Chapter 3
Impacts and sensitivities in agriculture

Uncertainty issues

The effects of climate change on agriculture are characterised by various forms of uncertainty. First, as previously mentioned, there are uncertainties concerning the rate and magnitude of climate change itself. Second, there are uncertainties around the biological response of agricultural outputs, for example with regard to CO_2 fertilization. Third, there are uncertainties as to how society responds — or even has the capacity to respond — to projected and expected impacts. Some aspects of climate change research are limited by fundamental, irreducible uncertainties. Some of these uncertainties can be quantified, but many simply cannot, leaving some level of irreducible ignorance in our understandings of future climate uncertainty (Dessai and Hulme, 2004).

Before highlighting some of the more important uncertainties inherent in understanding the impacts and sensitivities in agriculture, the point must be made that decisions will need to be made despite continuing uncertainty. The recently published *Garnaut Review* (Garnaut, 2008) in Australia highlights that uncertainty surrounding the climate change issue is a reason for disciplined analysis and decision, not for delaying decisions. A perceived lack of reliable predictions of future climate is sometimes argued to pose a major limit for effective adaptation to climate change. Often this argument is used to justify further investment in climate modelling capabilities in order to improve predictions of future climate (Hulme and Dessai, 2008). In an assessment of climate prediction and adaptation to climate change, Dessai *et al.* (2009) argue that society can (and indeed must) make adaptation decisions in the absence of accurate and precise climate predictions. Box 3.1 provides a description of how uncertainty is being tackled in the United Kingdom by the UK Climate Impacts Programme (UKCIP).

Part of the reason why there are diverging estimates of temperature and other variables into the future is associated with not knowing accurately how the climate system reacts to unprecedented emissions of greenhouse gases, or not knowing how clouds, forest, grasslands and particularly the world's oceans react to climate perturbations and how they feed back into the system. This uncertainty surrounding future climate projections is often manifest in ranges of estimates for particular climate parameters (as shown in Figure 2.1). Recent research (Lobell and Burke, 2008) finds that uncertainties in average growing season temperature changes and the associated crop responses represent a greater source of uncertainty for future impacts than associated changes in precipitation. This is contrary to the widely-held assumption that improved rainfall projections would reduce uncertainties in projections of climate change impacts on agriculture. The relative contribution of precipitation, temperature effects, extreme events, CO_2 fertilization effects, pests and diseases, solar radiation and the crop response to these factors is poorly understood. Box 3.2 provides a brief discussion of uncertainties associated with climate models.

Box 3.1. UKCIP scenarios and decision-making under uncertainty

The United Kingdom's Climate Impacts Programme (UKCIP) is developing an up-dated set of scenarios to replace the current widely-used scenarios (UKCIP02). The new scenarios will create a large ensemble simulation of future global climate. The results of each model version will be weighted according to how well it represents current climate, and its recent evolution, and these projections will be used to build a picture of the probability of different climate outcomes. Single model results from other IPCC climate models will be incorporated to address uncertainties resulting from the structures of different climate models, and the results will be down-scaled to provide more details about the changes expected across the United Kingdom. For each emissions scenario, users will be presented with a probabilistic distribution of outcomes to explore the uncertainties. This probabilistic representation of uncertainty is the key innovation of UKCIP09.

In addition to the scenarios, UKCIP provides a tool for supporting decision makers in identifying and managing their climate risk in the face of uncertainty. It is based on standard decision-making and risk principles and encourages users to consider their climate risks alongside their non-climate risks. As well as the framework, UKCIP provides guidance in the form of a technical report: Climate Adaptation: risk, uncertainty and decision-making (Willows and Connor, 2003).

See: www.ukcip.org.uk/images/stories/Pub_pdfs/08_booklet.pdf.

Changes in land cover, sometimes as direct response to predicted changes, may directly or indirectly feed back into the climate system. Research suggests that changes in land cover can provide an additional major forcing of climate, through changes in physical properties of the land surface (Denman *et al.,* 2007; Pielke *et al.,* 2002). Several studies have shown that changes in land-use such as deforestation, afforestation and the conversion of land to pasture or agriculture have the potential to affect the climate system (Chase *et al.,* 2000; Betts, 2000). Afforestation is a widely cited mechanism for sequestering CO_2 from the atmosphere, however in some cases afforestation could result in a positive radiative forcing, resulting in a net warming despite the removal of CO_2 from the atmosphere (Pielke *et al.*, 2002). This would occur, for example, in regions with significant snow cover becoming extensively reforested resulting in a lower surface albedo. Further examples include the potential release of carbon from soils under warming conditions, resulting in what was a carbon sink becoming a source. Drought and hydrological feedbacks associated with land-use change have a direct impact on the source or sink capabilities of terrestrial ecosystems. These issues create further uncertainty when attempting to understand the climate system and should be considered in land-use decision-making.

Box 3.2. Uncertainties in climate models

Climate model uncertainties

Estimates of future climate change are generated by climate models which are mathematical representations of the climate system, expressed as computer codes. **These** models have been developed and refined over many years now. For some climate variables, such as temperature, confidence in the estimates is relatively high, while for others, such as precipitation, there is a lower degree of confidence.

Climate models are based on established physical laws and a large number of observations. This provides a basis for confidence in their projections, as does the routine and extensive assessment and comparison of the simulations with real-life observations. In addition, models have been used to simulate ancient climates and can reproduce many historical climate features and observed aspects of climate change over the past centuries over the time records available. There are therefore many reasons to have confidence in climate models.

