Climate Change and Agriculture

IMPACTS, ADAPTATION AND MITIGATION

By Anita Wreford, Dominic Moran and Neil Adger

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Foreword

This report was prepared by Dr Anita Wreford and Dr Dominic Moran (Scottish Agricultural College, United Kingdom) with the assistance of Professor Neil Adger (The Tyndall Centre, University of East Anglia, United Kingdom) for the Joint Working Party on Agriculture and the Environment. The aim of the report is to help guide policy makers in the design of policy measures to address climate change issues in the agricultural sector.

It considers the economic and policy issues related to the impacts of climate change on agriculture and adaptation responses, and mitigation of greenhouse gases from agriculture; outlines research undertaken and underway in other national and international research agencies; and highlights some of the knowledge gaps in the impacts of climate change on food production and the uncertainties of those impacts in a global context that warrant further research efforts. A particular feature of the report is the analysis of marginal abatement cost curves – which show the relative costs of achieving reductions in greenhouse gas emission through implementing different actions in the agricultural sector.

The report was prepared for publication by Theresa Poincet.

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Glossary of Terms and Abbreviations

Abbreviations/ Acronyms	**Definition**	**Explanation (if necessary)**
ALULUCF	Agriculture, land-use, land-use change, and forestry	For the purposes of compiling a greenhouse gas inventory
AR4	Fourth Assessment Report of the IPCC	
CH_4	Methane	A greenhouse gas
CO_2	Carbon dioxide	A greenhouse gas
CO_2-e	Carbon dioxide equivalent	A measure used to compare non-CO_2 gases with CO_2 based on their global warming potential (GWP – see below)
EC	European Commission	
EC JRC	European Commission Joint Research Centre	
ENSO	El Niño Southern Oscillation	
ETS	Emissions trading scheme	
GHG	Greenhouse gas	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit *radiation* at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect (IPCC, 2007).

Terms	**Definition**	**Explanation (if necessary)**
GWP	Global Warming Potential	An estimate of the effectiveness of a gas in trapping heat in the atmosphere relative to CO_2 over a specific time horizon. Methane has a GWP of 25 over 100 years, and nitrous oxide 298.
IPCC	Intergovernmental Panel on Climate Change	
MACC	Marginal abatement cost curve	
N_2O	Nitrous Oxide	A greenhouse gas
SCC	Social cost of carbon	
SRES	Special Report on Emissions Scenarios	
SPC	Shadow price of carbon	
UNFCCC	United Nations Framework Convention on Climate Change	

Adaptation	Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2007)	The term is used in two literal senses: "adaptation" as a general process (of change); and "an adaptation" as a specific outcome of that process.
Adaptive capacity	The ability of a system to adjust to climate change (including variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (IPCC, 2007)	
Annex I country	Industrialised countries (in the context of the Kyoto Protocol)	
Anticipatory adaptation	Adaptation that takes place before the impacts of climate change are observed	
Autonomous adaptation	Does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems or by market or welfare changes in human systems.	

Terms	Definition	Explanation (if necessary)
Climate change	Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.	Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land-use (IPCC, 2007).
Mitigation	Policies and action to reduce the sources of (or enhance the sinks for) greenhouse gases. Also known as "abatement".	*E.g.* reduction of emissions from agriculture, fuel efficiency, carbon markets, reforestation, alternative energy sources.
Planned adaptation	Adaptation that is the result of a deliberate (usually policy) decision, based on an awareness that conditions have changed or about to change and that action is required to return to, maintain, or achieve a desired state.	
Probabilistic scenarios	The production of large ensembles of climate change scenarios enables the production of probability density functions to represent the range of projected change in a specific event.	Specific probabilities may be assigned to individual events or climate change impacts by incorporating model uncertainties within a large model ensemble.
Vulnerability	The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change. Vulnerability is a function of the character, magnitude and rate of climate change, and variation in which a system is exposed, and its sensitivity and its adaptive capacity.	

Executive Summary

This report considers some of the salient issues that underpin the economics of addressing climate change impacts in the agricultural sector; specifically, projected impacts of climate change on agricultural systems, adaptation responses to these scenarios, and the mitigation of sector greenhouse gas emissions. The report first describes current knowledge on the impacts of climate change on agriculture and related resources. It then examines the limits of the knowledge on the mechanisms that translate climate change into potentially serious impacts on food production, water stress, and ultimately food security. The report highlights remaining uncertainties in relation to impact categories and in terms of unequal global coverage of existing information.

This discussion is used to consider the options for climate change action. Recent reports, including *The Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2007b) and the *Stern Review* (Stern, 2006), highlight the importance of immediate action to address climate change, both in terms of reducing greenhouse gas (GHG) emissions to avoid the worst impacts of climate change in the future, and with regard to adapting our systems to cope with the unavoidable changes. Types of adaptations are discussed, together with their timing and responsibility. The link to policy intervention is addressed by distinguishing between private responsibility and public roles. Private responsibility is equated with autonomous or spontaneous actions undertaken by producers responding gradually, largely in response to market signals. This is distinct from public adaptations that may be necessary where private adaptations lead to unanticipated adverse public good outcomes, or where information failures or other barriers are manifest in terms of how to adapt. The paper provides examples of adaptation actions in agriculture currently underway in a variety of arable and livestock contexts.

On the basis of this discussion, the report suggests that there are three roles for public policy intervention to promote adaptation in the agricultural sector: reducing the vulnerability of those least able to adapt; provision of information to stimulate widespread adoption of adaptation techniques and opportunities; and an enhanced role for provision of public goods associated with agriculture. The report then suggests that successful adaptation should take account of effectiveness, efficiency and the equity and legitimacy of adaptation actions and policies.

Beyond adaptation, agriculture is also major source of global greenhouse emissions, accounting for an estimated emission of 5.1 to 6.1 giga tonnes (Gt) of CO_2-eq/yr in 2005. This represents 10-12% of total global anthropogenic emissions of greenhouse gases (Smith *et al.,* 2007), although scientific uncertainty also suggests this could be as high as 18-31%. Methane (CH_4), mainly from enteric fermentation, rice cultivation and manure handling, contributes 3.3 Gt CO_2-eq/yr:[1] nitrous oxide (N_2O) from a range of soil and land management practices contributes 2.8 Gt CO_2-eq/yr. Of global anthropogenic emissions agriculture is estimated to account for about 60% of N_2O and about 50% of CH_4.

Sector emissions are coming under increasing scrutiny as part of efforts to allocate emissions reductions implied by external obligations. However, even though they are largely outside the global agreements that are binding on other sectors, an important consideration is the assessment of the efficiency of reducing these emissions relative to the cost of reductions in other sectors of the economy. Such an assessment requires a better understanding of the abatement potential offered by a variety of agricultural mitigation measures, and the cost of implementing these measures in viable farm systems. This information can be depicted in the form of a marginal abatement cost curve (MACC), which shows the order in which measures can be implemented and the relative cost of mitigation measures.

Emerging MACC analysis suggests that many agricultural measures can mitigate emissions at low cost (USD per tonne of CO_2-equivalent) relative to benchmark costs provided by the cost of emissions permits or the notional shadow price of carbon. Importantly, the research suggests significant win-win potential where some measures can actually save input costs and reduce emissions. Such measures include the more accurate application of nitrogen fertilizer and manures.

Further abatement cost evidence is required for the variety of global farming systems. But marginal abatement cost curves can be a useful basis for identifying efficient emissions budgets, which in turn require appropriate policy instruments for delivery. A range of policy options are available to the sector. In the first instance the non-adoption of win-win mitigation

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[1] Methane and nitrous oxide can be converted to carbon dioxide equivalents (CO_2-eq) by multiplying by their global warming potentials of 21 and 310, respectively.

measures suggests that more attention needs to be directed at existing information and behavioural barriers that are handicapping voluntary mitigation. Beyond the potential of voluntary approaches, market-based approaches are being considered for parts of the sector. But specific problems exist in their application in agriculture, an industry that is characterised by many small producers operating in biologically complex systems.

It has been suggested that incentive mechanisms can be applied both at the supply and the demand side. This report does not consider demand-side measures; however, we do note that a move beyond the farm-gate opens up a range of complications in relation to the role of other actors in the food chain and the correct apportionment of life-cycle emissions associated with food production.

Finally, implementation of any emissions budget will need to be consistent with longer-term adaptation planning. This report concludes with recommendations for the OECD and more general research requirements.

A number of first steps can guide policy makers in the design of a rational economic response to climate change. The first and most obvious is to understand impacts and their associated costs. This economic picture provides an indication of the value at risk and therefore the basis of an economically efficient investment response to adaptation. This clearly requires some mapping of downscaled climate projections and their effect on vulnerable sectors of the economy. The second is to consider the range of adaptation responses, their associated costs and whether these fall within the categories of public or private responsibility. The latter includes a range of less tangible interventions, such as information barriers that should be addressed to facilitate private adaptation. The third first step is to design an efficient mitigation policy. Whatever the adaptation response, most countries are now party to international obligations on emissions reductions and these should be designed at least cost. The agriculture and land-use sector offers significant mitigation potential at low cost and countries should develop a sector emissions budget by concentrating on the identification of these low-cost measures. Once this budget is determined, a range of voluntary and/or market-based approaches can be used to provide incentives for their deployment in the sector.

Chapter 1
Introduction

Agriculture is essentially a man-made adjunct to natural ecosystems and is weather and climate dependent. It is also a significant source of anthropogenic emissions of greenhouse gases, which are coming under increasing scrutiny as countries seek to meet binding mitigation targets. New challenges are emerging in terms of how we interpret the impacts of warming, how farming systems adapt or are adapted to these changes, and how near-term emissions mitigation requirements can take place in ways that are consistent with longer-term adaptation plans. These increasingly urgent challenges coincide with a process of sector reform in many OECD countries, which is focussed on ways to rebalance the economic, social and environmental objectives for the sector. This process offers a window of opportunity for accommodating mitigation and adaptation options within new agri-environmental arrangements. But all these reforms will affect and be affected by a global agricultural trading system, which is increasingly being required to deliver on ancillary policy objectives (*e.g.* energy and food security, and poverty alleviation), but which itself is vulnerable to climate shocks.

In this report we consider how recent developments in the international literature on climate change inform the three elements of impacts, adaptation and mitigation. The aim is to suggest how policy can be informed by rudimentary considerations of effectiveness and efficiency. We also suggest that there are equity implications from policy responses, but we do not spend time mapping out analytical methods to evaluate these impacts. The analysis presented highlights how our understanding of impacts and the economic appraisal of adaptation and mitigation are complicated by the fundamental biological complexity that distinguishes agriculture from other sectors characterised by fewer firms, and common, relatively well-understood adaptation options and abatement technologies. In comparison, agriculture and land-use are more atomistic, heterogeneous and regionally diverse. These factors prevent generalisation about impact storylines and obviate generic messages about the effectiveness of adaptation and mitigation measures implemented in different systems. This complexity begs a number of relevant research questions that can inform robust economic analysis.

Climate factors constitute some of the main constraints on crop and livestock production and till recently have been assumed as exogenous and unchanging. While farming has a history of responding to changing conditions, whether they are economic, social, political or climate-related, the potential increase in frequency and intensity of extreme climatic events, and other challenges posed by climate change, now gives rise to a need to re-appraise the adaptive capacity of agricultural systems.

While governments throughout the world are assessing the diverse threats posed by climate change, the impacts on agriculture have been identified as potentially the most serious in terms of numbers of people affected and the severity of impacts on those least able to cope. Reflecting this priority, the ultimate objective of the UN Framework Convention on Climate Change (UNFCCC) is to prevent dangerous anthropogenic interference with the climate system. Agriculture is identified within the Convention as particularly vulnerable and particularly critical in terms of global impacts. International action should take place under the Convention "within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to *ensure that food production is not threatened* and to enable economic development to proceed in a sustainable manner" (UNFCCC, 1992, Article 2, our italics). Hence, maintaining agricultural production is central to the policy objectives of international climate change action. Given the diversity and the likely uneven distribution of impacts of climate change, potential agricultural impacts are also high on the agenda of policy-makers within national governments.

Current scientific evidence points to significant impacts of climate change in the future as well as some observed early signals and impacts of climate changes in the present day. The policy options on climate change at a global scale are to reduce emissions so as to avoid "dangerous anthropogenic interference" and to adapt to impacts as and when they occur. Given that impacts are already occurring, and that expected future impacts have economic costs in the present day (through anticipatory behaviour), adaptation is clearly necessary and inevitable. Projections of the magnitude of changes by the IPCC (IPCC, 2007b) suggest that given past emissions and present commitments to greenhouse gas emissions, global mean temperature are likely to rise by approximately 1.4-5.8°C by 2100. Such changes will have direct impacts on crop yields for example through heat stress, and indirect impacts through associated precipitation changes and through related enhanced atmospheric CO_2 (the CO_2 fertilization effect). The impacts on social risk and production variability are much more complex. The role of economic incentives in both adaptation to climate impacts, and in emission regulation and minimisation, are therefore critical to this important environmental issue.

This report first describes current knowledge on the impacts of climate change on agriculture and related resources. It then examines knowledge and limits of the knowledge on the mechanisms that translate climate change into potentially serious impacts on food production, water stress, and ultimately food security. This discussion is used to consider the nature and implications of adaptive response options that are either autonomous (private) or planned. The report then considers the question of emissions mitigation across the sector and associated questions raised by the need for agriculture to play a part in mitigation obligations. In the case of both adaptation and mitigation, policy responses need to be informed by effectiveness and efficiency considerations.

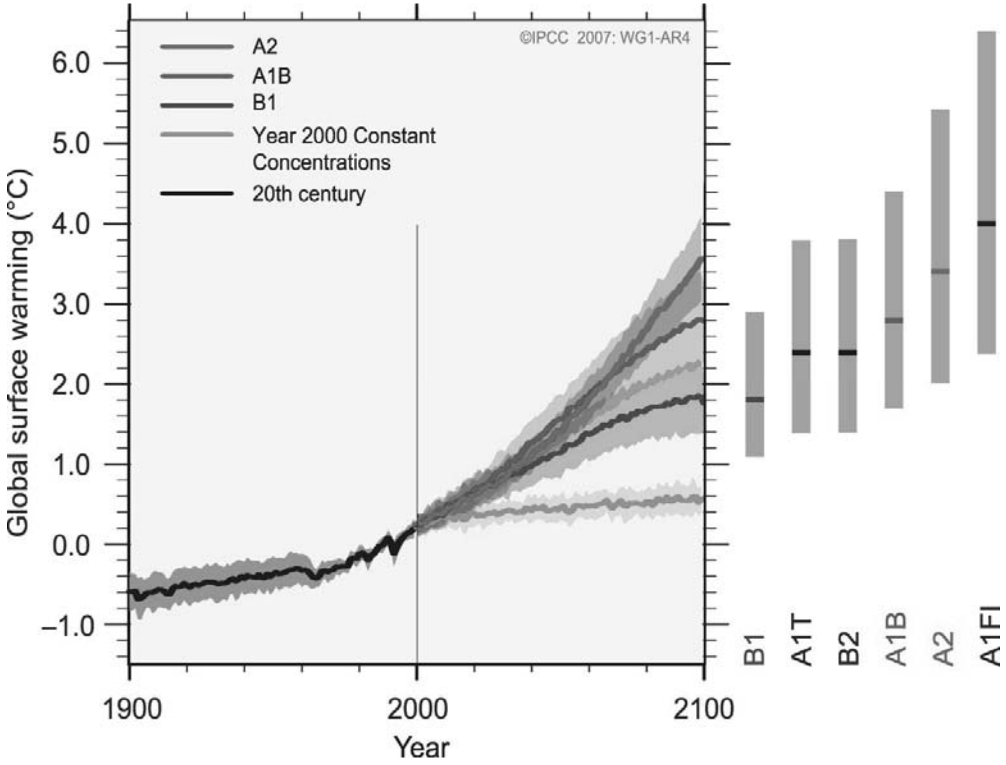
Chapter 2
Climate change projections

IPCC projections

The impacts of climate change are likely to be greater on those countries more dependent on primary sector economic activities, primarily because of the increase in uncertainty on productivity on these primary sectors. Impacts include reduction in water availability in already water-stressed areas, changes in the incidence of extreme events such as typhoons and droughts, and impacts of sea level rise in low-lying coastal areas (see Easterling *et al.* [2007] for a summary). Modern agriculture has tried to minimise the impacts of climatic and weather uncertainty through irrigation, the substitution of labour with energy-intensive practices and plant breeding for heat or water-stress tolerant crops. Thus adaptation in agriculture takes places either by farmers individually, by farmers and local institutions collectively, or through national level policy decisions which provide finance, research and development, and knowledge transfer, and property rights or legal frameworks to enable individual or collective action.

The impacts of climate change on agriculture come about through changes in variability, seasonality, changes in mean precipitation and water availability, and the emergence of new pathogens and diseases (Fischlin *et al.,* 2007). Each of these mechanisms is likely to become more significant with higher rising temperatures, and clearly the overall impacts of climate change in agriculture depends on the interactions between these mechanisms – where new pests, water availability and thresholds in temperature interact, for example. Figure 2.1 shows the range of projections of climate change to 2100 from the *Fourth Assessment Report* (AR4) of the IPCC (IPCC, 2007a). The range of projections (1.4-5.8°C by 2100) comes about both because of uncertainty in the physical models of climate forcing and response, and also from uncertainty about future emissions that are dependent on technological change, human population growth and other factors (O'Neill *et al.,* 2001). Much evidence within the IPCC Working Group report on impacts adaptation and vulnerability (IPCC, 2007b), suggests that there are impacts related to these projected temperature increases. These include impacts on water stress, on extreme events and on pathogens and diseases that also become more likely and more significant with the projected rising temperatures. In other words, the projected temperature increases for the incoming century in Figure 2.1 will be correlated with rising dangerous impacts of climate change on ecosystems, widespread aggregate impacts, and risk of catastrophic irreversible impacts (Mastandrea and Schneider, 2004; Schneider, 2004).

Figure 2.1. IPCC *Fourth Assessment Report* projections of global mean temperature for six representative emissions scenarios and a range of climate sensitivities



Source: IPCC (2007a).

Some impacts of climate change are already apparent in recent extreme events throughout the world. Drought, floods and heatwaves became more common in the 20th century, while the 1990s were the warmest decade in the so-called "instrumental" record of observed temperature around the world (Jones and Moberg, 2003). The warmest year of the entire series was 1998, with a temperature of 0.58°C above the 1961-90 mean. Nine of the ten warmest years in the series have now occurred in the past ten years (1995-2004). Observed impacts of climate change on physical and ecological systems over the past century (documented in IPCC [2007a] and Parmesan and Yohe, 2003, for example) are forerunners of things to come. Along with changes in mean climatic conditions, the earth potentially faces irreversible and catastrophic system feedbacks and impacts associated, for example, with collapse of thermohaline circulation, the melting of the Greenland ice sheet (Gregory *et al.,* 2004), or other singular events (Alley *et al.,* 2003). Societies, organisations and individuals have adjusted their behaviour in response to past climatic changes, and many are now contemplating adapting to altered future climatic conditions. Much of this adaptation is reactive, in the sense that it is triggered by past or current events, but it is also anticipatory, in the sense that it is based on some assessment of conditions in the future (Smit *et al.,* 2000).

In the IPCC *Fourth Assessment Report* projections of global mean temperature for six representative emissions scenarios and a range of climate sensitivities, the bars show, for each of the six main scenarios used by the IPCC (of 35 possible futures), the range of the model results in 2100. The grey bars at the right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints (IPCC, 2007a).

Agronomic research indicates that higher temperatures associated with climatic change will be harmful to the production of many crop and livestock groups. Where there is water stress, heat stress or a combination of the two, the world's cereal crops can be vulnerable to even minor changes in temperature. The agronomy of all crops will be affected by both temperature and precipitation change and by the increased atmospheric concentration of carbon dioxide. Rice, for example, is predicted to experience increased yield due to CO_2 fertilization at higher concentrations than present (around 380 ppmv). But it is estimated that the net yield increase turns negative as temperature increases by 3 or 4°C. However, these crop model projections often hold precipitation constant and it is seasonal water availability, which most heavily influences crop yield changes, that may, for example, affect the largest grain-growing areas of the Asian sub-continent (see Lal *et al.,* 1998 and Matthews *et al.,* 1997). The feedback impacts of climate change on production of the major crops such as rice and wheat are therefore highly uncertain (see discussion below). The IPCC reports from 1996, 2001 and 2007 (Reilly *et al.,* 1996; Gitay *et al.,* 2001; Easterling *et al.,* 2007) review the results of available studies and conclude that the overall direction suggests negative impacts on crop productivity and yields for the tropics, while there is contested evidence for beneficial effects for the high latitudes. At +2 to +3 degrees agricultural prices are expected to be affected, however the impact ranges from -10 to +20%, depending on the model used, however at +3 to +5 degrees agricultural prices are expected to increase by between 10 and 40%, while cereal imports of developing countries are likely to increase by 10-40% (Easterling *et al.,* 2007). The main findings are summarised in Table 2.1. The main projected impacts are discussed in further detail in the following chapter.

Primary effects and interactions

The food and fibre chapter in the most recent IPCC report, the AR4 (Easterling *et al.,* 2007) provides a comprehensive update of findings since the Third Assessment Report.

Effects of elevated CO_2: Studies at plot level over the last few decades have indicated that plant biomass and yield increase significantly at higher than present CO_2 levels. There are two responses involved; the photosynthetic response which leads to increased plant productivity, and the crop yield response. The crop yield response is lower than the photosynthetic response, however it could potentially lead to increases in yield of up to 20% (Nowak *et al.,* 2004; Ainsworth and Long 2005; Long *et al.,* 2004). The effects of elevated CO_2 on plant growth and yield however will depend on photosynthetic pathway, species, growth stage and management regime (Jablonski *et al.,* 2008; Kimball *et al.,* 2002; Norby *et al.,* 2003). It was recently suggested (Long *et al.,* 2005; 2006) that crop responses to elevated CO_2 were not as high as previously thought, however the latest research (Tubiello *et al.,* 2006) has confirmed the original findings with new results. Suggestions that current impact assessment simulation results are too optimistic in their assumptions about CO_2 response are now shown to be incorrect (Tubiello *et al.,* 2007).

While the effect of CO_2 may show positive effects on plant growth in experiments, the results of plot level experiments are likely to overestimate the reality of the CO_2 response because of complicating factors which occur in the real world and not in the experiments, such as pests and weeds, lack of and competition for other necessary resources, and extreme events. These interactions are not well understood at large scales nor well implemented in leading models (Easterling *et al.,* 2007).

