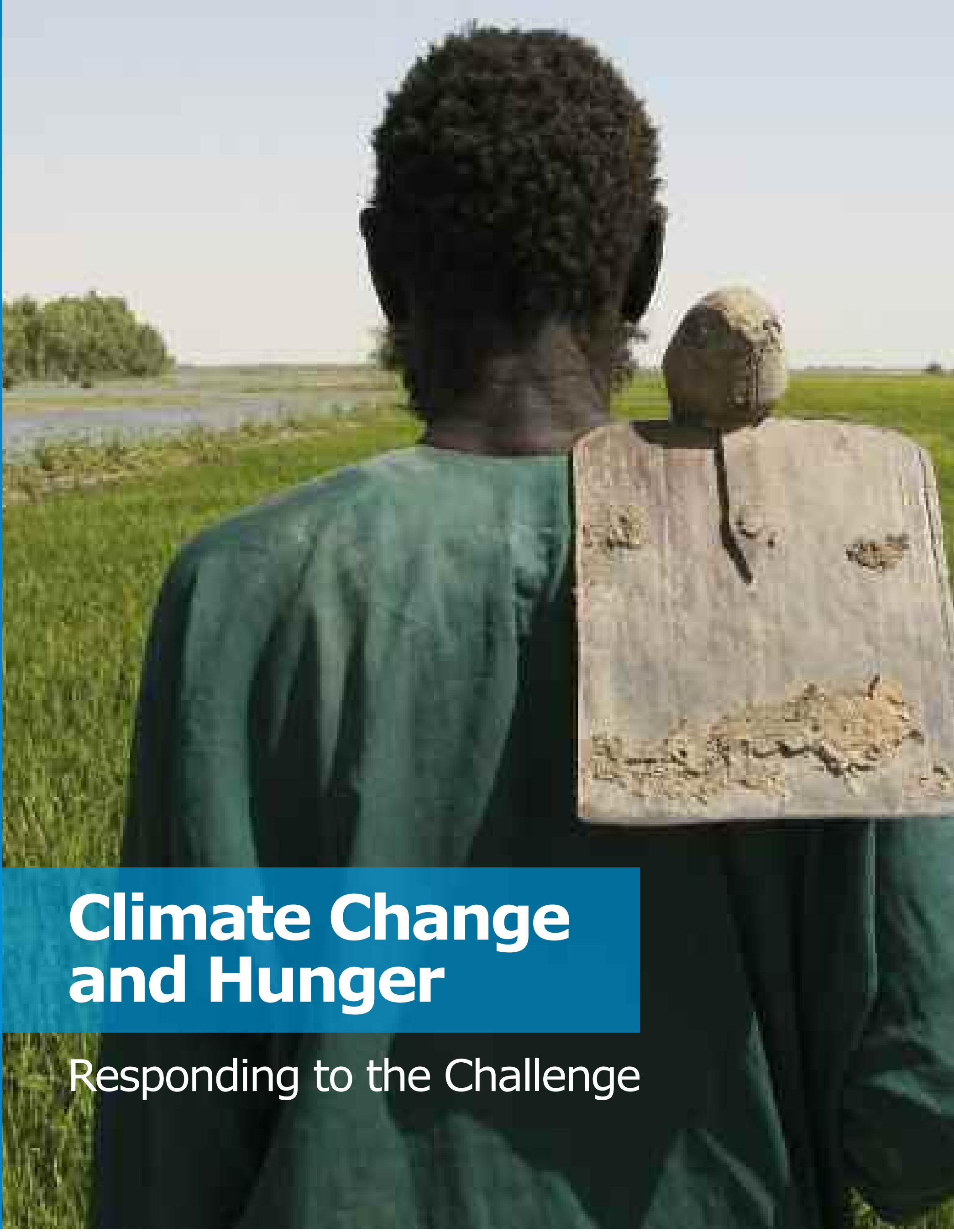
Fighting Hunger Worldwide



Climate Change and Hunger

Responding to the Challenge

WFP

World Food Programme

wfp.org

Published in 2009 by the
World Food Programme
Via C.G. Viola, 68-70, Rome 00148, Italy

Copies of WFP publications can be requested from:

PUBLICATIONS UNIT
Division of Communications and Public Policy
World Food Programme
E-mail: wfp.publications@wfp.org
Fax: (+39) 06 65132840
www.wfp.org

CLIMATE CHANGE AND HUNGER
Responding to the Challenge

by

Martin Parry, Alex Evans, Mark W. Rosegrant and Tim Wheeler

November 2009

Published by the World Food Programme, the International Food Policy Research Institute, the New York University Center on International Cooperation, the Grantham Institute at Imperial College London, and the Walker Institute, University of Reading (United Kingdom).

Contributors

Martin Parry is Visiting Professor at the Grantham Institute at Imperial College, University of London. Prior to this he was Co-Chair of the International Panel on Climate Change Working Group II on Impacts, Vulnerability and Adaptation. He is author of *Climate Change and World Agriculture* (Earthscan, 1995), and *The Impact of Climatic Variations on Agriculture* (Kluwer, 1988, 2 vols.) and has written about 100 papers on this subject. He wrote the section on projections of impact and edited this report.
martin@mlparry.com

Alex Evans is a Non-Resident Fellow at the Center on International Cooperation, New York University, where he runs its programme on Scarcity, Security and Global Public Goods. He is the author of *The Feeding of the Nine Billion: Global Food Security for the 21st Century* (Chatham House, 2009) and *An Institutional Architecture for Climate Change* (co-authored with David Steven; Center on International Cooperation, 2009), both of which can be downloaded from www.globaldashboard.org/documents/. He wrote the section on responses.
alex.evans@nyu.edu.

Mark W. Rosegrant is Director of the Environment and Production Technology Division at the International Food Policy Research Institute in Washington DC. He developed its International Model for Policy Analysis of Agricultural Commodities and Trade, which has become a standard for projections of global and regional food demand, supply, trade and prices. He is the author or editor of 12 books and over 100 refereed papers on climate change, biofuels, agricultural economics, water resources and food policy analysis. He contributed to the section on projections of impact.
m.rosegrant@cgiar.org

Tim Wheeler is Professor of Crop Science in the Walker Institute for Climate Systems Research at the University of Reading and a Senior Research Fellow at the United Kingdom Department for International Development. His research uses plant experiments and crop simulation to study the impacts of climate variability and change, on the basis of which he has authored 140 papers. He wrote the subsection on work in progress on projections of impact.
t.r.wheeler@reading.ac.uk

Foreword

Climate change is a defining challenge of our times. Its impact and implications will be global, far-reaching and largely irreversible. Climate change is already increasing the risk of exposure to hunger, malnutrition and food insecurity among the poorest and most vulnerable people. Natural disasters are becoming more frequent and intense, land and water are becoming more scarce and difficult to access, and increases in agricultural productivity are becoming more difficult to achieve.

The figures presented in this report reflect recent scientific evidence on the scale of the projected impacts of climate change. By 2050, the number of people at risk of hunger as a result of climate change is expected to increase by 10 to 20 percent more than would be expected without climate change; and the number of malnourished children is expected to increase by 24 million – 21 percent more than without climate change. Sub-Saharan Africa is likely to be the worst affected region.

There is growing consensus amongst the international humanitarian community that adaptation measures are urgently needed to help vulnerable people cope with the changing environments in which they are living. This requires adapting global and local food production methods through investments, technical capacity transfers and technological innovations, while also making existing agricultural production systems more resilient, sustainable and equitable.

Adaptation strategies must be supported by strong institutions and enabling policy and legal frameworks. They must also be complemented by other responses that address the immediate effects of climate change and protect those who cannot adapt. This entails enhancing social protection and safety net systems, programmes and capacities at regional, national and local levels to support the most vulnerable. It also involves developing capacities and systems in risk reduction and disaster management, and in emergency preparedness and response.

WFP has a crucial role to play in the global response to climate change. Vulnerability analysis and mapping, early warning systems and weather-based insurance programmes help governments and partners predict the onset of natural hazards and take appropriate measures to cushion their impacts. WFP also provides emergency relief food assistance when disasters strike, helping devastated families to recover and rebuild, while assisting vulnerable communities to adapt to more difficult and uncertain times. Responding to increased hunger and malnutrition caused by the effects of climate change is expected to be a major focus of WFP's work in the 21st century.

David Stevenson
Director
Policy, Planning and Strategy Division
World Food Programme

Table of Contents

Executive Summary

This report reviews current knowledge of the effects of climate change on hunger. It summarizes knowledge from global studies completed and provides an overview of actions that can be taken to address the challenge.

We believe that unless climate change is mitigated by substantial reductions of greenhouse gases it will greatly increase hunger, especially in the poorest parts of the world.

The scale of risk from climate change varies with assumptions about future development, especially future levels of poverty, but it is likely to affect tens to hundreds of millions of people.

It is expected that Africa will be most affected, especially the semi-arid regions north and south of the equator. This is mainly because of projected increases in aridity resulting from climate change and because of high vulnerability consequent on low levels of income. The poorest parts of southern and south-eastern Asia are likely to be substantially affected, with strong negative impacts on agricultural production. Food production in other regions, for example Central America, may also be impacted.

RESPONDING TO THE CHALLENGE

In the context of climate change and the risk of hunger, two areas of focus will be especially important.

The first important area of focus is food access. This will involve:

- scaling up humanitarian assistance capacity to cope with increased numbers of people needing help due to droughts, floods and storms and with new operating contexts;
- moving from crisis response to crisis prevention, for example by mainstreaming disaster risk reduction throughout national development programmes; and
- scaling up social protection systems, which are currently available to only 20 percent of the world's people; social protection systems have received less attention than disaster risk reduction as a core element of climate adaptation policy, but they have an important contribution to make in reducing vulnerability to climate change and other risks.

The second important area of focus is food production, where the challenge is not only to produce more food – 50 percent more by 2030 according to a World Bank estimate – but to do it in a way that is more resilient, more sustainable and more equitable given that three quarters of the world's poor live in rural areas. This will entail investment in giving farmers access to:

- knowledge and innovation – for example by reversing the 50 percent decline in public spending on agricultural research and development over the last 15 years and scaling up extension services to get cutting-edge technologies and techniques to hundreds of millions of farmers;
- assets – particularly water and land assets projected to become more scarce; natural resource governance will frequently be highly politicized, which implies a need for governments and donors to build institutional capacity in natural resource governance to enable poor people to make their voices heard;
- markets – both investment in infrastructure and communications technologies and mechanisms, to enable small farmers to aggregate their output to sell to large purchasers, and credit, which will be essential in helping farmers to access new technologies and avoid predatory lending; and
- risk management – to help farmers to cope with increased turbulence in climate and food prices; this involves physical assets such as crop storage systems and measures such as crop insurance or employment guarantee schemes that merge with social protection measures (see below).

Both areas of work will involve significant institutional reforms at the local, national and international levels. An important area of work will be moving towards more integrated assessments of financing needs for climate change adaptation, agriculture, food security and development aid, taking into account the overlaps between them. Another will be improving surveillance and early-warning systems. Above all, the cross-cutting nature of climate change puts a premium on inter-organizational coherence and politically sophisticated approaches that recognize that climate adaptation will rarely if ever be a purely technical endeavour.

These responses will however need to be guided by knowledge gained from scientific studies on climate change and its impact on hunger.

PROJECTED IMPACT ON HUNGER

Knowledge about the impact of climate change on hunger has evolved significantly over the last 15 years. Initial studies[1] concluded that decreases in yields of wheat, rice and maize caused by increased heat and water stress would be greatest in developing countries, and projected these decreases to be 9 percent to 11 percent. Consequent increases in global prices were projected at 25 percent to 150 percent and the related increase in hunger was estimated at 10 percent to 60 percent.

These estimations, however, did not consider the potential for adaptation in farming practices and institutions. With small-scale adaptations such as changes in planting times, the estimated increase in hunger could be reduced to between 5 percent and 50 percent; with substantial adaptations such as increased irrigation it could be reduced to 5 percent. A global response to climate change such as full liberalization of world food trade could reduce the estimated numbers at risk of hunger by a fifth in relation to a world unaffected by climate change.

Subsequent analyses using two different approaches[2,3] tend to confirm these estimates but offer more detail as to the effects in different pathways of global development (see Box for details):

- Under a development pathway of continuing high population growth and regional disparity of income (A2 in the Box), the number of people at risk of hunger is projected to increase 10-20 per cent by 2050 as a consequence of climate change.
- For pathways of lower population growth and more equitable income distribution (B1 and B2 in the Box), the additional numbers at risk would be 5 percent or less (data for 2050).

These analyses indicate that the impact of climate change on hunger will be more profound where social inequality in development is maintained. They also reaffirm the conclusion that Africa is the most at risk from climate change: about 65 percent of the global total increase in climate-related hunger is projected to occur in the continent.

Recent work by the International Food Policy Research Institute[4,5] confirms the magnitude and location of these impacts on food production and security in developing regions; these are most severe in sub-Saharan Africa and South Asia.

Critical impacts of climate change on food security include the effects in terms of calorie availability and the increase in the number of malnourished children. Child malnutrition will be affected by climate

Estimated global number of people (in millions) at risk of hunger: a) without climate change (= Reference), b) with climate change and full beneficial effects of carbon dioxide fertilisation (= CC), and c) with climate change without beneficial effects of carbon dioxide fertilisation (=CC, no CO2). DSSAT= estimates from crop modelling analysis. AEZ= estimates from analysis of shift of agro-ecological zones. Both analyses use the same global food model.

NB. An important element of uncertainty stems from the role which elevated levels of ambient atmospheric carbon dioxide may have. Assuming a fully beneficial effect on C3 crops such as wheat and rice, increased atmospheric CO2 could elevate yields significantly, but this estimation is drawn from laboratory experiments and may not be realised in farmers' fields

	2020		**2050**		**2080**	
Reference (millions)	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS
A1	663	663	208	208	108	108
A2	782	782	721	721	768	769
B1	749	749	239	240	91	90
B2	630	630	348	348	233	233
CC (millions)	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS
A1	666	687	219	210	136	136
A2	777	805	730	722	885	742
B1	739	771	242	242	99	102
B2	640	660	336	358	244	221
CC, no CO_2 (millions)	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS
A1	NA	726	NA	308	NA	370
A2	794	845	788	933	950	1320
B1	NA	792	NA	275	NA	125
B2	652	685	356	415	257	384

Source: Easterling and Aggarwal (2007);
based on: Parry *et al.* (2004); Fischer *et al.* (2002)

change as a result of impacts on food production, prices and consumption. The biggest impact is expected to be in sub-Saharan Africa, with a projected 10 million (26 percent) increase in the number of malnourished children in 2050 compared with a no-climate-change scenario. Globally, climate change is projected to increase the number of malnourished children by 24 million (21 percent) in 2050 compared with the no-climate-change case.

Actions to mitigate climate change by reducing greenhouse gas emissions would substantially reduce the risk of hunger. Stabilizing greenhouse gas concentrations at 500 ppm[6] could reduce the increase by 50 percent.[7] This illustrates the urgent need for substantial international action to cut greenhouse gas emissions.

SUMMARY OF PROJECTED IMPACTS

Results from studies based on a growing variety of methods indicate the following:

- Climate change will tend to reduce global agricultural production, increase food prices and intensify the risk of hunger and malnutrition.
- The number of people at risk of hunger is projected to increase by 10-20% by 2050 as a consequence of climate change.
- These impacts on food security could be even higher according to a 2009 study by IFPRI that projects a 24 million (21 percent) increase in the number of malnourished children in 2050 as a result of climate change.

- Almost all the increased risk of hunger will be in developing countries: most of the increase is projected to be in sub-Saharan Africa and parts of South Asia and Central America, particularly in terms of child malnutrition.
- Substantial international action to reduce greenhouse gas emissions could halve the increase of hunger from climate change.
- Adaptation of farming practices could halve the increase in hunger related to climate change; reform of institutions could reduce the impact further.