However, there are still significant uncertainties associated with some aspects of the models. Deficiencies regarding tropical precipitation, large-scale oscillations and the representation of clouds are some examples where limitations in scientific understanding or the availability of detailed observations lead to modeling errors. As a consequence, models display a substantial range of global temperature change in response to specified greenhouse gas forcing. Projections are thus presented as a range of values.

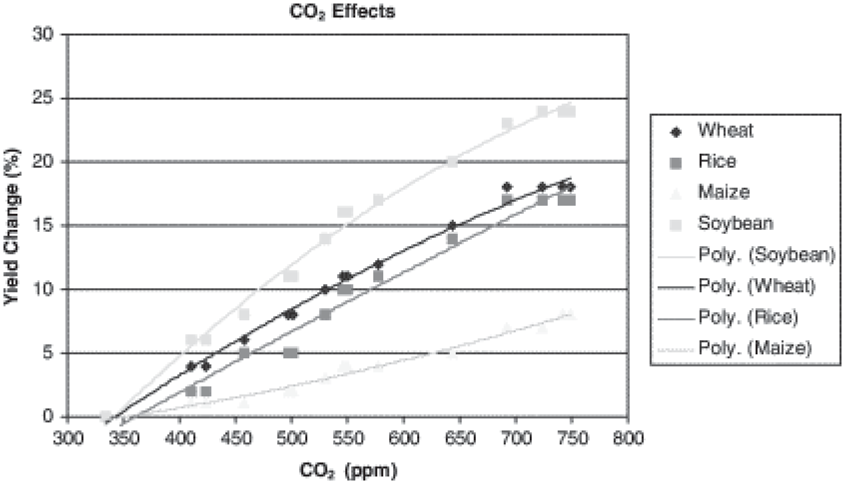
Source: Randall *et al.* (2007).

The greatest uncertainties in assessing impacts and responses are those associated with physical and biological processes, on the one hand, and of economic and social responses on the other. Climate model uncertainties translate into downstream uncertainties in projecting impacts of climate change. For the agricultural and water sectors inter-climate model differences in rainfall change, for example, represent a barrier to the effective use of climate change information for seasonal forecasting and other water users.

In terms of biological and physical processes, agronomy and agricultural meteorology have invested heavily in research over the past decade to understand field-level processes that will affect agricultural productivity and yield. Great strides have been made to estimate the combined response of agricultural crops to changes in water availability, temperature and elevated ambient CO_2 (now standing at 380 ppmv in the atmosphere compared to 270 ppmv in pre-industrial times). Most important agricultural crops exhibit higher rates of photosynthesis with higher ambient CO_2. High CO_2 also reduces transpiration per unit leaf area and hence may lead to improved water-use efficiency. Thus there are potential increases in yield from major crops from elevated CO_2 on its own, as shown in Figure 3.1. But of course the higher ambient CO_2 will also ultimately translate into changing climatic parameters – potential CO_2 effects on plant biomass depend on the availability of water and nutrients (Parry *et al.,* 2004). Hence, the positive impacts of elevated CO_2 can only be realised if other parameters of biological productivity are not limited. Current research on agricultural impacts now takes on board these issues into underlying crop models (Parry *et al.,* 2004; 2005). But emerging evidence from agronomic scale experiments of enhanced CO_2 and ozone show smaller increases in yield than anticipated from the experiments reported in Figure 3.1, as well as large yield losses of around 20% for the major rice crops under elevated tropospheric ozone (also projected to increase along with CO_2) (Long *et al.,* 2005). The case is therefore made by some agronomists that many results on global food security depend on optimistic assumptions concerning yield and hence underestimate the impacts of climate change on production and on welfare.

A further major issue is the availability of water for agriculture both for rain-fed and for irrigated systems. This is an area of greater uncertainty in the impacts of climate change than that of temperature change (or sea-level rise), with models needing to capture evapotranspiration, regional climates, albedo effects, and other feedbacks in the climate system in order to project precipitation rates (Arnell, 2003; Gordon *et al.,* 2005). Around 1.4 billion people are already estimated to be living in countries deemed to be suffering from water stress, withdrawing more than 20% of the available water resources and having little room for manoeuvre or scope to increased irrigated area. This situation is likely to be severely exacerbated by climate change, which is projected to cause significant drying in areas already under stress. Arnell (2004) estimates changes in populations experiencing water stress. He uses a measure of water availability *per capita* (a threshold of 1 000m^3 *per capita* per year) as the primary measure of water stress, rather than a measure of present or future withdrawals of water (perhaps more relevant for agriculture). Table 3.1 presents results for selected regions under two selected scenarios of climate from one well established model (HadCM3) and related socio-economic changes that represent changes in populations living in the regions and their location and settlement over time, as well as the rates of economic growth and the relative convergence of these rates in different parts of the world (for methodological discussion on these types of scenarios and on the detail of the so-called IPCC "storylines", see Berkhout *et al.* [2002] and Nakićenović *et al.* [2000]).

Figure 3.1. The potential increases in yield exhibited by wheat, rice, maize and soybean under elevated levels of CO_2



Source: Parry *et al.* (2004).

