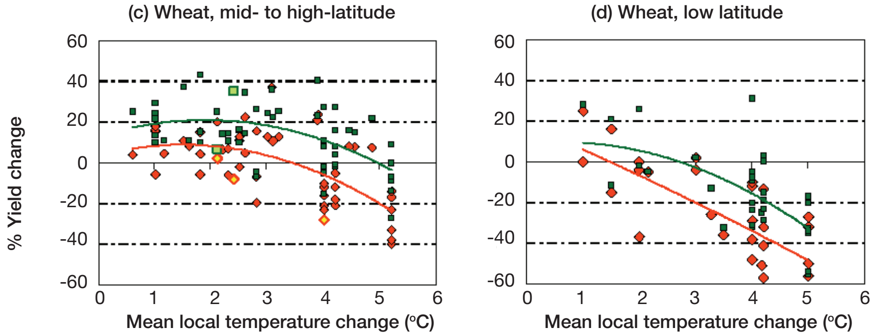
of CO_2; yield gains in these plants grown under elevated CO_2 are much more modest than for C3 plants – for example, no yield change is observed for maize (Long *et al*., 2006). There is a small improvement in the efficiency of water use for both C3 and C4 crops under enhanced CO_2 conditions.

Warmer temperatures affect the rate at which crops grow and develop, and potentially affect the survival of plants and seeds at extremes of temperature. The duration from sowing to flowering to crop harvest is determined by temperature regime and by day-length (Craufurd and Wheeler, 2009). In a warmer climate, we expect the areas where crops are grown to shift northwards in the northern hemisphere and southwards in the southern hemisphere. Where the appropriate genetic material is available, farmers at a particular location can adapt to these changes using new varieties or crops with longer durations; that is, with higher thermal requirements for crop development. Where longer-season varieties cannot be used, crop yields will decline with warmer temperatures because less radiation will be captured and used for crop yield in seasons of shorter duration. For example, an analysis of more than 20 000 variety trials of maize across Africa found that, for each degree day spent above 30°C, final maize yield was reduced by 1 percent under optimal rainfed conditions and by 1.7 percent under drought conditions (Lobell *et al*., 2011). In the future, with a shift to adapted varieties, some of the negative impacts of warmer temperature can be partly offset, although there are important differences among the world's major crops – such as between C3 and C4 crops, and between crops grown in temperate and tropical latitudes. For example, a synthesis of adaptation studies of wheat yield found that adaptation counteracted the equivalent of 4.5 to 5°C of warming in the mid to high latitudes, but only 1.5 to 3°C at low latitudes (Easterling *et al*., 2007). Beyond these values of temperature warming, the impacts of climate change exceed adaptive capacity.

Extremes of hot temperature will become more frequent under climate change (Figure 5). Even without any changes in the distribution of daily temperature, a warmer mean distribution will increase the frequency of extremely hot days. Increased climate variability, which is expected under climate change, will further increase the frequency of extreme temperatures. Where extremely hot days coincide with a sensitive stage of crop development, such as flowering, we find dramatic decreases in seed or grain yields (Wheeler *et al*., 2000). For example, an increase in maximum temperature above 30°C reduced the seed set of rice cultivar IR64 by 7 percent per degree increase in heat stress (Jagadish *et al*., 2007). What is

figure 5

Changes in wheat yields over a range of temperature changes with (green lines) and without (red lines) adaptation and at two latitude ranges (from Easterling *et al*., 2007)



less well understood is how these extremely hot temperatures may affect the quality of seeds and grains for food processing (Madan *et al*., 2012) or for animal feed.

4.1 Global studies of impacts on crop production and yield

The first attempts to examine the potential impacts of various scenarios of climate change on crop productivity were done using simulations at single sites. A crop model simulation would usually compare the output of a run of years under current climate conditions with a set of simulations using the current climate plus a change derived from a climate change scenario. Rosenzweig and Parry (1994) produced the first global assessment of the potential impacts of climate change scenarios on crops. They used the output of three General Circulation Models (GCMs), each with high temperature sensitivity (warming of 4-5.2°C) and run with twice the baseline atmospheric CO_2 equivalent concentrations. They used crop models for wheat, maize, soybean and rice, ran the simulations at 112 sites in 18 countries and aggregated the output to a national level by combining the climate change yield signal with crop production statistics. The projected change in crop yield varied with climate model and in different parts of the world. Most of the scenarios showing increases in yield were simulated in northern Europe, while yield change was negative across most of Africa and South America (Rosenzweig and Parry, 1994; Figure 6a).