There is work in progress to improve understanding of climate-related hunger: this includes more robust crop/climate models, use of more up-to-date scenarios of climate change and use of long-term climate projections from earth system models that couple land use with other parts of the land-ocean-atmosphere system.

References

[1] Rosenzweig, C. & Parry, M.L. 1994. Potential Impacts of Climate Change on World Food Supply. *Nature* 367:133–138.

[2] Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M. & Fischer, G. 2004. Effects of Climate Change on Global Food Production under SRES Emissions and Socio-Economic Scenarios. *Global Environmental Change* 14(1):53–67.

[3] Fischer, G., Shah, M. & Velthuizen, H. 2002. *Climate Change and Agricultural Vulnerability*. Vienna, International Institute for Applied Systems Analysis.

[4] International Food Policy Research Institute. 2009. *Building Climate Resilience in the Agriculture Sector of Asia and the Pacific*. Asian Development Bank, Mandaluyong: Philippines. 333 p. http://www.adb.org/Documents/Books/Building-Climate-Resilience-Agriculture-Sector/Building-Climate-Resilience-Agriculture-Sector.pdf

[5] Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, & D. Lee. 2009. *Climate Change: Impact on Agriculture and Costs of Adaptation*. Food Policy Report. International Food Policy Research Institute, Washington DC: USA. 30 p. http://www.ifpri.org/sites/default/files/publications/pr21.pdf

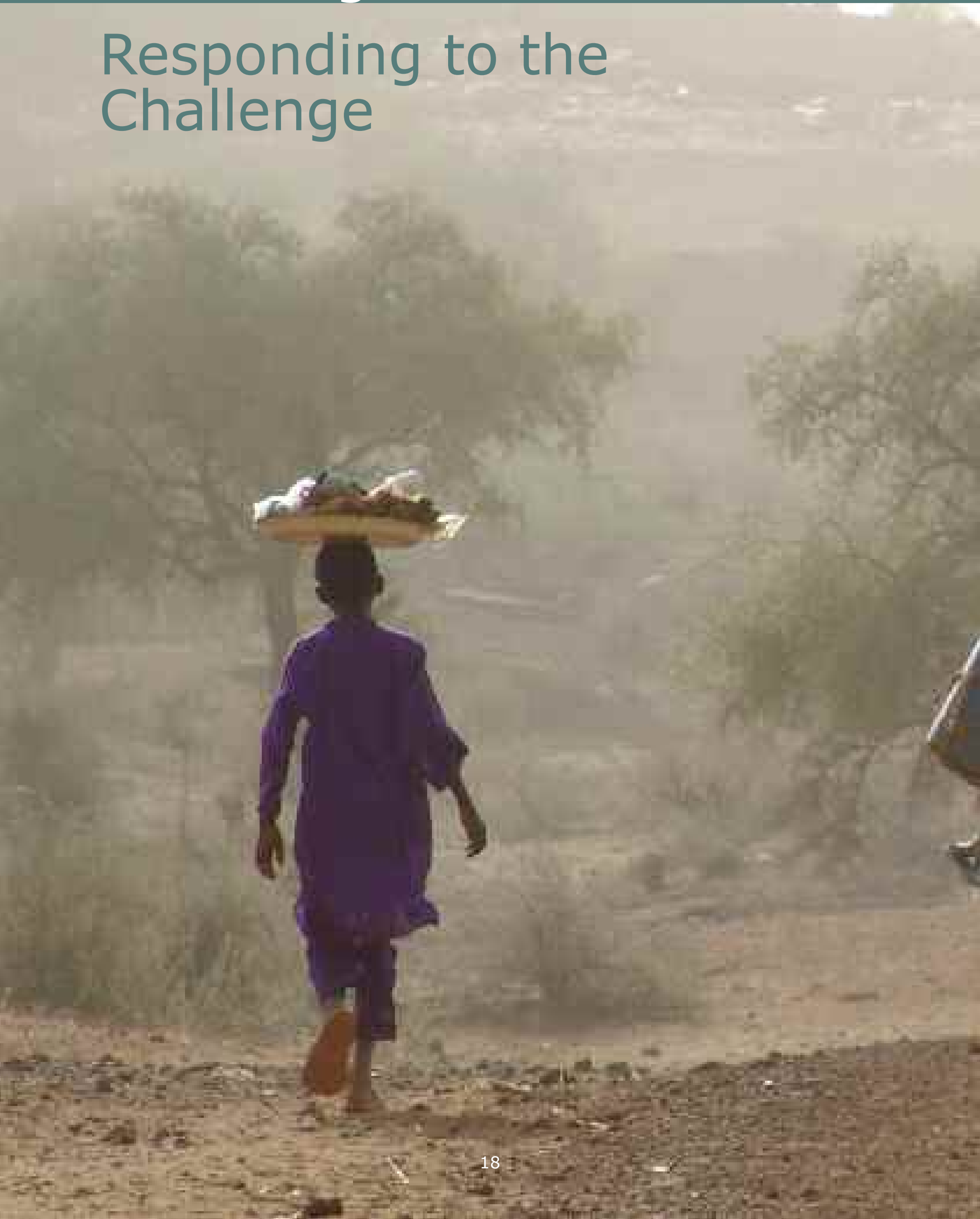
[6] ppm = parts per million of CO2 concentration in the atmosphere

[7] Arnell, N.W., Cannell, M.G.R., Hulme, M., Kovats, R.S., Mitchell, J.F.B., Nicholls, R.J., Parry, M.L., Livermore, M.T.J. & White, A. 2001. The Consequences of CO_2 Stabilization for the Impacts of Climate Change. *Climatic Change* 12:201–223.

WFP/Mario Di Bari/Ethiopia

Climate Change and Hunger:

Responding to the Challenge



WFP/Marcus Prior/Niger

INTRODUCTION

The Inter-Governmental Panel on Climate Change (IPCC) recently concluded that although there is extensive potential to adapt to small amounts of warming, at lower latitudes even small amounts of warming would tend to decreasing; and more than about 2 degrees of warming would reduce yields in almost all parts of the world (IPCC, 2007). The implications for food security are substantial at the global, regional and local scales. The Food and Agriculture Organization of the United Nations (FAO) estimates that at present approximately 1 billion people in the developing world are experiencing some form of shortage in food supply (FAO, 2009). The evidence is that climate change will increase this tendency.

This report evaluates our current knowledge on the subject and assesses how we might respond to the challenge. The first part considers how we might address the challenges; the second summarizes current estimates of potential impact.

WFP/Melese Awoke/Ethiopia

1. Responding to the Challenge

WFP/Michael Huggins/Mozambique

INTRODUCTION

Climate change is one among a range of risks affecting the food security of poor people and developing countries. The effects of climate change are not always easily discernable from the effects of other risks, particularly because the indirect consequences of climate change – such as those affecting livelihoods, health and migration – have the greatest impact on poor people.

Accordingly, the challenge of adapting to climate change in terms of food security and other sectors is far from being a stand-alone area of activity. On the contrary, the central requirements are to mainstream adaptation in national development programmes and to focus on ways of replacing vulnerability with resilience. This part of the report discusses ways of achieving this aim in the context of agriculture and access to food, focusing on the contribution that social protection systems can make to building resilience to climate change. The chapter concludes with a discussion of the institutional reform requirements implied by this agenda at the national and international levels.

CLIMATE CHANGE IN THE WIDER RISK CONTEXT

The need to adapt to climate change will be a fundamental driver of developments in agriculture, food security and work to achieve the Millennium Development Goals (MDGs). But the challenge posed by climate change is just one of a range of risks that affect agriculture and food security in developing countries.

Economic volatility, for example, has had a clear impact on food insecurity in developing countries over the last two years. Before the beginning of the food and fuel price spike in the summer of 2008, the global total of undernourished people was estimated at 854 million (United Nations High-Level Task Force on the Global Food Crisis, 2008). The World Bank estimates that between 73 and 105 million more people became poor between 2005 and 2007 as a result of increases in food prices (World Bank, 2008b). Yet even after food prices fell sharply from the summer of 2008 onwards and as the global economic downturn gathered pace, the disproportionate exposure of poor people to the effects of the downturn meant that the number of undernourished people continued to increase. By July 2009 the global total of undernourished people surpassed 1 billion for the first time (FAO, 2009).

The world's energy security outlook is similarly important in determining the outlook for food security. During the 2008 food and oil price spike, triple-digit oil prices pushed food prices up through a range of vectors that included higher costs for on-farm energy use, increased transport costs and increased prices for fossil fuel-based inputs such as fertilizer (Trostle, 2008). High oil prices also helped to increase the attractiveness of biofuels as a substitute for oil, with significant implications for food prices. The International Monetary Fund (IMF) estimates that although biofuels accounted for only 1.5 percent of demand for global liquid fuel in 2006–2007, the crops used to produce them accounted for half of the increase in consumption of major food crops, above all because of corn-based ethanol production in the United States (IMF, 2008).

Because of the ever closer links between the world's food and energy economies, the unprecedented transformation of energy systems entailed by the need to mitigate climate change has far-reaching implications for global food security. Agriculture will have to adapt not only to the direct impacts of climate change, but also to the impacts that emission reductions will have on the energy systems on which it depends, and indeed to the need for agriculture to reduce its own significant greenhouse gas emissions. Here too, climate change is not the only driver of change: many observers suggest that because the era of "easy" oil production is over, the long-term price outlook is upwards, and that in the short term the sharp decline in investment in new exploration and production caused by the global economic downturn may lead to a price crunch as the world economy recovers (International Energy Agency [IEA], 2008; Stevens, 2008; Ebrahimi, 2009).

Further complexity arises from the fact that although climate change can be expected to affect agriculture and food security, in particular by causing changes in the availability of natural resources, it is by no means the only driver of such changes.

Water scarcity, for example, is a major problem in its own right, even before the effects of climate change are considered. At the core of the issue is the combination of rising population and increasing average per capita water use, which rose from 350 m^3 per person in 1900 to 642 m^3 in 2000 (Clarke and King, 2004). Total annual global water withdrawal grew from 579 km^3 in 1900 to 3,973 km^3 in 2000; it is projected to rise to 5,235 km^3 by 2025.

Agriculture accounts for an estimated 69 percent of human water use. It is especially significant in this context in terms of its vulnerability to water scarcity and of its contribution to the problem. The rapid spread of irrigation has helped food production to keep pace with the world's rising population, but current irrigation systems are frequently highly wasteful, with efficiency rates of only 25–40 percent in many countries (Postel and Vickers, 2004). This contributes to the depletion of groundwater sources in many parts of the world, including most states in India and throughout northern China (Brown, 2005). Falling water tables are threatening water availability – and hence food supplies – in countries that are home to 3.2 billion people (Brown, 2005).

Competition for land is another significant resource scarcity risk in the global food security outlook. Even before the impacts of climate change are taken into account, FAO and the United Nations Environment Programme (UNEP) estimate that 16 percent of the world's productive land is already degraded (FAO/UNEP, 1997). Climate change will not only lead to further land degradation or desertification: it will reduce land availability because climate mitigation strategies – for example avoided deforestation, afforestation as a means of sequestering carbon dioxide, and biofuel production – require land that might otherwise be used for food production. Further sources of demand for land include fibre production for paper, demand for timber and the world's growing cities, which tend to be sited on the best agricultural land (FAO, 2006; World Bank, 2008a; Buringh and Dudal, 1987).

Additional demand for land will come from increasing food requirements as a result of a rising global population and an increasingly affluent "global middle class". Global population growth has slowed significantly since its peak in the early 1960s, but median United Nations projections show an increase to 9.2 billion by 2050 (United Nations Department of Economic and Social Affairs, 2006). Demand for food will also increase as more of the world's consumers switch to diets that are richer in meat, dairy products and processed foods, all of which are substantially more resource-intensive (Von Braun, 2007). The World Bank estimates that demand for food will rise by 50 percent by 2030, even before the effects of biofuels are factored in (World Bank, 2008a).

ENTRY POINTS FOR MAINSTREAMING ADAPTATION

The need to adapt to climate change must be seen in the context of a range of risks facing poor people and developing countries that are in many cases linked through complex inter-connections and feedback loops. To complicate matters further, climate change will intensify resource scarcity challenges and make itself felt through indirect "consequences of consequences" such as impacts on livelihoods, health, social exclusion and migration (Smith and Vivekananda, 2007).

Accordingly, climate change adaptation is not a discrete area of activity that can be regarded as separate from other areas of policy such as education, governance, housing, agriculture or food production. Adaptation must be mainstreamed in the development strategies of poor countries, as must anticipation and management of other risks such as those discussed above.

The need to manage climate-related risks in conjunction with other risks faced by poor people places a premium on development approaches that help to replace vulnerability with resilience. It also creates potential for synergies among the development practices most directly concerned with helping poor people to manage risks.

In the context of food, mainstreaming adaptation and building resilience will centre on two issues. The first is agriculture and food production. Agriculture faces the challenge of increasing food production by 50 percent in two decades. But increasing production is just one of the tasks that agriculture must fulfil: it must also become more resilient to climate change and increasing resource scarcity, more sustainable in terms of its own environmental and climate impact, and more equitable in that three quarters of the world's poor people live in rural areas and 2.5 billion people depend on agriculture.

The second issue is food access. Producing enough food to feed the world's people is no guarantee that all of them will actually enjoy access to it. This is reflected in the observation that although global food production is more than sufficient to feed 6.7 billion people, 1 billion are undernourished while 1 billion are overweight or obese (Alexandratos, 1995; FAO, 2009; World Health Organization [WHO], 2003). As the economist Amartya

Sen (1981) has observed that "… starvation is the characteristic of some people not having enough to eat. It is not the characteristic of there not being enough to eat."

Part of the food access challenge will be to increase capacity for humanitarian assistance, but crisis response will increasingly need to be matched by crisis prevention in terms of disaster risk reduction, particularly scaling up access to social protection systems.

The following sections examine what needs to be done in the areas of food production and food access and discuss the institutional reforms needed to implement these actions.

FOOD PRODUCTION AND NATURAL RESOURCE GOVERNANCE

The central challenge for agriculture in the century ahead is to become more productive while becoming more resilient, more sustainable and more equitable. This task has been termed a "doubly Green Revolution" or a "21st Century Green Revolution" (Conway, 1997; Evans, 2009).

Delivering such a change will be particularly important in countries that missed the benefits of the Green Revolution in the 20th century. This involves parts of Asia and particularly Africa, where some of the greatest potential productivity gains are to be found (Hazell *et al.*, 2007). But given that many of these countries are particularly exposed to the potential impacts of climate change, adaptation will be a critical determinant of success.

Smallholder agriculture has a special place in the outlook for agriculture in these countries. In part, this is because of the number of people that depend on small farms. Three quarters of the world's poor live in rural areas and agriculture is central to their prospects: of the 3 billion rural people in developing countries, 2.5 billion are involved in agriculture, of whom 1.5 billion live in small-farmer households (World Bank, 2008a). It is often argued that the best route out of poverty for such people is to seek new livelihood opportunities outside agriculture, but the data suggest that agriculture itself is potentially an effective route out of poverty. The World Bank 2008 World Development Report notes that the principal driver of poverty reduction in developing countries between 1993 and 2002 was the 29–37 percent decline in poverty in rural areas, of which 80 percent was a result of better conditions in rural areas rather than migration to cities.

So what needs to be done to deliver a 21st century Green Revolution? One obvious starting point is innovation: research and development (R&D) was a major driver of the 20th century Green Revolution. Numerous options for improving the efficiency of resource use in agriculture are already available, with more in the pipeline. Examples include: i) rainwater harvesting and drip irrigation to improve water use efficiency; ii) minimum tillage, whereby ploughing is minimized to reduce soil erosion and increase the soil's capacity to hold water and sequester CO_2; and iii) the use of biochar to store carbon in the soil and improve fertility (Postel and Vickers, 2004; Brown, 2005; Lehmann, 2007). More controversially, genetic modification of crops has concentrated on improving resistance to biotic stresses such as weeds and pests, but in future it is likely to focus on improving the capacity of plants to cope with abiotic stresses, many of which – extremes of temperature, insufficient or too much water, and salinized soils – may increase as a result of climate change.