Table 3.1 shows that there are significant changes in the number of people living with increased water stress, and in some cases living with decreased water stress, in many regions of the world. Changes in stress are also set as a threshold whereby stress occurs when the percentage change in mean is more than the standard deviation of the 30-year mean runoff (Arnell, 2004). Water availability is reduced by the 2050s in these scenarios of climate change in the Mediterranean, in parts of Europe, central and South America and in southern Africa. Clearly there are winners and losers in changing precipitation but the seasonality of precipitation is also extremely important. Greater intensity of precipitation events, such as those observed in the recent past in the United Kingdom (Osborn and Hulme, 2002), affect the changing incidence of floods and droughts. Table 3.1 also shows estimates of populations living in watersheds that are projected to have reduced water stress. But Arnell (2004) cautions that the increased runoff that produces this decrease in water stress (in southern and eastern Asia for example – Table 3.1) "may not be beneficial in practice because the increases tend to come during the wet season and the extra water may not be available in the dry season" due to lack of infrastructure to capture and manage this water for agriculture and other purposes. As with temperature and interacting effects, there are significant ranges in the estimates for water stress, compounding uncertain socio-economic and climatic futures. Nevertheless, a consistent picture emerges from Arnell (2004) and from similar studies (Alcamo *et al.,* 2003; UNEP, 2001; Vorosmarty *et al.,* 2000) – that water resources are likely to be more scarce in future due to climate change in regions already reaching critical thresholds, and that this scarcity will be compounded by changing seasonality and unpredictability in precipitation. Thus, agriculture will be competing for water as a scarce commodity in a warmer, more unpredictable world, where demand for agricultural outputs is higher due to parallel rises in global populations.

The third area of uncertainty relates to societal response to the impacts of climate change on agriculture. Here the uncertainty is characterised less by unreliable data or accurate models, but more fundamentally on contested theories of how societies adapt, the role of agriculture in economic development, and the role of over-arching parameters of global politics and policy choice. Future greenhouse gas emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. The way that society responds to changes in climate, as well as other challenges, is highly uncertain. In order to accommodate this type of uncertainty, global scenarios of alternative futures bring these issues together in the Special Report on Emissions Scenarios (SRES) of the IPCC (Nakićenović *et al.,* 2000). Box 3.3 (further below) describes the main assumptions underlying each family of scenarios. The scenarios are built on underlying model drivers that attempt to model global population projections and potential futures that attempt to analyse future worlds where, for example, free trade and global market integration occur, while in others, regional development and high environmental degradation drive policy choices (see Nakićenović *et al.* [2000]; Schiermeier [2006]; and Grubler *et al.,* [2006] for discussions of the controversies surrounding these scenarios).

Table 3.1. Number of people in the 2050s with an increase in water stress and with a decrease in water stress, for selected regions

	Scenarios of climate change + market-oriented high growth and convergence, free trade		**Scenarios of climate change + economic growth and convergence, high environmental consciousness and technological development**	
	Population living with increased water stress (mill.)	**Population living with decreased water stress** (mill.)	**Population living with increased water stress** (mill.)	**Population living with decreased water stress** (mill.)
OECD Regions				
North-west Pacific	0	546	20	445
Western Europe	183	0	140	6
Central Europe	80	0	59	0
Eastern Europe	15	0	7	0
Australasia	0	0	0	0
Canada	7	0	7	0
United States	85	6	37	0
Meso-America	33	0	34	0
Other Regions				
North Africa	218	3	138	129
West Africa	23	67	23	73
Central Africa	65	0	36	0
East Africa	13	35	100	19
Southern Africa	56	0	66	0
Mashriq	126	0	119	0

(Continued on next page)

Table 3.1 (continued)

	Scenarios of climate change + market-oriented high growth and convergence, free trade		**Scenarios of climate change + economic growth and convergence, high environmental consciousness and technological development**	
	Population living with increased water stress (mill.)	**Population living with decreased water stress** (mill.)	**Population living with increased water stress** (mill.)	**Population living with decreased water stress** (mill.)
Arabian Peninsula	23	153	4	145
Central Asia	7	0	6	0
South Asia	136	1 530	125	1 530
South-east Asia	0	6	0	6
Greater Mekong	0	0	0	0
Caribbean	21	0	21	0
South America	46	19	46	6

Notes: All results reported use the HadCM3 climate model and the IPCC SRES A1 and B1 storylines. Other models give diverging estimates for both increased and decreased numbers. Increased water stress is defined by a change to *per capita* water availability to below the threshold of 1 000 m^3 *per capita* per year. Reduced water stress is defined by a change to *per capita* water availability to above the threshold of 1 000 m^3 *per capita* per year.

Source: Arnell (2004).

There are, in addition, controversies on the ability of agriculture, and societies in general, to adapt to climate change. Adaptation is discussed in more detail in Chapter 4, however in the context of uncertainty, it is frequently assumed that the capacity of societies to adapt to climate risks is based on their level of economic development: the more economically "developed" a society, the greater the access to technology and resources to invest in adaptation (see discussion in Smit *et al.,* 2001; Adger and Vincent, 2005; Yohe and Tol, 2002; and Brooks *et al.,* 2005). Yet evidence from traditional societies demonstrates that the capacity to adapt in many senses depends more on experience, knowledge and dependency on weather-sensitive resources. Agricultural areas in the African Sahel have adapted to significant depletion of rainfall and resource availability in the course of the

20th century without apparently having major reserves or resources to invest in new livelihood sources (Mortimore and Adams, 2001). Similar evidence is emerging on adaptation in southern Africa (Thomas *et al.,* 2005). All these changes occur despite increased impacts and the scarcity of natural capital and even reduction in ecosystem services (both observed and projected [*e.g.* Schröter *et al.,* 2005, for Europe]). Uncertainty in the science of adaptation stems more from contested underlying theories of behaviour, politics and risk than from data and observation (Adger and Vincent, 2005). There is debate, for example, on what constitutes the capacity of a sector, region or country to adapt to climate change – are the elements of adaptive capacity generic and related to levels of economic development, or are they specific to climate risks faced?