Since 1994, more complete knowledge of the effects of climate on crop plant physiology has been gained and incorporated into crop simulation models, the simulation methods for impact studies are more advanced and the computing power and datasets to run global simulations have improved. As a consequence, more studies of the impacts of climate change on crop yield and production at a global scale have been published. Landmark studies include those by Cline (2007), Parry *et al.* (2004) and most recently the World Bank (World Bank, 2010; Figure 6b). These studies used different techniques for estimating climate change impacts; the study by Cline, using Ricardian statistical economic models, was quite different in method from the others, which used more traditional crop simulation model approaches.

Despite these differences in method and the 16-year period over which these studies were conducted, the general pattern of change in crop productivity has remained the same across all four global studies, although the magnitude of crop impacts varies at global scale. In general, crop yields experience more negative impact across many parts of the tropics, compared with higher latitudes where yield impacts can be positive, especially in the northern hemisphere. Precise projections vary according to the climate model scenario used and the time scale over which the projection is done – with simulations becoming more negative further into the future; however, the broad-scale pattern of climate change impacts has been consistent over the 20 years or so of research. It seems reasonable to conclude that there is a robust and coherent pattern of impacts of climate change on crop productivity, and most likely on food availability, at a global scale.

Within this consistent broad-scale pattern of climate change impacts on food availability it is also clear that many of the negative impacts occur in developing countries, where there is already a high level of food insecurity. Wheeler and von Braun (2013) showed a close spatial association between the global distribution of negative impacts on crops and areas where food insecurity is high, as quantified by the International Food Policy Research Institute (IFPRI) Global Hunger index (Von Grebmer *et al.*, 2012). A number of concerns for food security underlie this simple association. Many negative impacts on crops are projected in areas where current climate conditions are already marginal (hot or dry) for productive cultivation of crops. In addition, technologies and farm management systems that could aid adaptation to negative climate change impacts are absent or underutilized in many developing countries, where direct climate impacts are projected to be greatest. Such considerations led Wheeler and von Braun (2013) to suggest that climate change impacts will hinder progress towards a world without hunger.

Studies of crop yield impacts under climate change across Africa and South Asia have recently been the subject of a systematic review (Knox *et al*., 2012). Systematic methods for summarizing research evidence are rare in the field of agricultural research; they are found more commonly in the health and medical literature. Knox *et al.* (2012) reviewed 1144 existing studies of the impacts of climate change on a selection of crops (wheat, maize, sorghum, millet, rice, cassava and sugar cane) in Asian and African countries. Systematic review protocols require that each study be screened against a strict set of inclusion criteria. Of the initial studies, 52 were selected for meta-analysis on the basis of strict quality criteria. The projected average mean change in yield of all crops across both regions was -8 percent by the 2050s. Across Africa, yields changed by -17 percent for wheat, -5 percent for maize, -15 percent for sorghum and -10 percent for millet. Across South Asia yields changed by -16 percent for maize and -11 percent for sorghum under climate change averaged over studies examining projections from 2020 to 2080. The magnitude of yield impacts increased over this period. No mean change in yield was detected for rice, possibly because most of the simulations in Asia were of rice grown in paddies, which would tend to minimize any signal from changes in rainfall.

Within these mean yield impacts, Knox *et al.* (2012) were able to identify some common features of different impact methods. For example, variation in the projected mean yield change for all crops was smaller in studies that used an ensemble of more than three GCMs. Complex simulation studies using biophysical crop models showed the greatest variation in mean yield changes. The authors concluded that evidence of the impact of climate change on crop productivity in Africa and South Asia is robust for wheat, maize, sorghum and millet but is inconclusive, absent or contradictory for rice, cassava and sugar cane.

4.2 Local, national and regional studies of impacts on crop production and yield

The impacts of climate change are expected to vary from one part of the world to another and to change over time. Consideration of local contexts within the large-scale global trends discussed in the previous section is important for providing information to farmers and their advisers seeking to adapt to these new challenges, because many adaptation actions are undertaken at the farm or national scale. Global estimates generally simulate the impacts of changes in mean seasonal temperature and monthly rainfall on crop yields, whereas the evidence from crop experiments suggests that it is the extremes of climate, which are often local, that will have the most severe impact on crop productivity (Wheeler *et al.*, 2000). More detailed crop simulations, possible at country and regional scales, could also consider these finer time scales of weather extremes.