Table 2.1. Summary of selected conclusions from IPCC for food and fibre

Temperature change	**Sub-sector**	**Region**	**Finding**
+1 to +2°C	Food crops	Mid- to high latitudes	• Cold limitation alleviated for all crops • Adaptation of maize and wheat increases yield 10-15%; rice yield no change; regional variation is high
	Pastures and livestock	Temperate	• Cold limitation alleviated for pastures; seasonal increased frequency of heat stress for livestock
	Food crops	Low latitudes	• Wheat and maize yields reduced below baseline levels; rice is unchanged • Adaptation of maize, wheat, rice maintains yields at current levels
	Pastures and livestock	Semi-arid	• No increase in NPP; seasonal increased frequency of heat stress for livestock • Agricultural prices: -10 to -30%
+2 to +3°C	Food crops	Global	• 550 ppm CO_2 increases C3 crop yield by 17%; this is offset by temperature increase of 2°C assuming no adaptation and 3°C with adaptation
	Food crops	Mid- to high latitudes	• Adaptation increases all crops above baseline yield
	Pastures and livestock	Temperate	• Moderate production loss in swine and confined cattle

(Continued on next page)

(Table 2.1 continued)

Temperature change	Sub-sector	Region	Finding
	Fibre	Temperate	• Yields decrease by 9%
	Pastures and livestock	Semi-arid	• Reduction in animal weight and pasture production, and increased heat stress for livestock
	Food crops	Low latitudes	• Adaptation maintains yields of all crops above baseline; yields drop below baseline for all crops without adaptation
+3 to +5°C	Food crops	Low latitudes	• Adaptation maintains yields of all crops above baseline; yield drops below baseline for all crops without adaptation
	Pastures and livestock	Tropical	• Strong production loss in swine and confined cattle
	Food crops	Low latitudes	• Maize and wheat yields reduced below baseline regardless of adaptation, but adaptation maintains rice yield at baseline levels
	Pastures and livestock	Semi-arid	• Reduction in animal weight and pasture growth; increased animal heat stress and mortality

Source: Adapted from Easterling *et al.,* 2007.

Interactions of elevated CO_2 with other factors: Although an increase in CO_2 in isolation from other factors is shown to increase crop growth and productivity, these effects will often be countered in reality by other changes in the system. Higher temperatures during certain growth stages may be detrimental to yield and quality (Caldwell *et al.,* 2005; Baker, 2004; Thomas *et al.,* 2003). Increased growth caused by elevated CO_2 may lead to greater water demand (Xiao *et al.,* 2005), which in many parts of the world may be combined with increasing pressure on water resources, which may also be declining, and hence become a limiting factor. Climate impacts on crops may depend heavily on the precipitation scenario considered. Similarly, the availability of soil nutrients such as nitrogen and phosphorus may also prove to be limiting factors in the CO_2 response. Studies have shown that high soil N contents increase the relative response to elevated CO_2 concentrations (Nowak *et al.,* 2004).

Increased frequency of extreme events: The increased frequency and intensity of extreme events, such as floods, droughts, heat waves, and windstorms is likely to lead to greater production losses than any increase in mean temperature (Porter and Semenov 2005). Both short duration events such as heatwaves and floods, as well as longer-term events with sustained above normal temperatures have the potential to cause considerable damage to crops and yields depending on their occurrence in the growing season. Large-scale circulation changes such as the El-Niño Southern Oscillation (ENSO) have important impacts on production and therefore GDP. In Australia the effect of the drought in 2002-03 caused a reduction in GDP of 1.6% (O'Meagher 2005). The 2003 heatwave in Europe, which broke several temperature records, resulted in a fall in corn yield in Italy of 36% (Cias *et al.,* 2005), and is likely to be indicative of future summers (Schaer *et al.,* 2004). Understanding the links between increased frequency of extreme events and ecosystem disturbances is very important, however few models consider effects of climate variability as well as mean variables.

Impacts on weeds, pests, diseases and animal health: Although the qualitative picture of interactions between CO_2 and pests, diseases and weeds is understood, quantitative information is currently still lacking. Interactions between CO_2 and temperature are recognised as a key determinant in plant damage from pests in the future, and interactions between CO_2 and precipitation are also likely to be important (Zvera and Kozlov, 2006; Stacey and Fellows, 2002). However, most studies continue to investigate pest damage in response to either CO_2 (Agrell *et al.,* 2004; Chakraborty and Datta 2003; Chen *et al.,* 2005) or temperature, but not in combination.

Increased climate extremes may promote plant disease and pest outbreaks. Studies have shown that the spread of animal diseases from low to mid-latitudes is occurring already. Bluetongue, a disease affecting sheep and cattle, and is already spreading from the tropics to the mid-latitudes including France, the United Kingdom and Nordic countries, while cattle tick *(Boophilus microplus)* may affect the Australian beef industry.

Rosenzweig *et al.* (2000, 2001) review the major threats to agriculture associated with diseases and pests as well as drought and floods with global evidence and examples from the US. They highlight the 1988 drought in the US Midwest that cost USD 3 billion in compensation and subsidies. The Mississippi floods of summer 1993 affected 16 000 square miles of farmland with 11 million acres of crops damaged, with an estimated cost of USD 23 billion, as well as emergency measures to drain land in Iowa alone costing USD 222 million. In terms of pathogens, these floods contributed to the so-called "Dead Zone" of algal bloom in the Gulf of Mexico through nutrients and other chemicals runoff into the Mississippi (Rosenzweig *et al.,* 2001). The ranges of particular pests in the United States, including the soybean cyst nematode and corn grey leaf blight, have expanded since the 1970s due to increasingly favourable climatic conditions. Projections of climate change globally show that higher temperatures and greater precipitation (in some regions) are likely to result in the spread of novel pathogens and diseases. Shorter winters lead to less insect kill and wet vegetation promotes proliferation of bacteria, while prolonged dry periods (in other regions) encourage insect-promoted diseases. Such indirect impacts of climate change on agriculture are potentially important but a largely unknown impact.

Sudden changes in climate, such as severe weather events, often result in large losses to stock in confined cattle lots, as they have no prior conditioning to these events (Mader, 2003). High temperatures and droughts are likely to induce increases in mortality, yields and conception rates, for animals not accustomed to the higher temperatures (IPCC, 2007).

Interaction with air pollutants: Tropospheric ozone has been shown to have significant adverse effects on crop yields, pasture and forest growth, and species composition (IPCC, 2007). Direct and indirect interactions between global ozone and elevated CO_2 is likely to further modify plant dynamics (Fiscus *et al.,* 2005; Booker *et al.,* 2005). Although it has been shown that elevated CO_2 may minimise negative impacts from ozone, the interactions between the two have not been considered sufficiently in current risk assessments.

Vulnerability of carbon pools: Climate change has the potential to affect the global terrestrial carbon sink and to further perturb atmospheric CO_2 concentrations (Cias *et al.,* 2005; Betts *et al.,* 2004). Land-use planning and management practices, including set-aside policies, reforestation, and N fertilization, irrigation and tillage practices all have the potential to affect future changes in carbon stocks and fluxes. Carbon stored in soil organic matter has been shown to be affected by atmospheric CO_2 levels (Allard *et al.,* 2005; Gill *et al.,* 2002), temperature (Ciais *et al.,* 2005), and air pollution (Loya *et al.,* 2003; Booker *et al.,* 2005), although considerable uncertainty remains. These relationships highlight the importance of co-ordinating adaptation and mitigation strategies and considering the effects of climate policy on land-use change and long-term sustainability of production systems (Rosenzweig *et al.,* 2007).

Impact assessments: Results from integrated assessment and crop models over the 20 years indicate consistently that impacts in the agricultural sector are likely to be small in the first half of the 21st century – although they are likely to become increasingly negative in the second half, as mean temperatures increase (IPCC, 2007; 2001). However, uncertainties which could potentially alter these findings consist of a range of factors, from the strength and saturation point of the elevated CO_2 response of crops grown in real fields rather than experimental plots, to the timing and implementation of adaptation strategies and the interaction between mitigation and adaptation strategies (Tubiello *et al.,* 2007).

Food crop farming: The possibility for surprise events that are not considered in impact assessments cannot be ruled out. The most recent IPCC report lists three main factors which have not been considered in modelling to date:

- Increases in the frequency of climate extremes may lower crop yields beyond the impacts of mean climate change. Long-term yields may be affected by the increased occurrence of extreme weather events, which may directly damage crops at crucial developmental stages, or may make the timing of field applications more difficult, reducing the efficiency of farm inputs (Porter and Semenov, 2005, Antle *et al.,* 2004).

- Impacts of climate change on irrigation water requirements may be large. Recent studies have found that there may be a global increase of net crop irrigation requirements of 5-8% by 2070, with considerable regional variation (Döll, 2002). Increases in water stress are projected for the Middle East and south-east Asia (Fischer *et al.,* 2007; Arnell, 2004). These increases in irrigation water requirements may undermine any potential positive effect of CO_2 fertilization.

- Stabilisation of CO_2 concentrations reduces damage to crop production in the long term. Overall impacts on global crop production are projected to be significantly less under lower levels of CO_2 stabilisation (Arnell, 2004; Tubiello and Fischer, 2007) (*i.e.* at 550ppm compared to 750ppm or a BAU scenario). In the first half of this century, some regions may be worse off with mitigation than without, because of lower CO_2 levels and resulting lack of CO_2 stimulation effects on crops (Tubiello and Fischer, 2007).

Synthesis studies: Results of synthesis studies (although containing considerable uncertainty due to discrepancies between the models in precipitation change, poor representation of extreme events, and the assumed strength of CO_2 fertilization), indicate that moderate to medium local increases in temperature (up to 3°C) can have small beneficial impacts on the main cereal crops. However, further warming is expected to have increasingly negative impacts. In low-latitude regions, even moderate temperature increases are likely to have negative yield impacts for major cereal crops. Above 3°C, average impacts are stressful to all crops and in all regions (Easterling *et al.,* 2007). Global production potential, or Net Primary Productivity, may be threatened at +1° local temperature change and is likely to decline beyond 3°C. Precipitation changed may affect production responses beyond the temperature signal.

Figure 2.2 shows simulated crop yield changes by 2080s relative to the period 1961-90 according to a high emission scenario (SRES A2 – please refer to Box 3.3 for a description of the scenario) and two different climate models: (upper) HadCM3/HIRHAM; (lower) ECHAM4/RCA3, map elaboration by EC JRC/IES. These figures are produced as part of the PESETA project.[1] The PESETA results assume a relatively optimistic degree of adaptation where farmers can use as much additional irrigation water and/or fertilizers as wished, without any constraint. In these simulations, current land-use patterns are assumed to remain constant until 2085, as are agricultural policies.

The maps provide indications of the general spatial pattern of changes in agriculture yields across Europe. Results for two different global circulation models are presented, using the same socio-economic scenario and GHG emissions. The lower map generally shows larger changes in crop yields than the upper map, due to the different climate conditions.

Considerable research has been carried out on cereals but the effect of climate change on other crops, such as root crops, brassica and millet etc. has not been studied as much. These other crops are of considerable importance to the rural poor in many countries and this is therefore an important area of future research.

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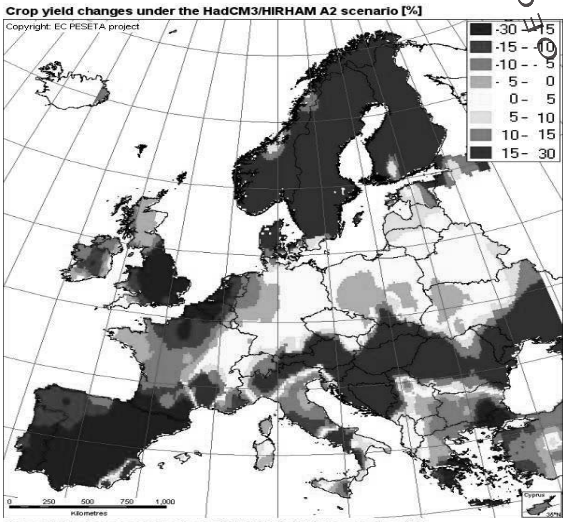
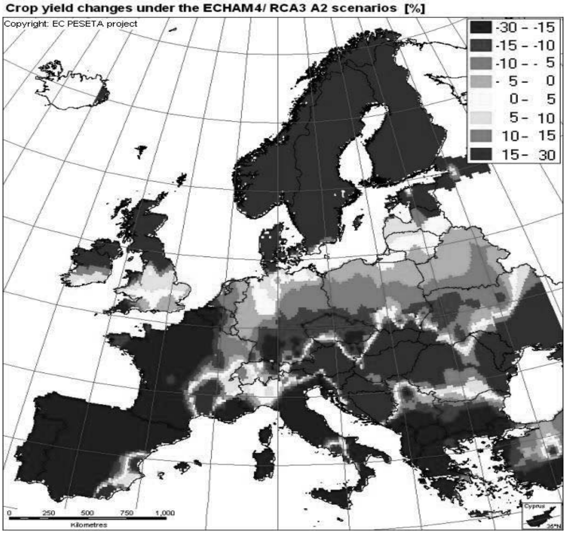
[1] http://peseta.jrc.ec.europa.eu/index.html.

Figure 2. 2. Simulated crop yield changes by the 2080s relative to the period 1961-90 according to a high emission scenario (IPCC A2) and two different climate models[1]





Note:

1. Upper: HadCM3/HIRHAM; Lower: ECHAM4/RCA3.

Map elaboration by EC JRC/IES (PESETA).

Source: http://peseta.jrc.ec.europa.eu/index.html.

Pastures and livestock production

It has been known since the third IPCC assessment (TAR) that the combination of increases in CO_2 concentration, together with changes in rainfall and temperature were likely to have significant impacts on grasslands and rangelands, with production generally increasing in humid temperate grasslands, but decreasing in arid and semi-arid regions. Since the TAR research has found that plant community structure is altered by elevated CO_2 and climate change (Easterling *et al.,* 2007). This means there may be rapid changes in species composition and diversity, leading to vulnerability of some species and possible implications for ruminant livestock. Areas that are already colonised by relatively unpalatable plant species (such as upland areas in the United Kingdom) may become even less suitable for grazing at elevated CO_2 levels, as species such as bracken, matt grass and tor grass could become more dominant. This would affect the nutritional value of extensive grasslands to grazing animals (Defra, 2000).

Thermal stress has been shown to decrease productivity and conception rates and is potentially life-threatening to livestock. Models of animal energetics and nutrition (Parsons *et al.,* 2001) have shown that high temperatures put a ceiling on milk production, regardless of feed intake. Increases in air temperature may potentially affect conception rates of animals not adapted to the conditions, particularly cattle. Model results from the United States show reductions in swine, beef and dairy milk production of 1.2%, 2.0%, and 2.2% respectively, for the 2050 scenario using the CGC (version 1) model, and 0.9%, 0.7%, and 2.1% for the HadCM2 model (Mader *et al.,* 2008).

Correspondingly, results since the TAR illustrate that increased climate variability and droughts may lead to livestock loss, both from exposure outdoors and due to poorly adapted housing and transportation methods. Extreme events and weather variability will have a far greater impact on animal productivity than effects associated with average changes in climate. Animals not adapted to weather events may suffer severe losses, particularly those confined in cattle feedlots (Hahn *et al.,* 2001). Additionally, economic losses from reduced cattle performance are estimated to exceed those associated with cattle mortality losses by several-fold (Mader, 2003). However, such a calculation depends on how regulatory standards on housing and transportation in many countries are reviewed to accommodate increased temperature extremes. ENSO events are expected to intensify with climate change, leading to changes in vegetation and water availability (Gitay *et al.,* 2001). Strong relationships exist between drought and animal death, especially in Africa and Mongolia (Easterling *et al.,* 2007). The combination of drought and heat stress in animals is also likely to lead to increased pressure on water resources.

Gradual temperature change, in conjunction with elevated CO_2 levels, is expected to increase grassland productivity in general, with the greatest positive effect expected at high latitudes (Rustad *et al.,* 2008). However, projected decreases in rainfall in some major grassland and rangeland areas may have important implications for productivity and plant species composition. Table 2.2 summarises the impacts on grasslands for different temperature changes.

Industrial crops

The AR4 indicates there is limited knowledge regarding the effects of climate change on industrial crops such as oilseeds, gums and resins, sweeteners, beverages, fibres, and medicinal and aromatic plants. Biofuel crops such as maize and sugarbeet will face similar effects as other crops discussed earlier in this report. Reduced rainfall may cause groundnut yields in Niger to reduce, while there may be large increases in cotton yields due to increases in ambient CO_2 concentration. However, changes in temperature and precipitation may negate these effects (Varaprasa *et al.,* 2003). Perennial industrial crops may be at greater risk than annual crops, as both damages (temperature stresses, pest outbreaks, increased damage from extremes) and benefits may accumulate with time.

Table 2.2. Impacts on grasslands of incremental temperature change

Local temperature change	**Sub-sector**	**Region**	**Impact trends**	**Sign of impact**	**Scenario/ Experiment**	**Source**
+0-2° C	Pastures and livestock	Temperate	Alleviation of cold limitation	+	SIM	Parsons *et al.,* 2001
			Increasing productivity		IS92a	Riedo *et al.,* 2001
			Increased heat stress for livestock	–	IS92a	Turnpenny *et al.,* 2001
		Semi-arid and Mediterranean	No increase in net primary productivity	0	EXP	Shall *et al.,* 2002; Dukes *et al.,* 2005
+3° C	Pastures and livestock	Temperate	Neutral to small positive effect (Depending on GMT)	0 to +	SIM	Parsons *et al.,* 2001; Reido *et al.,* 2001
		Temperate	Negative on swine and confined cattle	–	HadCM2, CGCM1	Frank and Dugas, 2001
		Semi-arid and Mediterranean	Productivity decline	–	HadCM3 A2 and B2	Howden *et. al.,* 1999

Table 2.2 (continued)

Local temp-erature change	**Sub-sector**	**Region**	**Impact trends**	**Sign of impact**	**Scenario/ Experiment**	**Source**
			Reduced ewe weight and pasture growth. More animal heat stress			Batima *et al.,* 2005
		Tropical	No effect (no rainfall change assumed)	– to 0	EXP	Newman *et al.,* 2001; Volder *et al.,* 2004
			More animal heat stress	–		

Note:
EXP = Experiment; SIM = Simulation without explicit reference to an SRES scenario; GMT = Global mean temperature.

Source: Easterling *et al.,* 2007.

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.

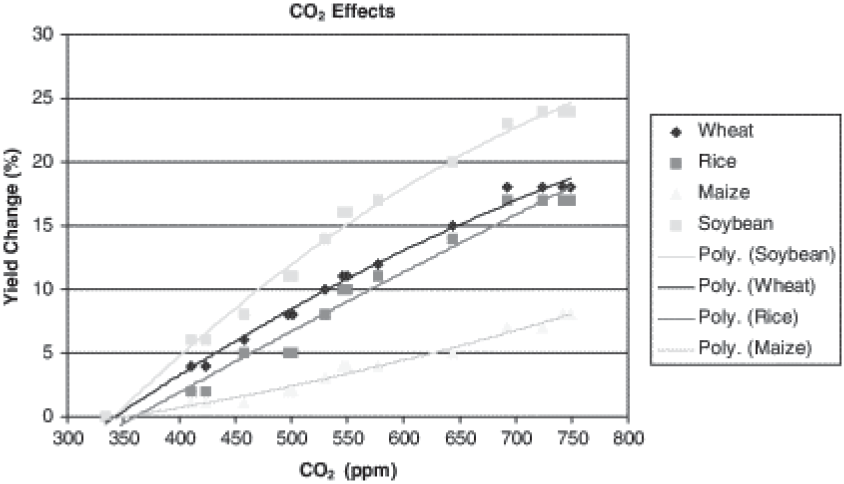
Source: Randall *et al.* (2007).

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.

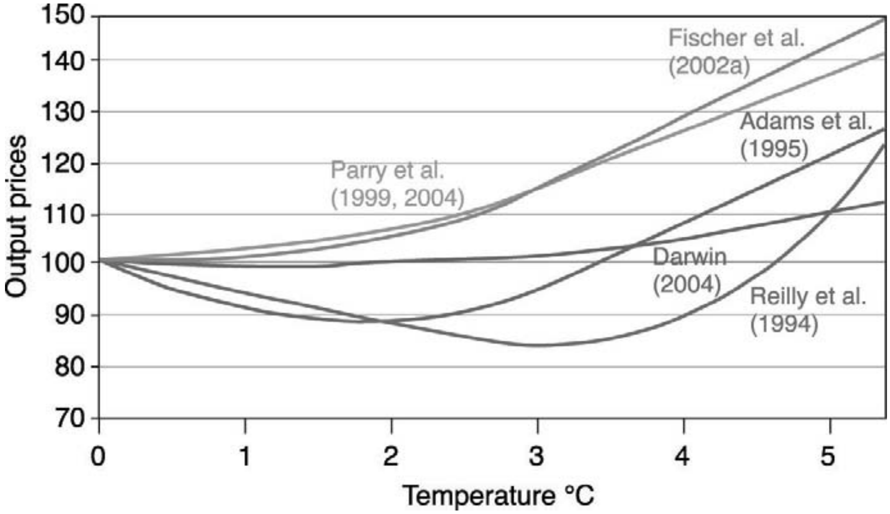
Estimates of global production, trade and food security

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.

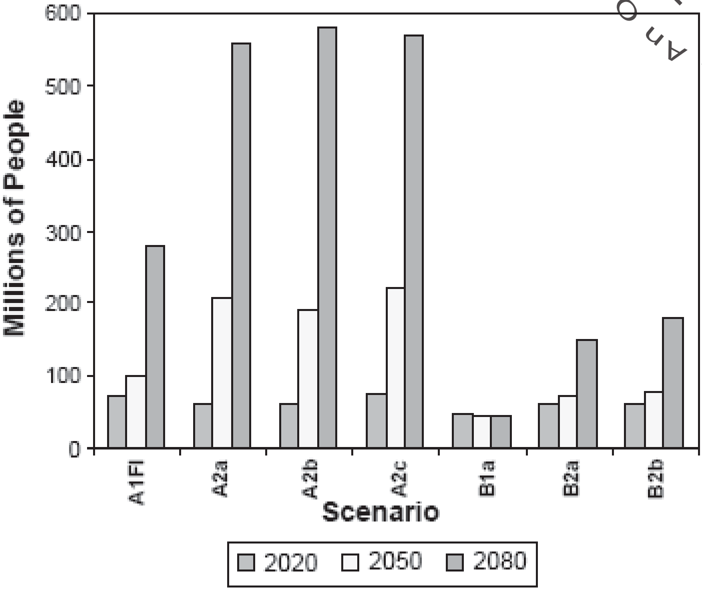
The results from these studies show, given the caveats above, that world cereal production is projected to continue to rise from 1 800 million tonnes presently to around 3 900-4 800 million tonnes by the 2080s. The wide range of projected production is dependent on the assumed technologies inherent in 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.

Chapter 4
Adaptation

The scope of adaptation

The chapters above have reviewed estimates of the major impacts of climate change on agriculture and related resources at the global scale. Faced with these threats and challenges, there are two major responses for policy intervention in agriculture. The first strategy is to reduce the rate and magnitude of climate change itself through reducing the human causes of climate change *i.e.* mitigation of greenhouse gases, which is discussed in detail in Chapter 5. The second (and complementary) option[1] is to promote adaptation to climate change to minimise the impacts and take advantage of new opportunities. Adaptation in the climate change context may also involve adjusting to changes resulting from climate impacts elsewhere in the world (such as the possible effects on markets, changing comparative advantage, increased migration) or changes resulting from mitigation actions (such as increased biofuel production and changes in land-use). There is also a need for a multi-sectoral planning approach, integrating the different aspects of agricultural production, particularly soil and water management.