But there are significant obstacles to realizing the full potential of agricultural R&D. One is a significant lack of public funding: this is especially important for poor farmers, given that private R&D spending tends to focus on the needs of high-value crops rather than staples grown in developing countries and on capital-intensive farms rather than smallholdings (Conway, 1997). Public R&D spending on agriculture has fallen by 50 percent in the last 15 years (Lumpkin and Ziegler, 2008). Another obstacle is the much greater investment needed to build up agricultural extension services and other ways to get modern technologies and techniques to hundreds of millions of small farmers (World Bank, 2008a).

Access to knowledge is just one of the principal requirements for more productive, sustainable, equitable and resilient agriculture. Another critical area will be access to assets, particularly to assets that are likely to become scarcer in future such as fisheries, forestry, water and land.

Small farmers' access to land in many parts of Africa and Asia is often obstructed by insecure property rights and illegal land seizures; high birth rates lead to smaller average farm sizes as holdings are divided through inheritance (World Bank, 2008a). Climate change could exacerbate these problems, but equitable land reform – which can provide significant benefits to poor people and contribute to greater economic growth – is potentially an important element in adaptation to climate change (Green, 2008).

The same need for equitable access to resources can be seen in the context of water. Policy measures such as community-based and household-based water harvesting can help poor people to improve their access to water assets, particularly in view of the changes in rainfall patterns that may occur as a result of climate change. More controversially, water property rights or water pricing, if properly designed with priority given to the needs of poor people, could help to increase incentives for more efficient and sustainable use of water resources. They could also help small farmers and poor people, who are often vulnerable to the effects of unsustainable water use and to the extensive corruption associated with water use and irrigation (Conway, 1997).

Natural resource governance is likely to be a major element of climate adaptation strategies and a critical aspect of managing resource scarcity. The underlying economic and political issues involve questions as to the ownership of assets, the rights to use and trade in them and the rules governing such trade (Hamilton, 2006).

Building government capacity in this area is therefore important in many developing countries. International organizations will have a significant role in supporting this work. But the challenge goes beyond technical work on institutional capacity-building: it includes contentious questions of political economy.

An IFPRI study of small farms notes the power of vested interests such as large farmers and suggests that it has been a major impediment to improving conditions for small farmers and poor people (Hazell *et al.*, 2007). To support genuinely pro-poor approaches to natural resource governance, governments and international agencies must adopt an approach based on understanding of these highly political questions and a clear sense of the political and economic drivers of change. Small farmers and poor people will need to organize themselves into an effective political and economic force: this will require support from governments and international organizations (Evans, 2009).

Two more priorities for enabling a 21st century Green Revolution are access to markets and access to credit. In its most obvious sense, access to markets implies the need for infrastructure such as rural roads; but other kinds of infrastructure such as communication technologies that allow farmers to find out up-to-date price information are also essential. To access markets, small farmers need mechanisms that help them to aggregate their output for sale to purchasers such as supermarkets or large food companies; this function could be performed by organizations such as parastatal marketing boards, farmers' cooperatives, non-governmental organizations or corporations (Green, 2008). Access to credit is vital to enable farmers to access new technology and innovation – which is particularly important in enabling small farmers to compete with larger farms – and to help them to cope with varying prices. Without access to credit, farmers become susceptible to predatory lending.

A final prerequisite for a 21st century Green Revolution is access to risk management mechanisms that help farmers to cope with volatility brought about by climate change and other risks. Some of these mechanisms relate to physical assets such as crop storage systems that can reduce post-harvest losses and exposure to price fluctuations (Hazell *et al.*, 2007). Others such as crop insurance or employment guarantee schemes cross the line into measures to reduce vulnerability, many of which can be used in various contexts and not just rural areas.

Food insecurity remains a major issue for the three quarters of the world's poor people who live in rural areas because most of them are net buyers of food. As a result, such people – including many small farmers – see high food prices as a negative rather than a positive factor (World Bank, 2008b). But food insecurity is by no means limited to rural areas. The next section discusses ways of replacing vulnerability to hunger and food insecurity with greater resilience through crisis response strategies such as humanitarian assistance and through long-term crisis prevention strategies such as social protection.

FOOD ACCESS, RISK REDUCTION AND SOCIAL PROTECTION

As governments and international agencies look for ways to support vulnerable people facing the impacts of climate change and other risks, the first task is to help people in acutely vulnerable situations through humanitarian assistance and emergency response.

The 2008 food price spike showed how major fluctuations in global food markets can have far-reaching implications for emergency relief. The World Food Programme (WFP), for example, had to raise an additional US$755 million at short notice in 2008 simply to continue feeding the 73 million people who depended on it for assistance (Office for the Coordination of Humanitarian Affairs [OCHA], 2008). The food price spike also led to a dramatic increase in the global total of undernourished people.

It seems clear that humanitarian response capacities must be scaled up substantially to cope with the effects of climate change on food security. An informal rule of thumb suggests that the United Nations humanitarian system can reach 100 million people at any one time – a small fraction of the 854 million people who were undernourished even before the 2008 food price spike (United Nations High-Level Task Force on the Global Food Crisis, 2008). This number had increased to 1 billion by July 2009 (FAO, 2009). There is also the projected impact of climate change on food security to consider, which will affect tens to hundreds of millions of people.

But the challenge for national and international humanitarian actors is not limited to reaching more people: they will also have to operate in increasingly unfamiliar contexts. Humanitarian assistance has historically been needed mainly in the aftermath of natural disasters or conflict, but the 2008 food price spike did not fit this pattern and caused changes in the composition of vulnerable groups in need of assistance.

“Traditional” humanitarian assistance has tended to focus on rural areas in developing countries. The 2008 price spike was certainly felt by the rural poor, but it also caused severe hardship in cities (United Nations High-Level Task Force on the Global Food Crisis, 2008). WFP Executive Director Josette Sheeran commented in early 2008 that “... there is food on shelves, but people are priced out of the market ... there is vulnerability in urban areas we have not seen before.” (Borger, 2008).

Such changes have the effect of blurring the lines between acute and chronic vulnerability, between emergency response and welfare provision, and between humanitarian assistance and long-term development. It is therefore not surprising that national and international agencies working in all these areas show increasing interest in moving from crisis response to crisis prevention.

One area where this trend can be seen is disaster risk reduction (DRR). Until recently, development programming often overlooked DRR, partly because it is a long-term, low-visibility process that does not always command a high priority, partly because in large international agencies there is often “a long-standing institutional gulf” between humanitarian and development offices, and partly because pressure to focus on the MDGs often leads development strategists to see disasters as a tangential concern in spite of the setbacks that they constitute to achievement of the MDGs (Department for International Development [DFID], 2005).

Recently, however, interest in DRR has risen significantly. In 2005, 168 governments adopted the Hyogo Framework for Action, a ten-year platform for integration of DRR into national development strategies and the work of international agencies (United Nations International Strategy for Disaster Reduction, 2005). Like climate adaptation, DRR is not a stand-alone area of activity: it is a priority that must be mainstreamed in development programming, which raises issues about institutional coherence at the national and international levels. But it is at least clear that DRR has risen significantly higher on the development agenda and is likely to continue to do so as awareness of the impacts of climate change continues to increase.

However, while there is increasing recognition of the role that DRR can potentially play in adapting to climate change, there is so far less awareness of the role that social protection can play in the same context.

Social protection is usually defined as public actions carried out by the state or privately that can enable people to deal more effectively with risk, vulnerability to crises or change and that help to tackle extreme and chronic poverty (DFID, 2006). More specifically, social protection policies are often classified into two categories: i) social insurance, where social security is financed by contributions and based on the insurance principle so that individuals or households can protect themselves by pooling resources with others; and ii) social assistance, where public actions are designed to transfer resources to needy people such as low-income or malnourished groups (Norton *et al.*, 2001).

In these two categories there are many different policies that can deliver social protection. Those with potentially direct relevance to food insecurity, climate change and resource scarcity include the following:

- Cash and in-kind transfers. Examples are: i) Kenya's Hunger Safety Net Programme, which aims to improve food security and nutrition and access to health and education by moving away from emergency relief responses towards predictable, guaranteed and sustained resource transfer; and ii) Ethiopia's Productive Safety Net Programme, which transfers cash and food during seasonal food insecurity through employment in public works (Davies *et al.*, 2008).
- Employment guarantee schemes. An example is India's National Rural Employment Guarantee Act, which since February 2006 has guaranteed 100 days of employment per year for poor people in 200 of the country's poorest rural districts, often in public works that can be used to invest further in climate resilience, for example strengthening embankments, planting trees or de-silting irrigation channels (Davies *et al.*, 2008).

- Mother-and-child health & nutrition and school feeding programmes. These are becoming increasingly important as means of social protection, especially as most countries now seek to provide schoolchildren with food at some scale (Bundy *et al.*, 2009).
- Weather-indexed crop insurance. In these schemes, a contract is written against an index that establishes a relationship between lack of rainfall and crop failure; farmers receive immediate financial assistance if the index reaches a threshold level, regardless of actual crop losses. This avoids perverse incentives and moral hazards for the farmer. (Davies *et al.*, 2008).
- Micro-finance services. These can enable poor people to save money, thus creating a buffer against shocks, and to access loans, which can be used to build up assets and which help poor people to avoid predatory lending, in both cases building assets that contribute directly to resilience (Norton *et al.*, 2001).
- Social pensions – non-contributory cash transfers independent of a record of contributions. These address the vulnerability faced by many elderly people and deliver wider benefits in that income is often redistributed to the recipient's extended family (Norton *et al.*, 2001).

To all these examples the common thread is the contribution of social protection measures in breaking vicious cycles that lead into chronic poverty traps. Droughts, for example, frequently force poor families to sell productive assets such as livestock; other kinds of shock often lead to families taking children out of school. In either instance, eventual recovery becomes more difficult as a result of the emergency measures. Repeated cycles of shock are often part of the reason why people become poor in the first place, and why escape from poverty is so difficult (Heltberg and Siegel, 2008). Significantly, environmental risks are among the most frequent and costly causes of such shocks: this problem can be expected to grow in line with the impacts of climate change (Heltberg and Siegel, 2008; Dercon, 2004).

As Nicholas Stern (2008) has emphasized, social protection could be a major element in the policy arsenal for effective adaptation to climate change in developing countries. Social protection systems offer a better approach to managing future food price spikes than less targeted measures such as price controls, which reduce the incentives for farmers to produce more food, or economy-wide subsidies, which are more of a burden on public sector budgets and contribute to inflationary pressures (United Nations High-Level Task Force on the Global Food Crisis, 2008).

There is a good deal to be done to realize this potential, particularly because many social-protection policies tend to ignore the long-term risks associated with climate change (Commission on Climate Change and Development, 2009).

More fundamentally, access to formal social protection systems remains very limited. Despite calls for a new target of universal access to social protection systems by 2020, only 20 percent of the world’s people have access to formal social protection (Chronic Poverty Research Centre, 2008).

Many poor people, particularly in Africa, cope with shocks and stresses through informal strategies that rely on family and community structures – gift exchanges, sharing food, migration, remittances, child labour, informal cash or in-kind loans, or sending children to live with relatives – rather than government or market-based instruments (Heltberg and Siegel, 2008). The challenge in scaling up social protection is not to replace all these informal approaches, but to complement them and give greater depth to livelihood protection strategies.

Scaling up social protection will be a collaborative task that brings together a range of actors: international aid donors, governments, civil society groups, community groups, farmers' organizations and local actors. In view of the extent to which social protection blurs the lines between emergency humanitarian relief and long-term development, such a collaborative approach will be essential.

Above all, the process will be iterative and characterized by trial, error and learning. It is argued that the period to the end of 2010 "… must be treated as a genuinely experimental phase …" for social protection (Chronic Poverty Research Centre, 2008). This applies particularly to social protection as a form of climate change adaptation, which is a relatively new concept. Heltberg and Siegel (2008) propose three areas for further testing:

- Using social funds to scale up external support for community-based adaptation. Negotiations organized by the United Nations Framework Convention on Climate Change (UNFCCC) on funding for national adaptation plans of action are sometimes criticized for being portfolios of top-down, government-run sector projects, but Heltberg and Siegel (2008) argue that social funds may be better suited to running small community-initiated projects in ecosystem management and restoration, water supply and sanitation, community forestry, coastal zone management, disaster preparedness and post-disaster assistance. Additional international funds could be channelled through social funds and community-driven development projects, even in countries with low capacity.

- Improving social safety nets for coping with natural disasters and climatic shocks by building country capacity for post-disaster and counter-cyclical cash transfers. Measures such as cash transfers, work programmes and disaster insurance can help households to cope with disaster losses. They could offer additional benefits if public employment programmes for securing cash transfers focus on investing in resilience; flood-proof roads are an example. The authors argue that "... the key is to have programmes in place before the onset of natural disasters with flexible targeting, flexible financing and flexible implementation arrangements."
- Facilitating changes in livelihoods through skills development, microfinance and assisted migration where adaptation in agriculture is not possible. Given that many livelihoods based on natural resources may decline as a result of climate change, social protection could contribute to positive transitions into new sectors, for example through training, microfinance, more orderly migration and access to safe and easy remittances.

The next section focuses on the institutional implications of the agendas set out above, starting with a discussion of financial implications followed by inter-organizational coherence issues.

INSTITUTIONAL IMPLICATIONS

It is important to consider the institutional requirements needed at the national and international levels to support agricultural development and food security in the context of climate change.

The first and most obvious institutional requirement is adequate and predictable financing for the measures discussed above. Estimates already exist of the cost of ensuring global food security in the future: i) the United Nations High-Level Task Force on the Global Food Crisis cited in 2008 an estimate of US$25–40 billion per year for "... food assistance, agricultural development, budget and balance of payments support ... to maintain progress towards MDG 1..."; ii) FAO has estimated that US$30 billion a year is needed for investment in agricultural productivity gains in low-income countries; and iii) the United Nations Secretary-General has suggested that US$15–20 billion a year is needed for the same purpose (United Nations High-Level Task Force on the Global Food Crisis, 2008; FAO, 2008; Rosenthal and Martin, 2008).

G8 aid donors have already made progress towards increasing their spending on food security, having pledged US$20 billion over three years for a global partnership for agriculture and food security (G8, 2009), but this must be set against a decline in the proportion of aid spent on agriculture in recent decades from 17 percent in 1980 to 3 percent in 2006 (Diouf, 2008).

These cost estimates are complicated because some focus on agriculture while others are broader in scope. The amount likely to be required for future humanitarian assistance, for example, is not included in the estimates by FAO or the United Nations Secretary-General. But given that the needs of WFP alone total US$6.4 billion in 2009, the humanitarian assistance requirements for dealing with food insecurity as a result of climate change are clearly a major variable (Dinmore, 2009).

Longer-term social protection requirements, meanwhile, suffer from a lack of quantified cost estimates, not surprisingly given that any estimate will depend on the breadth and level of social protection coverage envisaged. Among developing countries that provide their citizens with safety nets – non-contributory social protection systems as opposed to measures such as social insurance or labour market policies – the proportion of GDP spent on them varies considerably (Grosh *et al.*, 2008). Mauritius spends 7 percent, and Malawi, Ethiopia and Djibouti spend 4 percent; many other countries – for example Chile, China, Mexico, Pakistan, Peru, the Philippines and Senegal – spend 1 percent of GDP on safety nets – and of course many countries make no safety net provision at all (Grosh *et al.*, 2008). Financing social protection support is complicated by the fact that safety nets need to be financed in a counter-cyclical manner because needs are greatest when economic performance is weakest; few developing country governments manage this challenge effectively (Grosh *et al.*, 2008). Support from international donors is hence especially important for social protection, particularly in view of governments' frequent concerns about long-term fiscal sustainability (Chronic Poverty Research Centre, 2008).