Adaptive capacity is a vector of resources and assets that represent the asset base from which adaptation actions and investments can be made. This capacity may be latent and be important only when sectors or systems are exposed to the actual or expected climate stimuli. Vulnerability to climate change is therefore made up of a number of components including exposure to impacts, sensitivity, and the capacity to adapt. Adaptive capacity has diverse elements encompassing the capacity to modify exposure to risks associated with climate change, absorb and recover from losses stemming from climate impacts, and exploit new opportunities that arise in the process of adaptation.

Adaptation decisions taken by individuals (*e.g.* to use insurance, relocate away from threats, or change cropping patterns or seeds) take place within an institutional context that can act to facilitate or constrain adaptation. Some adaptation by individuals is undertaken in response to climate threats, often triggered by individual, extreme events (Reilly and Schimmelpfennig, 2000). Other adaptation is undertaken by governments on behalf of society, sometimes in anticipation of change but again, often in response to individual events. Government policies and individual adaptations are not independent of each other – they are embedded in governance processes that reflect the relationship between individuals, their capabilities and social capital, and the government. These ideas are elaborated in Chapter 4.

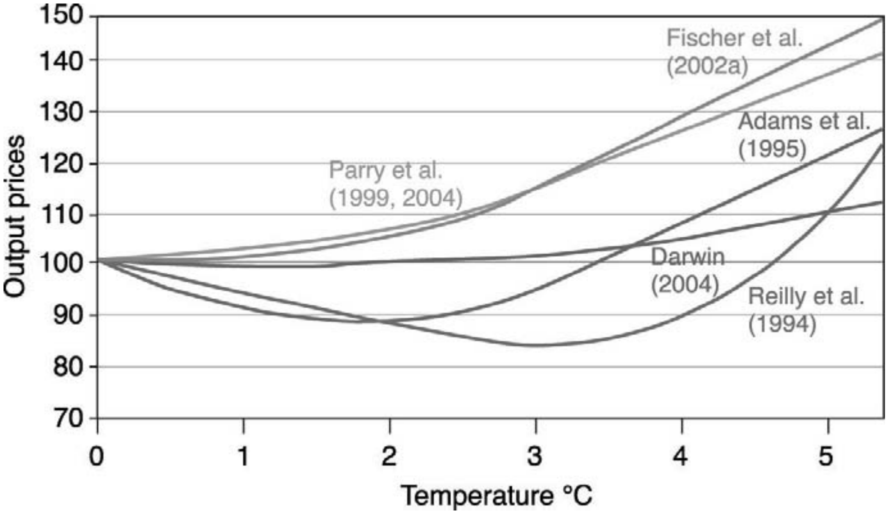
Estimates of global production, trade and food security

The most comprehensive global estimates of large-scale impacts of climate change are found in the work of Rosenzweig and Parry (1994) and subsequent studies (Parry *et al.,* 1999; 2004; 2005). They estimate the number of extra hungry people, cereal prices and yield changes that may be caused by diverse projections of climate change. These studies develop a model that uses crop yield projections using locally calibrated information from diverse regions of the world. They estimate aggregate production for countries and simulate trade in the major crops based on relative supply and demand due to increased income and population. The research has evolved to incorporate ever more accurate information on crop yields and an ever widening set of climate and socio-economic scenarios, most recently the SRES scenarios (details developed in Fischer *et al.,* 2005; Parry *et al.,* 2004). The major findings of this work are that the potential for increasing yield in high and mid-latitude countries (discussed below), is balanced by decreases in yields in the tropics and sub-tropics. These studies take this information one stage further through modelling trade and global production – this shows production shortfalls in south Asia and Africa due to climate change through the 21st century and that these lead to a risk of hunger in those regions, not only because of climate change but also due to rising populations. The measure of risk from hunger used in these studies is the number of people whose incomes do not allow them to purchase sufficient quantities of the staple cereals at prevalent prices (Parry *et al.,* 1999). These estimates must, of course, be treated with caution because they do not accurately reflect farmer adaptation and because the concept of food security and hunger is more dynamic than captured by the growth potential of the crops on which consumers and producers rely. In addition, rural economies are not necessarily reliant solely on agriculture and are often highly diversified (Ellis, 2000). Rising real cereal prices also affect demand for on-farm labour and farm profitability – such feedbacks are difficult to capture in the global modelling framework.

Figure 3.2 illustrates projects of cereal prices at changes in global mean temperature for a range of major modelling studies. Studies that incorporate trade effects point to real agricultural output price decline even up to 2.5°C mean temperature increase as long as there are modest increases in precipitation (Adams *et al.,* 1995; Darwin *et al.,* 1999 – review in IPCC report; Gitay *et al.,* 2001). However, the suite of results from Parry *et al.* (1999; 2004; 2005) shows real price increases whatever the global mean temperature rise, reflecting increasing real scarcity in agricultural production given variations in future global populations and real demand for food. But although small changes in climate parameters in the major growing regions of the world over the next one or two decades are not expected to produce significant impacts on prices or absolute scarcity, this aggregate analysis hides real vulnerability and food insecurity both at local geographical scales and even for some regions of the world.