Adaptation to climate change is typically characterised as an adjustment in ecological, social or economic systems in response to observed or expected changes in climatic stimuli and their effects and impacts, in order to alleviate adverse impacts of change or take advantage of new opportunities. Adaptation can therefore involve both building adaptive capacity – thereby increasing the ability of individuals, groups, or organisations to adapt to changes – and implementing adaptation decisions, *i.e.* transforming that capacity into action. Both dimensions of adaptation can be implemented in preparation for, or in response to, impacts generated

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[1] While in some senses mitigation and adaptation may be viewed as substitutes, in practice they are complementary actions and both will be necessary to address the challenge of climate change. Adaptation will be necessary to adapt to changes resulting from historical emissions and mitigation will be necessary to avoid the worse impacts of climate change.

by a changing climate. Hence adaptation is a continuous stream of activities, actions, decisions and attitudes that informs decisions about all aspects of life, and that reflects existing social norms and processes. There are many classifications of adaptation options (summarised in Smit *et al.*, 2000) based on their purpose, mode of implementation, or on the institutional form they take.

Reilly and Schimmelpfenning (2000) point out that some adaptation occurs without explicit recognition of changing risk, while other adaptations incorporate specific climate information into decisions. Since unintentional adaptation has the capacity to reduce the effectiveness of purposeful adaptation, the integration of adaptation actions and policies across sectors remains a key challenge to achieve effective adaptation in practice.

The major types of adaptation are:

- ***Reducing the sensitivity*** of the affected system, which can be achieved, for example, by investing in flood defences or increased reservoir storage capacity; planting hardier crops that can withstand more climate variability; or ensuring that infrastructure in flood-prone areas is constructed to allow flooding.
- ***Altering the exposure*** of a system to the effects of climate change, which can be achieved, for example, by investing in hazard preparedness and early warnings, such as seasonal forecasts and other anticipatory actions.
- ***Increasing the resilience*** of social and ecological systems, which can be achieved through generic actions which aim to conserve resources, but also include specific measures to enable specific populations to recover from loss (Tompkins and Adger, 2004).

Adaptation options in agriculture involve different agents and scales and include actions by producers, input and food industries and government agencies, with individuals acting for private benefit, and public agencies seeking to maximise public good aspects of adaptation. In the United Kingdom, for example, public policy investments have been made in education for the wider society on the potential impacts of climate change and society's role in creating and managing those impacts. These investments have been made through agencies such as the UK Climate Impacts Programme (UKCIP, 2003). Ultimately, the purpose of such investment is to alter behaviour and increase society’s ability to cope with future impacts. Such investment is expected to enable individuals to start to respond to climate change, to promote uptake of new technology, to enable them to internalise the costs of responding to climate impacts, and to reduce future investments in disaster management.

Table 4.1 classifies the responses as accruing in either the public or private domain. Some elements of investment in climate change response are "public" and include conservation of nationally or internationally important habitats. Others are effectively private. If private firms in the water industry invest in knowledge of climate change risks, the costs and the benefits of this response are private. Climate change planning by governments at present tends to concentrate on providing public goods such as scenario information, risk assessments in the public domain, and public awareness campaigns (UKCIP, 2003; Hulme *et al.*, 2002). Hence, many response programmes at present avoid providing subsidies to private adaptation decisions. But the public and private elements of responding to climate change are not fixed: they are shaped by institutional and regulatory features in each sector of the economy. Further, they can change from public, to private and back again over time. In the UK the water supply utilities invest substantially in projections of water demand and supply under climate change for the benefit of their shareholders, while the public regulatory agencies seek to fulfil the same objectives of sustainability for public good aspects of water availability (documented by Arnell and Delaney, 2006).

The major actions for adaptation in agriculture are summarised in Table 4.2, distinguishing between technological development (which can be induced by both public and private investment); technological adoption; government programmes and insurance; and farm-level financial management. This classification was developed by examining options in arable farming regions in Canada where farmers have a high awareness of potential impacts from climate change (Smit and Skinner, 2002). Each of the categories and types of adaptation are presently undertaken to some extent and most are broadly applicable throughout OECD countries. A comprehensive list of specific adaptation actions in agriculture is provided in AEA (2007), produced for the EU Commission.

In less-developed or poorer countries adaptation strategies are more about maintaining livelihoods and coping with climate variability. Agrawal (2008) discusses five basic coping strategies in the context of environmental risks to livelihoods: mobility, storage, diversification, communal pooling and exchange. *Mobility* pools risks across space, and is particularly useful if clear information about the spatial and temporal changes in climate is available. *Storage* pools risks across time, and, assuming well constructed infrastructure and low perishability, represents an effective measure at a given point in time. *Diversification* pools risks across assets and resources of households and farms. This can occur in relation to productive and non-productive assets and employment strategies. Diversification often involves a trade-off between returns and security. *Communal pooling* pools risks across households, and is characterised by joint action by members of a group with the objective of pooling both risks and resources. *Exchange* may be the most versatile option, and is of course the basis for most of our market and trading systems today. An example of market-based adaptation to climate change is weather-related insurance schemes designed for agricultural or pastoralist populations. Aspects of some of these more basic coping strategies may be utilised in developed-country agricultural systems as well.

Table 4.1. Examples of adaptation options by timing and by responsibility

		Timing of response	
		Anticipatory *(ex ante)*	**Reactive *(ex post)***
Responsibility for response	**Private**	Private insurance markets Private research and development and investments	Adjustments in insurance markets Identification of least-cost adaptation options
	Public	Public infrastructure provision (*e.g.* irrigation infrastructure) Risk communication to agricultural sector and public Publicly available research and development	Post-disaster recovery Compensation for impacts Insurance underwriting

Source: Adapted from Tompkins and Adger (2005); Smit *et al.* (2001).

Table 4.2. Types and examples of adaptation options at different levels in agriculture

Adaptation	Examples	Implementation
Technological development	Crop development	Public and private investment in new crop varieties and hybrids to increase tolerance to water and heat stress or other relevant adverse conditions
	Weather and climate information systems	Public and private investments in monthly and seasonal forecasting, and early warning systems
	Resource management innovations	Public and private investment in water management innovations to address moisture deficiencies and risk of drought and changing seasonality of precipitation
Technological adoption	Farm production innovations	Diversification of crop types and varieties including crop substitution. Diversifying livestock types and breeds and changing seasonality of feedlot practices
	Land-use changes	Changing location of crop and livestock production and fallow rotations to address economic risks associated with climate change
	Irrigation	Implement on-farm irrigation practices to avoid recurrent drought risk
	Timing of operations	Changing timing of operations to address changing duration of growing seasons and associated changes in temperature and moisture

(Continued on next page)

Table 4.2. (continued)

Adaptation	Example	Implementation
Government programmes and insurance	Agricultural support programmes	Modification of crop insurance programmes to influence farm-level risk management strategies. Changes in *ad hoc* compensation and assistance for extreme events and disasters (*e.g.* animal diseases). Modify support and incentive programmes to influence farm-management practices.
	Private insurance	Encouragement of markets for private insurance of production, infrastructure and income
	Complementary resource management programmes	Development of public policies for water resource conservation and complementary conservation objectives.
Farm financial management	Private crop insurance	Uptake of private (or publicly encouraged) crop insurance or income insurance
	Crop shares and futures	
	Income stabilisation and diversification	Diversification of household income to include less weather-sensitive options.

Source: Adapted from Smit and Skinner (2002).

Adaptation in agriculture observed

Not all adaptation actions require conscious knowledge of climate change risks (see Reilly and Schimmelpfenning, 2000). In the UK, Tompkins *et al.* (2005) have described over 340 adaptations to climate currently underway. Their inventory includes examples of adaptation to climate change in the public and private sectors, as well as community groups, non-governmental organisations (NGOs), other associations and networks (including, for example, trade associations) and individuals. In the United Kingdom, agriculture, in common with other sectors, is at an early stage in adaptation although the examples collected reveal some general patterns. Few of the observed and classified adaptation involve resource use change in the present day. Most examples reflect anticipatory planning for climate change. Planning for climate change impacts is implemented through scenario development and risk assessment. In the United Kingdom, the UK Climate Impacts Programme provides scenarios of change that are used by regional planning authorities and trade associations, including, for example, the Country Landowners' Association and National Farmers' Union, in setting priorities for action.

UK agriculture faces the challenge of climate change in coming decades. The impacts of higher mean temperature, increased precipitation and storms, and a rise in sea level all have serious implications for the United Kingdom's agricultural sector (Defra, 2005). It is widely anticipated that the range of arable crops currently grown will move northwards (area of forage maize has already been highlighted as an indicator of climate change): the area grown has risen from approximately 20 000 ha in 1985 to over 100 000 ha in 1995, only partly due to improved plant varieties (Subak *et al.,* 2000). Types of adaptation in the farming sector include switching to alternative crops, shifting crops from areas that are vulnerable to drought, or investing in equipment that helps to reduce the severity of the impacts of climate change.

It is anticipated that agricultural businesses will need to adapt to the effect of climate change to ensure economic viability. For example, the costs of the 1995 summer drought to the agriculture industry have been estimated at a loss of GBP 457 million due to reduced income and capital costs (Subak *et al.*, 2000). Evidence suggests that those farmers who implemented adaptation and management changes at that time secured advantages over others (Defra, 2005).

There are, however, also some policy changes and laws being implemented which will affect adaptation possibilities in the future. The majority of the adaptations in the UK identified by Tompkins *et al.* (2005) are occurring in the public sector. As yet, there is little evidence of behavioural change in either the public or private sector. Most of the examples are occurring at the national scale, in the devolved administrations and at the regional scale, with few examples at local levels. There appear to be very few, if any, adaptations that have been undertaken solely in response to expected climate change. This is in clear contrast to reported mitigation actions such as investment in biofuels as a contribution to renewable energy.

This result is common throughout the world. In Canada, most individual farmers respond primarily to extreme events such as prolonged drought and unseasonal or excessive rainfall. In a survey in Ontario, 80% of respondent farmers judged extreme events to be the most significant impact to which adaptation was required, rather than changing growing season length or heat stress (Smit *et al.*, 1996). However, in some parts of Canada, adaptation programmes are quite advanced, such as in Alberta, where the provincial government has established the Alberta Climate Change Adaptation Team, which initiated province-wide and multi-sectoral assessments of vulnerability and adaptation strategies. In many cases, significant adaptation could be achieved and supported with adjustments to existing programmes and policy mechanisms (Lemmen *et al.*, 2008).

There is some evidence from the United Kingdom to suggest that awareness of climate change and its impacts are generally high among agencies with responsibility for agriculture and farmers (Tompkins *et al.*, 2005). Yet there is little evidence of individually planned adaptation to the impacts of climate change. In this sector there are a number of research programmes and emerging government guidelines that aim to address the long-term impacts of climate change. These actions are largely helping to build adaptive capacity, *i.e.* building up the knowledge about the likely impacts of climate change and appropriate responses needed. Regulations and policies to promote land-use practices may, however, have adaptation co-benefits or act as entry points for projects and programmes to engage in adaptation measures. These include agri-environment schemes. It is, however, too early to determine whether these actions will be effective or considered successful in the face of evolving climate risks.

The evidence on present-day adaptations in the UK agricultural sector has highlighted a lack of initial adaptation response despite relatively high awareness. It is much easier to find unplanned adaptations than planned adaptations and most planned adaptations fall into the category "building adaptive capacity" rather than "implementing adaptation". This finding may underestimate the actual extent of implementation. Some of these schemes and regulations (such as the Countryside Stewardship Scheme) are already affecting individual land-owners' actions, albeit individuals may be responding to the scheme requirements or regulation rather than considering climate change *per se*. Regional examples of adaptation include efforts by the East of England Regional Assembly, which stresses in its East of England Climate Change Impacts Study (2004) the need to adapt to water resource pressures. The Environmental Stewardship Scheme and the Water Act could, for example, create business opportunities for irrigators to trade water, invest in water saving and so on. Trickle irrigation, which promises lower water use, has expanded to cover 5% of the irrigated area in England

and Wales (Knox and Weatherhead, 2005), and reports by farmers in 2001 indicate that over 50% of the irrigated area in England is now scheduled by methods that account for seasonal water availability (Weatherhead and Danert, 2002). Building farmer awareness of the possible impacts of climate change, communicating their adaptation options and their benefits, and working to remove any barriers to action are important roles for public policy.

In Australia, risk assessments for climate change impacts on various sectors of agriculture demonstrate that there are high potential returns to planned anticipatory adaptation. Howden and Jones (2004), for example, find that adaptation in the major arable-growing regions, through changing planting dates and varieties, is likely to be highly effective. They estimate impacts for a full range of climate scenarios over the incoming decades along with assessments of CO_2 fertilization response (Asseng *et al.*, 2004). They find high regional differences in impacts: Western Australian regions were likely to have significant yield reductions by 2070, while North-eastern Australia was likely to have moderate increases in yield. The benefits of adaptation in the wheat industry nationally are estimated to be substantial: benefits of around USD 160 million per year in present prices (though with a range of USD 70-350 million per year, depending on adoption rates, range of climatic stresses and other factors).

Virtually all present discussions of adaptation to climate change in agriculture involve water resource management and the potential for water stress as a key driver for change. A study of regional agricultural adaptation in the Okanagan Basin in British Columbia in Canada (Cohen *et al.*, 2004) highlights potential interventions for adaptation to increase efficiency in water use. Agriculture in this region currently extracts 200 million cubic metres of weather annually to support high-value fruit trees, vines and pasture and forage. A range of ongoing adaptations were identified that involved both agricultural and non-agricultural users, including domestic water metering, irrigation metering, wastewater reclamation and re-use and amalgamation of individual water utilities. These adaptations are required currently since projections of climate change suggest higher demand due to higher summer temperatures and reduced supply. Introduction of charges for irrigation reduced demand by 10% while domestic metering in the region also yielded water-use efficiency gains. The important element of the initiatives for adaptation in the Okanagan is that the stakeholders involved, both in agriculture and outside it, have heightened awareness of the demand and supply issues raised by climate change through major stakeholder dialogues. Hence the suite of policies implemented in the region has a higher degree of legitimacy and ultimately of endorsement by the key sectors involved (Cohen *et al.*, 2004).

In developing countries, many rural communities have developed responses to address high levels of current climate variability. In the Sahel, farmers face extreme irregularity in rainfall, with annual rainfall declining and drought frequency and intensity increasing. As a response to this, farmers have adapted their practices and adopted other income-generating activities in order to cope with this variability (Agrawal, 2008).

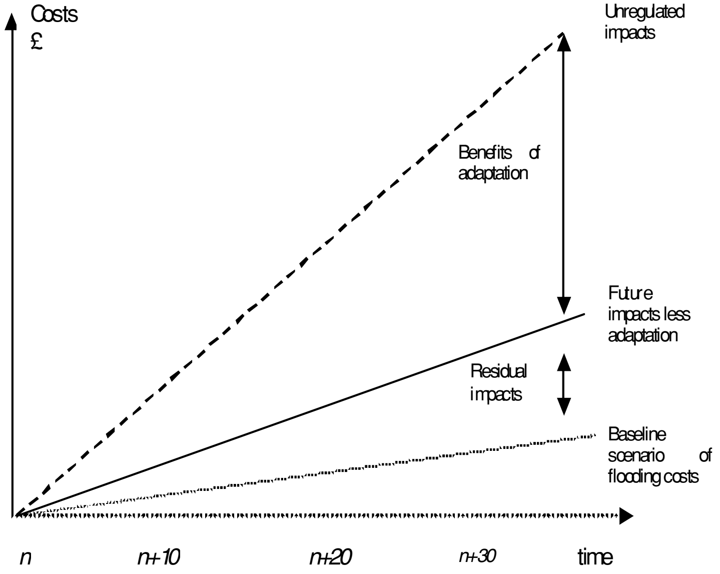
Estimating the costs and benefits of adaptation

It is only recently that studies examining the cost of adaptation have begun to emerge. Some, such as a report on the costs of adaptation to the global economy by the UNFCCC (UNFCCC, 2007), produce large-scale global costs, based on the investment and financial flows required to address climate change. For all sectors studied (which include agriculture) the investment and financial flows required to adapt to projected climate changes could be more than USD 100 billion per year several decades from now. This would be around 0.06-0.21% of projected GDP by 2030. Oxfam (2007) estimates the costs for financing adaptation in developing countries to be at least USD 50 billion per year, while the World Bank (World Bank, 2006) estimates costs of around USD 10-40 billion annually. Such estimates are useful for comparison with global mitigation costs.

However, large-scale global cost estimates mask the distributional impacts of adaptation and do not provide sufficient information for decision-making at a local or national level. In order to allocate finite resources and to prioritise alternative adaptation measures, a more detailed sectoral approach is required. Understanding the costs and benefits of adaptation actions is critical for practical decision-making.

Quantifying the costs and benefits of adaptation to climate change is, however, notoriously complex. Unlike mitigation, adaptation is a continual process, rather than a one-off action or outcome, and society, or farmers, are unlikely to be fully adapted to climate change. Indeed, we are vulnerable to current climate variability, and routinely bear climate-related losses as it is. These impacts are known in climate change literature as residual impacts, the impacts that society on some level has decided are acceptable. Residual impacts make costing adaptation difficult, as these must somehow be netted out of impact costing; *i.e.* not all the impacts will be avoided, therefore the cost of inaction does not necessarily translate directly into the benefits of adaptation. In addition, the baseline for comparison with inaction is also changing over time as climate change impacts are already routinely absorbed into management practices (or adapted to). Furthermore, many adaptation actions may have non-climate ancillary benefits, which may need to be taken into account in the valuation. These elements complicate any notion of efficient adaptation. Figure 4.1 illustrates the costs of climate impacts over time, for no adaptation (dashed line), with adaptation (solid line), and the baseline scenario of impacts with no climate change (dotted line). The baseline is increasing because the value of production and assets is assumed to increase over time. The difference between the solid and dashed lines represents the benefits of adaptation, while the difference between the dotted and solid lines represents residual impacts which will not be able to be adapted to. Residual impacts will vary both temporally and spatially.

Figure 4.1. Costs and benefits of adaptation



Source: Adapted from Metroeconomica (2004).

Literature on the costs of agricultural adaptation is limited. This may in part be because the focus of adaptation is on farm-level adjustments such as changes in timing of planting, or crop choices that are low cost. It is also the case that the distinction between public and private responsibilities has given rise to inertia in defining cost data and deriving overall estimates.

The European Environment Agency (EEA, 2007) highlights the need to monitor the effectiveness of adaptation strategies and actions, and provide an analysis of EU policy frameworks from an economic perspective. The report also highlights methodological issues in estimating costs of adaptation, and reviews studies on the costs of adaptation to date. Agrawala and Fankhauser (2008) provide a critical assessment of adaptation costs and benefits in key climate-sensitive areas, as well as across sectors at the national and global levels. They do not provide specific costs for agricultural adaptations, although they examine market and regulatory mechanisms that may be used to incentivise adaptation actions.

The role for public policy in adaptation

Given the combined public and private good nature of the benefits of adaptation in agriculture and related sectors, what is the role for public policy in tackling these climate change risks? This chapter considers rationales for public intervention in adaptation.

The public-private issue is important since it represents real trade-offs in policy. Governments in Europe, for example, continue to intervene in agricultural markets to reach public policy objectives of conservation, food security and farming and rural sector income support through the Common Agricultural Policy, even though the benefits may actually accrue to capital values in land (Allanson and Hubbard, 1999) But there may be less willingness to invest in climate change responses if all the benefits are perceived to be "private" – *i.e.* accrue to individual farmers, insurance companies or emerging weather futures markets. The mix of private and public good climate change impacts is the landscape against which government responses and investment priorities are determined.

The first rationale for promoting adaptation is to protect those parts of the agricultural sector and communities in rural areas that have the least ability to cope. As discussed above, agricultural regions facing climate change are subject to multiple stresses associated with market re-structuring, marginal productivity, and in the case of developing countries, lack of public infrastructure, high disease burden and many other factors that limit the ability to adapt. In addition, adaptation focussed on the most vulnerable is implicit in the Articles of the Framework Convention on Climate Change (Adger *et al.*, 2006), and is the basis for deriving potential international transfers to developing countries for adaptation (Baer, 2006). A survey of adaptation responses across the world by Adger *et al.* (2006) finds that adaptation is often directed towards greatest resource efficiency, rather than focussed on vulnerability reduction. Enhancing adaptive capacity, particularly that of disadvantaged rural populations, is likely to be more fruitful than identifying specifically how a given group in a particular area will be affected by climate change (Agrawal, 2008).

The second public policy response is the provision of high-quality information on the risks, vulnerability and threats posed by climate change. Such information includes scenarios of change at the global scale, as discussed in this report. But it also involves significant investment in the incorporation of climate information into land-use planning and other forms of regulation, hence the need for policy integration across government sectors, such as agriculture, planning and health, where climate change risks interact.

The third area of public policy response is in the provision and enhancement of the public good aspects of agricultural production and land-use. There are direct and demonstrable interactions between habitat and species protection with climate change impacts on water and vegetation and agricultural response (as demonstrated by Berry *et al.,* 2006 [for Europe]). Climate change impacts represent enhanced reasons for agri-environment policies and incentives to promote biodiversity conservation within the farming landscape, given the potential for habitat decline and species extinction throughout the world. Policies to promote food security at global and regional scales are also imperative, given the potential threats, and most importantly the potential uncertainty, in aggregate production in key regions such as South Asia and Russia.

In planning an adaptation strategy for the EU, the *White Paper on Adaptation* (European Commission, 2007) seeks to "define the role of the EU in adaptation policies so as to integrate adaptation fully into relevant European policies, to identify good, cost-effective practice in the development of adaptation policy and to foster learning".

The *White Paper* provided a first attempt at addressing the appropriate roles for public policy, arguing for a multi-level approach to adaptation governance in the EU, with specific roles at the European, national, regional and local levels. The main role at the European level was seen as the integration (or mainstreaming) of climate adaptation into policies across sectors, where the EU has specific competencies, including agriculture, fisheries, water, biodiversity, health, transport and energy.

Swart *et al.* (2009) analyse National Adaptation Strategies in ten European countries (Denmark, Finland, France, Germany, Latvia, the Netherlands, Portugal, Spain, Sweden and the United Kingdom). They find that the countries studied are adopting a variety of approaches based on their own cultural norms, political systems, and assessment of the risks posed by climate change. The report also identifies a number of common strengths and weaknesses in these plans, including a lack of co-ordination between sectors, and cross-sectoral conflicts. In addition, the national focus of most strategies ignores the threats (or opportunities) through global systems and networks.

Aaheim *et al.* (2008) argue that the role for public policy relating to adaptation covers seven objectives:

- Information, knowledge and learning;
- Early-warning and disaster relief;
- Facilitating adaptation in the market;
- Mainstreaming climate policy;
- Infrastructure planning and development;
- Regulating adaptations spillovers; and
- Compensating for the unequal distribution of climate impacts.