National scale assessments of the impacts of climate change on crops can potentially use information with finer resolution on climate, soils, and topography for crop simulation. This is especially relevant for large countries such as China, as its large natural climate variability adds a further level of uncertainty to projections. For example, interannual variation in the East Asian summer monsoon and the El Niño Southern Oscillation account for 14 percent and 16 percent, respectively, of the variation in maize yields from year to year (Tao *et al*., 2004), and national maize yields decline by 5 percent during an El Niño phase (Tao *et al*., 2004). Changes in some climate parameters, principally temperature and precipitation, during the last fifty years (Wang *et al*., 2004; Zhai *et al*., 1999) may have already advanced the harvest date of crops in China (Dong *et al*., 2009).

Much finer grid scales of 5-20 km place even greater limits on the skill of predictive science than national and global scales. Additional uncertainties arise from: the method by which the output of global-scale climate models is downscaled; whether input data (such as crop, soils, typography and management information) are available across the domain for crop simulation at this scale; and general questions about the skill of the simulation methods across a fine-scale domain. It is not surprising that the sheer complexity of food production systems at a very fine scale makes them difficult to reproduce in numerical models.

A simple visual comparison of fine-scale projections of climate change impacts for maize crops in East Africa illustrates the challenges of coping with uncertainty (Figure 7; Thornton *et al*., 2009). This projection gives fine-scale information that is completely absent from projections at the broad scale (Figure 6). However, comparison of different fine-scale impact studies often shows disagreement in both the signal and magnitude of the simulated changes in crop productivity at any one location. Of course, as in global studies, each regional study varies in terms of data inputs and simulation methods used, and so in a sense these studies reflect the uncertainty space for crop impacts under climate change at these fine scales. One further level of analysis is needed to help with the interpretation of small-scale impacts: a test of how well these fine-scale simulations compare with observations in the current climate. Such tests of model skill are found in some studies at the global scale – for example, Osborne *et al*. (2012).

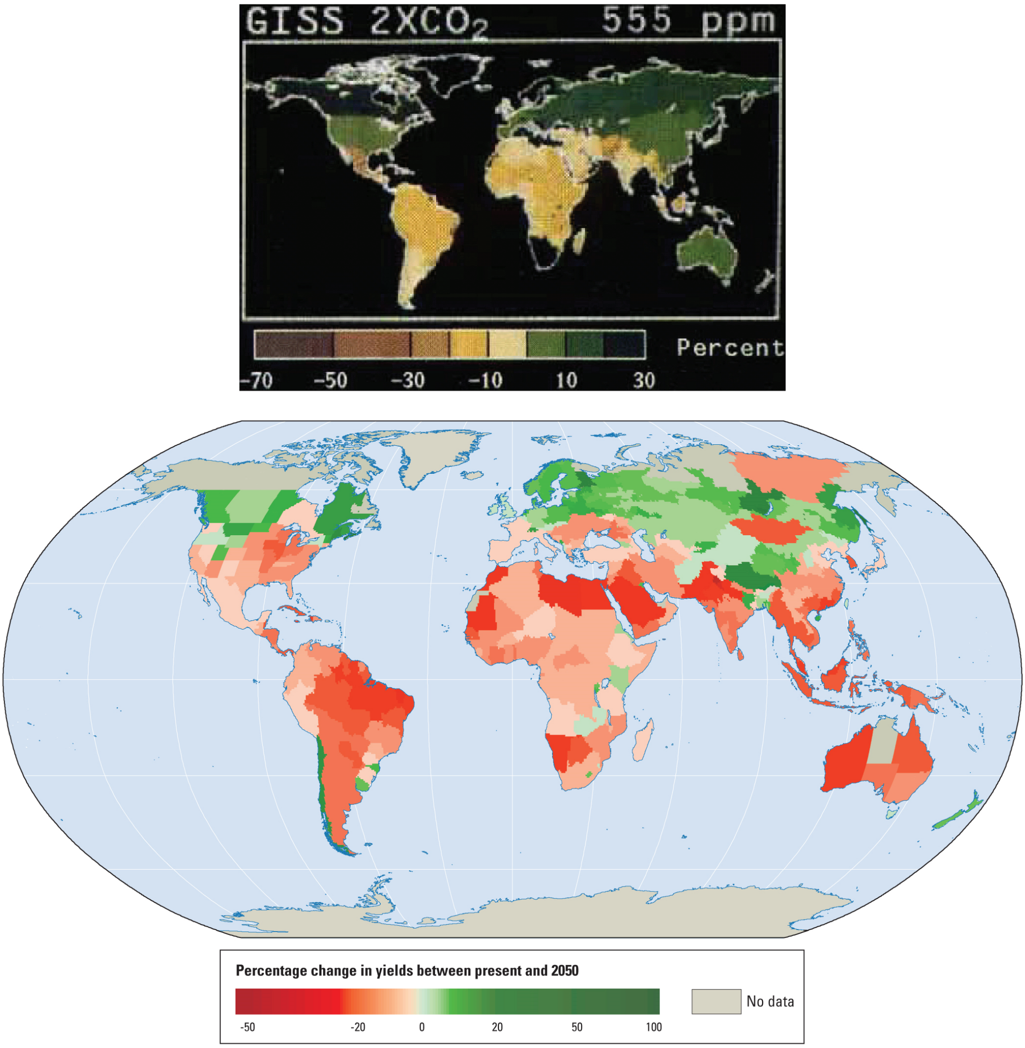
5. Impacts on food access, utilization and stability