The question of financial requirements is still further complicated when social protection systems are being built up with climate change adaptation requirements explicitly in mind, given current highly topical (and controversial) debates about how much adaptation finance developing countries will require. Estimates of the total costs of climate adaptation vary significantly. Many estimates are in the region of US$100 billion a year: the World Bank, for example, has estimated US$9–41 billion a year, the Stern Review US$4–37 billion and UNDP US$86–109 billion; the Government of the United Kingdom estimates US$100 billion a year by 2020, and the UNFCCC US$40–170 billion. A recent study by the Grantham Institute for Climate Change and the International Institute for Environment and Development argues that these figures are substantially lower than is warranted and that the true figure is two to three times higher than the UNFCCC estimate (Parry *et al.*, 2009; Brown, 2009).

Were such a volume of money to come entirely from public funds, it would be considerably larger than the global total for Official Development

Assistance (ODA), which was US$120 billion in 2008 (Organisation for Economic Co-operation and Development [OECD], 2009). Further complexity arises because not all climate adaptation work requires additional financing: some areas of adaptation overlap with development finance needs. United Kingdom Prime Minister Gordon Brown recently suggested that the amount of ODA spent on adaptation should be capped at 10 percent, but the debate remains highly polarized (Brown, 2009).

A significant amount of work remains to be done in assessing the individual costs of future work on climate adaptation, agricultural development, humanitarian assistance and social protection, and in integrating these assessments into an analysis that takes into account the extensive overlaps among these areas.

A second area for institutional reform centres on the need for upgraded systems for risk surveillance and early warning. A range of systems already provide data and early warning in the food context: examples are the FAO Global Information and Early Warning System, which provides data on supply, demand, stocks, export prices, trade, food aid and other variables for every country in the world, and the WFP vulnerability analysis and mapping system, which provides food security analysis reports and integrated maps of food insecurity.

But there are significant gaps in surveillance coverage. In particular, there is often a lack of granularity in the data on likely climate impacts in specific countries because the uncertainty inherent in global climate models makes it difficult to make confident predictions about local level impacts. As with the cost estimates discussed above, a fundamental issue is the lack of integration across different dimensions of resource scarcity and between scientific assessments of resource availability on one hand, and political economy, conflict risk and human vulnerability metrics on the other.

A recent move towards such a system is the planned United Nations global impact and vulnerability alert system, which national policymakers asked the United Nations Secretary-General to set up at the April 2009 G20 summit (G20, 2009). The system will look across multiple sectors and threat drivers, including scarcity issues, and link this data with real-time evidence of vulnerability and social impacts, raising “red flags” where necessary. It will also draw together multiple data sources, from United Nations agency reports to qualitative information collected on the ground or electronically.

Governments and donors will need to work together to build institutional capacity for adaptation and food security, particularly in the field of social protection. Successful social protection depends on selecting the right combination of policy instruments, for example the best mix of social insurance and social assistance for particular groups, which in turn often depends on a government developing a national social protection framework (DFID, 2006). Effective targeting of the poorest and most vulnerable people is also critical, and depends on policymakers understanding the context-specific vulnerabilities and the assets and capabilities that they can mobilize

(Norton *et al.*, 2001). Formulating such approaches demands significant institutional capacity, which in turn implies the need for international assistance in building this capacity.

It is important to recognize that the governance dimensions of scaling up social protection are not merely technical. The Chronic Poverty Report notes that social protection systems can have a transformative political impact as drivers of progressive social change and through building a social contract in which states act to reduce the risks faced by their citizens in return for their commitment to the state (Chronic Poverty Research Centre, 2008). Norton *et al.* (2001) observe that "… defining the role of the state in [provision of protection against risk] is highly contentious, and can only be handled through political processes … the use of tax funded transfers to assist the poorest requires very high levels of support within society to be politically sustainable – these are among the greatest challenges that systems of democratic government face." The challenge of building political support for social protection may be compounded where measures are designed to react to climate change, because the issue is often considered long-term or unimportant.

Another priority for capacity-building will be to scale up mechanisms for supporting agricultural development, and particularly small farmers. Such mechanisms are needed for a variety of roles from disseminating the latest innovations to the field to aggregating small farmers' production and from helping small farmers to access credit to helping them to influence natural resource governance and other political processes. In the past some of these roles were undertaken by bodies such as state marketing boards, but in many developing countries these were rolled back or abolished under structural adjustment programmes during the 1980s and 1990s. As noted earlier, there are alternatives to parastatal organizations such as public-private partnerships or cooperatives; the issue is delivery of the function, not the form of the delivering organization (Evans, 2009).

There is also the question of what happens in fragile countries with limited state capacity where it is not feasible for the state to run complex mechanisms such as social protection systems. In view of the long-term iterative nature of state development, the immediate challenge is often to increase autonomous adaptive capacity at the grassroots level because citizens will not be able to rely on the state for social protection. In some cases international actors will be able to provide social protection directly; but since the development of social protection systems can change the relationship between citizens and state, it is essential that international donors providing direct social protection do not supplant the responsibilities of the state.

There is also a need to improve organizational coherence at the national and international levels. The nexus of climate change adaptation, food security and social protection is a cross-cutting issue that will involve multiple actors of different kinds.

The United Nations High-Level Panel on Threats, Challenges and Change (United Nations, 2004) notes that the international system suffers from fragmentation stemming largely from the same problem in governments:

> “The fragmented sectoral approaches of international institutions mirror the fragmented sectoral approaches of Governments: for example, finance ministries tend to work only with the international financial institutions, development ministers only with development programmes, ministers of agriculture only with food programmes and environment ministers only with environmental agencies. Bilateral donors correctly call for better United Nations coordination but show little enthusiasm for similar efforts on their own account.”

Work on improving coherence in development and humanitarian assistance was taken forward by the subsequent High-Level Panel on United Nations System-Wide Coherence (United Nations, 2006), but it made only passing reference to the operational challenges that climate adaptation, food security or resource scarcity would present for international agencies; no reference was made to social protection systems or safety nets, and the panel had no mandate to tackle the underlying problem of incoherence and fragmentation in governments.

The main challenges for governments and international organizations are to be found in addressing these challenges and in setting risk reduction and resilience building as core objectives for development and humanitarian policy. Work to improve system coherence in agriculture, food security and climate adaptation is an ongoing challenge requiring significant attention by governments and international agencies.

WFP/Giorgio Gentile/Mauritania

WFP/Marco Frattini/Philippines

CONCLUSION

Climate change is likely to exert a critical influence on the prospects for food production and food security: it will pose major challenges for citizens, states and international actors alike.

Climate change will make itself felt at a time when various global risks are influencing the outlook for poverty reduction and development in interconnected ways that are complex, uncertain and volatile. The impacts of climate change will in practice merge with those of other risks: a farmer facing water scarcity, or an urban consumer coping with a food price spike, will be preoccupied with the immediate problem rather than global climate change issues.

Citizens and national and international policymakers cannot tackle climate change in isolation, or indeed any of the other risks faced by poor people and developing countries. The challenge is more fundamental: to identify the sources of vulnerability among poor people and focus on replacing vulnerability with resilience.

The challenge of building resilience will have to involve entire governments and the whole international system, from the farms where food is produced to the homes where it is consumed. This will require policy actors to work in radically different ways, abandoning preoccupations with organizational territory and developing new partnerships and mechanisms for cooperation. Recent attempts to improve coherence in the international system are a modest first step towards this objective. The real work remains to be done.

2.Projections of Impact:

A Summary of Current Knowledge

WFP/Debbi Morello/Sudan

INITIAL ANALYSES USING LOW-RESOLUTION CLIMATE MODELS WITH 2XCO$_2$ SCENARIOS

The first model-based studies of effects on global food supply were published in the early 1990s. The general conclusions of that work still hold today: that climate change is likely to reduce global food potential and that the risk of hunger will increase in the most marginalized economies (Rosenzweig and Parry, 1994). These studies addressed two main tasks:

i) the effects on crop yields were modelled: these models covered wheat, rice, maize and soybean, which account for 85 percent of traded grains and legumes (Rosenzweig and Iglesias, 1995; International Benchmark Sites Network for Agrotechnology Transfer [IBSNAT], 1989); and

ii) the effects of yield changes on food production, prices and the number of people at risk of hunger were projected on the basis of estimated yield changes in a world food trade model (Fischer *et al.*, 1988).

The climate change scenarios for these early studies were 2xCO$_2$, which are broadly equivalent in current thinking to continued high rates of emissions. The enhanced effect on crop growth from elevated CO$_2$ was included in yield calculations. The non-climate scenarios, which are immensely important in determining the sensitivity of risk of hunger to climate change, were:

i) a world population of 10.2 billion by 2060, the United Nations median estimate;

ii) 50 percent trade liberalization in agriculture, introduced gradually by 2020;

iii) moderate economic growth ranging from 3.0 percent per year in 1980–2000 to 1.1 percent per year in 2040–2060; and

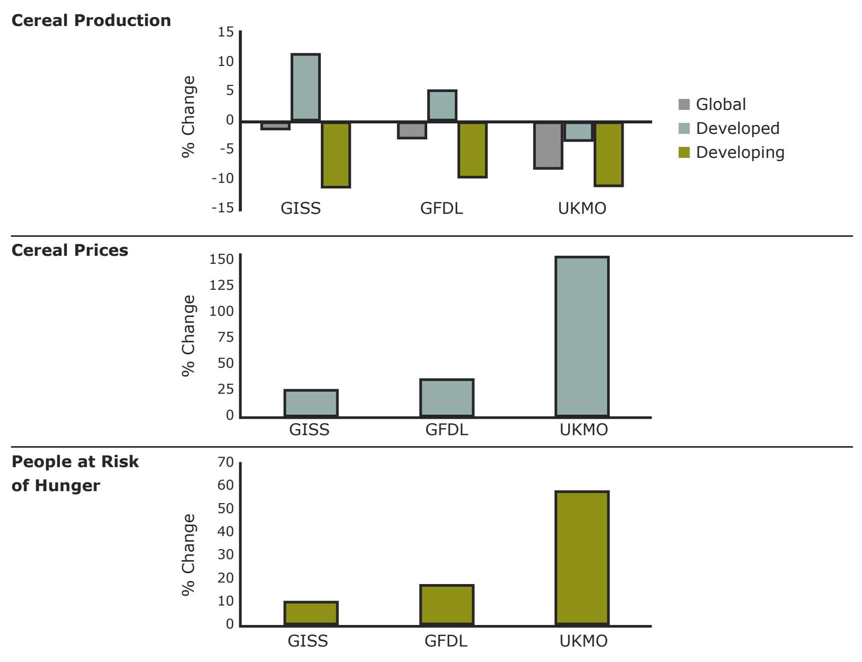
iv) increases in crop yields of 0.7 per cent per year in developing countries and 0.6 percent in developed countries.

EFFECTS ON YIELDS AND PRODUCTION

In these scenarios, world cereal production is estimated to decrease by between 1 percent and 7 percent, depending on the General Circulation Model (GCM) scenario adopted (see Figure 1). The largest negative changes, averaging -9 percent to -11 percent, occur in developing countries. By contrast, production in developed countries is estimated to increase for all but the United Kingdom Meteorological Office scenario of +11 percent to -3 percent. The explanation for this difference in effect is that growing seasons in mid-latitudes and high-latitudes, which are often temperature-constrained, are extended by higher temperatures under conditions of climate change; at lower latitudes, growing seasons are more determined by water availability and therefore more likely to be shortened by increased evapo-transpiration and reduced water availability.

Current disparities in crop production between developed and developing countries are thus estimated to increase. Decreases in production are estimated to lead to 25 percent to 150 percent increases in prices and 10 percent to 60 percent increases in hunger involving 350 million people[1] (see Figure 1).

Figure 1.
Estimated effects of climate change in 2060 on cereal production, cereal prices and risk of hunger. Reference case without climate change assumes: Cereal production = global 3 286 mmt, developed 1 449 mmt, developing 1 836 mmt. Cereal prices 1970 = 100. People at risk of hunger = 641 million.



Source: Rosenzweig and Parry (1994).
GISS – Goddard Institute for Space Studies.
GFDL – Geophysical Fluid Dynamics Laboratory.
UKMO – United Kingdom Meteorological Office.

---

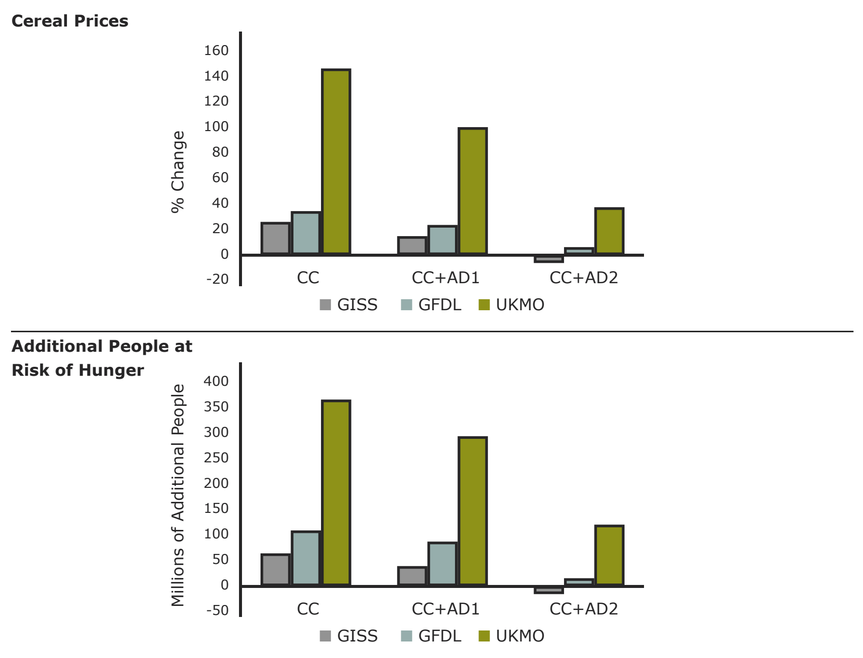
[1] 60 per cent increase in risk of hunger means 350 million more people given the model assumed a reference case (i.e. no climate change) figure of 641.

EFFECTS UNDER DIFFERENT LEVELS OF ADAPTATION

The study tested the efficacy of two levels of adaptation. Level 1 adaptation included shifts in planting date that do not imply major changes in the crop calendar, additional application of water to crops already under irrigation and changes to crop varieties better adapted to the projected climate. Level 2 adaptation included large shifts in planting dates, increased fertilizer application, development of new varieties and installation of irrigation systems.

Level 1 adaptations largely offset the negative effects of climate change in developed countries, which improved their comparative advantage in world markets. In these regions, cereal production increased by 4 percent to 14 percent more than the reference case. But in developing countries, such minor adaptations appeared insufficient to accommodate the more significant reductions in crop potential: production in these regions under the adaptations is reduced by -9 percent to -12 percent. Average global production is altered by between 0 percent and -5 percent from the reference case. As a consequence, world cereal prices are estimated to increase by 10 percent to 100 percent, and the number of people at risk from hunger would rise by 5 percent to 50 percent – an additional 50 million to 300 million (see Figure 2).

Figure 2.
Change in cereal prices and people at risk of hunger for climate change scenarios (CC) and with adaptation levels 1 and 2 (AD1 and AD2). Scenarios and reference case are the same as in Figure 1.



Source: Rosenzweig and Parry (1994); Rosenzweig *et* al. (1993).

Level 2 adaptation is projected to reduce impacts by a third; in some cases it virtually eliminates them. But reduction in the comparative advantage of developing countries in these scenarios is projected to lead to reduced areas under cereals. Cereal production in developing countries still declines by 5 percent, but global cereal prices increase by only 5 percent to 35 percent and the additional number of people at risk from hunger is reduced to between 10 million and 50 million (see Figure 2). This suggests that substantial adaptations are required to mitigate the negative effects of climate change, and indicates that such adaptations would not eliminate them in developing countries.