Given these policy imperatives for adaptation there is also a need to recognise how adaptation fits with other policy objectives of sustainability and whether certain adaptations themselves are desirable (see also Adger *et al.,* 2005; Mendelsohn, 2000; Hanneman, 2000; Burton *et al.,* 2002; Berkhout, 2005). Adaptation to climate change therefore can be evaluated through generic principles of policy appraisal seeking to promote equitable, effective, efficient and legitimate policies and investments harmonious with wider sustainability (Adger *et al.,* 2003; 2005). Defining success simply in terms of the effectiveness of meeting these objectives, however, is not sufficient for two reasons. First, whilst an action may be successful in terms of one stated objective, it may impose externalities at other spatial and temporal scales – what appears successful in the short term turns out to be less successful in the longer term. The rush to install domestic and commercial air-conditioning in western Europe following summer heatwaves, for example, represents an effective adaptation for its adopters, but is based on energy- and emissions-intensive technologies and therefore may not be sustainable in the long term (unless the energy is derived from renewable sources). Second, whilst an action may be effective for the adapting agent, it may produce negative externalities and spatial spillovers, potentially increasing impacts on others or reducing their capacity to adapt. Such adaptations are known in the literature as maladaptations. This may be particularly relevant in agriculture, where the success of farm-scale adaptations (in terms of both private and public good outcomes) is dependent on responses in contiguous areas of land on other farms.

Effectiveness relates to the capacity of an adaptation action to achieve its expressed objectives. Effectiveness can either be gauged through reducing impacts and exposure to them or in terms of reducing risk and avoiding danger and promoting security. The effectiveness of an adaptation action may depend on the future uncertain state of the world. Two key indicators of the effectiveness of an adaptation action are therefore robustness to uncertainty and flexibility, or ability to change in response to altered circumstances.

Efficiency in adaptation requires avoidance of under- or over-investment in adaptation technologies. In agriculture some investments in buildings, water infrastructure and land improvement are long-term investments where over- or under-shooting is a distinct possibility (Mendelsohn, 2000). These are known as the costs of misplaced foresight. While there is presently some theoretical research on adaptation to climate change as a learning strategy (Kelly *et al.,* 2005; Ingham *et al.,* 2007), this issue has yet to be examined in any detail in agriculture. Kelly *et al.* (2005) estimate so-called "adjustment" costs for farming regions in the United States' Midwest, simulating learning from one climate change state to the next through assuming a restricted profit function. They found that these adjustment costs were 1.4% of land rents for one simulated unanticipated climatic shock. A further issue in the efficiency of adaptation response is the valuation issues surrounding public good provision. Any assessment of the efficiency of an adaptation that incorporates only goods with market proxies (such as property, human health, or economic production) risks seriously underestimating both costs and benefits. Government-led adaptation to climate change often stresses public good elements of the problem such as ecological and aesthetic impacts and non-traded ecosystem goods and services, as much as private market impacts (Fankhauser *et al.,* 1999; Azar, 1998).

Equity of outcome in adaptation intervention and legitimacy of decision-making are both central to the resilience and ultimate perceived success of adaptation. They are important for instrumental reasons: development which is inequitable undermines the potential for welfare gains in the future, and developments which lack legitimacy have less chance of full implementation (see Cohen *et al.*, 2004; Adger *et al.*, 2006).

Policy instruments for adaptation

In agriculture, possible policy instruments may include price signals and market mechanisms; insurance instruments; microfinance; and R&D incentives (Fankhauser *et al.,* 2008).

The insurance sector (risk sharing) is likely to play a key role in future adaptation decisions, whether through traditional indemnity-based insurance, or through other options that may be more suitable for climate-based insurance, such as index-based schemes, weather derivatives or catastrophe bonds. For more detail on these schemes refer to Barnett and Mahul (2007); Fankhauser *et al.* (2008); and Mills (2007). Ideally, insurance can create incentives for adaptation and reducing risk by sending market signals about the climate risk and encouraging risk-reducing behaviour through discounted premiums. However, in reality this may not occur in exactly this way, because of uncertainty about actual climate impacts, budget constraints and structural, social and cultural barriers which prevent individuals and businesses from adapting, particularly if relocation would be the most appropriate adaptation. While insurance is likely to be an important mechanism in distributing risk and may create incentives for adaptation, subscribing to private insurance may not in itself necessarily lead to an adaptation of activity. In addition, as climate risks increase, insurance costs will also increase and may prove to be too costly for some actors, leaving them highly vulnerable to climate change. Insurance is in most cases a private decision rather than a public policy, and in some cases public intervention may be necessary to facilitate the sharing of climate risks between the insurance sector and the state.

EU member states use agricultural insurance to varying extents. Variation arises from the types of risks that are insured, how they are bundled (*e.g.* single-risk insurance, combined insurance, yield insurance), and how they are shared between the private and public sectors. In some cases the public sector heavily subsidises insurance premiums, while in other cases *ad hoc* aid and calamity funds are offered by the government.

Spain has one of the most advanced and elaborate agriculture insurance systems in the EU, based on the principle that the cost of subsidising insurance premiums is less costly than emergency relief payments following a disaster. In the event that public funds are provided for drought relief, farmers who opted not to buy crop insurance when it was available are not eligible for government funds to provide relief. Insurance coverage is close to 45% for all the agricultural production (and above 70% for winter cereals and fruits). In addition, Spain has an Insurance Compensation Scheme, a public organisation which acts as a reinsurer of agricultural risks (among others).

Table 4.3 shows a comparison of some EU insurance regimes. In France there is very low government subsidisation of insurance premiums (2.4%) compared to the other Mediterranean countries. However, the French government provides significantly greater *ad-hoc* aid – EUR 156 million per year on average over the 1996-2005 period, compared to less than EUR 5 million on average per year for both Spain and Portugal.

Table 4.3. Comparison of agriculture insurance systems for EU Mediterranean countries

	Single-risk insurance	Combined insurance	Yield insurance	Calamities fund	*Ad hoc* aids	Premium insured value (%)	Insurance subsidies (%)
France	P	P	PS	GS	–	1.7%	2.4%
Greece	G	GC+GS+G	–	–	GF	2.5%	no data
Italy	PS	PS	PS	GF	–	7.4%	67.0%
Portugal	PS	PS	–	GS	–	8.4%	68.0%
Spain	PS	PS	PS	–	GF	6.3%	41.0%

Legend:
S = Subsidised; P = Private, non-subsidised; PS = Private, partially subsidised; G = Public, non-subsidised; GS = Public, partially subsidised; GF = Public, free; – = Non-existing.

Source: European Commission (2006).

The differences in insurance coverage between countries may influence the adaptations that take place in those countries. As well as reducing reliance on disaster aid *ex post,* insurance can act as an important vehicle in shaping behaviour. In attempting to reduce vulnerability to extreme weather, insurance cover may be made conditional on appropriate risk-reducing measures being taken. In this way adaptation can be encouraged to a much greater extent than through unconditional post-disaster aid.

Fankhauser *et al.* (2008) discuss the role of environmental pricing, particularly in water markets, in encouraging and promoting adaptation to climate change. More generally, the appropriate pricing of natural resources can in fact improve the resilience of ecosystems and enable them to cope better with climate change. The identification and protection of ecosystem services, such as watershed protection through appropriate agricultural management and/or forest cover, can provide protection against flooding and erosion, as well as regulating the water table and minimising water pollution.

Public-private partnership is also an area that could contribute usefully to facilitating adaptation. As well as the financial benefits, public sector involvement sends a clear signal to private industry and individuals that the public sector takes adaptation seriously and is committed to it. Barriers to adaptation identified in some sectors include uncertainty regarding future policy commitment to adaptation: therefore, if the public sector is itself engaged in adaptation activities, this may remove some of these barriers. Examples of public-private partnership exist in other sectors, such as health, education and research and development. In agriculture, the most relevant public-private partnership is likely to occur in R&D, where the development of technology may facilitate adaptation. Examples already exist in crop development — for example, the Drought Tolerant Maize for Africa (DTMA) project, which links scientists with national agricultural research institutions, NGOs and private-sector seed companies.[2]

Figure 4.2 illustrates a schematic representation of how public-private partnerships might work as a first step to analysing how institutions across the public, civic and private boundaries could work jointly to help facilitate adaptation. This was developed in Agrawal (2008) and is based on the premise that institutions and organisations in both the private and public domains have inherent limitations through the nature of their specific focus. By collaborating with other organisations they may be able to fill gaps or remove weaknesses and provide a more comprehensive approach to addressing climate change.

In summary, there are significant challenges in promoting adaptation to climate change through policy intervention in agriculture at global and national scales. This report has concentrated on some more generic adaptation issues rather than focussing on specific adaptation measures that might be adopted within farming systems. While economic efficiency (*i.e.* cost-benefit analysis) provides a rational basis for adaption planning, it is important to recognise a number of complicating factors that limit adaptation responses relative to mitigation action. The first is that while mitigation is likely to be more of a mandatory requirement with immediate one-off actions, adaptation responses are continual processes requiring constant refinement as damage scenarios become more certain and/or impacts become increasingly apparent. The costs of on-going adaptation and the residual impacts lead to complications in identifying the costs and benefit of adaptation, and in determining the distributional impacts of future adaptation.

A second complication is in terms of co-ordinating how private adaptation responses can be reconciled with desirable public good outcomes. We have noted that the proper valuation (and conservation) of environmental public goods can increase resilience, and we note that their conservation often requires collective action by landowners. But little is known about how the promotion of private adaptation will impact on those

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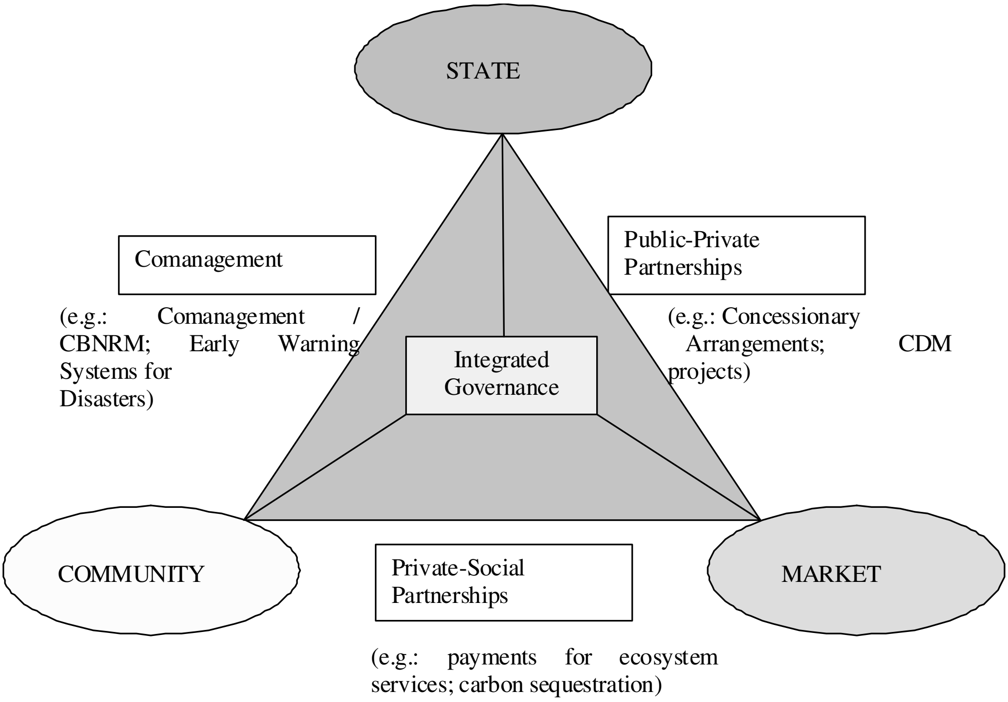
[2] http://dtma.cimmyt.org/.

same public goods, or how these impacts can be minimised through co-operative adaptation planning. This leads to a final observation on the respective private and public good roles. There is clearly a public interest role in the conservation of public goods, and in the facilitation of private resilience. But in the absence of more definitive impact scenarios, that role is largely limited to information provision and investment in research to understand how co-ordinated action can work. There is currently a limited evidence base on comprehensive adaptation measures, particularly on livestock systems and their costs. Part of the public good role should be to develop inventories of adaptation measures and reconcile these with mitigation requirements.

Figure 4.2. Diagram of collaborative institutional arrangements for environmental action in the context of climate change



Source: Agrarwal, (2008).

Chapter 5
Mitigation

Agriculture as a source of emissions

Emerging scientific evidence on temperature thresholds has injected greater urgency into discussions about how to avoid the consequence of dangerous climate change (IPCC, 2007). This agenda has been supported by *The Stern Review of the Economics of Climate Change* (Stern, 2006), which provides a compelling if contested economic basis for advancing greater spending on mitigation strategies. In most OECD countries there is now a proactive programme to determine where emissions reductions should take place.

Agriculture is a major source of global greenhouse emissions, accounting for an estimated emission of 5.1 to 6.1 Gt CO_2-eq/yr in 2005. This represents 10-12% of total global anthropogenic emissions of greenhouse gases (GHGs) (Smith *et al.,* 2007), although scientific uncertainly also suggests this could be as high as 18-31%. Methane (CH_4), mainly from enteric fermentation, rice cultivation and manure handling, contributes 3.3 Gt CO_2-eq/yr,[1] nitrous oxide (N_2O), from a range of soil and land management practices, contributes 2.8 Gt CO_2-eq/yr. Of global anthropogenic emissions agriculture is estimated to account for about 60% of N_2O and about 50% of CH_4. Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is estimated to be approximately balanced, with CO_2 emissions around 0.04 Gt CO_2/yr only (emissions from electricity and fuel-use are covered in the buildings and transport sector, respectively).

Agriculture and land-use also have large potential to act as sinks of carbon. Forests hold an enormous amount of carbon; however, significant volumes are also stored in soils and peatland. Changes in land-use and tillage practices can result in this carbon being released to the atmosphere.

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[1] Methane and nitrous oxide can be converted to carbon dioxide equivalents (CO_2-eq) by multiplying by their global warming potentials of 21 and 310, respectively.

In addition, climate change itself may lead to the degradation of these resources and their subsequent release of carbon (Pielke *et al.*, 2002) so it is vital to understand the role of land-use (including agriculture, horticulture and forestry) as both an emissions source and sink, and how this could change over time and with increasing levels of climate change.

Globally, agricultural CH_4 and N_2O emissions have increased by nearly 17% from 1990 to 2005, an average annual emission increase of about 60 Mt CO_2-eq/yr. During that period, the five regions composed of Non-Annex I countries showed a 32% increase, and were, by 2005, responsible for about three quarters of total agricultural emissions. The other five regions, mostly Annex I countries, collectively showed a decrease of 12% in the emissions of these gases. OECD (2008) provides a breakdown for member states since 1990.

Without abatement measures, emissions are likely to climb steadily by 1.1% per year, from 6.2 Gt of CO_2 equivalent, to 8.2 Gt CO_2e in 2030 – equal to a 31% increase in emissions over the period, according to McKinsey & Company (2009). The increase is driven mainly by population growth and greater world demand for meat, linked to increased *per capita* GDP. These projections are, however, speculative, depending on demand-side changes (Fiala, 2008). Increasing concern about the magnitude of these emissions has been expressed in relation to the need to distribute mitigation between developing and developed countries (FAO, 2007). In some countries, estimated emissions have already fallen, largely due to falling livestock numbers and, in some regions, further spontaneous cuts are anticipated to deliver similar savings over the next decade or so. However, more aggressive emissions targets need to be developed with some consideration of the economic potential for mitigation within agriculture relative to other sectors. Current estimates suggest that this potential is approximately 1.5-1.6 Gt CO_2e/year (by 2030), which is less than the total technical potential, of around 5.5-6 Gt CO_2e/year (UNFCCC, 2008).

Ultimately there is a need to address agricultural emissions without compromising other objectives for the sector such as food security, environmental sustainability and poverty alleviation.

Agricultural emissions inventory

Quantifying agricultural emissions raises a number of other complicating factors that increase the uncertainty inherent in the definition of sector abatement budgets, and that distinguish agriculture from emissions budgeting undertaken in other sectors characterised by fewer firms, a common, relatively well-understood set of abatement technologies, and ways of recording attributable emissions reductions. In comparison, agriculture and land-use are more atomistic, heterogeneous and regionally diverse. These factors can alter the abatement potentials and the effectiveness of measures implemented in different systems. As with other sectors, the effectiveness of measures is also influenced by interactions between measures and their environment. It is technically possible to reduce this uncertainty by explicit consideration of interactions of mitigation measures in the field. But it is clear that further work is required to derive more targeted abatement potentials, *e.g.* across a variety of farm types and on a regional basis.

An important point to note is that national inventories of GHG emissions typically account for emissions in accordance with guidelines produced by the IPCC (IPCC, 2006). These guidelines take account of GHG production and removal by using empirically based emission factors that are not comprehensive in terms of attributing emissions reductions to some indirect measures that can be undertaken in the sector. Thus, for example, reducing herd populations can be recorded as an unambiguous direct mitigation measure (animal numbers multiplied by an emissions factor per animal). However, a modification that, for example, reduces emissions per animal (*e.g.* probiotics), but leaves herd population unchanged, represents an indirect reduction that may not be counted under current inventory convention. Since there is considerable scope for such indirect measures in agriculture, it is important that inventory methods are adapted to reflect accurately the available scope attributable to the agricultural budget. In many countries this is a result of a lack of data and reliable measurement methods, resulting in the use of default rather than country-specific emission factors. Improving measurement techniques, data collection and transfer of best practice between countries is important in addressing this issue to ensure that inventories are as accurate a reflection of reality as is possible.

In agriculture, as in any sector, there is the potential for emission reduction through simply reducing production of a particular commodity, for example through reducing animal numbers. This has a direct effect on methane and nitrous oxide emissions for a country: however, if consumption of the product does not adjust accordingly, the emissions will simply have "leaked" to another part of the world. Overall, therefore, emissions may not be reduced, or may in fact have increased if the methods of production in the new location are more energy intensive.

The economics of mitigation

Agricultural GHG emissions are a production externality, and there is currently no national or global architecture that provides an incentive for the sector to modify behaviours and internalise global damage costs. That is, emissions from the sector are largely regulated on a voluntary basis and are not included in any trading regime. This market failure can potentially be addressed by a range of voluntary and market-based instruments that are applicable in other sectors. But, as in other sectors, the choice of mitigation measures raises interesting issues of effectiveness (of the range of measures), their efficiency and, because of the global split, equity.

In this chapter we consider progress on mitigation from the viewpoint of effectiveness and efficiency and, specifically, assessing cost-effectiveness of abatement measures in a country's agricultural sector. The welfare and equity debates are largely outside the remit of this report, though it is worth noting in passing that many of the most cost-effective interventions may be in non-OECD countries. Further, the issues dealt with here will largely be confined to the measurement of *production* emissions rather than those associated with the *consumption* of agricultural produce (for the significance of this distinction, see Druckman *et al.*, 2008). These emissions will be those within the farm-gate rather than a more holistic evaluation of whole life-cycle emissions in agriculture. However, it should be noted that some of the mitigation measures that are emerging in the literature do need to be considered in a life-cycle context for a full assessment of their effectiveness.

Cost effectiveness and efficient mitigation

The basic cost effectiveness criterion is posed by the consideration of where it is cheapest to mitigate one tonne of CO_2e. If mitigation is cheaper within agriculture relative to another sector (*e.g.* transportation), it makes sense to prioritise agricultural mitigation measures. After taking this decision, it is important to be clear on the relative effectiveness of mitigation measures within different farming systems (*i.e.* provide the largest volumes of gas abatement); and which among these are cheapest. In other words, to seek the cost per tonne mitigated. Note that this assessment of cost-effectiveness does not guarantee economic efficiency.

From a public perspective (*i.e.* government) the economic appraisal of emissions abatement through any route should compare the costs of investment in any mitigation option(s) with the benefits in terms of avoided emissions damages. This takes us a step nearer a definition of economic efficiency, where compliance costs associated with a given environmental *benefit* are minimised (OECD, 1989). Here, the benefit in question can be approximated by the shadow price of carbon (SPC), which is derived from the best estimate of the present value of damages associated with the release of a tonne of greenhouse gas. The current figures are a focal point of much research in the economics of climate change (Pearce, 2003; Tol, 2008; and Watkiss and Downing 2008). Accordingly an alternative benchmark can be provided by the European Union Emission Trading Scheme (EU ETS) price,[2] which provides a notional opportunity cost approach to assessing whether a specific mitigation measure is worthwhile, relative to the purchase of an emissions reduction in the international marketplace.

Considering for convenience the SPC, the figure that emerges can be adopted as an element for judging regulatory policy. For example, Defra (2007) sets out SPC estimates to be used in appraisal of public mitigation policies (Table 5.1). These figures are rising through time to reflect increasing marginal damage of a tonne added to a growing stock. This SPC is useful because it provides a benchmark against which to judge the efficiency of mitigation options. Put simply, the marginal abatement cost of a tonne of greenhouse gas should not exceed the social benefit (avoided damage) as measured by the SPC. More technically, abatement strategies need to look across industries to apply the principle of equalising the marginal cost of abatement across sectors. So an important mitigation agenda comes down to working out whether agricultural emissions are least cost relative to other sectors (*i.e.* industry and households).

Table 5.1. Defra shadow price of carbon to 2040
(2007 prices, 2% per annum increase)

Year	2007	2010	2015	2020	2025	2030	2040	2050
GBP/ t CO_2e	25.4	26.9	29.7	32.8	36.2	40.0	48.8	59.6

Source: Defra/Committee on Climate Change (2008).

A notional comparison of marginal cost and benefits is presented in Figure 5.1, which shows the rising cost of mitigation relative to the shadow price for any given year. The mitigation cost curve rises to reflect the fact that initially, tonnes of carbon can be mitigated at low or even negative cost. Thereafter, more costly interventions imply that each successive unit of greenhouse gas mitigation is achieved at a successively greater cost. At some point the cost of the last unit locked up through whichever method

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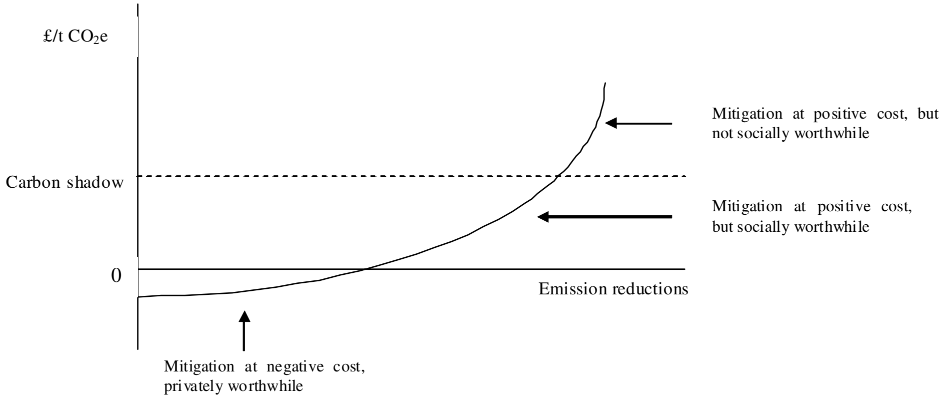
[2] Trading at a spot price of 11.64 euro/tonne CO_2 (1 February 2009) www.eex.com/de/Marktinformation/Emissionsberechtigungen/EU%20Emission%20Allowances%20%7C%20Spotmarkt.

is just equal to the damage it would cause. In many OECD countries, the cost of some agricultural mitigation strategies can be shown to fall below the shadow price threshold.