Climate change impacts on food access, utilization and stability are often less direct than those on food availability; however, these dimensions of food security do have strong links to climate change. Perhaps because the impacts are more indirect, the evidence is less well-developed for these dimensions of food security. Wheeler and von Braun (2013) reviewed the evidence of food security impacts of climate change following publication in 1990 of the first IPCC report. They concluded that studies of the impacts of climate change on the food availability dimension of food security dominated the evidence base, with 70 percent of publications on this single dimension alone. Wheeler and von Braun (2013) summarized the main indirect effects of climate change on food access, utilization and stability as described in the following paragraphs.

Access to food depends on levels of household and individual income. Two approaches have been used to assess the impacts of climate change on access to food: top-down models

figure 6

Global Global impacts of climate change on crop productivity from simulations published in 1994 (top, from Rosenzweig and Parry, 1994) and in 2010 (bottom, from World Bank, 2010)



Source: Wheeler and von Braun, 2013

that attempt to link macro shocks to household level responses and adaptation outcomes; and community and household level studies that try to assess climate change effects from the bottom up. The International Food Policy Research Institute's (IFPRI) International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model is an example of a top-down approach. It connects climate change scenarios with food supply effects and market and price outcomes, and traces the economic consequences of food availability drivers to access and utilization of food, including food energy consumption and children's nutrition (Brian *et al*., 2009; Nelson *et al*., 2010).

Studies at the micro level of communities and households that are exposed to climate shocks capture more adaptation capabilities than macro models such as IMPACT – for example, asset drawdown, job-switching migration, social policy responses and collective action for assistance (Kato *et al*., 2011; Silvestri *et al*., 2012; Trærup, 2012). Although these approaches provide fine-scale detail, they omit the associated risks of climate change that cut across broad regions. Given the expected changes in the geography of agricultural production under climate change, the comparative advantage to producing certain products at regional and international levels is also likely to alter. This will have production implications for all agricultural output – food, feed, fuels and fibres – and that will affect food trade flows, with implications for farm incomes and access to food (Hertel, *et al*., 2010).

The utilization of food is closely linked with the general health environment and with water and sanitation. Any impact of climate change on the health environment also has an impact on food utilization. The clearest link found in the literature on climate change is the research on freshwater resources. There is widespread agreement that climate variability and change will have an impact on water resources and the availability of clean drinking water (Kundzewicz *et al*., 2007; Delpa *et al*., 2009). Hygiene is also likely to be affected by extreme weather events, such as flooding in environments where sound sanitation is absent (Griffith *et al*., 2006; Hashizume *et al*., 2008; Shimi *et al*., 2010). Additionally, uptake of micronutrients is affected negatively by diarrheal diseases, which are strongly correlated to temperature (Schmidhuber and Tubiello, 2007).

Other indirect impacts of climate change on nutrition may be seen through risks to the safety and quality of food. Contamination of food by mycotoxins is a major health and nutrition issue in areas where changes in climate could increase human exposure to toxins in the food chain. For example, the soil-borne fungus *Aspergillus flavus* can infect the pods of groundnut or developing grains of maize, where under certain conditions it produces the mycotoxin, aflatoxin. The chain of influence on the processes that lead to contaminated produce are complex, but they are partly dependent on weather conditions close to the time of harvest and during crop storage. Increased storage costs and storage pest attacks may result from ecological shifts in a warmer world (Paterson and Lima, 2010; Tefera, 2012). Science and innovation have a role to play here, such as the progress in recent years on improving food utilization through fortification and biofortification[3], which connects food availability with the utilization dimension of food security, such as through the development of vitamin A-enhanced sweet potato varieties (Bouis, 2003; Nestel *et al*., 2006).