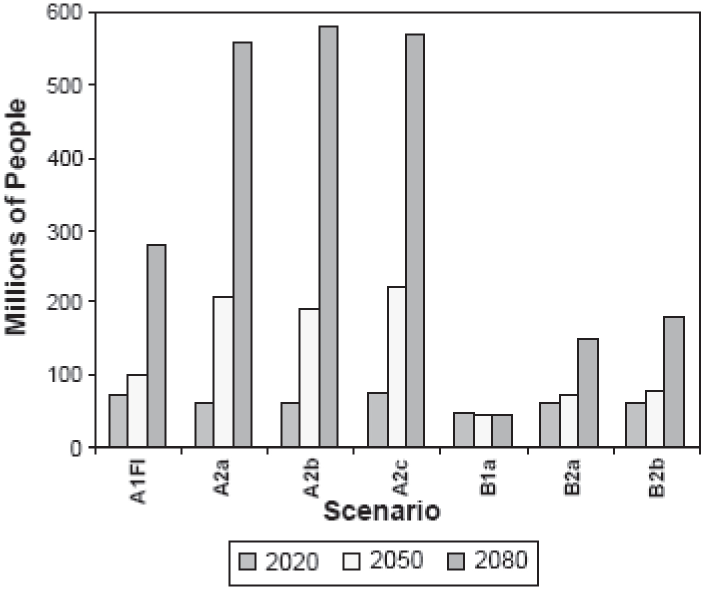
The results from these studies show, given the caveats above, that world cereal production is projected to continue to rise from 1 800 million tonnes presently to around 3 900-4 800 million tonnes by the 2080s. The wide range of projected production is dependent on the assumed technologies inherent in the SRES storylines as well as the relative demand for cereals compared to meat and other foods that have positive income elasticities of demand (the scenarios assume rising real incomes in all parts of the world over the 21st century). Real cereal prices rise under all scenarios of change and the ultimate impact on people at risk from hunger is shown in Figure 3.3 from Parry *et al.* (2004). Figure 3.3 shows a large range, from 100 million to almost 300 million extra people at risk from hunger by the 2050s and up to 550 million extra by the 2080s due to climate change (assuming no offsetting [but highly uncertain] CO_2 fertilization effects on yield). The vast range in these estimates is driven by human population – the A2 storylines in column 3 of Figure 3.3 assumes a total global population in the 2050s of 15 billion, compared to 7 billion in the scenario known as A1F1 in the first column (see Box 3.3 for a description of the SRES scenarios). What is clear is the need for significant adaptations to offset these potential negative impacts, particularly in low latitude developing countries. Parry *et al.* (2005) suggest that the potential for adaptation is greater in more developed economies (coupled with more favourable effects of climate change on yields) and hence that climate change will "on balance bring more positive effects to the North and more negative effects to the South; in other words to aggravate inequalities in development potential" (Parry *et al.,* 2005).

Figure 3.2. Cereal prices (% of baseline) *versus* global mean temperature change for major modelling studies



Source: From Easterling *et al.* (2007).

Figure 3.3. Additional millions of people at risk from hunger (incomes less than price of necessary purchase of staple foods), compared to no climate change reference case, under seven climate change and socio-economic scenarios



Source: Parry *et al.* (2004).

While these results appear to be based on stylised accounts of production without significant adaptations and notions of food insecurity, they are backed by increasing evidence of localised impacts of singular weather events, such as drought and floods, on agricultural production and coping of the agricultural sector (Subak *et al.,* 2000; Rosenzweig *et al.,* 2001). Extreme events, such as hurricanes, impact on small and large farming sectors in the Americas and in Asia. Hurricane Mitch in 1998, for example, had well-studied impacts on agriculture in Honduras, Nicaragua and El Salvador. In Honduras one in five households lost assets as a direct result of the storm and many hundreds of people lost their lives. Economic policies that promote export-driven agriculture have been argued to have contributed to the scale of the impacts and the vulnerability of small farming populations. And there is some evidence that farmers who had adopted "modern" management practices suffered greater losses than those who had more traditional agro-ecological practices. Evidence from Nicaragua (Holt-Giminez, 2002) found that that the differences in impact between traditional farms and commodity-oriented farms actually increased with increasing storm-intensity: farming practices associated with integration into global markets were much more susceptible to economic and physical loss (see also Mainville [2003], on recovery strategies in Honduras). There were also unexpected impacts and risks in agricultural regions, such as seventy tonnes of pesticides released into the environment in Honduras from the destruction of a number of warehouses (Jansen, 2003), exposing rural populations to long-term harm. In economies highly dependent on subsistence agriculture, drought has been shown to have impacts on the most vulnerable populations. At the extreme, vulnerable households cope through selling off productive assets such as livestock. But equally some households benefit: those with resources to take advantage of distress sales and the high prices of agricultural commodities (Roncoli *et al.,* 2001; Little *et al.,* 2001). The globalisation of agriculture and integration of agricultural markets has the potential to minimise the effect of regional climate change through trade, conversely the impacts may be exacerbated by increased specialisation.

Food security is made up of four main elements (FAO definition): availability, stability, access and utilisation. Most studies focus on the impacts on food availability and access to food, without considering the likely effects of climate change on food safety and vulnerability (stability).