Figure 5.1. Notional marginal abatement cost schedule for CO_2e



Source: Authors.

Mitigation measures

There is an extensive list of technically possible options for mitigating emission ns in agriculture and land-use. For example, ECCP (2001) identify a list of 60 possible options; Weiske (2005) considers around 150; and Moorby *et al.* (2007) identify 21. Moran *et al.* (2008) identify more than 100 crop/soil and livestock measures potentially applicable in the United Kingdom. Measures may be categorised as: reducing emissions *via* improved farming efficiency, including genetic improvement; displacing fossil fuel emissions *via* alternative energy sources; and enhancing the removal of atmospheric CO_2 *via* sequestration into soil and vegetation sinks. Some mitigation options, typically current best management practices, deliver improved farm profitability as well as lower emissions and thus might be adopted without government intervention beyond continued promotion/revision of benchmarking and related advisory information services.

However, the majority of mitigation options entail additional cost to farmers. This raises questions regarding: Which measures can be implemented on farm? Where, when, and at what cost? What effect will different measures have on emissions? The derivation of efficient mitigation options requires some understanding of the relative cost of measures in terms of cost per tonne of CO_2e. This information defines the marginal abatement cost curve, which shows higher emission savings becoming increasingly expensive to achieve in terms of extra effort or income foregone. Consequently, cost-effective mitigation is likely to be significantly less than the technically feasible potential: the absolute size of emissions from a particular activity is less important than the cost of reducing its size, since it is avoidable rather than total emissions that are of interest. In addition, understanding farmers' decision making processes and behaviours is critical as even many of the win-win options are not currently being adopted. Identifying the reasons for this and how behaviour could be influenced to encourage greater uptake of options is needed in order to achieve real reductions in emissions.

Recent empirical literature about GHG emissions from agriculture highlights different elements of effectiveness and efficiency. There are several attempts to consider technical feasibility of measures and complementarity and the trade-off between them. Some of this literature considers cost but, in the absence of benefits, does not consider efficiency. These papers typically attempt to specify marginal abatement cost function for the agricultural sector (De Cara and Jayet, 2001; Deybe and Fallot, 2003; Gillig *et al.,* 2004; De Cara *et al.,* 2005; and Hediger *et al.,* 2005). Other literature considers costs, but in the context of aggregate welfare assessments of specific policies on mitigation (Gallagher *et al.,* 2003; Saunders *et al.,* 2006; Wier *et al.,* 2002; and Wong and Alavalapati, 2003).

MACC exercises

The marginal abatement cost curves depicted in Figure 5.1 can be derived from top-down or bottom-up approaches. Bottom-up engineering-based MACCs use detailed technology-rich models modelling abatement potential and costs for individual technologies and measures. These do not consider wider macro-economic effects of measure implementation in aggregate. They are particularly useful for the assessment of options at a sectoral level; *e.g.* agriculture and land-use. The alternative MACC approach that dominates the abatement cost literature for other sectors, such as energy, can use a top-down approach to assess the economy-wide effects of mitigation policy options. These capture macro-economic and market feedbacks, but tend to have less detail on specific technological options. They are particularly useful in informing on cross-sectoral and economy-wide effects. Note that there is a merging of the two domains, either through integrating models (*e.g.* as in the EU studies which combine a suite of models and link the outputs) or through hybrid models, for example where top-down models incorporate technological options, or bottom-up models incorporate macroeconomic aspects (*e.g.* MARKAL-Macro).

Agricultural abatement cost curves have been estimated at various scales (see Bosello *et al.,* 2007). A more top-down perspective is provided Perez *et al.* (2003), Marginal abatement cost curves have been estimated on a member-state basis by Perez *et al.* (2003), using the CAPRI modelling system. Perez *et al.* provide a regional assessment of the impacts of an EU-wide 10% reduction of total agricultural emissions. Following a similar approach, Perez and Britz (2003) and Perez *et al.* (2004) examine the implementation of a carbon credit system in EU agriculture, and the issue of transaction costs associated with inter-regional permit trading. Deybe and Fallot (2003) use more combined modelling, as do McCarl and Schneider (2001), who provide a comprehensive assessment of GHG abatement costs in US agriculture (see also Schneider and McCarl, 2003). De Cara and Jayet (1999; 2000) investigate abatement costs in French agriculture. In addition to N_2O emissions from the use of synthetic fertilizers and CH_4 emissions from enteric fermentation, the authors account for the possibility of carbon sequestration in agricultural soils and explore the conversion of set-aside land into forests. De Cara *et al.* (2005) move closer to a bottom-up approach in developing a linear programme model for European agriculture and deriving a marginal abatement cost curve for different levels of an emissions tax.

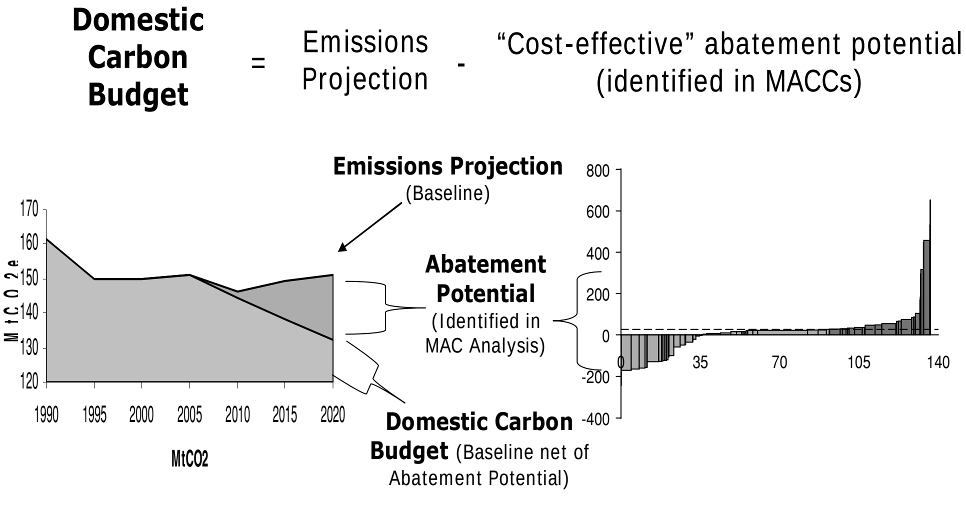
On the whole, because of the more technology-rich, bottom-up MACC approach, it is most illustrative of the potential range of mitigation methods. In their most aggregated form, global bottom-up MACCs suggest considerable potential for agricultural budget (McKinsey & Company, 2009). Inevitably, as agricultural emissions come under increasing regulatory scrutiny, this global potential has to be translated into actual country or producer-specific information on how mitigations can fit inside an economically efficient budget. Such an approach has recently been undertaken in the United Kingdom under the auspices of the recently formed Climate Change Committee (CCC).

Carbon budgeting in UK agriculture

The CCC was set up under the recently passed Climate Change Act 2008, and has the task of delivering interim budgets as part of the UK's longer-term commitments on GHG mitigation. Budgets are derived for 2012, 2017 and 2020 using a bottom-up MACC approach in all sectors including agriculture, land-use, land-use change and forestry.

The bottom-up MACC provides a static "snap shot" illustration of the annual potential to reduce emissions and average costs of doing so for a wide variety of technologies and abatement measures for a given year relative to an assumed baseline. Ranking abatement measures in order of decreasing cost effectiveness – such that measures to the left of the curve and below the x-axis indicate negative costs of savings to society, and costs to the right and above the x-axis illustrate costs to society – permits technologies and measures to be compared at the margin (*i.e.* the steps of the curve) and provides an invaluable tool for cost-effectiveness analysis. These volumes are taken as annual emission savings for a given year, additional from initial fixed baseline. As such, the emission savings should be constructed from the difference between CO_2e emitted in the baseline or business as usual scenario and emissions in the abatement scenario where a particular technology or abatement measure is employed across a reasonable counterfactual characterised by likely adoption within a reasonable policy environment (see Figure 5.2).

Figure 5.2. An illustrative MACC and its relationship to a carbon budget



Source: Defra/Committee on Climate Change (2008).

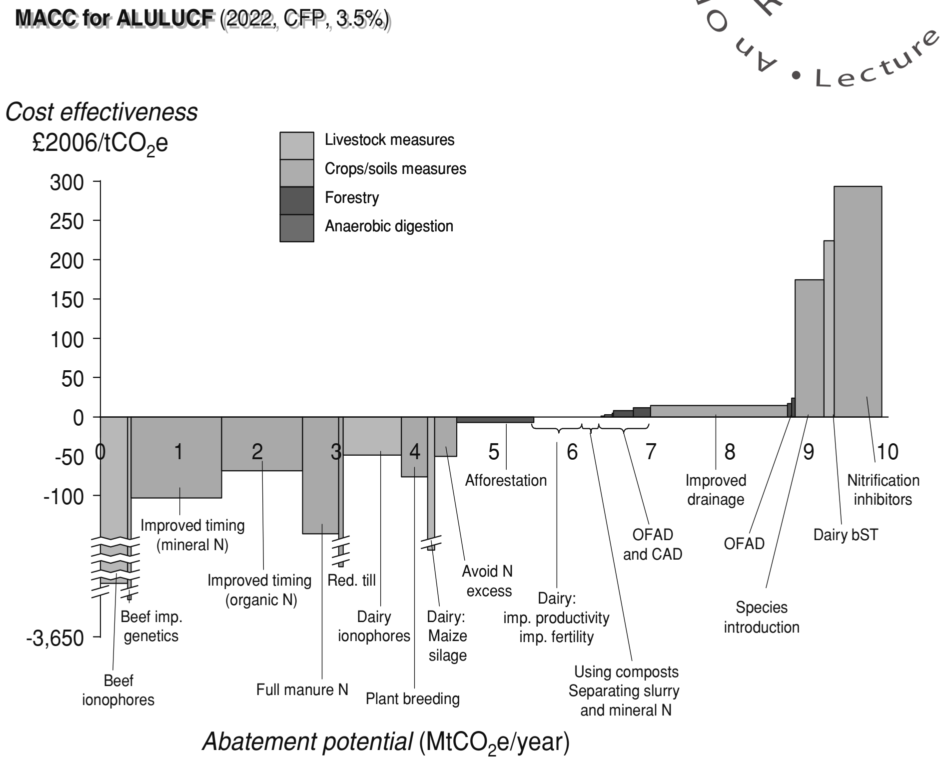
Development of the marginal abatement cost schedules is data-demanding in terms of screening the range of crop, soil and livestock mitigation methods and their associated adoption costs. The MACC provides a measures hierarchy showing mitigation costs (in this case GBP per million tonnes of CO_2 equivalent) and effectiveness (volume of gas), showing which deliver cheapest to most expensive savings of CO_2 (Figure 5.2). Assuming a policy environment that allows or promotes the adoption of emissions mitigation measures, the UK analysis suggests that by 2012, agriculture, land-use, land-use change and forestry (ALULUCF) could be mitigating around 6% of current greenhouse gas emissions (reported to be 45.25 Mt CO_2e in 2005). By 2022, this rises to nearer 25%.

The central feasible MACC shown in Figure 5.3 is backed by a number of important assumptions about the adoption rates of measures (*i.e.* the spatial scale of application for a measure), the way the potential of some measures can be reduced by interaction with other measures, and the need to reduce costs to a present value equivalent using a specific discount rate. The figure demonstrates considerable negative cost (*i.e.* win-win) potential inherent in measures related to better management of fertilizers and animal breeding. A notional efficient budget is defined as the applicability of these win-win options plus measures up to the threshold provided by either the SPC or an EU ETS price. Note also that many of the measures considered are truncated as high cost and that this figure excludes relevant forestry bars.

A number of caveats are noteworthy when considering the accuracy of the budget emerging from this particular exercise. The first is that the results do not include a quantitative assessment of ancillary benefits and costs, *i.e.* other positive and negative external impacts likely to arise when implementing some greenhouse gas abatement measures. Reduced water pollution related to more efficient use of nitrogen fertilizer is a classic example. While emissions abatement and water pollution may be positively correlated, the same is not always true for the effect of some abatement measures on biodiversity. Some ancillary impacts will be significant, and they ideally need to be quantified and added to the cost estimates. The inclusion of these effects will likely tend to make crops and soils measures more attractive, and livestock measures less so.

A similar caveat applies to the need to extend the consideration of costs to the life-cycle impact of some measures. Qualitative analysis suggests that crops and soils measures will have co-benefits in reducing emissions from fertilizer production.

Figure 5.3. Illustrative marginal abatement cost curve for UK agriculture



Source: Defra/Committee on Climate Change (2008).

A third point is to reiterate that there is some uncertainty about the extent to which some of the identified measures are counted directly in the current UK national emissions inventory format. As currently compiled, some measures may only reduce emissions indirectly and it is important to try and identify how a measure can qualify as being of direct mitigation potential. Removing indirect measures can have the effect of reducing abatement potential by around one-third. There is clearly a need to clarify how measures qualify for inclusion in national inventory formats.

Policy instruments for mitigation

Managing emissions is a new challenge for farming in all OECD countries and the level of awareness of regulatory requirements among farmers and producers is progressing slowly. As national obligations become more stringent, there is an increasing likelihood that agricultural emissions will be scrutinised for regulation. To date, there is in most countries a general presumption in favour of a voluntary approach to the adoption of best-management practices, which coincidentally deliver both water and greenhouse gas benefits. But several governments, including the UK, New Zealand and Canada, have progressed in the exploration of the potential for introducing domestic market-based approach to agricultural emissions reductions. The Canadian Offset system is open to a range of agricultural/land-based proposals including afforestation, soil management and biodigesters, and does not have a minimum project size. It is currently a voluntary system (Environment Canada, 2008). In the United Kingdom, Nera (2007) explored the feasibility of alternative cap and trade and project-based emissions pricing approaches. A basic problem revealed by this research is the implicit transaction costs associated with regulating many small emissions sources. This inherent structure of agriculture contrasts with other industries characterised by fewer larger emissions sources. Partly in response to the same barrier, New Zealand appears to be more advanced in plans to introduce emissions trading regime by 2013 (see Box 5.1).

In the New Zealand case, the main question relates to the feasibility of moving the point of obligation for holding emissions permits from farmers onto other parts of the food chain that are more easily monitored. In this case fertilizer manufacturers appear to be the prime target for inclusion in a trading scheme. It is currently unclear how acceptable this suggestion is to the industry or how effective this approach will prove. In the UK exploratory work funded by Defra is considering the relative merits of alternative trading schemes for livestock producers and fertilizer merchants. Alternative approaches include the introduction of specific emissions obligations under forms of cross compliance, or a specific agricultural climate change agreement that would entail a climate change levy on producers with rebates for those signing-up and complying with good practice agreements.

In considering the development of carbon credit instruments, it is important to consider how these might develop on a global basis to provide the incentive for developing country agriculture, which is estimated to account for about 74% of total emissions from the sector. Developing-country production is also thought to offer large abatement potential at low cost and so the policy challenge is to unlock this, along with large co-benefits for sustainable development (food security, poverty reduction among the 70% of the poor living in rural areas, environmental services) and for climate change adaptation (improving agro-ecosystem resilience). Tubiello *et al.* (2009) highlight that significantly larger financial flows than are possible under the current carbon market could be created by adding a range of land-based activities within post-2012 climate mitigation and adaptation mechanisms. They point specifically to reduced deforestation and degradation, agricultural land restoration and soil carbon sequestration, agro-forestry, and many land-conservation practices.

Box 5.1. The New Zealand Emissions Trading Scheme

The proposed Emissions Trading Scheme (ETS) (which, following a change in government, is under review) involves all significant GHGs and all sectors, including agriculture. Forestry will be the first sector to be involved in the ETS. Agriculture is due to be included (as the last sector) in January 2013.

The agricultural sector includes GHGs from pastoral agriculture, horticulture and arable production – methane from livestock emissions and nitrous oxide from animal urine and dung and synthetic fertilizer.

Participants can voluntarily report their emissions in 2011 and are required to report their emissions in 2012, but they are not required to pay for their emissions in these years until 2013. The Act sets the point of obligation for agriculture emissions at processor level. This means meat and dairy processors and fertilizer companies will be responsible for the emissions that occur on farms. The Act allows the government to change this to farm-level before a cut-off date of 30 June 2010. Applying the point of obligation on processors may remove incentives for emission reduction at the farm level; however, imposing individual obligations on each emitter would entail significant transactions and regulatory costs.

Concerns around the ETS as a whole focus on liquidity in and access to international carbon markets, leakage of production and emissions from trade-exposed emissions-intensive sectors, and the likely overall economic impact of the system (Kerr and Sweet, 2008).

For more information on the NZ ETS, refer to Kerr and Sweet (2008) and New Zealand government documents, available at: www.climatechange.govt.nz/nz-solutions/reducing-our-footprint.shtml.

FAO (2009) sets out the hurdles before this potential (much of it from smallholder agriculture) may be realised under a future global climate change agreement. It addresses quantifying mitigation and dealing with uncertainty issues associated with soil carbon sequestration, enabling institutional and policy environments required to link carbon finance to mitigation from smallholder agricultural sector and modalities/mechanisms needed to effectively link carbon finance to agricultural sources of mitigation, including financing options for agriculture, including smallholder agriculture. The focus is on soil carbon sequestration in view of its high mitigation potential, relevance to smallholders, and its current exclusion from the Clean Development Mechanism. Tubiello *et al.* (2009) point to the barriers that exist between the rural poor and access to financial mechanisms, including governance issues, technical capacity, high transaction costs and a lack of appropriate baseline and monitoring methodologies.

While there is scope to overcome many of the identified hurdles, there is a need to create enabling conditions for further work on mitigation from agriculture in the next climate agreement. At country level, pilot activities are needed to test measurement, reporting and verification methodologies and incentive/payment schemes, supported by capacity building, technology transfer and institutional mechanisms. Beyond the Conferences of the Parties to the Kyoto Protocol in Copenhagen in December 2009, in the transitional period leading up to 2012, ways of realising terrestrial carbon sequestration from all land-uses may need to be explored to enable better management of synergies and trade-offs across different land-uses and land-use changes. Highlighting the ancillary benefits of mitigation (and indeed adaptation) actions, such as any impacts on water pollution, biodiversity and other public goods, as well as possible cost savings, may be a mechanism for encouraging mitigation action.

Chapter 6
Integrating mitigation and adaptation

At present, research and policy relating to mitigation and adaptation are generally separate agendas, driven by different policy requirements and often handled by different agencies. Arguably, legally binding emissions reductions agreements have given more urgency to domestic mitigation agendas, which have, in part, eclipsed resource allocation for adaptation. The latter is often perceived as a longer-term agenda that can be partly assigned as a private rather than public responsibility. While this may be the case, there is nevertheless likely to be a public-good interest at stake when considering the outcome of private adaptation decision making in agriculture. At a minimum therefore the public role should be one of imparting relevant impact information as and when it becomes available and in seeking out the synergies in co-ordinated adaptation and mitigation planning.

The division of mitigation and adaptation polices between different agencies means that viable options relating to one of these climate change responses may undermine or directly conflict with the other agenda. While it is acknowledged that agriculture has been successfully adapting to changing conditions for centuries, and is often carried out on a decentralised basis as a response to local variations in conditions, an integrated adaptation and mitigation framework is important to ensure that trade-offs between the two are minimised and synergies encouraged. For example adaptation of livestock using alternative housing may give rise to specific emissions problems related to manure handling or energy use (maladaptations). Mitigation policy may encourage the production of energy crops, or forestry, in areas that are vulnerable to extreme events or are very water-intensive, which undermine the ability of the sector to adapt to the changing climate (See Box 6.1 for a discussion on the role of biofuels as a mitigation strategy). Increased irrigation needs under climate change may result in a reduction in water available for hydro-power (mitigation). Policies to reduce emissions, such as carbon taxes, may increase costs to producers, leaving them with less resources to adapt to the changing climate.

Box 6.1. Biofuels as a mitigation strategy

Biofuels have been proposed and developed as an alternative energy source with the potential to improve the security of energy supply, reduce GHG emissions, and increase incomes for farmers. However, while they have considerable potential in meeting these aims, their production and use has been controversial, particularly with regard to their effectiveness at reducing net GHG emissions and their competition with food resources and associated increase in food prices.

Currently the US and Brazil are the largest ethanol producers globally, producing 48% and 31% of global ethanol in 2007, respectively, while the EU accounts for around 60% of global biodiesel production (von Lampe, 2008). With respect to their effectiveness at reducing GHG emissions, ethanol based on sugar cane generally reduces emissions by 80% or more over the whole production and use cycle, relative to emissions from fossil fuels. However, current support policies in most countries other than Brazil tend to target feedstocks that reduce emissions to a lesser extent (wheat, sugarbeet or vegetable oils provide emissions reductions of between 30-60%, while corn-based ethanol generally provides savings of less than 30%). Additionally, where forests are cleared to make way for new energy crops, emissions can be higher than for fossil fuels.

The UK Government recently undertook a review into the indirect effects of biofuel production (Gallagher, 2008). The review found that while there is probably sufficient land for both food and fuel production globally, biofuel production must target marginal and idle land and not compete with food-producing land. Lower national targets for biofuel use and more stringent regulation are required. In this regard, the EU has recently introduced a caveat that 40% of its 10% biofuel use in transport target comes from land that does not compete with food production.

Second-generation biofuels offer much greater potential, and incentives for research into these technologies are required. The possible benefits that biofuels have in reducing GHG emissions should not be lost through inappropriate policies that produce more negative outcomes than positive. A targeted and forward-looking approach to biofuel incentives and policy is necessary.

Conversely, there may be synergies that can enhance the success of both adaptation and mitigation. From an economic perspective, adaptation and mitigation are closely linked, in that the more mitigation takes place, the less adaptation (in the longer term) will need to occur. Similarly, the more that climate change impacts are adapted to, the less they will cost and hence the optimal level of mitigation will be lower. Decisions on adaptation and mitigation are often made at different governance levels, ranging from individual producers, to national planning agencies and international agreements (Klein *et al.*, 2007). Closer communication between the adaptation and mitigation agendas would enhance the capacity for synergies to be developed. Indeed, there is recent discussion on whether the current distinction between adaptation and mitigation is even valid. For many decision makers responding to the challenge of climate change, including farmers, the separation between mitigation and adaptation actions may not be very constructive.

Oleson and Porter (2009) summarise the effects of a range of mitigation measures on six main factors relevant to adaptation in agriculture (with a particular focus on arable systems), as part of the PICCMAT[1] project. Some of these are shown in Table 6.1, which is not exhaustive but shows instead some examples of where mitigation measures can have positive (or negative) implications on the adaptive capacity of a system. Mitigation measures generally aim to reduce nutrient losses in the system. This is mainly achieved through increasing the nutrient and water retention in the systems and preventing soil degradation, which also helps to make the system more resilient to droughts and flooding. Similarly, adaptation actions can affect mitigation efforts, particularly those that reduce soil erosion, leaching of nitrogen and phosphorus; those that conserve soil moisture; those that increase the diversity of crop rotations; those that modify the microclimate to reduce temperature extremes and provide shelter, those that involve land-use change, involving the abandonment or extensification of existing agricultural land or the cultivation of new land (Oleson and Porter, 2009).