While problems of insufficient and poor-quality food persist, changes in the global environment are creating new nutritional issues, such as the "nutrition transition"—a process by which globalization, urbanization and changes in lifestyle are linked to changes in diet towards excess caloric intake, poor-quality diets, and low physical activity. Together, such changes can lead to rapid rises in obesity and chronic diseases, even among the poor in developing countries (Popkin *et al*., 2012). The nutrition transition will unfold in parallel with the climate change process in coming decades.

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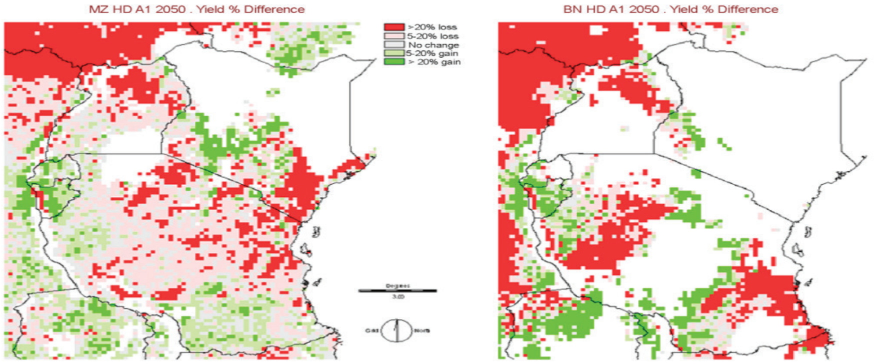
[3] Biofortificationapplies plant breeding techniques to enhance desirable nutrient elements. Fortification is adding desirable nutrients to food intake in whatever form.

figure 7

Projected yield changes for maize in East Africa for the year 2050
(from Thornton *et al*., 2009)



Wheeler and von Braun (2013) concluded that the stability of entire food systems may be at risk under climate change, largely because of short-term variability and extreme events in agricultural markets. Climate change is likely to increase food market volatility from the production and supply side (see, for example, Mearns *et al*., 1996). Stability can also be endangered from demand-side shocks, such as bioenergy subsidy and quota policies (Beckman *et al*., 2012), and a broader set of risks that can trigger ripple effects for broader destabilization of food security. These include: the risk of high and volatile food prices, which temporarily limit poor people’s food consumption (Arndt *et al*., 2012; Campbell *et al*., 2010; de Brauw, 2011; Torlesse *et al*., 2003); financial and economic shocks, which lead to job loss and credit constraints (Smith *et al*., 2002); and risks posed by political disruptions and failed political systems (Berazneva and Lee, 2013). These complex system risks can assume a variety of patterns, and can become catastrophic in combination.

6. Mitigation and adaptation in the agricultural sector

A key incentive for adaptation in the agricultural sector is that the world is already committed to some degree of climate change resulting from past emission of greenhouse gases (IPCC, 2007b) and can expect a further degree of climate change from future greenhouse gas emissions. A need already exists for adaptation to the impacts on global food security that will be experienced because of emission of greenhouse gases in the past. Adaptation can address potential negative impacts or it may exploit any opportunities that may arise from climate change (for example, Figure 6). It is important to recognize possible opportunities even though negative impacts, quite rightly, get the bulk of attention, particularly in developing countries.

Local context and detail are vital to adaptation in practice. Autonomous adaptation is likely to take place spontaneously. In the farming sector, for example, a sorghum farmer – without any new technology or climate-smart policy incentives – can make decisions about the timing of sowing and harvesting, the choice of crop types from those available, and the management of labour, providing that he or she has access to a range of technologies and the knowledge to use them effectively. However, this does not rule out features of adaptation that operate at much larger scales, such as the development of agrotechnologies and the importance of national and international policies. Clearly, there are both large-scale and small-scale aspects to adaptation to climate change impacts.

Planned adaptation requires investment and significant lead times, to cover capital costs and/or for development of technology. For example, the development of heat-tolerant crop varieties, or the installation of post-harvest storage facilities for a warmer climate, require considerable expertise, capital investment and long lead times. However, many production-related adaptation actions will remain local by nature. More broad-scale adaptations are often trade-related and/or public policy-related, such as social protection for nutrition.