Stability is related to climate variability and the ability of the system to cope with extreme weather events. Some important agricultural areas routinely cope with high levels of climate variability, such as the Midwest of the United States, southern Africa or south-east Australia, and adaptation to climate variability is nothing new in agriculture. However, areas subject to high climate variability are likely to expand in the future (Schmidhuber and Tubiello, 2007) and the rates of projected change may exceed historical experience in some regions. Climate change will also affect food safety and food security through the increased incidence of disease and including probable increases in food poisoning and water-borne diseases (IPCC, 2007).

Schmidhuber and Tubiello (2007) extract several key messages in relation to food security from existing studies. The first is that it is very likely that climate change will increase the number of people at risk of hunger compared with reference scenarios with no climate change: however, the magnitude of the climate impacts is likely to be small in comparison with the impact of socio-economic development. In addition to the socio-economic pressures, food production may increasingly compete with energy production in coming decades. Sub-Saharan Africa is likely to surpass Asia as the most food-insecure region, although this is largely independent of climate change and mostly the result of the socio-economic changes assumed in the SRES scenarios. Higher CO_2 fertilization is not likely to affect global projections of hunger.

In addition to localised studies of the impacts of extreme weather events, there is emerging evidence on how climate variability affects the ability of rural areas to thrive, even in present climates. Mendelsohn *et al.* (2006), for example, examine correlations between incomes in rural districts in the United States and in Brazil with parameters of present climate and physical parameters of agricultural productivity. They argue that climate affects agricultural productivity which, in turn, affects *per capita* income (even when this is defined as both farm and non-farm incomes for a district). Both Brazil and the United States are large and diverse enough in terms of climate to undertake such analysis. The study shows that higher temperatures reduce *per capita* income in districts in both countries and that increases in land value, net revenue per hectare and the percentage of land used for arable are all associated with higher *per capita* rural incomes. Hence, Mendelsohn *et al.* (2006) conclude that climatic changes that reduce productivity may have direct consequences on rural poverty: "hostile climates make it difficult for rural families to earn a living through agriculture".

Impacts on food prices

The main messages from studies investigating the likely impacts of climate change on food prices are that on average, food prices are expected to rise moderately, in line with moderate increases of temperature (until 2050), then after 2050 prices are expected to increase more substantially with further increases in temperature (Darwin *et al.,* 1995; Fischer *et al.,* 2002), together with an increased population.

Rosenzweig and Tubiello (2007) develop a series of metrics for analysing the magnitude and timing of climate change impacts on agriculture. Developing metrics may be useful in order to facilitate the evaluation of policy options as well as to assess the long-term risks of climate change and perhaps identify thresholds beyond which foreseeable adaptation techniques may not be sufficient to ensure successful adaptation. Their general framework for agricultural metrics for impact assessment is shown in Table 3.2. This work is still at an early stage and more research needs to be done to test the framework, however it may provide useful information for evaluating and communicating the benefits of climate change policy on agricultural systems.

Table 3.2. Proposed framework for agricultural metrics for impact assessment

Categories	Vulnerability Criteria	Measurement Class
Biophysical indicators	Exposure	Soil and climate Crop calendar Water availability and storage Biomass/yield
Agricultural system characteristics	Sensitivity	Land resources Inputs and technology Irrigation share Production
Socio-economic data	Adaptive capacity	Rural welfare Poverty and nutrition Protection and trade Crop insurance
Climate policy	Synergies of mitigation and adaptation	Kyoto commitment capacity Regional Support Policy (*e.g.* CAP) Carbon sequestration potential CDM projects: in place and planned Bio-energy Irrigation expansion projects Land expansion plans Change in rotations/cropping systems

Source: Rosenzweig and Tubiello (2007).

Identifying vulnerable regions and socio-economic groups

Analysis of impacts of climate change on agriculture fails to capture the complexity of the potential impact on food security by ignoring the political economy aspects of agricultural resource use and allocation (Bohle *et al.*, 1994). In seeking to understand processes of adaptation in their wider context, analysis is required which explicitly highlight the winners and losers from impacts in agriculture. Drèze and Sen (1989), for example, show that food insecurity is exacerbated by underlying social conditions of vulnerability as well as by external factors such as civil strife or population movements. Famine and food shortage are short-run unexpected phenomena, while food insecurity and climate change are long-term trends. Thus, although overall projected changes in local crop and agricultural production are uncertain but may not represent a global shortage of food, regions and particular social groups are likely to be continually vulnerable to food insecurity.

The capacity to adapt to climate change is not evenly distributed across or within nations. Yohe and Tol (2002) identify a number of factors that account for differences in national adaptive capacity including institutional, technological and equity factors. However, adaptive capacity is also highly differentiated within countries, where multiple processes of change interact to influence vulnerability and shape outcomes from climate change. In India, for example, both climate change and trade liberalisation are changing the context for agricultural production. Some farmers are able to adapt to these changing conditions, including the discrete events such as drought and rapid changes in commodity prices. Other farmers may experience predominantly negative outcomes from these simultaneous processes. Identifying the areas where both processes are likely to have negative outcomes provides a first step in identifying options and constraints in adapting to changing conditions.