While it is possible to develop an efficient mitigation strategy, effective mitigation ultimately relies on concerted action at a global level, while many adaptation decisions are made locally and by individuals. From a policy perspective, it is vital that adaptation and mitigation are integrated as much as possible and that strategies which maintain or increase the resilience of production systems, as well sequestering soil carbon and/or reducing fluxes from farm activities, are promoted. In addition effective integration of adaptation and mitigation may well result in lower overall costs.

Because some climate impacts are immediate and may affect the financial viability of an agricultural producer right now, in contrast with the longer-term impacts that mitigation addresses, adaptation decisions are likely to take precedence over mitigation decisions (Rosenzweig and Tubiello, 2007b). Because of this, it is important that the public sector is involved in integrating both adaptation and mitigation, and ensuring that perverse incentives (including farm support policies) do not lead to increasing vulnerability in the longer term.

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[1] www.climatechangeintelligence.baastel.be/piccmat/index.php.

Table 6.1. Mitigation measures affecting adaptation in agricultural systems

Mitigation Measure	Adaptation Issue	Soil erosion control	Nutrient loss reduction	Soil and water conservation	Genetic diversity	Micro-climate modification	Land-use change
Catch crops		+	+	-			
Reduced tillage		+		+			
Residue management		+		+		-	
Extensification							+
Fertilizer application			+				
Fertilizer type			+				
Rotation species		+	+		+		
Adding legumes		+	+		+		
Permanent crops		+	+	-	+		
Agro-forestry		+	+			+	
Peatland management							+

Source: Adapted from Oleson and Porter (2009).

An understanding of the interactions between different policies and sectors and potential spillovers is a vital first step in integrating both adaptation and mitigation policy across all sectors. Even within the agricultural sector, policies (*e.g.* the CAP) can create both positive and perverse incentives for mitigation or adaptation. It has been recognised that existing institutional mechanisms are probably the most appropriate starting point for addressing adaptation objectives, and for reinforcing mitigation measures. Agriculture has been mentioned as an important starting point for addressing integration in the EU, through future adjustments of the CAP to examine ways of better integrating climate change objectives in agricultural support programmes.

Chapter 7
Relevant climate research in other agencies

Climate change is now a mainstream concern for governments across the OECD area, with most member countries also funding research into differing aspects of national impacts, adaptation and mitigation. In this chapter we focus predominantly on work that is developing appraisal and evaluation frameworks of relevance to agriculture, specifically any work aimed at improving the efficiency of responses.[1]

The EU has been pioneering in its development of efficient mitigation strategies, with the ETS being its flagship instrument to regulate industrial emissions. While agriculture is not part of the traded sector at present, the potential for inclusion has stimulated research into effective and efficient mitigation options in agriculture. The EU is in the process of developing its adaptation framework with a *White Paper* on adaptation to climate change in Europe (European Commission, 2009). A principal consideration of the *White Paper* is the extent of the EU's responsibility to assist adaptation in developing countries.

The EU also funds specific projects on climate change research. Two are of particular interest in developing frameworks and the economics of climate change: ADAM (Adaptation and Mitigation Strategies: Supporting European Climate Policy) aims to provide a better understanding of the trade-offs and conflicts that exist between adaptation and mitigation policies. ADAM will support EU policy development in the next stage of the development of the Kyoto Protocol and will inform the emergence of new adaptation strategies for Europe. In terms of agriculture, however, ADAM only has a small focus and that is on crops, with no focus on livestock. The main objective of the PESETA project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) is to contribute to a better understanding of

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[1] For a list of the main organisations involved in climate change and agriculture research, see Annex A.

the possible economic impacts induced by climate change in Europe over the 21st century, again focusing predominantly on crops.

The FAO (Food and Agriculture Organization of the United Nations) plays an important role in research on climate change across its divisions. Recently the FAO identified some key features that would be required in relation to funding mitigation from agriculture:

- Aggregation (carbon finance, where up-scaled and broad approaches can be applied – *e.g.* sector, programme, ecosystem – facilitates the involvement of large numbers of smallholder farmers, covering a wide area and range of ecosystems, with influence on the development of needed policies and technologies);
- Financing arrangements that address the specific needs of smallholder agriculture mitigation adoption, including the need for investment capital, technologies and risk management/transfer (insurance);
- A range of options for mobilising both private and public funds, including use of compliance market credits, voluntary market credits, publicly funded programmes and agricultural product labels, with adequate flexibility to adjust to the specific agro-ecological, institutional and technological situations of Parties, and
- An enabling environment with appropriate policies, institutions, capacity building and an agreed system of property use/rights/access in order to link farmers, including smallholder farmers, to carbon financing (FAO, 2009).

The FAO also has a broad programme aimed at ensuring food security under climate change, which is outlined in Annex A.

In the United Kingdom, UKCIP was established in 1997 to co-ordinate scientific research into the impacts of climate change, and to help organisations adapt to those unavoidable impacts. UKCIP is funded mostly by the Department for the Environment, Food and Rural Affairs (Defra) and is responsible for generating widely used scenarios of climate change impacts (UKCIP02 and UKCIP09), as well as developing frameworks and support for assessing costs of impacts and adaptation measures. UKCIP provides information on current agricultural research relating to adaptation, and the tools developed by UKCIP can be applied to agriculture: however, it does not focus specifically on agriculture itself. Defra also has a strong interest in furthering work into both mitigation and adaptation in the agricultural sector, both in terms of identifying impacts, developing adaption (technology) inventories and cost-effective responses. Of specific interest is that Defra is currently funding a number of projects focussing on impacts and adaptation on livestock sectors, which have been poorly represented in other research conducted by – for example – the EU.

The Spanish Government established the Spanish Research Institute on Climate Change in 2008, in Zaragoza, which co-ordinates research on climate change in Spain.

The Climate Change Impacts and Adaptation Division of Natural Resources Canada focuses on two main activities, The Regional Adaptation Collaboratives (RACs) programme, and the Tools for Adaptation Program. This RACs programme will provide a mechanism for collaboration between different levels of government, private sector entities, and community organisations on complex adaptation issues that address federal, sectoral, or regional priorities. The objective of this initiative is to equip decision makers with the information and advice that they need to make policy, operational, and management changes that respond to regional opportunities and threats from a changing climate. The Government of Canada published a comprehensive report in 2008 on impacts and adaptation to a changing climate (Lemmen *et al.*, 2008), assessing current and future risks and opportunities for Canada.

The Economic Research Service of the United States Department of Agriculture (USDA) has investigated some aspects of the economics around climate change and agriculture, particularly the economics of sequestering soil carbon.

As mentioned, Australia has recently conducted a large-scale report on the likely effect of human-induced climate change on Australia's economy, environment, and water resources. The *Garnaut Review* also focused on the costs and benefits of various international and Australian interventions on economic activity, where the agricultural sector was included in considerable depth. It concludes that the development of biosequestration technologies could greatly help reduce the costs of emissions reduction in Australia, although the realisation of this would require comprehensive emissions accounting.

New Zealand conducts considerable research into climate change and agriculture, as agriculture is an important sector of the economy and contributes almost 50% of the country's GHG emissions. Aside from the ETS, which is outlined in Box 5.1, considerable research is conducted across a range of institutions, primarily regarding the mitigation of emissions from agriculture. The Pastoral Greenhouse Gas Research Consortium (PGgRC) aims to provide New Zealand livestock farmers with the knowledge and tools to mitigate greenhouse gas emissions from the agricultural sector. The PGgRC is made up of several research institutions and government bodies. The New Zealand Ministry of Agriculture and Forestry (MAF) supports a range of projects relating particularly to the quantification and reduction of GHG emissions from agriculture (www.maf.govt.nz/climatechange/slm/gg-grants.htm).

The World Bank, the UNFCCC and the UNDP all have research programmes investigating the global costs and investment flows required to address adaptation (mostly in developing countries but some of these are global). Because of the scale of the estimates, much sectoral detail is lost; however, the research programmes themselves provide valuable frameworks and methodology (World Bank 2006; UNDP, 2007; UNFCCC , 2007).

Chapter 8
Future research needs

It is possible to identify at least five areas of research and policy advocacy relevant for the OECD in relation to furthering the economics of climate change in agriculture. These are:

- Integrated impact assessment leading to valuation of market and non-market impacts;
- The promotion of adaptation frameworks based on cost-benefit analysis;
- The development of marginal abatement cost modelling to develop emissions budgets;
- Research on the application of alternative voluntary and market-based instruments in relation to food and farming; and
- Behavioural change in farming and consumer behaviours.

Valuation of climate change impact scenarios

The valuation of climate change impacts is a logical extension of integrated modelling of downscaled climate forecasts. In agriculture, national climate scenarios ideally need to be downscaled and translated into regionally-specific monetary damage estimates to crops, livestock and other non-market impacts that arise as adaptation takes place. This valuation exercise is challenging since the range of impacts requires the output of a range of integrated biophysical and epidemiological models including risk. But this valuation is useful for two reasons: first, as an input to cost-benefit analysis of adaptation plans; and second, as an input to the global damage cost estimates that inform the calculation of the Shadow Price of Carbon (see Watkiss and Downing, 2008).

The promotion of adaptation frameworks (based on cost-benefit analysis)

There is currently very little research at a local scale investigating the cost-effectiveness of options for adaptation in agriculture. While some organisations and reports (World Bank, 2006; UNFCCC, 2007; Stern, 2006) have developed large-scale studies assessing the likely costs of adaptation (loosely defined) at a global scale, systematic and policy-relevant estimates at a local sectoral level are lacking in agriculture. Even frameworks or methodology to enable this to be carried out are very limited. An exception is the UKCIP costing tool.[1]

Addressing the role of national and regional policy in facilitating or creating barriers for adaptation is an important area, as is the need to co-ordinate mitigation and adaptation planning, possibly by the development of inventories of the complementarities or conflicts between adaptation and mitigation measures. EU agri-environmental policies are potential vehicles for adaptation and mitigation actions; however, they can also create perverse incentives and barriers to both forms of action. Subsidies for water-intensive crops in Mediterranean areas where water is projected to become more scarce in future is one example. Disaster relief funds may encourage moral hazard and reduce the penetration of insurance into agricultural markets. A large-scale assessment of potentially perverse policies and those which facilitate adaptation and increase resilience in OECD countries (and beyond) is an area for further research.

Similarly, policies in other sectors may affect the ability of the agricultural sector to adapt to climate change. This is likely to occur predominantly in relation to changes in trade policy and global trading patterns, which again may create incentives to produce crops not suitable for the local conditions, or barriers to adaptation. An assessment of the types of external influences on the ability of agriculture to adapt to climate change would be very important.

The development of marginal abatement cost modelling to develop emissions budgets

As previously noted, there are methodological differences in the development of marginal emissions abatement costs information for agriculture. While the literature has been dominated by top-down modelling, there is a need to understand whether this provides accurate information on area-specific mitigation costs developed with a more localised bottom-up

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[1] www.ukcip.org.uk/index.php?option=com_content&task=view&id=69&Itemid=185.

approach. We note that there are no comparative studies reconciling abatement cost information for agriculture. This is possibly due to the shortage of bottom-up studies.

Existing bottom-up abatement cost analysis suggests that there is likely to be a broad range of mitigation options in crop/soils and livestock and that there is scope for implementing a range of measures that in fact reduce emissions and improve the economic performance of the farm (win-win). However, the diversity and biological complexity of agricultural systems complicates our ability to deliver generic messages on efficient mitigation potential. While this message appears to be true using national level analysis, to determine the scope for a sector budget requires more targeted MACC analysis focussed on defined regions and/or farm types. This analysis would account for regional and local biophysical conditions and potentially be based on different assumptions on uptake from those detailed in the UK example.

The development of specific MACC information opens up a range of related issues regarding the nature of mitigation costs and benefits. For example, what is the effect of adding other ancillary external benefits attributed to mitigation measures? Should costs and benefit of mitigation be limited to those counted within the farm boundary, or should a more comprehensive MACC account for life-cycle impacts (*e.g.* reduction of nitrogen use)? This last question leads inexorably to a broader question of whether we should be counting production or consumption emissions. This question is beyond the scope of this report, but, assuming we stay with IPCC conventions, the MACC framework is useful for accommodating these other issues.

Research on the application of alternative voluntary and market-based instruments in relation to food and farming

The OECD has considerable experience in expounding on the properties of market-based instruments for environmental management. The same approaches are potentially applicable to adaptation and mitigation but specific complexities in agriculture hinder their easy application. In the context of emissions reduction the issue is what can be achieved by voluntary approaches, or when it may be necessary to move beyond these and focus on an effective mix of cap and trade and project-based trading. When it comes to these approaches the issue lies in how to minimise transactions costs and the potential to regulate emissions liabilities elsewhere in the food chain (the so-called point of obligation), which may not be within the farm-gate.

Meanwhile, adaptation measures are likely to require co-operation between farms to safeguard other public goods. Co-operation can be notoriously problematic for observable farm activities, so this issue will need to be addressed with appropriate incentives.

A further issue to note is that the primary focus of discussions to date has been on the reduction of production emissions rather than the development of demand-side measures. Demand-side measures could include, for example, methods to "edit" consumer demand for livestock products. There is an emerging opinion that climate change will require a more concerted effort to affect supply- and demand-side behaviours, although little is currently known about the cost-effectiveness of demand-side mitigation measures.

Behaviours

The switch in focus onto demand side raises a more general question about behaviours and behavioural change in relation to mitigation and adaptation. While it is one thing to identify efficient mitigation and adaptation potential, it is another to affect the changes that are required to ensure the adoption of the relevant measures. The fact that win-win mitigation potential is not exploited indicates more complex technical and behavioural barriers that need further exploration before appropriate instruments can be promoted. Similarly, the longer-term nature of impacts means that adaptation attitudes are uncertain and postponement may be privately rational though socially sub-optimal. Such behavioural "anomalies" are observed in other spheres of agricultural management and there is a body of work considering attitudes and behaviour responses in relation to agri-environmental schemes. If a voluntary approach to emissions is to be pursued then more targeted work on behaviour and technical barriers to mitigation options would be valuable. The behavioural approach appears to be finding favour in some academic and government spheres and there is a growing literature attempting to apply the main findings to environmental management (NEF 2005; Shogren and Taylor, 2008). Behavioural studies in relation to climate change adaptation do exist (Whitmarsh, 2007; Lorenzoni *et al.,* 2007), but few that we are aware of focus on the agricultural sector.

Annex A

Other international institutions' activities

The Food and Agriculture Organization of the United Nations (FAO)

The FAO plays an important role in assisting member countries with climate change issues related to climate change and food security. FAO's programme on climate change considers the major objective of ensuring food security, which includes:

- the promotion of practices for the mitigation and adaptation of agricultural systems,
- the reduction of emissions from the agricultural sector,
- the development of practices aimed at reducing vulnerability and increasing the resilience of agricultural systems to climate related risks,
- strengthening national and regional climate observing systems and networks,
- climate and/or disaster risk management in agriculture and allied sectors, and
- data and information collection, early warning and dissemination.

FAO's projects are targeted towards providing better solution for climate related risks in member countries. The field programmes are supported by the Organization's core budget and extra-budgetary resources received from multilateral and bilateral donors.

www.fao.org/climatechange/53598/en/

The United Nations Environment Program (UNEP)

UNEP works to facilitate the transition to low-carbon societies, support climate proofing efforts, improve understanding of climate change science, and raise public awareness about this global challenge.

International Food Policy Research Institute (IFPRI)

Climate change research at IFPRI focuses on the assessment of, adaptation to, and mitigation of climate change risks. Strategic, cost-effective, and pro-poor policy reforms that enhance human welfare in equitable and sustainable ways form the core of IFPRI's Global Change Program. The programme analyses the complex interrelations between climate change and agricultural growth, food security, and natural resource sustainability.

IFPRI's comprehensive approach to climate change analysis looks at the key drivers of climate change and their possible evolution over time. A scenario-based framework is used to forecast how these major drivers of change will impact food and agricultural systems and food security. Based in part on these projections, IFPRI is developing adaptation and mitigation strategies, including ones that show how alternative climate policy regimes in a post-Kyoto Protocol world will affect agriculture, food security, and poor people. Developing countries could finance climate adaptation and mitigation strategies through cap-and-trade and carbon-tax instruments that support agricultural and rural development, but the impacts of these and other approaches need to be better understood. Effective adaptation and mitigation can generate income in rural areas, further increasing local capacity to adapt to climate change, but the best means of encouraging these outcomes need to be identified.

Specific research programmes include:

- Global Food and Natural Resources
- IMPACT Special Project: Global Trends in Food Supply and Demand
- Strategies for Adapting to Climate Change in Rural Sub-Saharan Africa: Targeting the Most Vulnerable
- Strategies for Low Carbon Growth Greenhouse Gas Mitigation in India through Land-Use Change
- Food and Water Security under Global Change.

The World Bank

The World Bank is involved in several climate change projects and programmes, mostly in developing countries. It is also involved in programmes run by external groups, such as CGIAR. Although predominantly focused on developing countries, some of the research is nonetheless highly relevant to developed countries.

The World Bank is working with six pilot countries – Bangladesh, Bolivia, Ethiopia, Ghana, Mozambique and Vietnam on a study funded by the Governments of the United Kingdom, Netherlands, and Switzerland to help decision makers in developing countries better understand and assess the risks posed by climate change and to better cost, prioritise, sequence and integrate robust adaptation strategies into their development plans and budgets in a context of high uncertainty, competing needs and limited financial resources.

Consultative Group on International Agricultural Research (CGIAR)

CGIAR and their partners in government and civil society organisations have been helping farmers cope with the effects of variable and severe weather for nearly three decades. Specifically, they seek ways to protect water and other natural resources under extreme weather conditions and other pressures, to develop crop varieties that are adapted to harsh climates, and to identify policy and institutional innovations that better enable countries and communities to cope with these conditions. Through this work, CGIAR researchers have generated a wealth of improved crop germplasm, knowledge, technologies, methods and policy analysis, which can lessen the vulnerability of marginalised rural people and places through more sustainable management of crops, livestock, soils, water, forests, fisheries and biodiversity.

The CGIAR Challenge Program, "Climate Change, Agriculture and Food Security" (Climate Change Challenge Program, CCCP) is a major collaborative endeavour between the CGIAR and its partners, and the Earth System Science Partnership (ESSP). It is aimed at overcoming the additional threats posed by a changing climate to achieving food security, enhancing livelihoods and improving environmental management in the developing world.

The Challenge Program's main objectives are to:

- Overcome critical gaps in knowledge of how to enhance – and manage the trade-offs between – food security, livelihood and environmental goals in the face of a changing climate.

- Develop and evaluate options for adapting to a changing climate to inform agricultural development, food security policy and donor investment strategies.
- Assist farmers, policymakers, researchers and donors to continually monitor, assess and adjust their actions in response to a changing climate.

International Energy Agency (IEA)

The IEA's activities on energy efficiency and future emission scenarios are also of direct relevance to climate change policy issues. In 2005, in Gleneagles, the G8 leaders mandated the IEA to provide advice on a range of energy policy issues linked to climate change.

Since 1999, the IEA has also maintained a database of its member countries' policies and measures to reduce greenhouse gas emissions, as well as databases on energy efficiency and renewable energy policy.

Together with the OECD's Environment Directorate, the IEA provides a Secretariat for the Annex I Expert Group (AIXG) on the UNFCCC, providing analysis of technical issues of relevance to the development of the Convention.

European Environment Agency (EEA)

The EEA works on supporting the implementation of the Kyoto Protocol in the EU, including producing the annual European Community GHG inventory, supporting the IPCC and the UNFCCC on methodological issues and reviews related to GHG inventories; producing an annual indicator report on GHG emission trends and projections, and a regular evaluation of the implementation within member states of the emissions trading directive.

The EEA also works on impacts and adaptation, which includes:

- Assessment of impacts of Europe's changing climate: a report first published in 2004, and updated in 2008;
- Climate change state and impact indicators (global and European temperature and greenhouse gas concentrations in the atmosphere) as part of the *EEA core set of indicators;*
- Analysis of vulnerability of specific regions to climate change,
- Analysis of *climate change and water adaptation* issues, including an overview of countries' adaptation actions;

- Methodologies to calculate the *costs of climate change impacts and adaptation to climate change.*

The European Topic Centre on Air and Climate Change (ETC/ACC) assists the EEA in its support to EU policy in the field of air pollution and climate change. The ETC/ACC is a consortium of European institutes with MNP as its lead organisation.

The ETC/ACC reports on the progress of EU environmental policy on air quality, air emission and climate change issues. It participates in European Environmental Outlook reports of the EEA, it collects data concerning the current state of the environment and further harmonises European monitoring networks and reporting obligations

Country/regional activity

European Union

The European Union has an extensive research programme on climate change, including agriculture and land-use planning to benefit the environment.

In terms of mitigation policy, the EU has a GHG monitoring scheme, and an emissions trading scheme (ETS). At present agriculture is not included in the ETS. Emissions from sectors not included in the EU ETS – such as transport, housing, agriculture and waste – will be cut by 10% from 2005 levels by 2020. Each member state will contribute to this effort according to its relative wealth, with national emission targets ranging from -20% for richer member states to +20% for poorer ones.

With regard to adaptation to climate change, the EU released a *White Paper* on adaptation to climate change in Europe in 2009. Agriculture is discussed in this *White Paper*.

The Commission also has an Energy Policy, which includes biomass for heating and electricity, and biofuels. The Commission's proposal for FP7 gives a high priority to biomass research.

The Commission funds several research projects relating to climate change. The most relevant projects are summarised below:

Adaptation and Mitigation Strategies: supporting European climate policy (ADAM)

Funded by the European Commission and co-ordinated by The Tyndall Centre for Climate Change Research in the United Kingdom, ADAM is an integrated research project that will lead to a better understanding of the trade-offs and conflicts that exist between adaptation and mitigation policies. ADAM will support EU policy development in the next stage of the development of the Kyoto Protocol and will inform the emergence of new adaptation strategies for Europe.

Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis (PESETA)

The main objective of the PESETA project is to contribute to a better understanding of the possible economic impacts induced by climate change in Europe over the 21st century.

The project is co-ordinated by the European Commission's Joint Research Centre's Institute for Prospective Technological Studies (IPTS). PESETA largely benefits from DG research projects that have developed models to project impacts of climate change (*e.g.* the DIVA model) and climate scenarios for Europe. PESETA uses the climate data provided by the PRUDENCE project (*e.g.* temperature, precipitation) together with the Rossby Centre. All maps have been processed by the Joint Research Centre's Environment Institute.

PESETA examines climate change impacts on the following sectors: coastal systems, energy demand, human health, agriculture, tourism, and river basin floods. This enables a comparison between them and therefore provides a notion of the relative severity of the damage inflicted. For each of these sectoral categories, a corresponding sectoral-based study is developed by the project partners.

CIRCE

The CIRCE Integrated Project, funded under the European Commission's Sixth Framework Programme, aims to highlight impacts and possible adaptation actions of the climate change in the Mediterranean region, including Europe, North Africa and Middle East.