There will never be "perfect" adaptation of agriculture to climate change. Some negative impacts are likely to remain even after adaptation actions and investment. This "residual damage" may result in increased food insecurity and dealing with it requires a degree of resilience to climate change (Pingali *et al*., 2005). The concept of "resilience" came from the field of ecology and describes the ability of an ecological system to recover from a shock, climatic or otherwise. In recent years, those working on adaptation to climate change have applied these concepts to other natural and social systems. The thinking is that better resilience to climate variability and change can be increased by building institutional capacity to respond to shocks, investing in infrastructure, establishing social protection measures and the like. An appealing aspect of this approach is that it does not matter what the precise degree of projected climate change is for a particular location or time frame – a more resilient agricultural system, better able to cope with the impacts of variability in the current climate, should be better prepared for climate change.

Crop technologies that provide better protection against extreme weather events can be a useful contribution to more resilient food production systems and, in many cases, can be the only effective approach. For the example of heat stress effects on flowering, described in Section 4, the impact of extreme heat depends on the timing of the sensitive crop phase (flowering), the degree of heat at that time and the genetic tolerance of that crop variety to heat during this sensitive phase (Wheeler *et al*., 2000). The duration of the heat-sensitive phase is often short – a matter of a few days, or even just the morning hours within the day (Prasad *et al*., 1999). Agricultural management options to mitigate these impacts are therefore limited. In theory a more heat-tolerant crop variety could be sown at the start of a season when hotter than average weather conditions are forecast by seasonal climate models, but this strategy contains two serious drawbacks. First, no climate model can forecast, three to six months ahead of time, the air temperature in a particular location at the fine time scale required to anticipate heat stress at flowering. Second, even if a robust forecast of heat wave conditions were available at the time of sowing, it is unlikely that there would be a supply of seed of alternative varieties available in sufficient quantities to allow large numbers of farmers to change their sowing plans at the last moment. The seed system itself would need to be responsive to changes in agricultural decisions about sowing, and that requires large-scale, concerted, sector-wide management long before the time of sowing.

Crop improvement programmes that provide planting material with increased tolerance for extreme weather in current varieties – or varieties that are at least as acceptable as current ones – are a valuable part of an adaptation and resilience strategy. For the crop heat stress example, Jagadish *et al.* (2008) have identified more heat-tolerant genotypes of rice based on the N22 variety. Considerable progress has also been made throughout Asia in breeding rice with tolerance to flooding. Flash floods and typhoons often result in heavy production losses for paddy rice. In Bangladesh and India alone, such losses amount to an estimated 4 million tonnes of rice per year – enough to feed 30 million people. Five days of complete submergence will destroy most rice crops. However, identification of submergence tolerance displayed by an Indian variety, called FR13A, has led to successful breeding of submergence-tolerant varieties known as "scuba" rice that can withstand up to 17 days of complete submergence. Marker-assisted backcrossing was used to transfer flood-tolerant traits, such as the gene *sub1A,* into commercially valuable rice varieties without losing useful characteristics – such as high yield, good grain quality or pest and disease resistance.

Typically, during a flood, rice plants will extend the length of their leaves and stems in an attempt to escape submergence. The *sub1A* gene is activated when the scuba rice plant is submerged, effectively making the plant dormant and allowing it to conserve energy until the floodwater recedes. This gene also induces tillering (production of lateral branches), once water has receded. Six rice "mega varieties" – flood-tolerant versions of high-yielding local rice varieties, popular with farmers and consumers – were tried and tested on farmers' fields across Asia. The first variety developed, *Swarna-Sub1*, showed high survival under submerged conditions compared to the original variety *Swarna*, and gave yield advantages of 1 to 3 tonnes per hectare over *Swarna* when submerged. The improved *Swarna-Sub1* variety is now targeted to replace *Swarna* on some 5 to 6 million hectares of rice in eastern India and Bangladesh. The development of new Sub1 varieties is now underway in Cambodia, Indonesia, Lao PDR, Myanmar, the Philippines, Thailand and Viet Nam. Salt tolerance has already been introduced into *Sub1* varieties and the introduction of drought tolerance and tolerance to stagnant flooding is currently being examined.

A recent programme developed by the International Livestock Research Institute seeks to increase the stability of the livelihoods of small-scale herdsman in northern Kenya, who are vulnerable to drought. An innovative insurance product has been developed that uses satellites to detect the "greenness" of the natural pasturelands as an indicator of potential mortality of livestock. Herdsman pay about one-third of the cost of one animal as the premium to insure 10 animals. When a shortage of pasture is detected, the insurance pays out. The Government of Kenya intends to roll out the livestock insurance product further in 2014, providing herdsmen with improved financial resilience to climate variability.