EFFECTS ASSUMING FULL TRADE LIBERALIZATION AND LOWER ECONOMIC AND POPULATION GROWTH RATES

If agricultural trade liberalization were to be 100 percent rather than 50 percent by 2020, there would be more efficient resource use, a global 3.2 percent increase in value added in agriculture and a 5.2 percent increase in agricultural gross domestic product (GDP) in developing countries (excluding China) by 2060, compared with the reference case. This scenario places 20 percent fewer people at risk from hunger.

Estimates were also made of impacts in a scenario of 10 percent lower economic growth than the reference case: this leads to a tighter supply situation, higher prices and more people below the hunger threshold; prices are 10 percent higher, and the number of people at risk from hunger is 20 percent greater.

Assuming the United Nations low estimate rather than the mid-estimate gives a population of developing countries (excluding China) in 2060 of 5.9 instead of 7.3 billion, and leads to a model estimate of higher GDP/capita (about 10%) and 40% fewer people at risk from hunger compared with the reference scenario.

SUBSEQUENT ANALYSES USING HIGHER RESOLUTION CLIMATE MODELS, AND FOR DIFFERENT TIME PERIODS

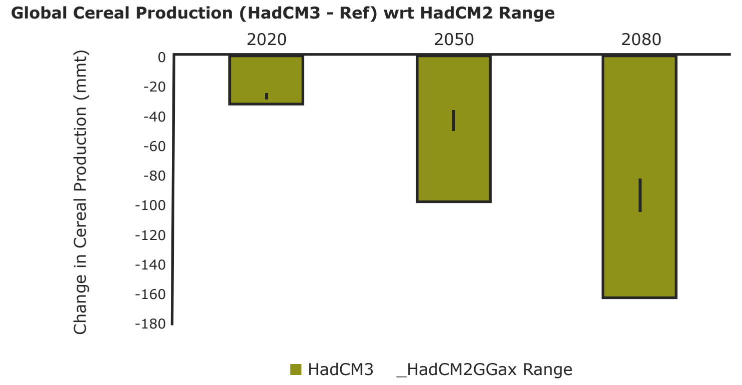
Since the mid-1990s the spatial resolution of models of the atmosphere – the GCMs – has increased and their simulation of air/ocean interactions and other feedback mechanisms has improved. This substantially enhanced the accuracy of their projections of climate change resulting from greenhouse gas forcing. Many models became capable of producing time-dependent scenarios, thus enabling the evaluation of climate change impacts at different time horizons in this century.

In the next suite of experiments (Parry *et al*., 1999) the crop models were run for three future climate conditions in the 2020s, 2050s and 2080s predicted by the United Kingdom Hadley Centre GCMs known as HadCM2 and HadCM3 (Mitchell *et al*., 1995; Hulme *et al*., 1999). All climate change scenarios were based on a "business-as-usual" future of greenhouse gas emissions, termed IS92a by IPCC, and economic development and population growth.

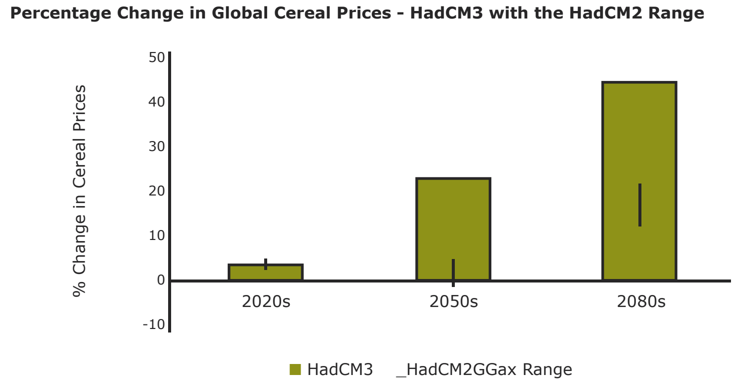
Under the HadCM2 scenarios, cereal prices increase by as much as 17 percent (+/- 4.5 percent) by the 2080s (see Figure 3). These production and price changes were estimated to increase the number of people at risk of hunger by 90 million (see Figure 3). The HadCM3 model, which projected slightly higher amounts of warming for the same emissions, gives climate conditions leading to 125 million additional people at risk of hunger by the 2080s.

Figure 3.

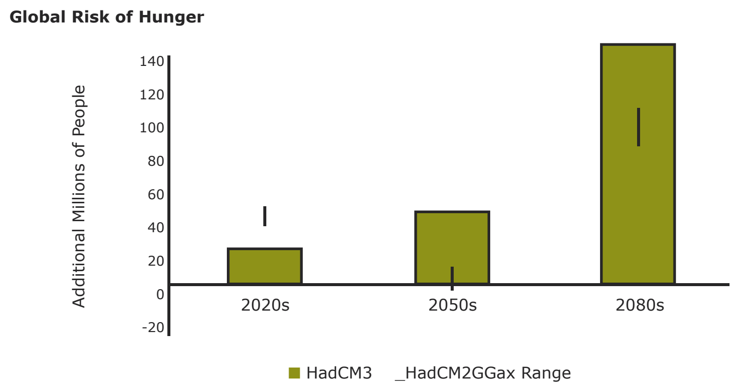
(a) Changes in global cereal production (mmt). Blocks are the production change projected under the HadCM3 climate change scenario compared with the reference case. Bars depict the range of change under the four HadCM2 ensemble simulations.



(b) Percentage change in cereal prices. Blocks are the price changes projected under the HadCM3 climate change scenario relative to the reference case. Bars depict the range of price change under the HadCM2 ensemble experiments.



(c) Global estimates of the additional number of people at risk of hunger because of climate change compared with the reference case. HadCM3 estimates are represented by the blocks. Bars represent the range of results under the fourHadCM2 ensemble simulations. Effects of elevated CO2 on crop growth are included.



Source: Parry *et* al. (1999).

The distribution of this additional risk of hunger is shown in the top part of Figure 5. Africa is the region most affected; parts of South Asia and Central America also show significant increases in risk related to climate change.

ANALYSES FOR DIFFERENT DEVELOPMENT PATHWAYS

More recently, the projected effects of climate change on global food supply have been considered in different pathways of socio-economic development expressed in terms of population and income level. These have been established by the Special Report on Emissions Scenarios (SRES) of the IPCC. Different trajectories of population growth and economic development will affect climate change and the responses of agriculture at the regional and global scales. The goal of the study was to understand the nature of these complex interactions and how they affect people at risk of hunger in the coming decades (Parry *et al.*, 2004).

EFFECTS ON YIELD

The effects of climate change under the SRES scenarios result in decreases in crop yield in developing countries and increases in developed countries similar to those projected in the preceding studies (see Table 1). The A1FI and A2 scenarios, which assume high global temperatures, show the greatest regional and global decreases in yields, especially by the 2080s. The decreases are especially significant in Africa and parts of Asia, with expected losses of up to 30 percent. In these regions, the effects of temperature and precipitation changes on crop yields are beyond the inflection point of the beneficial direct effects of CO_2. In North America, Southeast Asia, South America and Australia the effects of CO_2 on crops partly compensate for the stress imposed by the A1FI climate conditions and result in small yield increases. Climate change scenarios with smaller temperature increases such as B1 and B2, which reflect slower population growth but higher per capita income, generally lead to smaller cereal yield decreases. Table 1 illustrates the complex regional patterns of projected climate variables, CO_2 effects and agricultural systems affecting crop production under climate change, CO_2 and development futures.

Table 1.
Aggregated developing/developed country differences (%) in average crop yield changes from baseline for the HadCM2 and HadCM3 scenarios

	HadCM3 – 2080s							HadCM2 - 2080s	
Scenario	**A1FI**	**A2a**	**A2b**	**A2c**	**B1a**	**B2a**	**B2b**	**S550**	**S750**
World	-5	0	0	-1	-3	-1	-2	-1	1
Developed	3	8	6	7	3	6	5	5	7
Developing	-7	-2	-2	-3	-4	-3	-5	-2	-1
Difference (%) Developed-Developing	10.4	9.8	8.4	10.2	7.0	8.7	9.3	6.6	7.7

Source: Arnell *et al.* (2001); Rosenzweig and Iglesias (2006)

EFFECTS ON RISK OF HUNGER

Table 2 shows the estimated additional numbers of people at risk of hunger because of climate change. The main conclusion here concerns the differential effect of development on the impacts of climate change:

i) for a pathway of continuing high population growth and regional disparities of income (Table 2, A2) the numbers at risk of hunger because of climate change are projected at 10 percent to 20 percent above the number expected without climate change (data for 2050); and

ii) for a pathway of lower population growth and more equitable income distribution (Table 2, B1 and B2) the additional numbers at risk are estimated to be 5 percent or less (data for 2050).

Table 2.

Estimated global number of people (in millions) at risk of hunger: a) without climate change (= Reference), b) with climate change and full beneficial effects of carbon dioxide fertilisation (= CC), and c) with climate change without beneficial effects of carbon dioxide fertilisation (=CC, no CO2). DSSAT= estimates from crop modelling analysis. AEZ= estimates from analysis of shift of agro-ecological zones. Both analyses use the same global food model.

NB. An important element of uncertainty stems from the role which elevated levels of ambient atmospheric carbon dioxide may have. Assuming a fully beneficial effect on C3 crops such as wheat and rice, increased atmospheric CO2 could elevate yields significantly, but this estimation is drawn from laboratory experiments and may not be realised in farmers' fields

	2020		**2050**		**2080**	
Reference (millions)	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS
A1	663	663	208	208	108	108
A2	782	782	721	721	768	769
B1	749	749	239	240	91	90
B2	630	630	348	348	233	233
CC (millions)	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS
A1	666	687	219	210	136	136
A2	777	805	730	722	885	742
B1	739	771	242	242	99	102
B2	640	660	336	358	244	221
CC, no CO_2 (millions)	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS
A1	NA	726	NA	308	NA	370
A2	794	845	788	933	950	1320
B1	NA	792	NA	275	NA	125
B2	652	685	356	415	257	384

Source: Easterling and Aggarwal (2007);
based on: Parry *et al.* (2004); Fischer *et al.* (2002)

In these analyses, the conclusion remains that Africa is the region with most increases of hunger risk because of climate change: 65 percent of the global total is projected to occur in the continent.

An important element of uncertainty stems from the possible role of elevated levels of ambient atmospheric CO_2. Assuming a fully beneficial effect on crops such as wheat and rice, increased atmospheric CO_2 could elevate yields significantly. But this estimate is drawn from laboratory experiments and may not be replicated in the field. A reasonable guess is that half of the full effect might occur: that is, the mid-point between the numbers given in Table 2 for full effect (CC) and no effect (CC, no CO_2) is a best guess of the combined effect of climate change and elevated CO_2. Table 2 shows similar conclusions for the risk of hunger on the basis of different modelling methods such as the agro-ecological zone (AEZ)-basic linked system (BLS), which is discussed below.

COMPARABLE RECENT STUDIES

A 2009 study projected the responses of rice, wheat and maize to climatic variability under the SRES A2 scenario using the National Center for Atmospheric Research (NCAR) CCM3 and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) Mk3.0 models (International Food Policy Research Institute [IFPRI], 2009; Nelson *et al.*, 2009). The results incorporate the biophysical effects of climate change on crop production, the changes in crop production including biophysical and economic changes from higher prices induced by the initial biophysical shock and the resulting impacts on calorie availability and child malnutrition.

Table 3 presents the results for the direct biophysical effects of the two scenarios, with and without CO_2 fertilization, on production of the three crops modelled with the Decision Support System for Agrotechnology Transfer (DSSAT). Production declines in all regions in 2050 because of climate change, compared with no climate change when there is no CO_2 fertilization. Irrigated and rainfed wheat and irrigated rice are especially hard hit. In China, some crops fare reasonably well because higher future temperatures are favourable in locations where current temperatures are at the low end of the optimal temperature for the crop. India and other parts of South Asia are particularly hard hit by climate change. With the CO_2 fertilization effect the drop in production is lower in all regions; rainfed maize has small improvement in production under CSIRO in developed countries; rainfed wheat production increases in Latin America and the Caribbean under CSIRO and NCAR.

Table 3.
Climate change effects on crop production, including biophysical effects, % change in production compared with a reference scenario with no climate change, 2050.

	CSIRO NoCF	CSIRO CF	NCAR NoCF	NCAR CF
Maize, irrigated				
East Asia and the Pacific	-8.19	-7.75	-9.40	-8.81
Europe and Central Asia	-12.61	-12.58	-13.68	-13.63
Latin America and the Caribbean	-23.89	-23.47	-24.04	-23.65
Middle East and North Africa	-30.51	-30.85	-31.23	-31.32
South Asia	-25.99	-24.44	-25.33	-23.80
Sub-Saharan Africa	-39.67	-39.55	-39.53	-39.36
Developing countries	-15.67	-15.16	-16.39	-15.78
Developed countries	-3.22	-3.19	-10.55	-10.40
World	-8.86	-8.61	-13.19	-12.84
Maize, rainfed				
East Asia and the Pacific	-19.03	-17.29	-13.70	-12.21
Europe and Central Asia	-24.40	-19.41	-74.80	-72.68
Latin America and the Caribbean	-11.24	-8.89	-12.96	-10.98
Middle East and North Africa	-24.54	-23.00	-57.40	-57.14
South Asia	-36.83	-34.78	-25.50	-22.95
Sub-Saharan Africa	-14.64	-14.80	-15.15	-15.32
Developing countries	-15.56	-13.90	-16.57	-15.20
Developed countries	-6.04	2.23	-14.67	-7.20
World	-12.73	-9.11	-16.01	-12.83
Rice, irrigated				
East Asia and the Pacific	-21.94	-6.33	-28.31	-11.64
Europe and Central Asia	-32.96	-19.80	-40.62	-26.06
Latin America and the Caribbean	-24.91	-20.74	-20.06	-13.80
Middle East and North Africa	-46.50	-37.18	-56.74	-47.46
South Asia	-19.79	-3.12	-23.69	-6.23
Sub-Saharan Africa	-39.43	-27.75	-41.28	-29.98
Developing countries	-22.61	-7.60	-27.26	-11.32
Developed countries	-17.27	-5.00	-19.00	-6.84
World	-22.30	-7.44	-26.78	-11.05
Rice, rainfed				
East Asia and the Pacific	-8.46	-0.88	-10.84	-2.60
Europe and Central Asia	-31.00	-25.70	-36.89	-6.34
Latin America and the Caribbean	-20.66	-15.14	-25.76	-19.56

Middle East and North Africa	-100.00	-100.00	-100.00	-100.00
South Asia	-16.41	-11.33	-12.62	-8.46
Sub-Saharan Africa	-11.48	-9.19	-10.05	-7.59
Developing countries	-13.09	-7.11	-12.70	-6.79
Developed countries	-30.50	-26.82	-34.59	-30.45
World	-13.13	-7.15	-12.75	-6.84
Wheat, irrigated				
East Asia and the Pacific	-19.22	-13.92	-24.42	-19.15
Europe and Central Asia	-46.77	-43.22	-53.39	-50.43
Latin America and the Caribbean	-21.47	-16.56	-26.11	-20.94
Middle East and North Africa	-30.13	-24.57	-35.49	-30.45
South Asia	-50.12	-41.84	-57.67	-50.28
Sub-Saharan Africa	-34.45	-30.14	-34.00	-28.61
Developing countries	-37.49	-30.96	-43.85	-37.85
Developed countries	-22.59	-18.94	-28.91	-25.34
World	-35.54	-29.39	-41.89	-36.21
Wheat, rainfed				
East Asia and the Pacific	-34.42	-27.18	-39.14	-34.13
Europe and Central Asia	-46.61	-41.74	-51.27	-46.55
Latin America and the Caribbean	-4.91	4.31	-3.06	3.99
Middle East and North Africa	-20.26	-10.86	-24.28	-16.01
South Asia	-54.67	-42.05	-57.73	-45.95
Sub-Saharan Africa	-32.82	-23.58	-35.69	-27.55
Developing countries	-30.99	-23.35	-33.78	-27.31
Developed countries	-17.11	-11.95	-22.11	-16.74
World	-24.52	-18.03	-28.34	-22.38

Source: Nelson *et al.* (2009)

The results in Table 2 reinforce the findings of the earlier studies reported above, but the negative impacts of climate change on production are larger, especially because the results are for 2050 rather than 2080 as in most of the earlier work. The effects of climate change on agricultural production are more negative in developing countries than in developed countries. Global impacts on production are negative in all cases compared with the small positive impacts found in some of the earlier studies. Although results vary by crop, Africa and South Asia suffer the most negative impacts on production, which is consistent with earlier studies.