Ensembles

This project aims to develop an ensemble prediction system for climate change based on the principal state-of-the-art, high resolution, global and regional Earth System models developed in Europe, validated against quality controlled, high resolution gridded datasets for Europe, to produce for the first time, an objective probabilistic estimate of uncertainty in future climate at the seasonal to decadal and longer timescales.

The project aims to quantify and reduce uncertainty in the representation of physical, chemical, biological and human-related feedbacks in the Earth System (including water resource, land-use, and air quality issues, and carbon cycle feedbacks), and to maximise the use of the results by linking the outputs of the ensemble prediction system to a range of applications, including agriculture, health, food security, energy, water resources, insurance and weather risk management.

NitroEurope IP

The NitroEurope IP – or NEU for short – project addresses the question of what is the effect of reactive nitrogen (Nr) supply on net greenhouse gas budgets for Europe? NEU aims to advance the fundamental understanding of C-N interactions at different scales and deliver: process-based models, landscape-level assessments, European maps of C-N pools, Nr fluxes and NGE, and independent verification of GHG inventories, as required under the Kyoto Protocol.

In FP7 (2007–13), climate relevant research is dealt with across various themes such as "Environment (including Climate Change)", "Energy and ‘"Food, Agriculture, Fisheries and Biotechnology". Targeted climate change research fall under the theme "Environment (including climate change)", Activity 6.1 Climate Change, Pollution and Risks", focusing in particular on the following issues:

- The earth system and climate, and related abrupt changes
- Natural and anthropogenic emissions
- The global carbon cycle
- Greenhouse gases
- Future climate
- The natural, social and economic impacts of climate change

- Mitigation and adaptation strategies, including novel responses to climate change
- Natural climate-related hazards such as floods, droughts, storms or forest fires
- Climate change impacts on health.

Canada

The Climate Change Impacts and Adaptation Division of Natural Resources Canada has funded several projects on impacts of and adaptation to climate change since 1998. At present the division focuses on two main activities, the The Regional Adaptation Collaboratives (RACs) programme, and the Tools for Adaptation programme. This RACs programme will provide a mechanism for collaboration between different levels of government, private sector entities, and community organisations on complex adaptation issues that address federal, sectoral, or regional priorities. The objective of this initiative is to equip decision-makers with the information and advice that they need to make policy, operational, and management changes that respond to regional opportunities and threats from a changing climate.

The Tools for Adaptation programme will develop adaptation tools to support decision-making on whether and how to adapt to a changing climate. An adaptation tool is a method that guides non-climate change experts through a series of analytical steps to examine the implications of climate impacts on their policies, plans, and operations; and determine appropriate response options. There is a need to make climate change information relevant and useful to potential users from a variety of different sectors. An efficient way to meet this need is to develop tools tailored to meet user needs.

Previously, Natural Resources Canada established the Canadian Climate Impacts and Adaptation Research Network (C-CIARN), with the mandate of promoting and encouraging research on climate change impacts and adaptation. This network closed in 2007 after successfully meeting its mandate.

Examples of projects funded by the Canadian government include:

Assessment of Climate Change Impacts on Agricultural Land-Use Suitability: Spring Seeded Small Grains on the Prairies – where researchers used climate models to project climate change impacts on land suitability for prairie agriculture. They found that by 2040-69, climate change would lead to a change in limitations over much of the Prairies' agricultural regions and some new opportunities may develop in northern areas. Appropriate adaptation measures are required to maintain the sustainability of spring-seeded small grain crops on the southern prairies and to take advantage of new potential opportunities.

Canadian Economic and Emissions Model for Agriculture (CEEMA) – The CEEMA report is one in a series of three Technical Reports which document an integrated agro-ecological economic modelling system, which can be used to simultaneously assess the economic and GHG emission impacts of agricultural policies.

Cost Benefit Analysis for Using Climate-based Models as a Risk Management Strategy in Saskatchewan – this analysis examines the feasibility of developing a system that uses climate-driven risk management products to help Saskatchewan farmers deal with the risks associated with climate variability. By studying a similar system in Manitoba, it was found that, with certain adjustments, such a system could also work in Saskatchewan.

The Canadian government also established Drought Watch, whose goal is to provide timely information of the impacts of climatic variability on water supply and agriculture, and to promote practices that reduce drought vulnerability and improve management during a drought.

United States

The United States' Climate Change Science Program (CCSP) integrates federal research on climate and global change, as sponsored by thirteen federal agencies and overseen by the Office of Science and Technology Policy, the Council on Environmental Quality, the National Economic Council and the Office of Management and Budget.

Published in May 2008, the Synthesis and Assessment Product 4.3 (SAP 4.3): The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States is the most extensive examination of the impacts of climate change on important US ecosystems undertaken to date. SAP 4.3 is one of a series of 21 Synthesis and Assessment Products being produced under the auspices of the United States Climate Change Science Program (CCSP), which co-ordinates the climate change research activities of U.S. government agencies

New Zealand

See earlier discussion on the ETS in New Zealand.

Australia

Australia's department for Agriculture, Fisheries and Forestry has an AUD 46.2 million Climate Change Research Program as part of Australia's Farming Future. It will fund research projects and on-farm demonstration pilots that address the following priorities:

- Reducing greenhouse pollution
- Better soil management
- Adapting to a changing climate.

Reducing greenhouse pollution will include research into:

- Reducing methane emissions
- Reducing nitrous oxide emissions
- Life-cycle analysis.

Better soil management will include research into carbon in soils.

Adaptation will include research into new adaptation technologies and new techniques.

The Climate Change Research Program will support large-scale collaborative projects that involve a range of stakeholders (research providers, producers and state governments). It will encourage the development of tools for producers that will make a real difference in building their adaptability and resilience to climate change.

Land and Water Australia includes within its research programmes The Managing Climate Variability Program, which was created to focus research investment on important issues of climate variability and climate risk management for agriculture and natural resource management.

In addition, Australia recently produced the *Garnaut Review* which has been discussed earlier in this report.

Academic institutions[1]

The Tyndall Centre has a specific programme on adaptation, which focuses both on conceptual issues relating to adaptation, and more specific projects including coastal adaptation, water basin management in Africa, and dealing with uncertainty. Although the programme does not relate

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[1] This list is not exhaustive.

specifically to agriculture, much of the thinking and conceptual frameworks provide important background to understanding adaptation.

The ***Potsdam Institute for Climate Impact Research (PIK)*** has a number of programmes which relate to land-use and agriculture. In the Biosphere 2100 programme they specifically question what trade-offs are to be made between land and water use for food production, bioenergy production, and nature conservation? In their regional impacts and strategies programme they focus on the consequences of climate change for various sectors including climate change.

The ***International Institute for Applied Systems Analysis (IIASA).*** The Land Use Change and Agriculture (LUC) Programme at IIASA has developed methodologies and modelling tools, and compiled detailed ecological and economic databases to analyse global, regional and national food and agricultural policies, against the background of global change. LUC provides science-for-policy insight on key global problems: reduction of hunger and poverty while ensuring environmental sustainability, international agricultural trade reforms and elimination of distorting subsidies, and integration of climate change adaptation and mitigation strategies. The Risk and Vulnerability Programme (RAV) provides analysis into adaptation and resilience to weather extremes.

The ***Centre for International Climate and Environmental Research, Oslo (CICERO)*** conducts a range of climate research, including work on the economics of adaptation, public/private responsibilities, policy options and sectoral impacts, including agriculture.

The ***Stockholm Environment Institute (SEI)*** develops alternative approaches to the neoclassical economic models in order to assess the costs of action and inaction in ways that are relevant for national and international climate policy. SEI also investigates market mechanisms for climate mitigation, including carbon trading and carbon offsetting.

Bibliography

Aaheim, A., F. Berkhout, D. McEvoy, R. Mechler, H. Neufeldt, A. Patt, P. Watkiss, A. Wreford, Z. Kundzewicz, C. Lavalle and C. Egenhofer, (2008), "Adaptation to climate change: why is it needed and how can it be implemented?", *CEPS Policy Brief,* 161, www.ceps.eu.

Abildtrup, J., E. Audsley, M. Fekete-Farkas, C. Giupponi, M. Gylling, P. Rosato and M. Rounsevell (2006), "Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach", *Environmental Science and Policy,* 9.

Adams, R.M., R.A. Fleming, C.C. Change, B.A. McCarl and C. Rosenzweig (1995), "A reassessment of the economic effects of global climate change in US agriculture", *Climatic Change,* 30.

Adams, R.M. *et al.* (1999), "The economic effects of climate change on US agriculture" in R. Mendelsohn and J.E. Neumann (eds), *The Economic Impact of Climate Change on the Economy of the United States*, Cambridge University Press, Cambridge.

Adger, W.N. and K. Brown (1994), *Land Use and the Causes of Global Warming,* Wiley, Chichester, United Kingdom.

Adger, W.N., D. Pettenella and M. Whitby (eds) (1997), *Climate Change Mitigation and European Land Use Policies,* CAB International, Wallingford, United Kingdom.

Adger, W.N. and K. Vincent (2005), "Uncertainty in adaptive capacity", *CR Geoscience,* 337.

Adger, W.N., J. Paavola, S. Huq and M.J. Mace (eds) (2006), *Fairness in Adaptation to Climate Change*, MIT Press, Cambridge.

AEA (2007), *Adaptation to climate change in the agricultural sector*, AEA Energy and Environment and Universidad de Politécnica de Madrid, AGRI-2006-G4-05.

Agrell, J., P. Anderson, W. Oleszek, A. Stochmal and C. Agrell (2004), "Combined effects of elevated CO_2 and herbivore damage on alfalfa and cotton", *J. Chem. Ecol.*, 30.

Agrawal, A. (2008), "The role of local institutions in livelihoods adaptation to climate change", paper presented at The World Bank Social Dimensions of Climate Change Workshop, 5-6 March, Washington D.C., United States.

Agrawala, S. and S. Fankhauser (2008), *Economic Aspects of Adaptation to Climate Change,* OECD, Paris.

Ainsworth, E.A. and S.P. Long (2005), "What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analysis of the responses of photosynthesis, canopy properties and plant production to rising CO_2", *New Phytol.*, 165.

Alcamo, J., P. Döll, T. Heinrichs, F. Kaspar, B. Lehner, T. Rösch and S. Siebert (2003), "Global estimates of water withdrawals and availability under current and future business-as-usual conditions", *Hydrological Sciences Journal,* 48.

Allanson, P. and L. Hubbard (1999), "On the comparative evaluation of agricultural income distributions in the European Union", *European Review of Agricultural Economics,* 26.

Alley, R.B. *et al.* (2003), "Abrupt climate change", *Science,* 299.

Antle, J.M., S.M. Capalbo, E.T. Elliott and K.H. Paustian (2004), "Adaptation, spatial heterogeneity, and the vulnerability of agricultural systems to climate change and CO_2 fertilisation: an integrated assessment approach", *Climate Change*, 64.

Arnell, N.W. (2003), "Effects of IPCC SRES emissions scenarios on river runoff: a global perspective", *Hydrology and Earth System Science,* 7.

Arnell, N.W. (2004), "Climate change and global water resources: SRES emissions and socio-economic scenarios", *Global Environmental Change,* 14.

Arnell, N.W. and E.K. Delaney (2006), "Adapting to climate change: public water supply in England and Wales", *Climatic Change*.

Asseng, S. *et al.* (2004), "Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO_2", *Field Crops Research,* 85.

Audsley, E. *et al.* (2006), "What can scenario modelling tell us about future European scale agricultural land use, and what not?", *Environmental Science and Policy,* 9.

Azar, C. (1998), "Are optimal emissions really optimal? Four critical issues for economists in the greenhouse", *Environmental and Resource Economics,* 11.

Baer, P. (2006), "Adaptation: who pays whom?" in W.N. Adger *et al.* (eds), *Fairness in Adaptation to Climate Change*, MIT Press, Cambridge, Mass., United States.

Baker, J.T (2004), "Yield responses of southern US rice cultivars to CO_2 and temperature", *Agr. For. Meterol.*, 122.

Barnett, B.J. and O. Mahul (2007), "Weather index insurance for agriculture and rural areas in lower income countries", *American Journal of Agricultural Economics*, Vol. 89, No. 5.

Berkhout, F. (2005), "Rationales for adaptation in EU climate change policies", *Climate Policy,* 5.

Berkhout, F., J. Hertin and A. Jordan (2002), "Socio-economic futures in climate change impact assessment: using scenarios as learning machines", *Global Environmental Change,* 12.

Berry, P.M., M.D.A. Rounsevell, P.A. Harrison and E. Audsley (2006), "Assessing the vulnerability of agricultural land use and species to climate change and the role of policy in facilitating adaptation", *Environmental Science and Policy,* 9.

Betts, R.A. (2000), "Offset of the potential carbon sink from boreal forestation by decreases in surface albedo", *Nature,* 408.

Betts, R.A., P.M. Cox, M. Collings, P.P. Harris, C. Huntingford and C.D. Jones (2004), "The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming", *Theor. Appl. Climatol.,* 78.

Bohle, H.G., T.E. Downing and M. Watts (1994), "Climate change and social vulnerability: toward a sociology and geography of food insecurity", *Global Environmental Change,* Vol. 4, No. 1.

Booker, F.L., S.A. Prior, H.A. Torbert, E.L. Fiscus, W.A. Pursley and S. Hu (2005), "Decomposition of soybean grown under elevated concentrations of CO_2 and O_3", *Global Change Biology*, 11.

Bosello, F.C., A. Giupponi and A. Povellato (2007), "A review of recent studies on cost effectiveness of GHG mitigation measures in the European Agro-Forestry Sector", *Nota di Lavoro,* 14.2007, Fondaziones Eni Enrico Mattei.

Brooks, N., W.N. Adger and P.M. Kelly (2005), "The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation", *Global Environmental Change,* 15.

Burton, I., S. Huq, B. Lim, O. Pilifosova and E.L. Schipper (2002), "From impacts assessment to adaptation priorities: the shaping of adaptation policy", *Climate Policy,* 2.

Caldwell, C.R., S.J. Britz and R.M. Mirecki (2005), "Effect of temperature, elevated carbon dioxide, and drought during seed development on the isoflavone content of dwarf soybean [*Glycine max* (L.) Merrill] grown in controlled environments", *J. Agr. Food Chem.,* 53.

De Cara S., M. Houzé and P.-A. Jayet (2005), "Methane and Nitrous Oxide Emissions from Agriculture in the EU: A Spatial Assessment of Sources and Abatement Costs", *Environmental & Resources Economics*, Vol. 32.

De Cara, S. and P.-A. Jayet (1999), "Evaluation et régulation de L'effet de serre d'origine agricole", *L'Actualité Economique,* Vol. 75, No. 4.

De Cara, S. and P.-A. Jayet (2001), "Agriculture and climate change in the European Union: greenhouse gas emissions and abatement costs", *AAEA Annual Meeting*, Chicago, United States.

Chakraborty, S. and S. Datta.(2003), "How will plant pathogens adapt to host plant resistance at elevated CO_2 under a changing climate?", *New Phytol,* 159.

Chase, T.N., R.A. Pielke, Sr., T.G.F. Kittel, R.R. Nemani and S.W. Running (2000), "Simulated impacts of historical land cover changes on global climate in northern winter", *Climate Dynamics*, 16.

Chen, F.J., G.E. Feng and M.N. Parajulee (2005), "Impact of elevated CO_2 on tritrophic interaction of *Gossypium hirsutum, Aphis, gossypii*, and *Leis axyridis", Environmental Entymology*, 34.

Ciais, P. *et al.* (2005), "Europe-wide reduction in primary productivity caused by the heat and drought in 2003", *Nature,* 437.

Cohen, S., D. Nielsen and R. Welbourn (2004), "Expanding the Dialogue on Climate Change and Water Management in the Okanagan basin, British Columbia", *Environment Canada*, Vancouver, Canada.

Darwin, R.F. (1999), "A Farmer's View of the Ricardian Approach to Measuring Agricultural Effects of Climatic Change", *Climatic Change,* Vol. 41, No. 3 and No. 4.

Darwin, R., M. Tsigas, J. Lewandrowski and A. Raneses (1995), *World agriculture and climate change: economic adaptations,* Agricultural Economic Report 703, US Department of Agriculture, Washington, D.C., United States.

Department for the Environment, Food and Rural Affairs [Defra, United Kingdom] (2000), *Climate Change and Agriculture in the United Kingdom,* Defra, London, United Kingdom.

Defra (2005), *The Impacts of Climate Change on Agriculture – A Vision for our Rural Landscape,* Defra, London, United Kingdom.

Defra/Committee on Climate Change (2008), "UK marginal cost curves for the agriculture, forestry, land-use and land-use change sector out to 2022 and to provide scenario analysis for possible abatement options out to 2050", RMP4950, Report to The Committee on Climate Change, http://hmccc.s3.amazonaws.com/pdfs/SAC-CCC;%20UK%20MACC%20for%20ALULUCF;%20Final%20Report%202008-11.pdf.

Denman, K.L. *et al.* (2007), "Couplings between Changes in the Climate System and Biogeochemistry" in *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* S. Solomon *et al.* (eds), Cambridge University Press, Cambridge, United Kingdom; and New York, United States.

Dessai, S. and M. Hulme (2004) "Does climate adaptation policy need probabilities?", *Climate Policy*, 4.

Dessai, S., M. Hulme, R. Lempert and R. Pielke, Jr. (2009),"Climate prediction: a limit to adaptation?" in W.N Adger, I. Lorenzoni and K. O'Brien (eds), *Adapting to Climate Change: Thresholds, Values, Governance,* Cambridge University Press.

Deybe, D. and A. Fallot (2003), "Non-CO_2 greenhouse gas emissions from agriculture: analysing the room for manoeuvre for mitigation, in case of carbon pricing", in *25th International Conference of Agricultural Economists,* 16-22 August, Durban, South Africa.

Döll, P. (2002), "Impact of climate change and variability on irrigation requirements: a global perspective", *Climatic Change,* 54.

Dreze, J. and A. Sen (1989), *Hunger and Public Action,* Clarendon Press, Oxford, United Kindgom.

Druckman P., E. Papathanasopoulou and T. Jackson (2008), "Measuring progress towards carbon reduction in the UK", *Ecological Economics,* 594-604.

Easterling, W.E. *et al.* (2007), "Food, fibre and forest products" in M.L. Parry *et al.* (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, United Kingdom.

East of England Regional Assembly (2004), "Living with climate change in the east of England", www.eera.gov.uk/.

European Climate Change Programme [ECCP, Brussels] (2001), *Agriculture. Mitigation Potential of Greenhouse Gases in the Agricultural Sector,* Working Group 7, Final report of the ECCP, COMM(2000)88, European Commission, Brussels, CRC version_CLIMATE 210by297.doc.

European Environment Agency [EEA, Copenhagen] (2007), *Climate change: the cost of inaction and the cost of adaptation,* EEA Technical Report, EEA, Copenhagen, Denmark.

Ellis, F. (2000), *Rural Livelihoods and Diversity in Developing Countries,* Oxford University Press, Oxford, United Kingdom.

European Commission [EC, Brussels] (2006), *Agricultural Insurance Schemes*, D-G Agriculture and D-G Joint Research Centre, Final Report, Brussels, November.

EC (2009*), "*Adapting to Climate Change – towards a European framework for action", *White Paper,* COM/2009/0147final, Commission of the European Communities, Brussels.

Fankhauser, S. (1995), *Valuing Climate Change: the Economics of the Greenhouse,* Earthscan, London, United Kingdom.

Fankhauser, S., S. Agrawala, D. Hanrahan, G. Pope, J. Skees, C. Stephens and S. Yasmin (2008), "Economic and policy instruments to promote adaptation" in S. Agrawala and S. Fankhauser (eds), *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments,* OECD, Paris, France.

Fankhauser, S., J.B. Smith and R.S.J. Tol (1999), "Weathering climate change: some simple rules to guide adaptation decisions", *Ecological Economics,* 30.

Fiala, N. (2008), "Meeting the demand: An estimation of potential future greenhouse gas emissions from meat production", *Ecological Economics.*

Fischer, G., M. Shah, F.N. Tubiello and H. van Velhuizen (2005), "Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990-2080", *Philosophical Transactions of The Royal Society: Biological Sciences,* 360.

Fischer, G., M. Shah and H. van Velthuizen (2002), "Climate change and agricultural vulnerability", special report prepared as a contribution to the World Summit on Sustainable Development, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Fischlin, A. *et al.* (2007), "Ecosystems, their properties, goods, and services" in M.L. Parry *et al.* (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press.

Fiscus, E.L., F.L. Booker and K.O. Burkey (2005), "Crop responses to ozone: uptake, modes of action, carbon assimilation and partitioning", *Plant Cell Environment.*

Food and Agriculture Organization of the United Nations [FAO, Rome] (2007), *Livestock's long shadow: environmental issues and options,* CRC version_CLIMATE 210by297.doc.

FAO (2009), "Enabling agriculture to contribute to climate change mitigation. A submission by the Food and Agriculture Organization to the UNFCCC", http://unfccc.int/resource/docs/2008/smsn/igo/036.pdf.

Gallagher, E. (2008). *The Gallagher review of the indirect effects of biofuels production,* The Renewable Fuels Agency, United Kingdom, www.dft.gov.uk/rfa/_db/_documents/Report_of_the_Gallagher_review.pdf.

Gallagher, P.W., H. Shapouri, J. Price, G. Schamel and H. Brubaker (2003), "Some long-run effects of growing markets and renewable fuel standards on additives markets and the US ethanol industry", *J. Policy Model.*

Gill, R.A. *et al.* (2002) "Nonlinear grassland responses to past and future atmospheric CO_2", *Nature*, 417.

Gillig, D., B.A. McCarl and R.D. Sands (2004), "Integrating agricultural and forestry GHG mitigation response into general economy frameworks: developing a family of response functions", *Mitigat. Adapt. Strat. Global Change,* 9.

Gitay, H., S. Brown, W. Easterling and B. Jallow (2001), "Ecosystems and their goods and services" in J.J. McCarthy *et al.* (eds), *Climate Change*

2001: Impacts, Adaptation and Vulnerability. IPCC Working Group II, Cambridge University Press, Cambridge.

Gordon, L.J., W. Steffen, B.F. Jonsson, C. Folke, M. Falkenmark and A. Johannessen (2005), "Human modification of global water vapor flows from the land surface", *PNAS,* 102.

Gregory, P.J., J.S.I. Ingram and M. Brklacich (2005), "Climate change and food security", *Philosophical Transactions of The Royal Society, B*, 360.

Grubler, A., B. O'Neill and D. van Vuuren (2006) Avoiding hazards of best-guess climate scenarios, *Nature,* 440.

Hahn, G.L. *et al.* (2001), "Heat wave impacts on feedlot cattle: considerations for improved environmental management" in R.R. Stowell *et al.* (eds), *American Society of Agricultural Engineering,* St. Joseph, Michigan, United States.

Hanemann, W.M. (2000), "Adaptation and its measurement", *Climatic Change,* 45.