Mapping vulnerability of the agricultural sector to both climate change and trade liberalisation at the district level in India, O'Brien *et al.* (2004) considered adaptive capacity as a key factor that influences outcomes. Vulnerability analysis for Europe shows similar interaction between socio-economic driving forces of change and the changing climate. Audsley *et al.* (2006), for example, show how scenarios of climate change and technologies and prevalent prices in agriculture could affect land-use in Europe over the next half century. They find that a few specific regions, such as Finland, are likely to increase their agricultural area in either intensive or extensive agriculture, while others in the so-called "agriculturally marginal" areas of Europe could be faced with reduction in land area under agriculture or extensification. These estimated results are based on scenarios of climate impacts including water availability, technological change and socio-economic changes in demand and supply of agricultural outputs (described in detail in Abildtrup *et al.,* 2006). Some parameters exhibit positive change over the incoming decades. Crop suitability is projected to increase in northern regions of Europe and some yield increases are significant for some crops and grassland. Crop yield declines in southern Europe are greater for spring-sown crops such as maize (Audsley *et al.,* 2006). The model used for these projections assumes irrigation is available and does not impose any limit on water use, which may represent unsustainable levels of water extraction in some regions, notably Spain and Portugal.

These estimates could be interpreted as positive impacts of climate change if taken in isolation. However, the estimates involve only changing the climate and do not incorporate changes in the socio-economic scenarios that actually drive the climate change. In other words, farmers in 2050 will experience a changed climate but also will face different demand and supply for inputs as well as outputs, use different technologies and have different policy regimes. Across all scenarios, demand for agricultural outputs rises, with particular demand for "luxury" products, such as wine, while labour and effective price of water all rise, and farm size also rises over time. But different scenarios deviate in how the price of energy changes and on how policy reform changes subsidies and quotas (Abildtrup *et al.,* 2006). Hence, these other changes can potentially swamp the impacts of climate change.

Indeed, Audsley *et al.* (2006) show negative consequences for farming in southern areas of Europe in terms of production in the northward march of arable farming and in the viability of grassland farming in these northern regions. Significant differences in production exist because of the variation in what are known as the socio-economic "storylines". For a brief description of the socio-economic scenarios used in the IPCC, see Box 3.3; for more detailed discussions on the exact nature of these storylines for this analysis, see Abildtrup *et al.* (2006) and, in general, Berkhout *et al.* (2002) and Nakićenović *et al.* (2000). Finland, depending on the range of socio-economic drivers, significantly increases its intensively farmed area (from 2.1 million hectares [mha] presently, to 19 mha in 2050), at the expense of forest area, as it estimates that intensive farming will always be more profitable than commercial forestry. However, this particular scenario analysis cannot handle in detail demand for conservation and policy decisions to protect conservation land or forests from agricultural development.

Box 3.3. Special Report on Emissions Scenarios (SRES) description

SRES emissions scenarios storylines

- **A1**: Rapid economic growth, low population growth, rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in *per capita* income. The A1 scenario family develops into four groups that describe alternative directions of technological change in the energy system.

- **A2**: Heterogeneous world. Underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and *per capita* economic growth and technological change are more fragmented and slower than in other storylines.

- **B1**: Convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

- **B2**: World in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Source: Nakićenović *et al.* (2000).

Clearly there are likely to be significant policy conflicts over changing availability of land suitable for agriculture and demands for conservation measures on-farm and in protected areas over the coming decades in Europe and elsewhere. Berry *et al.* (2006) show that increased vulnerability of farming regions to major changes in crops and the viability of farming has spillover consequences into the status of vulnerable and threatened species, such as grassland bird species and others. Potential changes in agriculture in Europe can impact both directly and indirectly on the vulnerability of species. Benefits for conservation could be realised through extensification or land abandonment, facilitating habitat re-creation or movement of the range of plant and animal species. But under many scenarios examined by Berry *et al.* (2006) species are affected negatively through intensification of arable land and management practices resulting in loss or reduced quality and fragmentation of habitats. These impacts on vulnerability of both natural and social elements of agricultural land-use can, of course, be ameliorated by policy action. Policy frameworks for adaptation of the agricultural sector in the face of climate change will need to account for both ecological and economic changes – there are significant opportunities for planned adaptation through support for extensification of land-use practices in marginal areas in Europe and these will become ever more amplified given projected changes in both climate and in changing socio-economic circumstances.

Emerging case for immediate action

The impacts and vulnerabilities highlighted in the preceding parts of this report have given greater urgency to the need for concerted international action. Indeed, there has been an observable shift in policy perspectives onto the economic basis for accelerating mitigation responses. *The Stern Review on the Economics of Climate Change* in the UK (Stern, 2006), made a compelling statement that significant early action was vital in tackling climate change and the costs to the global economy would be minimal in comparison with the damage costs of no action. The *Stern Review* was relatively unusual at the time in that it was commissioned by the Chancellor of the Exchequer of the United Kingdom and gave a very different message from that of most mainstream economists at the time. The report provides evidence showing that ignoring climate change will eventually damage economic growth and create risks of major disruptions to economic and social activity in the later part of the century. The report's treatment of future damage costs (*i.e.* the discount rate assumptions) were not universally accepted by some economists. However, it brought the economic issues around climate change to the forefront of national and international policy and showed that climate change was an issue important to sectors beyond the environment and agriculture. The *Stern Review* estimated that the overall costs and risks of climate change would be equivalent to losing at least 5% of global GDP each year, now and forever, if no action is taken. If a broader collection of risks and impacts is taken into account, damages could increase to 20% of GDP or more. On the positive side, Stern estimates that the costs of taking action to avoid the worst impacts of climate change could be limited to around 1% of global GDP per year. The review does not disaggregate sectoral costs and therefore does not provide figures specifically for agriculture.