WORLD PRICES

The direct and indirect effects of climate change on agriculture operate through the economic system: they alter prices, production, productivity investments, food demand, food consumption and ultimately human well-being.

World prices are the most useful single aggregate indicator of the effects of climate change on agriculture. Table 4 shows the price effects of various permutations of climate change, with and without the CO_2 fertilization effect. With no climate change, world prices for rice, wheat and maize will increase between 2000 and 2050, driven mainly by population increase and income growth; productivity growth will decrease. Climate change results in higher price increases in 2050 compared with the no-climate-change case: prices in 2050 would be 35–37 percent higher for rice, 99–102 percent higher for wheat and 58–62 percent higher for maize. A worse scenario is expected in 2060, in which cereal price increases are projected at 25 percent to 150 percent using BLS, as discussed above. But if CO_2 fertilization is effective in the field the price increases resulting from climate change are reduced, though still significantly higher in 2050 than in the no-climate-change scenarios.

Table 4.
Projected world prices of selected crops and livestock products (US$/mt).

	2000	2050				
		No climate change	NCAR No CF	CSIRO No CF	NCAR CF effect (%)	CSIRO CF effect (%)
Rice	190	305	419	414	-17.41	-16.36
Wheat	113	132	263	267	-10.39	-11.37
Maize	95	100	158	162	-11.41	-13.50

Note: Prices are in 2000 US$. The last two columns report the % difference between the price in 2050 with and without the CO2 fertilization effect. For example the NCAR GCM, assuming CO2 fertilization is effective in the field, results in a 17.41% decline in the world rice price in 2050 compared with the no CO2 (CF) price.
Source: Nelson *et al.* (2009)

Table 5 reports effects of climate change on crop production, combining rainfed and irrigated systems without CO_2 fertilization. It accounts for the biophysical effects of climate change on area and yield with autonomous adjustments in these two variables resulting from price effects induced by the biophysical climate-change shock and indirect effects from water stress in irrigated crops. The negative effects on production shown in Table 4 are lower than those in Table 2 because the autonomous economic response to the biophysical climate change shocks is included.

Table 5.
Climate change effects on crop production, including biophysical and economic effects, no CO2 fertilization, % change in production compared with a reference scenario with no climate change, 2050.

	South Asia	East Asia and the Pacific	Europe and Central Asia	Latin America and the Caribbean	Middle East and North Africa	Sub-Saharan Africa	Developed Countries	Developing Countries
Maize								
CSIRO (%)	-23	-12	-10	0	-26	-3	11	-9
NCAR (%)	-15	5	-25	-2	-22	-1	2	-2
Rice								
CSIRO (%)	-11	-12	-3	-20	-41	-16	-9	-13
NCAR (%)	-12	-13	0	-16	-44	-13	-8	-14
Wheat								
CSIRO (%)	-40	-13	-44	11	-14	-30	-6	-32
NCAR (%)	-40	-2	-46	15	-15	-35	-10	-31

Source: Nelson *et al*. (2009)

The rows in Table 5 show the difference in production between the GCM and no-climate-change scenarios for 2050. Under CSIRO, for example, maize production in South Asia is projected to fall by 23 percent in comparison with the 2050 reference scenario of no climate change: this is compared with a drop of 26 percent for irrigated maize and 37 percent for rainfed maize in a scenario where yield and area responses to the increases in commodity prices induced by the biophysical climate change shock were not considered (see Table 3). In the CSIRO scenario (see Table 5), maize production in developing countries will decline by 9 percent, rice by 13 percent and wheat by 32 percent; these are less negative than the results in Table 3 because of autonomous adaptation to changes in crop prices.

ALLOWING FOR LARGE-SCALE CHANGES IN LAND USE

One of the drawbacks of the preceding studies is that they do not allow for changes in land use and assume that crops that experience changes in yield will continue to be grown in the same areas in the future. But a logical response by farmers would be to change to crops that experience smaller reductions in yield and hence achieve a comparative advantage over others. A study using Ricardian models has examined the difference in outcome that might occur if such changes were considered (Cline, 2007).

The results differ only in degree from those of the previous studies. Global agricultural output is estimated to decrease by 16 percent assuming no CO_2 fertilization and by 3 percent with full CO_2 fertilization. The regional pattern shows strong adverse effects on yields in tropical areas, especially Africa, the Middle East and South Asia.

ANALYSES BASED ON CHANGES IN AGRO-ECOLOGICAL ZONES

An approach that is different from point-based crop-growth modelling is the study of the ways in which zones of crop suitability, or agro-ecological zones, may shift in response to changes of climate. When combined with modelling of the length of crop growing seasons in response to changes in moisture or heat availability, this method enables evaluation of changes in yield at any given place combined with changes in the extent of suitability (Fischer *et al.*, 2002).

The conclusions of this study regarding the effects on the risk of hunger are given in Table 2, where they are shown as AEZ-BLS to enable comparison with DSSAT-BLS, which are data from the preceding studies based on crop modelling. Both use the same BLS global food model, but they adopt different methods for modelling altered crop yields. However, their conclusions regarding the numbers of additional people at risk of hunger as a result of climate change are similar, which lends greater certainty to estimates of the effects on hunger.

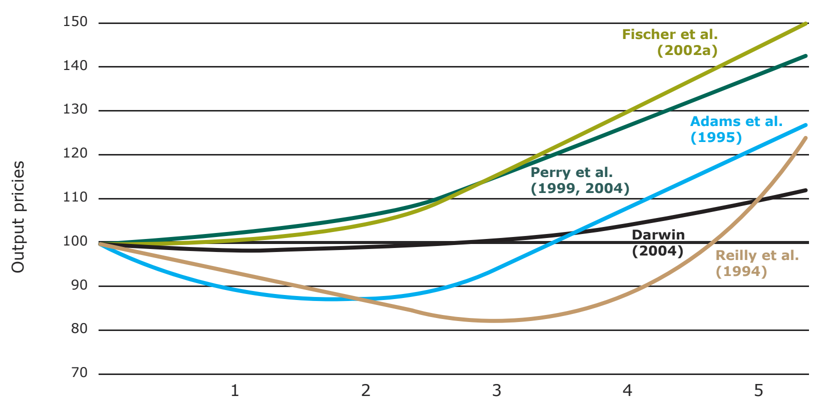
COMPARING THE RANGE OF ANALYSES

Other studies have used a macro-economic approach or yield estimates from previous crop modelling as inputs to different economic models.

One (Darwin, 2004) uses six land classes and analyses changes in their extent as a result of altered moisture and temperature, with yield results that are similar to those from crop model analyses. But the economic assumptions, especially changes in land use, eliminate three quarters of the climate-induced declines in production, at least until high levels of warming above 3°C start to reduce land suitability markedly.

All the approaches used by the IPCC show a reduction in output and consequent rise in prices, but vary in terms of when these would occur on a pathway of increasing global temperature (Easterling and Aggarwal, 2007). The crop modelling and agro-ecological analyses conclude that prices will rise even with small amounts of warming of 1°C or 2°C. The other analyses suggest that prices will first decrease because of increased potential from extended growing seasons at higher latitudes, then increase when temperature increases exceed 2°C or 3°C (see Figure 4). This point of inflection from a positive to a negative effect on global food output, and whether it occurs at a 1°C, 2°C or 3°C increase in global temperature, is central to the debate as to whether global warming may have a beneficial effect in the initial decades. But as we have seen, such a point of inflection depends on the uncertain mix of positive effects from higher CO_2 and negative effects from higher temperature.

Figure 4.
Cereal prices (% of baseline) versus global mean temperature change for major modelling studies. Prices interpolated from point estimates of temperature effects.



Source: Easterling and Aggarwal (2007).

In tropical and equatorial regions the pattern is of decreases in yield potential even with small amounts of climate change, because crops are often grown near their temperature and moisture, and changes in heat and water availability can easily stress them. One consequence is that even if global production potential were to increase with small amounts of global warming before declining with greater warming (and this point remains unclear), production potential in developing countries is projected to fall with even small amounts of climate change. The risk of hunger at the regional level in poorer parts of the world is therefore likely to increase in all scenarios of climate change.

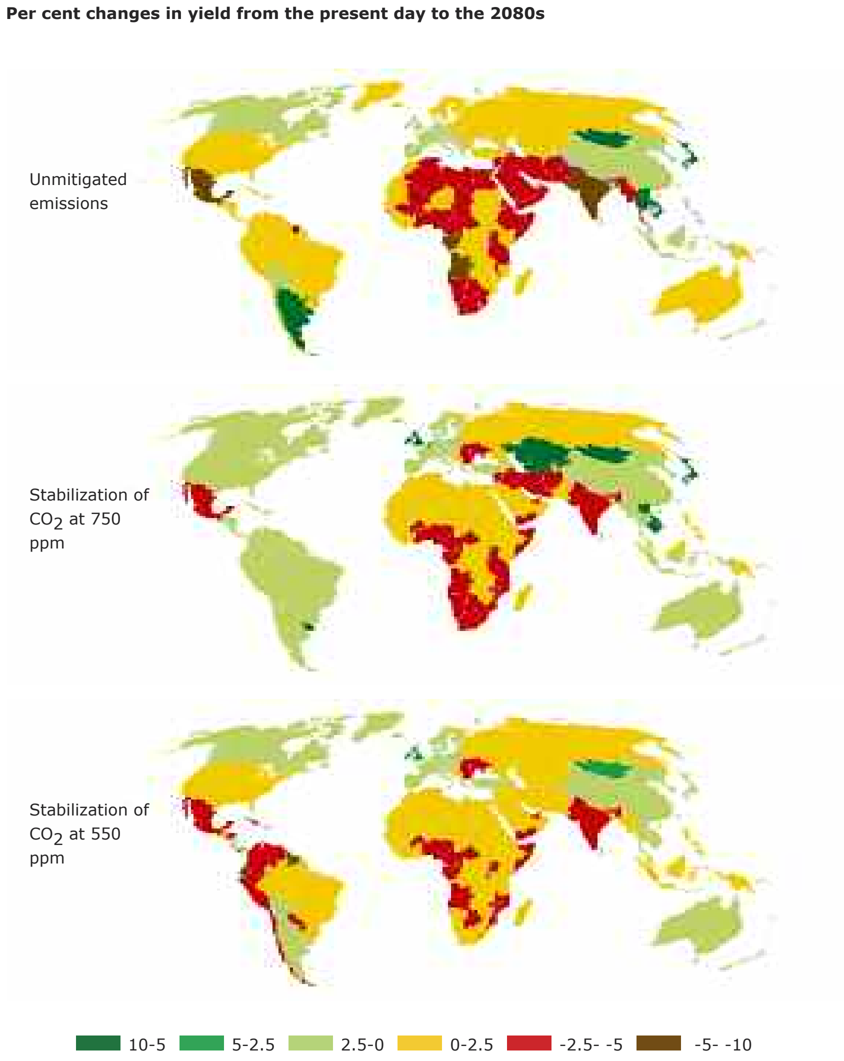
REDUCING IMPACTS BY STABILIZING CO_2 CONCENTRATIONS AT LOWER LEVELS

This section explores the effect on the risk of hunger of stabilizing CO_2 concentrations at defined levels (Arnell *et al.*, 2009). These scenarios are among the set defined by the IPCC (IPCC, 1997) stabilizing at 550 ppmv and 750 ppmv compared with the unmitigated emissions scenario IS92a (Mitchell *et al.*, 2000).

EFFECTS ON YIELD POTENTIAL

Figure 5 shows the estimated changes in potential national grain yield by the 2080s, assuming no changes in crop cultivars, under the three emissions scenarios. Under unmitigated emissions, positive changes in middle and high latitudes are overshadowed by reductions in yield in the lower latitudes. These reductions are particularly substantial in Africa and the Indian subcontinent. However, many of the mapped changes in yield are small and indistinguishable from the effects of natural climate variability.

Figure 5.
Changes in national cereal crop yields by the 2080s under three different emissions scenarios: unmitigated (IS92a: top map); S750 (middle map); and S550 (bottom map).



Source: Arnell *et al.* (2001).

Stabilization at 550 ppmv produces fewer reductions in yield than the unmitigated case, but there would still be reductions in the Indian subcontinent, most of the Pacific Islands, Central America and most African nations. Stabilization at 750 ppmv produces intermediate changes.

IMPLICATIONS FOR RISK OF HUNGER

Stabilization at 750 ppmv reduces the unmitigated impacts by 75 percent; stabilization at 550 ppmv achieves a reduction of 50 percent (see Tables 6 and 7). The assumption of full CO_2 effects appears to explain this: the beneficial effects of higher levels of CO_2 at 750 ppmv compensate for the adverse effects of higher temperatures. Under less favourable conditions of CO_2 effects, the reverse would be likely. Another study projects a 12 percent to 16 percent increase in the number of people at risk of hunger in an unmitigated scenario of >800 ppmv relative to a reference scenario; in a 550 ppmv mitigated scenario there is a reduction of 80 percent to 95 percent from the unmitigated scenario (Tubiello and Fischer, 2007).

Table 6.
Average annual cereal production (million mt).

	No climate change	Unmitigated	S750	S550
1990	1 800			
2020s	2 700	2 670–2 674	2 672	2 676
2050s	3 500	3 475	3 973	3 477
2080s	4 000	3 927	3 987	3 949

Notes: i) The estimates assume no change in crop cultivar, and come from the Basic Linked System. ii) The range in estimates for the unmitigated scenario represents the range between the four ensemble partners.
Source: Arnell *et al.* (2001)

Table 7.
Number of people at risk of hunger (millions).

	No climate change	Unmitigated	S750	S550
1990	521			
2020s	496	521–531	546	540
2050s	312	309–321	319	317
2080s	300	369–391	317	343

Note: The range in estimates for the unmitigated scenario represents the range between the four ensemble partners.
Source: Arnell *et al.* (2001)

Global figures, however, conceal considerable regional variations: 65 percent of the additional people at risk of future hunger are in Africa. This partly reflects the above average reduction in yields in Africa as a result of climate change, but it is also a reflection of higher levels of vulnerability. It also appears that the beneficial effects of stabilization are less. In a 750 ppmv situation, the additional number of people at risk of hunger is reduced by 30 percent. In a 550 ppmv future, the reduction in the climate-induced impact is only 20 percent. Because this conclusion assumes full CO_2 effects, more analysis is needed of the consequences of mitigation assuming partial effects of CO_2 fertilization.

Similar asymmetries appear in a comparable study by Tubiello and Fischer (2007). Some regions apparently become worse off with mitigation by not fully realizing positive agronomic impacts or economic benefits. But the substantial general effect of mitigation by stabilization of greenhouse gas concentrations is to reduce global additions to the risk of hunger from climate change.

OTHER MEASURES OF THE RISK OF HUNGER

In the recent analysis by IFPRI, the primary measures of the welfare effects of climate change are the change in calorie availability and the change in the number of malnourished children in 2050 without climate change and with various climate change scenarios (IFPRI, 2009; Nelson *et al.*, 2009).

Diminishing consumption of cereals in particular translates into large declines in calorie availability as a result of climate change. The analysis indicated that without climate change calorie availability would increase throughout the world between 2000 and 2050, except for a small decline in Latin America and the Caribbean (see Table 8). The largest increase – 12.6 percent – would be in sub-Saharan Africa; people in Asia would also consume 3.5 percent to 7 percent more.