Hediger, W., M. Hartmann, S. Peter and B. Lehmann (2005), "Costs and policy implications of greenhouse gas reduction in Swiss agriculture", *Proceedings of the XIth International Congress of the European Association of Agricultural Economists: The Future of Rural Europe in the Global Agri-Food System,* Copenhagen, Denmark.

Hitz, S. and J. Smith (2004) "Estimating global impacts from climate change", *Global Environmental Change,* 14.

Holt-Gimenez, E. (2002), "Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management and impact monitoring", *Agriculture, Ecosystems and Environment,* 93.

Howden, M. and R.N. Jones (2004), "Risk assessment of climate change impacts on Australia's wheat industry" in *New directions for a diverse planet: Proceedings of the 4th International Crop Science Congress,* Brisbane, Australia.

Hulme, M. and S. Dessai (2008) "Predicting, deciding, learning: can one evaluate the 'success' of climate scenarios?", *Environmental Research Letters*, 3 045013, doi:10.1088/1748-9326/3/4/045013.

Hulme, M. *et al.* (2002), *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report,* The Tyndall Centre for Climate Research, University of East Anglia, Norwich, United Kingdom.

Ingham, I., J. Ma and A. Ulph (2007), "Climate change, mitigation and adaptation with uncertainty and learning", *Energy Policy,* 35.

Intergovernmental Panel on Climate Change [IPCC] (2001), *Climate Change 2001. The IPCC Third Assessment Report*, Cambridge University Press, Cambridge, United Kingdom.

IPCC (2006), *IPCC Guidelines for National Greenhouse Gas Inventories: 2006*, prepared by the National Greenhouse Gas Inventories Programme, IPCC, Japan.

IPCC (2007a), "Summary for Policymakers", in S. Solomon *et al.* (eds), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, United Kingdom; and New York, United States.

IPCC, (2007b), M.L. Parry *et al.* (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom.

Jablonski, L.M., X. Wang and P.S. Curtis (2008), "Plant reproduction under elevated CO_2 conditions: a meta-analysis of reports on 79 crop and wild species", *New Phytology,* 156.

Jansen, K. (2003), "Crisis discourses and technology regulation in a weak state: responses to a pesticide disaster in Honduras", *Development and Change*, Vol. 34, No. 1.

Jones, P.D. and A. Moberg (2003), "Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001", *Journal of Climate,* 16.

Kandlikar, M. and J. Risbey (2000), "Agricultural impacts of climate change: if adaptation is the answer, what is the question?", *Climatic Change,* 45.

Kelly, D.L., C.D. Kolstad and G.T. Mitchell (2005), "Adjustment costs from environmental change", *Journal of Environmental Economics and Management,* 50.

Kerr, S. and A. Sweet (2008), "Inclusion of agriculture in a domestic emissions trading scheme: New Zealand's experience to date", *Farm Policy Journal,* Vol. 4.

Kimball, B.A., K. Kobayashi and M. Bindi (2002), "Responses of agricultural crops to free-air CO_2 enrichment", *Adv. Agron,* 77.

Klein, R.J.T. *et al.* (2007) "Inter-relationships between adaptation and mitigation", in M.L. Parry *et al.* (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, United Kingdom.

Knox, J.W. and E.K. Weatherhead (2005), "The growth of trickle irrigation in England and Wales: data, regulation and water resource impacts", *Irrigation and Drainage*, Vol. 54, No. 2.

Kommen, M.H.C. and J.H.M. Peerlings (1997), "The effects of the Dutch 1996 energy tax on agriculture" in W.N. Adger *et al.* (eds), *Climate Change Mitigation and European Land Use Policies,* CAB International, Wallingford, United Kingdom.

van Kouten, C.G. and H. Folmer (1997),"Economic instruments and the pasture-crop-forest interface" in W.N. Adger *et al.* (eds), *Climate Change Mitigation and European Land Use Policies*, CAB International, Wallingford, United Kingdom.

Kurukulasuriya, P. and M.I. Ajwad (2006), "Application of the Ricardian technique to estimate the impact of climate change on smallholder farming in Sri Lanka", *Climatic Change*.

Lal, M., K.K. Singh, L.S. Rathore, G. Srinivasan and S.A. Saseendrean (1998), "Vulnerability of rice and wheat yields in north-west India to future changes in climate", *Agriculture and Forest Meteorology,* 89.

von Lampe, Martin (2008), *Biofuel Support Policies – An Economic Assessment,* OECD, Paris.

Lemmen, D.S., F.J. Warren, K. Lacroix and E. Bush (eds) (2008), "From impacts to adaptation: Canada in a changing climate 2007", Government of Canada, Ottawa.

Little, P.D., K. Smith, B.A. Cellarius, D.L. Coppock and C.B. Barrett (2001), "Avoiding disaster: diversification and risk management among East African herders", *Development and Change,* 32.

Lobell, D.B. and M.B. Burke (2008), "Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation", *Environmental Research Letters,* 3.

Long, S.P., E.A. Ainsworth, A.D.B. Leakey and P.B. Morgan (2005), "Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields", *Philosophical Transactions of The Royal Society: Biological Sciences,* 360.

Long, S.P., E.A. Ainsworth, A.D.B. Leakey, J. Nosberger and D.R. Ort (2006), "Food for thought: lower expected crop yield simulation with rising CO_2 concentrations", *Science*, 312.

Lorenzoni, I., S. Nicholson-Cole and L. Whitmarsh (2007), "Barriers perceived to engaging with climate change among the UK public and their policy implications", *Global Environmental Change*, Vol. 17, No. 3 and No. 4.

Loya, W.M., K.S. Pregitzer, N.J. Karberg, J.S. King and J.P. Giardina (2003), "Reduction of soil carbon formation by tropospheric ozone under increased carbon dioxide levels", *Nature*, 425.

Mader, K.L, T.L. Mader, J.A. Harrington, G.L. Hahn and M.S. Davis (2008), "Climate change effects on livestock production in the Great Plains" in R.R. Stowell *et al.* (eds.), *American Society of Agricultural Engineering*, St Joseph, Michigan, United States.

Mader, T.L. (2003), "Environmental stress in confined beef cattle", *J. Anim. Sci.*, 81.

Mainville, D.Y. (2003), "Disasters and development in agricultural input markets: bean seed markets in Honduras after Hurricane Mitch", *Disasters,* 27.

Mastrandrea, M.D. and S.H. Schneider (2004), "Probabilistic integrated assessment of dangerous climate change", *Science,* 304.

Matthews, R.B., M.J. Kropff and D. Bachelet (1997), "Simulating the impact of climatic change on rice production in Asia and evaluating options for adaptation", *Agricultural Systems,* 54.

McCarl, B.A. and U. Schneider (2003), "Economic Potential of Biomass Based Fuels for Greenhouse Gas Emission Mitigation", *Environmental and Resource Economics,* Vol. 24, No. 4.

McCarl, B.A. and U. Schneider (2001), "Greenhouse gas mitigation in U.S. agriculture and forestry", *Science,* 294.

McKinsey & Company (2009), "Pathways to a low-carbon Economy – Global Greenhouse Gases (GHG) Abatement Cost Curve", http://globalghgcostcurve.bymckinsey.com/ Version 2 of the Global Greenhouse Gas Abatement Cost Curve, January.

Mendelsohn, R. and A. Dinar (1999), "Climate change, agriculture and developing countries: does adaptation matter?" *World Bank Research Observer,* 14.

Mendelsohn, R., A.B.P. Kurukulasuriya and A. Dinar (2006), "Climate and rural income", *Climatic Change,* Vol. 81, No. 1.

Mendelsohn, R., W. Morrison, M.E. Schlesinger and N.G. Andronova. (2000) ,"Country-specific market impacts of climate change", *Climatic Change,* Vol. 45.

Metroeconomica (2004), *Costing the Impacts of Climate Change in the UK: Overview of Guidelines*, UKCIP Technical Report, UKCIP, Oxford, United Kingdom.

Mills, E. (2008), "Synergisms between climate change mitigation and adaptation: an insurance perspective", *Mitigation and Adaptation Strategies for Global Change,* 12.

Moorby J., D. Chadwick, D. Scholefield, B. Chambers and J. Williams (2007), "A review of research to identify best practice for reducing greenhouse gases from agriculture and land management", IGER-ADAS, Defra AC0206 report.

Moran, D. *et al.* (2008), "UK marginal cost curves for the agriculture, forestry, land-use and land-use change sector out to 2022 and to provide scenario analysis for possible abatement options out to 2050", www.theccc.org.uk/reports/supporting-research/.

Mortimore, M.J. and W.M. Adams (2001), "Farmer adaptation, change and ‘crisis’ in the Sahel", *Global Environmental Change*, Vol. 11, No. 1.

Moxey, A. (2008), *Reviewing and Developing Agricultural Responses to Climate Change*, report prepared for the Scottish Government Rural and Environment Research and Analysis Directorate (SG-RERAD), Agricultural and Climate Change Stakeholder Group (ACCSG), Report No. CR/2007/11, Pareto Consulting, Edinburgh, United Kingdom.

Nakićenović, N. *et al.* (2000), *Special Report on Emissions Scenarios,* Cambridge University Press, Cambridge.

Nera (2007), *Market Mechanisms for Reducing GHG Emissions from Agriculture, Forestry and Land Management,* report for Defra, United Kingdom.

Norby, R.J. *et al.* (2003), "Leaf dynamics of a deciduous forest canopy; no response to elevated CO_2", *Oecologia,* 136.

Nowak, R.S., D.S. Ellsworth and S.D. Smith (2004), "Tansley Review: functional responses of plants to elevated atmospheric CO_2 – Do photosynthetic and productivity data from FACE experiments support early predictions?", *New Phytol.*, 162.

O'Brien, K.L. *et al.* (2004) "Mapping vulnerability to multiple stressors: climate change and globalization in India", *Global Environmental Change,* 14.

OECD (1989), *Economic Instruments for Environmental Protection*, OECD, Paris.

OECD (2008), *Environmental Performance of Agriculture in OECD Countries since 1990,* OECD, Paris.

Oleson, J. and J.R. Porter (2009), "Deliverable 10: Adaptation and mitigation", PICCMAT project report, www.CRC version_CLIMATE 210by297.doc.

O'Meagher, B. (2005), "Policy for agricultural drought in Australia: an economics perspective" in L.C. Botterill and D. Wilhite (eds), *From Disaster Response to Risk Management: Australia's National Drought Policy,* Dordrecht: Springer.

O'Neill, B.C., F.L. MacKellar and W. Lutz (2001), *Population and Climate Change,* Cambridge University Press, Cambridge.

Osborn, T.J. and M. Hulme (2002), "Evidence for trends in heavy rainfall events over the UK", *Philosophical Transactions of The Royal Society: Mathematical and Physical Sciences,* 360.

Oxfam (2007), "Adapting to climate change: What's needed in poor countries, and who should pay", *Oxfam Briefing Paper,* 104.

Parmesan, C. and G. Yohe (2003), "A globally coherent fingerprint of climate change impacts across natural systems", *Nature,* 421.

Parry, M., C. Rosenzweig, A. Iglesias, G. Fischer and M. Livermore (1999), "Climate change and world food security: a new assessment", *Global Environmental Change,* 9.

Parry, M., C. Rosenzweig, A. Iglesias, M. Livermore and G. Fischer (2004), "Effects of climate change on global food production under SRES emissions and socio-economic scenarios", *Global Environmental Change,* 14.

Parry, M., C. Rosenzweig and M. Livermore (2005) "Climate change, global food supply and risk of hunger", *Philosophical Transactions of The Royal Society: Biological Sciences,* 360.

Parsons, D.J. *et al.* (2001), "Integrated models of livestock systems for climate change studies. 1. Grazing systems", *Global Change Biology*, 7.

Pearce, D.W. (2003), "The Social Cost of Carbon and its Policy Implications", *Oxford Review of Economic Policy,* Vol. 19, No. 3, November.

Perez, I. and W. Britz (2003), "Reduction of Global Warming Emissions in European Agriculture through a Tradable Permit System. An Analysis with the Regional Agricultural Model CAPRI", *Schriften der Gesellschaft fü Wirtschafts- und Sozialwissenschaften des Landbaues,* e.V. Bd. 39.

Perez, I., W. Britz and K. Holm-Müller (2004), "The Use of Tradable Permits in the European Agriculture as a Feasible and Cost-Effective Mitigation Strategy" in *GHG Emissions from Agriculture. Mitigation Options and Strategies (Conference Proceedings).*

Perez, I., W. Britz and C. Wieck (2003), "Modeling of Passive Environmental Indicators for the European Agriculture: The Role of Marginal Abatement Costs", paper contributed to the 12th Annual Conference of the EARE, Bilbao, Spain.

Pielke, R.A., Sr, *et al.* (2002), "The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases", *Philosophical Transactions of The Royal Society, A,* 360.

Porter, J.R. and M.A. Semenov (2005), "Crop responses to climatic variation", *Philosophical Transactions of The Royal Society, B, 360.*

Randall, D.A. *et al.* (2007), "Climate Models and their Evaluation" in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* S. Solomon *et al.* (eds), Cambridge University Press, Cambridge, United Kingdom; and New York, United States.

Reilly, J.N., W. Baethgen and F.E. Chege (1996), "Agriculture in a changing climate: impacts and adaptations" in R.T. Watson, M.C. Zinyowera and R.H. Moss (eds), *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change,* Cambridge University Press, Cambridge.

Reilly, J. and D. Schimmelpfennig (2000), "Irreversibility, uncertainty, and learning: Portraits of adaptation to long-term climate change", *Climatic Change,* 45.

Roncoli, C., K. Ingram. and P. Kirshen (2001), "The costs and risks of coping with drought: livelihood impacts and farmers' responses in Burkina Faso", *Climate Research,* 19.

Rosenzweig, C., A. Iglesias, X.B. Yang, P.R. Epstein and E. Chivian (2000), *Climate Change and U.S. Agriculture: The Impacts of Warming and Extreme Weather Events on Productivity, Plant Diseases, and Pests*, Center for Health and the Global Environment, Harvard Medical School, Cambridge, United States.

Rosenzweig, C., A. Iglesias, X.B. Yang, P.R. Epstein and E. Chivian (2001), "Climate change and extreme weather events: implications for food production, plant diseases, and pests", *Global Change and Human Health,* 2.

Rosenzweig, C. and M.L. Parry (1994),"Potential impact of climate change on world food supply", *Nature,* 367.

Rosenzweig, C. *et al.* (2007), "Assessment of observed changes and responses in natural and managed systems" in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry *et al.* (eds), Cambridge University Press.

Rosenzweig, C. and F. Tubiello (2007a), "Metrics for Assessing the Economic Benefits of Climate Change Policies in Agriculture", ENV/EPOC/GSP(2006)12/FINAL, OECD, Paris.

Rosenzweig, C. and F. Tubiello (2007b), "Adaptation and mitigation strategies in agriculture: an analysis of potential synergies", *Mitigation and Adaptation Strategies for Global Change,* 12.

Rustad, L.E. *et al.* (2008), "A meta-analysis of the response of soil respiration, net nitrogen mineralisation, and aboveground plant growth to experimental ecosystem warming", *Oecologia,* 126.

Saunders, C., A. Wreford and S. Cagatay (2006), The impact of trade policy changes on greenhouse gas emissions from the dairy sectors in New Zealand and the European Union", *Australian Journal of Agricultural and Resource Economics,* Vol. 50, No. 4.

Schär, C. *et al.* (2004), "The role of increasing temperature variability in European summer heatwaves", *Nature,* 427.

Schiermeier, Q. (2006), *The costs of global warming,* 439.

Schneider, S.H. (2004), "Abrupt non-linear climate change, irreversibility and surprise", *Global Environmental Change,* 14.

Schröter, D. *et al.* (2005), "Ecosystem service supply and vulnerability to global change in Europe", *Science,* 310.

Schmidhuber, J. and F.N. Tubiello (2007), "Global food security under climate change", *Proceedings of the National Academy of Sciences,* 104.

Shogren, J. and L. Taylor (2008), "On Behavioural-Environmental Economics", *Review of Environmental Economics and Policy,* 2.

Smit, B. *et al.* (2000), "An anatomy of adaptation to climate change and variability", *Climatic Change,* 45.

Smit, B. *et al.* (2001), "Adaptation to climate change in the context of sustainable development and equity" in J.J. McCarthy *et al.* (eds), *Climate Change 2001: Impacts, Adaptation and Vulnerability. IPCC Working Group II,* Cambridge University Press, Cambridge.

Smit, B., D. McNabb and J. Smithers (1996), "Agricultural adaptation to climatic variation", *Climatic Change,* 33.

Smit, B. and M.W. Skinner (2002), "Adaptation options in agriculture to climate change: a typology", *Mitigation and Adaptation Strategies for Global Change,* 7.

Smith, P. *et al.* (eds) (2007), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, United Kingdom; and New York, United States, www.mnp.nl/ipcc/pages_media/FAR4docs/.

Stacey, D.A. and M.D.E. Fellows (2002), "Influence of elevated CO_2 on interspecific interactions at higher trophic levels", *Global Change Biology*, 8.

Stern, N. (2006), *The Stern Review of the Economics of Climate Change*, HM Treasury, London, United Kingdom.

Subak, S. *et al.* (2000), "The impact of the anomalous weather of 1995 on the UK economy", *Climatic Change,* 44.

Swart, R. *et al.* (2009), *Europe adapts to climate change. Comparing National Adaptation Strategies,* PEER Report No. 1, Partnership for European Environmental Research, Helsinki, Finland.

Thomas, D., H. Osbahr, C. Twyman, W.N. Adger and B. Hewitson (2005), *Adaptations to climate change amongst natural resource-dependent societies in the developing world: across the Southern African climate gradient,* Technical Report 35, The Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, United Kingdom.

Thomas, J.M.G. *et al.* (2003), "Elevated temperature and carbon dioxide effects on soybean seed composition and transcript abundance", *Crop Science*, 43.

Tol, R. (2008), "The Social Cost of Carbon: Trends, Outliers and Catastrophes", *Economics: The Open-Access, Open-Assessment E-Journal,* Vol. 2, 2008-25, CRC version_CLIMATE 210by297.doc.

Tompkins, E.L. and W.N. Adger (2004), "Does adaptive management of natural resources enhance resilience to climate change?" *Ecology and Society,* Vol. 9, No. 2, www.ecologyandsociety.org/vol9/iss2/art10.

Tompkins, E.L. and W.N. Adger (2005), "Defining a response capacity for climate change", *Environmental Science and Policy,* 8.

Tubiello, F. and G. Fischer (2007), "Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000-2080", *Technol. Forecasting Soc. Change*, 74.

Tubiello, F., A. Rahman, W. Mann, J. Schmidhuber, M. Koleva and A. Muller (2009), "Carbon financial mechanisms for agriculture and rural development: challenges and opportunities along the Bali Roadmap. An Essay", *Climatic Change,* DOI 10.1007/s10584-009-9611-5.

Tubiello, F.N., J.-F. Soussana and S.M. Howden (2007), *Crop and pasture response to climate change. Proceedings of the National Academy of Sciences,* Vol. 104, No. 50.

United Nations Development Program [UNDP] (2007), *Fighting Climate Change: Human Solidarity in a Divided World*, Human Development Report 2007/2008, UNDP, Palgrave Macmillan, New York, United States.

United Nations Environment Program [UNEP] (2001), *Global Environment Outlook-3*, Earthscan, London, United Kingdom.

United Nations Framework Convention on Climate Change [UNFCCC] (1992), United Nations Framework Convention on Climate Change, UNEP/WMO, Geneva, Switzerland.

UNFCCC (2007), "Investment and financial flows to address climate change. Background paper on analysis of existing and planned investment and financial flows relevant to the development of effective and appropriate international response to climate change", UNFCC, Geneva, Switzerland.

UNFCCC (2008), *Challenges and opportunities for mitigation in the agricultural sector,* Technical paper, FCCC/TP/2008/8.

United Kingdom Climate Impacts Programme [UKCIP] (2003), *Building Knowledge for a Changing Climate. The impacts of climate change on the built environment,* UKCIP and the Engineering and Physical Sciences Research Council, Oxford, United Kingdom.

Varaprasa, P.V. *et al.* (2003), "Super-optimal temperatures are detrimental to peanut (*Arachis hypogaea* L.) reproductive processes and yield at both ambient and elevated carbon dioxide", *Global Change Biology,* 9.

Vörösmarty, C.J., P.J. Green, J. Salisbury and R.B. Lammers (2000), "Global water resources: vulnerability from climate change and population growth", *Science,* 289.

Watkiss, P. and T. Downing (2008),"The social cost of carbon: Valuation estimates and their use in UK policy", *Integrated Assessment,* Vol. 8, No. 1 http://journals.sfu.ca/int_assess/index.php/iaj/article/view/272/236.

Weatherhead, E.K. and K. Danert (2002), *Survey of irrigation of outdoor crops in 2001 in England,* Cranfield University, Silsoe, United Kingdom.

Wier, M., J.M. Andersen, J.D. Jensen and T.C. Jensen (2002), "The EU's Agenda 2000 reform for the agricultural sector: environmental and economic effects in Denmark", *Ecol. Econom,* 41.

Weiske, A. (2005), *Survey of technical and management-based mitigation measures in agriculture,* MEACAP WP3 D7a, Institute for Energy and Environment paper under EU Sixth Framework Programme, Priority 8: Policy-Oriented Research.

Whitmarsh, L. (2007), "Are flood victims more concerned about climate change than other people? The role of direct experience in risk perception and behavioural response", *Journal of Risk Research*, DOI: 10.1080/1366987071552235.

G.Y. Wong and Y.R. Alavalapati (2003), "The land-use effects of a forest carbon policy in the U.S.", *Forest Policy Econom.,* 5.

World Bank (2006), *Investment framework for clean energy and development*, World Bank, Washington, D.C., United States.

Xiao, G., W. Liu, Q. Xu, Z. Sun and J. Wang (2005), "Effects of temperature increase and elevated CO_2 concentration, with supplemental irrigation, on the yield of rain-fed spring wheat in a semi-arid region of China", *Agr. Water Management*, 74.

Yohe, G. and R.S.J. Tol (2002), "Indicators for social and economic coping capacity: moving toward a working definition of adaptive capacity", *Global Environmental Change,* 12.

Zvereva, E.L. and M.V. Kozlov (2006), "Consequences of simultaneous elevation of carbon dioxide and temperature for plant – herbivore interactions: a meta-analysis", *Global Change Biology*, 12.

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Climate Change and Agriculture

IMPACTS, ADAPTATION AND MITIGATION

By Anita Wreford, Dominic Moran and Neil Adger

Climate change is likely to have significant impacts on the agricultural sector to which farmers will have to adapt. While agriculture is a significant contributor to greenhouse gas emissions, it is also a source of carbon storage in soils. This report examines the economic and policy issues related to the impacts of climate change on agriculture and adaptation responses and to the mitigation of greenhouse gases from agriculture. It outlines research undertaken and underway in other national and international research agencies. It also highlights some of the knowledge gaps on the impacts of climate change on food production and the uncertainties of those impacts in a global context that warrant further research efforts. In particular, the report analyses marginal abatement cost curves, which show the relative costs of achieving reductions in greenhouse gas emission through the implementation of different actions in the agricultural sector. The aim of the report is to help guide policy makers in the design of policies to address climate change issues in agriculture.

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