In the same year, the IPCC produced its *Fourth Assessment Report* (AR4), which produced more evidence and stronger statements regarding the anthropogenic influence on the climate and changes in physical and biological systems. The report stated that as well as mean warming, some large-scale climate events have the potential to cause very large impacts, especially after the 21st century, including very large sea-level rises resulting from widespread deglaciation, as well changes in circulation systems. The AR4 also summarised research on costs of climate change, reporting that global mean losses could be 1-5% of GDP for 4°C of warming. The IPCC also made the strong statement that unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt.

In 2008, the Australian Government commissioned its own review of climate change, the *Garnaut Review* (Garnaut, 2008). The central question the review addressed was what extent of global mitigation provides the greatest gains from reduced risks of climate change over costs of mitigation. The review also addressed adaptation to climate change and the specific role of Australia in global mitigation. Like Stern, the review highlights the point that continued high emissions growth with no mitigation action carries high risks, also for the Australian climate, which already experiences problems associated with water shortages. The review promotes the use of international emissions trading as a means of reducing emissions.

A number of large research projects have been carried out in recent years assessing various aspects of climate change, including PESETA, ADAM and Ensembles. More detail on these projects is provided in Annex A.

Global economic assessments provide a compelling policy message on the need to advance intervention on emissions reductions. These assessments are built up from more detailed sector-specific information. Decision-making and prioritising adaptation and mitigation at a local, or even national, level require targeted information on sector-specific economic impacts. Sectoral studies investigating the impact costs on agriculture use diverse analytical tools primarily based on agronomic approaches and so-called Ricardian approaches and models. Agronomic research examines the impact of climate change parameters on particular crops in order to extrapolate to wider environments and situations with an altered climate, while Ricardian models draw analogues from the differential climate affecting farming areas and use land values or other proxies to extrapolate the impact of a changed climate. All of these approaches are reviewed in Reilly *et al.* (1996); Mendelsohn *et al.* (2000) and others.

Impact costs inevitably become entangled with adaptation costs and benefits, so while this chapter focuses predominantly on impact costs, adaptation benefits cannot be ignored, although adaptation is discussed in much greater depth in Chapter 4. The key advances in assessing the costs of climate change to agriculture and, hence, the benefits of adaptation come from recognising that farmers and agrarian societies are constantly adapting to changing policy, price and climatic conditions. Thus, models that reflect how these actions interact and translate into a flow of economic benefits over time capture the economic costs of impacts. If productivity declines, then ultimately the value of capital assets, particularly agricultural land, could be reduced. This is the basis of the so-called Ricardian approach, whose proponents argue that variation in capital values better reflect the economic costs of climate change and incorporate adaptation actions by farmers. Alternatively, market simulation research proceeds on the basis that each farmer makes decisions on the basis of profit and yield and will freely switch between crops, given changing suitability of their resources to a changing climate. Research based on these approaches predicts that farmers will adapt and hence climatic change will have less impact than agronomic models predict. Adams *et al.* (1999) project small overall negative impacts on US agriculture when they consider switching between crops, but where there are opportunities to switch to tomatoes, citrus fruits and other heat-tolerant farming activities, crop yields may actually improve.

Evidence from the Ricardian approach is derived from the use of cross-sectional analysis to isolate the impact of climate regime in determining agricultural profitability. The proxy taken of profitability in this approach is that of land values which reflect the underlying Ricardian rent available from such assets. This approach was first utilised to examine impacts in the United States and has subsequently been applied in the cases of India and Brazil (see Mendelsohn and Dinar, 1999; Mendelsohn *et al.,* 2000). All these countries are large and have diverse climatic zones, enabling the researchers in effect to examine the impact of climate change by spatial analogy. This approach explains adaptation by examining how farmers have adapted in the present day, so may be limited in terms of its applicability to worst-case scenarios, where climate changes more than expected. Nevertheless, results show that impacts of projected future climate scenarios are negative, but smaller than those under agronomic approaches. For India, for example, 2°C warming would reduce net income by around 4%, while even a 3.5°C warming (at the extreme of predicted ranges) would result in loss of net income in the range 15-20% (Mendelsohn and Dinar, 1999).

It is argued that agronomic approaches systematically understate the extent to which adaptation can occur by focussing only on crops, while Ricardian approaches to estimating climate change costs represent adaptation better because they capture full adaptation possibilities as well as the option to switch from agriculture to other land-uses. The differences between the approaches represent estimates of the benefits of adaptation. But Ricardian analyses do not fully reflect adaptation in all forms of agriculture for various reasons. First, land and other factor prices are subject to externalities and policy distortions – the Ricardian approach assumes long run equilibrium in factor markets. Second, land markets do not exist for those important farming systems in marginal agro-ecological zones, including subsistence farming in developing countries (see Hanemann, 2000; Kandlikar and Risbey, 2000). This problem may be overcome to an extent by examining net farm revenues as the measure of value of agricultural activities (given that land values in Ricardian analysis are the discounted stream of net future revenues). Kurukulasuriya and Ajwad (2006) implement such an analysis for the impacts of climate change on Sri Lanka and find significant negative potential impacts in particular regions (losses in potential revenue of up to 67% at the extreme). Adaptation in agriculture is discussed in detail in the following chapter.

Climate Change and Agriculture

Impacts, Adaptation and Mitigation

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