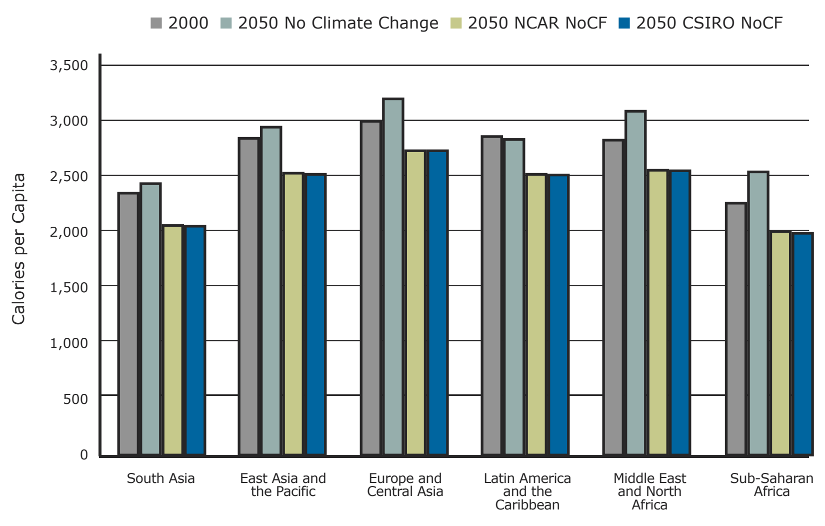
Table 8.
Daily per capita calorie availability with and without climate change.

	2000	2050				
		No climate change	NCAR No CF	SIRO No CF	NCAR CF effects (%)	CSIRO CF effects (%)
South Asia	2 381	2 464	2 089	2 088	4	4
East Asia and Pacific	2 870	2 979	2 553	2 555	4	4
Europe and Central Asia	3 017	3 231	2 760	2 759	3	3
Latin America and Caribbean	2 879	2 862	2 545	2 546	3	3
Middle East and North Africa	2 846	3 112	2 594	2 595	3	3
Sub Saharan Africa	2 282	2 570	2 033	2 017	6	6
Developed countries	3 438	3 606	3 213	3 213	2	2
Developing countries	2 677	2 750	2 318	2 315	4	4

Source: Nelson *et al.* (2009)

With climate change, however, calorie availability is not only lower than the no-climate-change scenario in 2050 (see Figure 6), it actually declines relative to 2000 levels throughout the world. With CO_2 fertilization, the declines are 3 percent to 6 percent less severe but still large relative to the no-climate-change scenario. There is almost no difference in effect between the two scenarios.

Figure 6.
Daily per capita calorie availability with and without climate change.



Source: Nelson *et al.* (2009).

Table 9 reports statistics for the child malnourishment indicator. With no climate change, only sub-Saharan Africa projects an increase in the number of malnourished children between 2000 and 2050. All other parts of the developing world have reductions in the number of malnourished children as a result of rapid growth in incomes and agricultural productivity. Climate change eliminates much of that improvement. In East Asia and the Pacific, in both scenarios, there would be 16.5 million malnourished children in 2050 instead of 12 million (an increase of 38 per cent); in South Asia, there would be 58.1 million instead of 52.3 million (an increase of 11 per cent). In sub-Saharan Africa, climate change increases the number of malnourished children in 2050 by 10 million compared with the no-climate-change case (an increase of 24 per cent). Globally, climate change is projected to increase the number of malnourished children by 24 million in 2050 compared with the no-climate-change case (an increase of 21 per cent). If CO_2 is in fact effective in the field, the negative effect of climate change on

Table 9.
Projected number of malnourished children in 2000 and 2050 (thousands of children under 5).

	2000	2050				
		No climate change	NCAR No CF	CSIRO No CF	NCAR CF effect (%)	CSIRO CF effect (%)
South Asia	75 621	52 374	58 165	58 170	-3	-3
East Asia and Pacific	23 810	12 018	16 553	16 521	-8	-8
Europe and Central Asia	4 112	2 962	3 907	3 910	-4	-4
Latin America and Caribbean	7 687	5 433	6 731	6 724	-4	-5
Middle East and North Africa	3 459	1 148	2 016	2 016	-10	-10
Sub Saharan Africa	32 669	38 780	48 725	49 024	-5	-5
All developing countries	147 357	112 714	136 097	136 366	-4	-5

Note: The last two columns in this table report the percentage difference between the number of malnourished children in 2050 with and without the CO2 fertilization effect. For example, the NCAR GCM, assuming CO2 fertilization is effective in the field, results in a 3% decline in the number of malnourished children in South Asia in 2050 relative to the climate change outcome without CO2 fertilization.
Source: Nelson *et al.* (2009).

child malnutrition is reduced, but not enough to offset the negative effects of climate change.

STUDIES IN PROGRESS

We now consider research in progress, which will provide new information on climate change and food security in the next three years. The focus will still be on global or regional studies that go beyond projections of change in production alone. Our interest in each case is the ways in which current research are likely to increase our knowledge of climate change and future food security.

We have seen that general conclusions about impacts on food systems can be identified from different studies, even though they use different input conditions. Studies of climate-change impacts differ in terms of regions, impact sectors and socio-economic and climate scenarios, which makes it difficult to form a consistent picture of climate change impacts at the global level. It is hence difficult to assess the effectiveness of proposed measures to reduce greenhouse gas emissions with a view to limiting the impacts of climate change. The ideal would be to compare similar studies using the same input conditions to build an evidence base for decision-making.

The Quantifying the Earth System-Global Scale Impacts of Climate Change (QUEST-GSI) project, available at www.met.reading.ac.uk/research/quest-gsi/, tries to do this. Research in QUEST-GSI uncouples the link between impact projections and choice of climate model/emission scenario/time-slice by creating and using scenarios for different amounts of climate forcing that postulate global temperature increases of 0°C to 5°C in 0.5°C increments and a set of emission scenarios. Impacts are therefore linked to measures of climate change (ΔT or ΔCO_2) scenarios using climate pattern-scaling approaches rather than to specific SRES scenarios. QUEST-GSI includes the construction of generalized relationships between climate forcing and impacts.

The AVOID project (www.avoid.uk.net/) takes this generalized use of climate change projections further. Among other objectives, AVOID aims to identify the climate consequences of an even wider range of climate policies on the basis of greenhouse gas emission pathways and temperature and CO_2 changes. For impacts on food security, AVOID will assess what is considered an acceptable risk of climate change impacts and what level of global climate change should be avoided for a given consequence. QUEST-GSI and AVOID show how current climate change impact studies examine what climate changes lead to given consequences and are coming closer to defining what constitutes dangerous climate change. A potential advantage of this new approach is that it is aligned with the provision of policy advice.

There is a need for better sampling of the uncertainties in projections of impacts on food security. All projections of the impacts of climate change on agriculture and food security are uncertain to some extent – that is, we should not expect a single projection of the impact of climate change on food systems but a range of possible outcomes. Uncertainties arise from different climate models, greenhouse gas emission pathways and agricultural impact models; the uncertainty of the impact projection reflects all of these combined. The global studies reviewed so far, sample some of this uncertainty by using the output of more than one climate model or greenhouse gas emission pathway (see Table 2 for example).

The uncertainties in projected changes in food security must be communicated to policy-makers correctly and effectively. Ongoing projects sample and communicate uncertainties in projections in increasingly sophisticated ways: QUEST-GSI, for instance, samples uncertainty arising from climate model parameter uncertainty, climate model structural uncertainty, greenhouse gas emission pathway uncertainty and impact model parameter uncertainty. A common feature of early crop impact studies was the reporting of impacts “with” and “without” the effects of elevated CO_2 to reflect uncertain knowledge of the CO_2 fertilization effect in crops (see Table 2 for example). Crop scientists are now debating the extent of yield enhancement (Long *et al*., 2006). When this uncertain yield enhancement is multiplied across the globe and for all crops, it is still an important source of uncertainty in the impacts of climate change on global food production. Ongoing projects seek to represent this uncertainty in the extent of the beneficial effect for most crops by using different parameter values based on new analyses of crop experiments as well as older studies. With regard to linking agricultural change to changes in livelihoods, some ongoing studies link changes in global crop production under climate change with measures of livelihoods. For example, QUEST-GSI combines changes in farm-level crop productivity from a large-area crop model (Challinor *et al*., 2004) with land-use changes from the IMAGE 2.3 model (van Vuuren *et al*., 2006) to calculate changes in crop production levels. Together with population projections from IMAGE (www.mnp.nl/en/themasites/image/), these feed into FAO food balance sheets (Jacobs and Sumner, 2002) for each country to give the percentage of population undernourished by country and calories per capita per day. Impacts of climate change on health indicators such as deaths and disability-adjusted life years are calculated from the percentage of population undernourished by country and age-group.

The Program on Food Security and Environment at Stanford University is looking at the poverty effects of climate impacts on agriculture using the Global Trade Analysis Project equilibrium global trade model (www.gtap.agecon.purdue.edu) and disaggregated household data for a number of countries. This project is showing that the poverty impacts of climate-induced agricultural shocks are highly dependent on where a household earns its income and that with farming households gain in many countries even as productivity drops (Marshall Burke, pers. comm.). Other studies by this group of changes in migration across Africa are examining whether and how migration is driven by climate variability and/or food security (David Lobell, pers. comm). Studies of changes at the household level across East Africa are using very high resolution climate data to simulate changes in the productivity of maize and beans under climate change (Thornton *et al*., 2009). A range of responses to climate change is found on this small spatial scale, leading to livelihood changes that range from beneficial effects on household food security and income in some tropical highland areas to areas where cropping ceases to be viable and a change to livestock systems or a move out of agriculture may be necessary (Philip Thornton, pers. comm.). These studies are using the latest research techniques to add detail as to the response of agricultural households to climate change.

Agriculture has to be coupled with changes occurring on the planet. Processes in the atmosphere, oceans and land are coupled in that they interact on timescales from fractions of seconds to thousands of years. Crops cover a quarter of the global land area; regional climate can be very sensitive to large-scale changes in crop areas, which can result from changes in economic or climate conditions (Osborne *et al.*, 2004). A new approach to assessing agricultural impacts is, therefore, to couple crop simulations with models of land and atmosphere processes.

In recent years five groups have succeed in coupling crop simulations with climate models: Bondeau *et al.* (2007), Gervois *et al.* (2004), Kucharik (2003), Osborne *et al.* (2007) and Stehfest *et al.* (2007). One group has shown that in some parts of the world the impact of changes in crop areas on regional surface temperature can be of the same magnitude as regional human-induced climate change (Osborne *et al.*, 2009). This raises the question of whether or not new fully coupled climate change impact studies will revise previous estimates of food security impacts.

The full coupling of crop simulations with global climate models offers new possibilities for studies of the impact of climate change on agricultural production that capture some of the complex feedbacks in the Earth system. These techniques will soon be incorporated into regional climate models such as the Providing Regional Climates for Impacts Studies regional model of the United Kingdom Meteorological Office Hadley Centre (http://precis.metoffice.com/). With groups such as the Joint United Kingdom Land Environment Simulator (www.jchmr.org/jules/) now looking to add socio-economic components to their Earth system models, the next generation of global projections of the impacts of climate change on food security will probably use fully coupled Earth system models.

CONCLUSIONS ABOUT PROJECTED IMPACTS ON THE RISK OF HUNGER

Studies using a variety of models are consistent on the major issues:
i) climate change will reduce agricultural production in most of the world, increase food prices and increase food insecurity and malnutrition;
ii) the scale of the impacts is in the order of tens to hundreds of millions of additional people at risk from hunger due to climate change (roughly a 10 to 20% increase); iii) developing countries will be hit harder than developed countries, and the most food-insecure regions – sub-Saharan Africa and South Asia – will be hit hardest; and iv) adaptation of farming practices could halve this impact. Reform of institutions, as discussed in part one of this report, could reduce the impact further.

WFP/Susannah Nicol/Afghanistan

References

Adams, R.M., Fleming, R.A., Chang, C.C., McCarl, B.A., Rosenzweig, C., 1995 . A reassessment of the effect of global climate change on US agriculture. *Climatic Change,* 30:147-167.

Alexandratos, N. (ed.) 1995. *World Agriculture: towards 2010. An FAO Study*. Chichester, UK, Wiley & Sons.

Arnell, N.W., Cannell, M.G.R., Hulme, M., Kovats, R.S., Mitchell, J.F.B., Nicholls, R.J., Parry, M.L., Livermore, M.T.J. & White, A. 2001. The consequences of CO_2 Stabilisation for the Impacts of Climate Change. *Climatic Change* 12:201–223.

Ban Ki-Moon. 2008. *Address by the Secretary-General. High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy*. Available at: http://www.fao.org/fileadmin/user_upload/foodclimate/statements/un_ki_moon.pdf

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M. & Smith, B. 2007. Modelling the Role of Agriculture for the 20th Century Global Terrestrial Carbon Balance. *Global Change Biology* 13:679–706.

Borger, J. 2008. "Feed the world? We are fighting a losing battle, UN admits". *The Guardian*, 26 February 2008.

Brown, G. 2009. *Roadmap to Copenhagen*. Speech, 26 June. Available at: http://www.number10.gov.uk/Page19813

Brown, L. 2005. *Outgrowing the Earth: the Food Security Challenge in an Age of Falling Water Tables and Rising Temperatures*. London, Earthscan Books.

Bundy, D., Burbano, C., Grosh, M., Gelli, A., Jukes, M. & Drake, L. 2009. *Rethinking School Feeding: Social Safety Nets, Child Development, and the Education Sector*. Washington DC, World Bank/WFP.

Buringh, P. & Dudal, R. 1987. Agricultural Land Use in Space and Time. *In*: M.G. Wolman and F.G.A. Fournier (eds.) *Land Transformation in Agriculture*. New York, Wiley.

Challinor, A.J., Wheeler, T.R., Craufurd, P.Q. & Slingo, J.M. 2004. Design and Optimization of a Large-Area Process-Based Model for Annual Crops. *Agricultural and Forest Meteorology* 124:99–120.

Chronic Poverty Research Centre. 2008. *The Chronic Poverty Report 2008-09*. Manchester, UK.

Clarke, R. & King, J. 2004. *The Atlas of Water*. London, Earthscan Books.

Cline, W.R. 2007. *Global Warming and Agriculture: Impact Estimates by Country*. Washington DC, Center for Global Development.

Commission on Climate Change and Development. 2009. *Closing the Gaps: Disaster Risk Reduction and Adaptation to Climate Change in Developing Countries*. Report. Stockholm.

Conway, G. 1997. *The Doubly Green Revolution: Food for All in the Twenty-First Century*. London, Penguin Books.

Darwin, R. 2004. Effects of Greenhouse Gas Emissions on World Agriculture, Food Consumption and Economic Welfare. *Climatic Change* 66:191–238.

Davies, M., Oswald, K., Mitchell, T. & Tanner, T. 2008. *Climate Change Adaptation, Disaster Risk Reduction and Social Protection*. Briefing note. Brighton, UK, University of Sussex, Institute of Development Studies Centre for Social Protection.

Department for International Development. 2005. *Disaster Risk Reduction: a Development Concern*. Briefing paper. London.

Department for International Development. 2006. *Social Protection in Poor Countries*. Social protection briefing note no. 1. London.

Dercon, S. 2004. *Insurance against Poverty*. Oxford, OUP.

Dinmore, G. 2009. "G8 to commit US$20 billion for food security". *Financial Times*, 10 July 2009.

Diouf, J. 2008. *Address by Mr Jacques Diouf, Director-General of the Food and Agriculture Organization, on the Occasion of the High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy*. 3 June. Available at:

http://www.fao.org/fileadmin/user_upload/foodclimate/statements/fao_diouf.pdf (in French).