The agriculture sector is a major contributor to human-induced climate change, through emissions of greenhouse gases and changes in land use. Estimates vary regarding the contribution of the agriculture sector to climate forcing, but are usually in the range of 20 to 25 percent of the global total (IPCC, 2007b). The latest IPCC report estimates that the net temperature change attributable to the agriculture sector will be about 1°C over a 100-year time horizon (IPCC, 2013b). Processes such as methane generation from paddy rice cultivation and from ruminant livestock, nitrous oxide release from fertilizers applied to soils and agricultural energy use are the dominant contributors. Smith *et al.* (2013) termed these factors supply-side options. They can be targeted to reduce climate forcing from agriculture, depending on the balance of costs. In contrast, demand-side options address both climate mitigation and food security targets; examples include reduction of waste throughout the food chain and large-scale changes in diet towards more efficient and lower-emission options. Smith *et al.* (2013) identify these demand-side mitigation options as potentially the most effective interventions for achieving multiple gains from the agricultural sector.

7. Understanding and working with uncertainty about climate change impacts on food security

Many aspects of climate change are subject to uncertainties, although those who study climate change impacts are better equipped than those in other disciplines for trying to quantify these. It is important to acknowledge a fair degree of uncertainty in the evidence of climate change impacts on food security that arise from projections of climate change, sources of natural variability in climate and future emissions of greenhouse gases, as well as uncertainties in our understanding of the underlying science, both of climate and impacts. Hawkins and Sutton

(2009) showed how the uncertainties from intrinsic variability, climate models and emission scenarios on global temperature can change over time. Such trends in sources of uncertainty over time will also be apparent with respect to impacts on food systems. Food systems, however, are ultimately driven by people and their behaviour, responding to real and perceived changes in their local climate. Additional uncertainties regarding the impacts of climate change on people arise because there are many influences on people's lives other than climate, making it difficult to second-guess how individuals, communities and countries will respond to climate change and its impacts on food systems.

Most evaluations of possible climate change impacts use the output from a climate model, usually a GCM. Models of climate change impact on agriculture vary in scale from global to local. Whichever scale is chosen, there is a reliance on GCMs to accurately simulate changes in climate variables, which are then averaged for a likely regional value or downscaled to give an indication of local change. Climate models are not always able to accurately simulate current climates (Semenov and Barrow, 1997) and the uncertainty inherent in any modelling process should be taken into consideration in any assessment of climate change impacts. Climate models are particularly prone to errors in rainfall, which is sometimes excluded (Mall *et al*., 2004) or modified (Žalud and Dubrovsky, 2002) in agricultural impact assessments. Most studies use present-day climate maps to train the models, and adjust these using modelled differences ("anomalies") between current and future results from the GCM in order to project future impacts.

GCM models typically operate on spatial scales of about 200 km, which is much larger than the spatial scale of most crop models (Hansen and Jones, 2000; Challinor *et al*., 2003). To overcome differences in spatial scale, climate data can be downscaled to the scale of a crop model (e.g., Wilby *et al*., 1998), or a crop model can be matched to the scale of climate model output (e.g., Challinor *et al*., 2004).

Simulation modelling of crop growth, development and yield has traditionally focused on field-scale simulations, using detailed information on soils, climate, crops and management as inputs to the modelling. Therefore, for climate change impact studies, there is a spatial disparity between the scale of projections of climate derived from GCMs at grid sizes of 200 km or more and field-based crop simulations. One method that addresses this difference in spatial scale and the heterogeneity of small-scale crop management is to upscale crop parameter values. A Bayesian approach[4] has been developed to upscale crop parameter values for paddy rice in Japan using a crop parameter ensemble to represent small-scale heterogeneity in crop characteristics (Iizumi *et al.*, 2009).

Climate input for crop simulation models can also be downscaled to field scale. For example, the computing power of the Earth Simulator supercomputer at the Japan Agency for Marine-Earth Science and Technology in Yokohama, Japan, is being used to run higher resolution global climate models at grid sizes of 25 km. Crucially, higher resolution produces weather-resolving climate models with improved descriptions of water and other fluxes between the land surface vegetation and the atmosphere. Statistical downscaling using weather generators can also provide weather data directly at a point scale, for input to crop simulation models based on the features of observed weather at that point. For example, the Long Ashton Research Station (LARS) weather generator has been used to study the impacts of extremes of weather on wheat; for simulations in the United Kingdom, this approach has revealed the importance of extremes of high temperature for the yield of wheat under climate change (Semenov, 2009).