Easterling, W. & Aggarwal, P. 2007. Food, Fibre and Forest Products. *In*: M.L. Parry, O.F. Canzianai, J.P. Palutikof, P.J. van der Linden & C.E. Hanson. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pp.273–313. Cambridge, UK, CUP.

Ebrahimi, H. 2009. "IEA warns of oil 'supply crunch'". *Daily Telegraph*, 16 February 2009.

Evans, A. 2009. *The Feeding of the Nine Billion: Global Food Security in the 21st Century*. London, Chatham House. Available at:

http://www.chathamhouse.org.uk/publications/papers/download/-/id/694/file/13179_r0109food.pdf

Evans, L.T. 1998. *Feeding the Ten Billion: Plants and Population Growth*. Cambridge, UK, CUP.

FAO. 1996. *Sixth World Food Survey*. Rome.

FAO. 1999. *The State of Food Insecurity in the World*. Rome.

FAO. 2006. *Livestock's Long Shadow: Environmental Issues and Options*. Rome.

FAO. 2008. "The world only needs 30 billion dollars a year to eradicate the scourge of hunger". News release, 3 June. Available at: http://www.fao.org/newsroom/en/news/2008/1000853/index.html

FAO. 2009. "1.02 billion people hungry". News release, 19 June. Available at: http://www.fao.org/news/story/en/item/20568/icode/

Fischer, G., Frohberg, K., Keyzer, M.A. & Parikh, K.S., 1988. *Linked National Models: a Tool for International Food Policy Analysis*. Dordrecht, Netherlands, Kluwer.

Fischer, G., Hizsnyik, E., Prieler, S., Shah, M. & van Velthuizen, H. 2009. *Biofuels and Food Security*. Laxenburg, Austria, International Institute for Applied Systems Analysis.

Fischer, G., Shah, M., and Velthuizen, H., 2002. *Climate Change and Agricultural Vulnerability*. International Institute for Applied Systems Analysis: Vienna.

G8. 2009. L'Aquila Joint Statement on Global Food Security (L'Aquila Food Security Initiative). Available at: http://www.g8italia2009.it/static/G8_Allegato/LAquila_Joint_Statement_on_Global_Food_Security%5B1%5D,0.pdf

G20. 2009. Global Plan for Recovery and Reform: the Communiqué from the London Summit. Available at: http://www.londonsummit.gov.uk/en/summit-aims/summit-communique/

Gervois, S., de Noblet-Ducoudre, N., Viovy, N., Ciais, P., Brisson, N., Seguin, B. & Perrier, A. 2004. Including Croplands in a Global Biosphere Model: Methodology and Evaluation at Specific Sites. *Earth Interactions* 8:1–25.

Green, D. 2008. *From Poverty to Power: How Active Citizens and Effective States can Change the World*. Oxford, UK, Oxfam.

Grosh, M., del Ninno, C., Tesliuc, E. & Ouerghi., A. 2008. *For Protection and Promotion: the Design and Implementation of Effective Safety Nets*. Washington DC, World Bank.

Hamilton, K. 2006. *Where is the Wealth of Nations? Measuring Capital for the 21st Century*. Washington DC, World Bank.

Hazell, P., Pulton, C., Wiggins, S. & Dorward, A. 2007. *The Future of Small Farms for Poverty Reduction and Growth*. IFPRI policy brief no. 75. Washington DC, IFPRI.

Heltberg, R. & Siegel, P.B. 2008. *Climate Change: Challenges for Social Protection in Africa*. Paper for conference on social protection for the poorest in Africa. Washington DC, World Bank.

Hulme, M., Mitchell, J., Ingram, W., Johns, T., New, M. & Viner, D. 1999. Climate Change Scenarios for Global Impacts Studies. *Global Environmental Change* 9(4):s3–s19.

IEA. 2008. *World Energy Outlook 2008*. Paris.

International Food Policy Research Institute. 2009. *Building Climate Resilience in the Agriculture Sector of Asia and the Pacific*. Asian Development Bank, Mandaluyong: Philippines. 333 p. http://www.adb.org/Documents/Books/Building-Climate-Resilience-Agriculture-Sector/Building-Climate-Resilience-Agriculture-Sector.pdf

IMF. 2008. *World Economic Outlook*. Washington DC.

IBSNAT. 1989. *Decision Support System for Agrotechnology Transfer Version 2.1*. Honolulu, HI, University of Honolulu Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resources.

IPCC. 1997. *Stabilization of Atmospheric Greenhouse Gases: Physical, Biological and Socio-Economic Implications*. Technical paper no. III. Geneva.

IPCC. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability – Contribution of Working Group II to the IPCC Fourth Assessment*. Eds/ Parry, M.L. Canziani, O., Palutikof, J and Hansen, C., Cambridge, UK, CUP.

Jacobs, K. & Sumner, D.A. 2002. *The Food Balance Sheets of the Food and Agriculture Organization*. Rome, FAO.

Johns, T.C., Gregory, J.M., Ingram, W.J., Johnson, C.E., Jones, A., Lowe, J.A., Mitchell, J.F.B., Roberts, D.L., Sexton, D.M.H., Stevenson, D.S., Tett, S.F.B. and Woodage, M.J. 2003. Anthropogenic Climate Change for 1860 to 2100 Simulated with the HadCM3 Model under Updated Emissions Scenarios. *Climate Dynamics* 20:583–612.

Kucharik, C.J. 2003. Evaluation of a Process-Based Agro-Ecosystem Model (Agro-IBIS) across the US Corn Belt: Simulations of the Inter-Annual Variability in Maize Yield. *Earth Interactions* 7:1–33.

Lehmann, J. 2007. A Handful of Carbon. *Nature* 447:143–144.

Lumpkin, T. & Ziegler, R. 2008. Open Letter to Mr. Robert Zoellick, President of the World Bank Group, 14 April. Available at: http://solutions.irri.org/index.php?option=com_content&task=view&id=45&Itemid=67.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P. & Naylor, R.L. 2008. Prioritizing Climate Change Adaptation Needs for Food Security in 2030. *Science* 319(5863):607–610.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nösberger, J. & Ort, D.R. 2006. Food for Thought: Lower-than-Expected Crop Yield Stimulation with Rising CO_2 Concentrations. *Science* 312:1918 – 1921.

Mitchell, J.F.B., Johns, T.C., Ingram, W.J. & Lowe, J.A. 2000. The Effect of Stabilizing Atmospheric Carbon Dioxide Concentrations on Global and Regional Climate Change. *Geophysical Research Letters* 27:2997–3100.

Mitchell, J.F.B., Johns, T.C., Gregory, J.M. & Tett, S. 1995. Climate Response to Increasing Levels of Greenhouse Gases and Sulphate Aerosols. *Nature* 376:501–504.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, & D. Lee. 2009. Climate Change: Impact on Agriculture and Costs of Adaptation. Food Policy Report. International Food Policy Research Institute, Washington DC: USA. 30 p. http://www.ifpri.org/sites/default/files/publications/pr21.pdf

Norton, A., Conway, T. & Foster, M. 2001. *Social Protection Concepts and Approaches: Implications for Policy and Practice in International Development*. Working paper no. 143. London, Overseas Development Institute.

OECD. 2009. *Development Aid at its Highest Level Ever in 2008*. Available at: http://www.oecd.org/document/35/0,3343,en_2649_34447_42458595_1_1_1_1,00.html

Osborne, T.M., Lawrence, D.M., Challinor, A.J., Slingo, J.M. & Wheeler, T.R. 2007. Development and Assessment of a Coupled Crop-Climate Model. *Global Change Biology* 13:169–183.

Osborne, T. M., Lawrence, D.M., Slingo, J.M., Challinor, A.J. & Wheeler, T.R. 2004. Influence of Vegetation on Local Climate and Hydrology in the Tropics: Sensitivity to Soil Parameters. *Climate Dynamics* 23:45–61.

Osborne, T.M., Slingo, J.M., Lawrence, D.M. & Wheeler, T.R. 2009. Examining the Interaction of Growing Crops with Local Climate using a Coupled Crop-Climate Model. *Journal of Climate* 22:1393–1411.

Parry, M.L., Arnell, N., Berry, P., Dodman, D., Fankhauser, S., Hope, C., Kovats, S., Nicholls, R., Satterthwaite, S., Tiffin, R. & Wheeler, T. 2009. *Assessing the Costs of Adapting to Climate Change: a Review of the UNFCCC and Other Recent Estimates*. London, Imperial College, Grantham Institute for Climate Change.

Parry, M.L., Fischer, C., Livermore, M., Rosenzweig, C. & Iglesias, A. 1999a. Climate Change and World Food Security: a New Assessment. *Global Environmental Change* 9:s51–s67.

Parry, M.L., Rosenzweig, C., Iglesias, A., Fischer, G. & Livermore, A.T.J. 1999b. Climate Change and World Food Security: a New Assessment. *Global Environmental Change* 9(Supplemental Issue):s52–s67.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M. & Fischer, G. 2004. Effects of Climate Change on Global Food Production under SRES Emissions and Socio-Economic Scenarios. *Global Environmental Change* 14(1):53–67.

Postel, S. & Vickers, A. 2004. Boosting Water Productivity. *State of the World 2004*. Worldwatch Institute. New York, W.W. Norton & Co.

Reilly, J., Hohmann, N., Kanes,& Kanes,S., 1995. Climate change and agricultural trade. *Global Environmenatal Change* 4:24-36

Ritchie, J.T. & Otter, S. 1985. Description and Performance of CERES-Wheat: a User-Oriented Wheat Yield Model. *In*: W.O. Willis (ed.) *ARS Wheat Yield Project*. Washington DC, Department of Agriculture, Agricultural Research Service ARS-38.

Ritchie, J.T., Singh, U., Godwin, D. & Hunt, L. 1989. *A User's Guide to CERES-Maize V2.10*. Muscle Shoals, AL, USA, International Fertilizer Development Center.

Rogers, H.H., Bingham, G.E., Cure, J.D., Smith, J.M. & Surano, K.A. 1983. Responses of Selected Plant Species to Elevated Carbon Dioxide in the Field. *Journal of Environmental Quality* 12:569–574.

Rosenthal, E. & Martin, A. "Leaders speak of their own issues at a conference addressing food shortages". *New York Times*, 5 June 2008.

Rosenzweig, C. & Parry, M.L. 1994. Potential Impacts of Climate Change on World Food Supply. *Nature* 367:133–138.

Rosenzweig, C. & Iglesias, A. 1994. *Implications of Climate Change for International Agriculture: Crop Modeling Study*. Washington DC, United States Environmental Protection Agency.

Rosenzweig, C. & Iglesias, A. 2006. *Potential impacts of Climate Change on World Food Supply: Data Sets from a Major Crop Modelling Study*. New York, Columbia University Goddard Institute for Space Studies.

Rosenzweig, C., Parry, M.L., Fischer, G. & Frohberg, K. 1993. *Climate Change and World Food Supply*. Research report no. 3. Oxford, UK, University of Oxford Environmental Change Unit.

Sachs, J. 2008. *Common Wealth: Economics for a Crowded Planet*. London, Penguin Books.

Sen, A. 1981. *Poverty and Famines: an Essay on Entitlement and Deprivation*. Oxford, Clarendon Press.

Smith, D. & Vivekananda, J. 2007. *A Climate of Conflict: the Links between Climate Change, Peace and War*. London, International Alert.

Stehfest, E., Heistermann, M., Priess, J.A., Ojima, D.S. & Alcamo, J. 2007. Simulation of Global Crop Production with the Ecosystem Model DayCent. *Ecological Modelling* 209:203–219.

Stern, N. 2008. *Key Elements of a Global Deal on Climate Change*. London, London School of Economics and Political Science.

Stevens, P. 2008. *The Coming Oil Supply Crunch*. London, Chatham House.

Thornton, P.K., Jones P.G., Alagarswamy, A. & Andresen J. 2009. Spatial Variation of Crop Yield Responses to Climate Change in East Africa. *Global Environmental Change* 19:54–65.

Trostle, R. 2008. *Global Agricultural Supply and Demand: Factors Contributing to the Recent Increase in Food Commodity Prices*. Washington DC, United States Department of Agriculture Economic Research Service.

Tubiello, F.N. & Fischer, G. 2007. Reducing Climate Change Impacts on Agriculture: Global and Regional Effects of Mitigation, 2000–2080. *Technological Forecasting and Social Change* 74(7):1030–1056.

United Kingdom House of Commons International Development Committee. 2008. *The World Food Programme and Global Food Security: Tenth Report of Session 2007–08*. HC 493-1. London, Her Majesty's Stationery Office.

United Nations. 1989. *World Population Prospects 1988*. New York.

United Nations. 2008. *Human Development Report 2007/08. Fighting Climate Change: Human Solidarity in a Divided World*. New York, UNDP.

United Nations Department of Economic and Social Affairs. 2006. *World Population Prospects: the 2006 Revision*. New York.

United Nations High Level Panel on United Nations System-Wide Coherence in the Areas of Development, Humanitarian Assistance and the Environment. 2006. *Delivering As One*. Available at: http://www.un.org/events/panel/.

United Nations High Level Panel on Threats, Challenges and Change. 2004. *A More Secure World: Our Shared Responsibility*. Available at http://www.un.org/secureworld/.

United Nations High Level Task Force on the Global Food Crisis. 2008. *Comprehensive Framework for Action*. New York.

United Nations International Strategy for Disaster Reduction. 2005. *Hyogo Framework for Action: Building the Resilience of Nations and Communities to Disasters*. Extract from the final report of the World Conference on Disaster Reduction (A/CONF.206/6). Kobe, Japan.

United Nations Office for the Coordination of Humanitarian Affairs. 2008. *OCHA Regional Office for Central and East Africa Humanitarian Funding Update*, July. Nairobi.

Van Vuuren, D., Lucas, P.L. & Hilderink, H. 2006. Downscaling Drivers of Global Environmental Change: Enabling Use of Global SRES Scenarios at the National and Grid Levels. *Global Environmental Change* 17:114–130.

Von Braun, J. 2007. *The World Food Situation: New Driving Forces and Required Actions*. Washington DC, IFPRI.

Webster, M., Ginnetti, J., Walker, P., Coppard, D. & Kent, R. 2008. *The Humanitarian Costs of Climate Change*. Medford, MA, Tufts University Feinstein International Center.

Wilson, C.A. & Mitchell, J.F.B. 1987. A Doubled CO_2 Climate Sensitivity Experiment with a Global Climate Model including a Simple Ocean. *Journal of Geophysical Research* 92(13):315–343.

World Bank. 2008a. *World Development Report 2008*. Washington DC.

World Bank. 2008b. *Double Jeopardy: Responding to High Food and Fuel Prices*. Working paper for G8 Hokkaido-Toyako summit, 2 July. Washington DC.

WHO. 2003. *Obesity and Overweight*. Briefing paper. Geneva.

You, L. & Wood, S. 2006. An Entropy Approach to Spatial Disaggregation of Agricultural Production. *Agricultural Systems* 90(1/3):329–347.

Acronyms used in the document

AEZ-BLS	Agro-ecological zone - Basic Linked System
CSIRO	Commonwealth Scientific and Industrial Research Organization
DFID	Department for International Development
DRR	disaster risk reduction
DSSAT	Decision Support System for Agrotechnology Transfer
FAO	Food and Agriculture Organization of the United Nations
GCM	General Circulation Model
GDP	gross domestic product
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IMF	International Monetary Fund
MDG	Millennium Development Goal

NCAR	National Center for Atmospheric Research
OCHA	Office for the Coordination of Humanitarian Affairs
ODA	Official Development Assistance
OECD	Organisation for Economic Co-operation and Development
QUEST-GSI	Quantifying the Earth System-Global Scale Impacts of Climate Change
R&D	research and development
SRES	Special Report on Emissions Scenarios
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WFP	World Food Programme
WHO	World Health Organization

World Food Programme

Via Cesare Giulio Viola, 68/70
00148 Rome, Italy

Printed: November 2009 - Front Cover: WFP/Shannon Hayes/Mali

WFP
World Food Programme
wfp.org