Another approach to bridging the scales of climate and crop models is to use an intermediate complexity crop model that is run at the same spatial scale as a climate model. The General

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[4] A statistical approach based on probabilistic inferences.

Large Area **Model** (GLAM) for crops takes this approach and, because it is process-based, it is able to reproduce the effects of variability in climate on crop yields (Challinor *et al*., 2004). In addition to climate, crop management and agricultural technology have strong influences on yields attained in farmers' fields.

Projections of impacts on food systems to date have used the output of climate models to drive crop simulations for future conditions. However, climate and land surface processes are intrinsically linked by feedbacks – for example, in the exchange of energy, carbon and water. The dynamic nature of natural vegetation change has often been included in the land surface schemes of climate models or integrated Earth system models; these have been used to explore the role of land surface processes in global environmental change but croplands have only recently been included (for example, Osborne *et al*., 2008). Cultivating crops that require management such as irrigation, fertilizer application and harvesting, will also affect the interaction between the land surface and atmosphere.

The research science community routinely explores the uncertainty in climate change impacts and understanding of the contributions of different sources of uncertainty to climate change projections of some aspects of food security continues to increase. However, real issues may arise regarding how this uncertainty is communicated to those who want to use research evidence. Despite the very real uncertainties in the underlying science, decisions still need to be made by a whole range of decision-makers, from policy-makers to practitioners in the agricultural sector. Moreover, decisions can only be made using the best evidence that is available at the time and they cannot wait until "perfect" knowledge is achieved.

8. Towards climate-compatible food policies

A reasonable aspiration for many of those working in national and international policy bodies is to use evidence from the research community to develop new policies and to inform policy-relevant decisions. Although original research outputs can be important sources of evidence for policy, synthesis reports are particularly vital. Clearly, there is an important role for regular synthesis reports, such as those of the IPCC and relevant reports of series such as the World Development Reports, whose 2010 edition concerned development and climate change. However, such extensive reports require considerable commitment from thousands of experts over long periods of time. Although these reports have good coverage of emerging consensus findings from the evidence on climate change impact, they inevitably lack a lot of country- or location-specific detail. In addition, the period between major synthesis reports can be quite long – such as the seven years that elapsed between the IPCC 4th and 5th assessment reports. So there is also an important role for national and international organizations, such as think tanks and consultancy organizations, to provide finer-level and more rapid analyses tailored to specific policy requirements for information and knowledge. Web-based global knowledge networks have also been created to disseminate climate change knowledge – for example, the Climate and Development Knowledge Network (www.cdkn.org) – and these can be portals for sharing more experiences and lessons of policy initiatives. For all these sources of information for policy-makers, the way in which knowledge is communicated is paramount.

9. Conclusions

Much attention has been focused recently on how the global food system can cope over the coming decades with increases in the human population, changes in diet, and greater demands on energy and water resources. Climate variability and change will add further stresses to food production in the future. Understanding these complex impacts on food crops is a grand global challenge for research. The impacts of climate change on food security will vary from one part of the world to another and they will change over time. Local context within large-scale global trends is important for providing information to farmers and their advisers seeking to adapt to these new challenges. Adaptation strategies and investment will be needed in response to climate change, from developing new technologies – such as improved crop and livestock varieties – to building resilience to climate within agricultural communities.

In addition to these challenges from climate change, there is clearly a need for a more productive agricultural sector, in order to meet the increasing demand for food products expected over the coming decades and hence to contribute to global food security. On balance, we should anticipate substantial risks to the volume, volatility and quality of food crop and animal feed supply chains as the result of climate change. Adaptation strategies and investment informed by high-quality research evidence will be needed, both to respond to climate change and to meet the anticipated higher demand for food products in the years to come. Those making policy decisions will need robust, evidence-based advice on which to base their actions.

Based on the current evidence regarding climate change impacts on food security, one clear message for decision-makers, whether as policy-makers, retailers or practitioners, is that there is no single trajectory of climate change impacts for the future. Instead, there will be a range of possible outcomes – some more likely than others – and all of them will depend on the part of the world being considered. Nevertheless, we can be confident about one thing: the climate change risks to agricultural output, to food systems and to food security will increase over time and therefore must not be ignored by those making medium- and long-term planning decisions about food security.

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