Climate Change and Agricultural Vulnerability

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A special report, prepared by the
International Institute for Applied Systems Analysis
under United Nations Institutional Contract Agreement No. 1113
on “Climate Change and Agricultural Vulnerability”
as a contribution to the
World Summit on Sustainable Development, Johannesburg 2002

This report presents the results of research done by the Land-Use Change Project at IIASA and summarizes them for a wide readership. The findings, interpretations, and conclusions expressed in this report are entirely those of the authors and should not be attributed to the International Institute for Applied Systems Analysis.

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IIASA Director's Message

During the past three decades, IIASA has accumulated vast experience in applying integrated scientific analysis to design policy response to regional and global environmental, social, and economic problems in a holistic, multidimensional, and interdisciplinary manner.

IIASA maintains continually evolving models and data sets on subjects ranging from population to energy and natural resources that have been compiled over the course of several long-running research efforts. The Institute perceives its role as a center for international collaboration, for meeting the technological, intellectual, and policy challenges of globalizing societies. IIASA's enduring objective is to provide science-based insight into critical policy issues in international and national debates on global change.

This comprehensive global assessment on "Climate Change and Agricultural Vulnerability" focuses on the plight of the poor and vulnerable people who rely on agriculture for their livelihood. It addresses the ecological and environmental pressures on human populations in a comprehensive spatial manner, and analyses food policy options and opportunities.

IIASA has both a responsibility and the scientific know-how and experience to contribute to the 21st century challenges of achieving sustainable development.

Leen Hordijk
Director of IIASA

Foreword

On the eve of the 2002 World Summit on Sustainable Development in Johannesburg, we are convinced that we can move toward an implementation program for Agenda 21: a global plan of action for sustainable development adopted at the 1992 Earth Summit in Rio. Today, we have a strong global political alliance for change. At the Millennium Summit in 2000, the heads of government from around the world took the unprecedented step of committing to concrete time-bound goals related to poverty, hunger, water, education, and health.

Scientific and technological progress combined with systemic socioeconomic understanding has given us the tools to achieve sustainable development in the 21st century. In the next half-century, 3 billion people will join the current world population of 6 billion. There is no way of tackling food-security and poverty concerns without first addressing the issues of sustainable agriculture and rural development.

Natural resources are threatened, as people strive to get the most out of land already in production or push into virgin territory. The damage is increasingly evident: arable land lost to erosion, salinity and desertification; water shortages; disappearing forests; and threats to biodiversity. We now also face the new challenge of climate change that will impact dramatically on the world's ecosystems.

This special report, commissioned by the United Nations and prepared by the International Institute for Applied Systems Analysis for the 2002 WSSD, makes an important contribution to sustainable agricultural development by spatially quantifying the agro-ecological impacts of climate change, assessed within the economic context of the world food system.

This study, with global coverage of all countries, developed and developing, integrates spatial agro-ecological potentials into a world economic and trade policy framework and evaluates the impact of climate-change projections by the major General Circulation Models, as well as all the scenarios of the Third Assessment of the Intergovernmental Panel on Climate Change.

The policy implications and resource information provide an ecological–economic systems framework for sustainable agricultural development in the medium and long term. Detailed results are available for all countries.

Nitin Desai
Secretary General
World Summit on Sustainable Development,
Johannesburg, 2002

Abstract

The challenge of agriculture in the 21st century requires a systemic integration of the environmental, social, and economic pillars of development to meet the needs of present generations without sacrificing the livelihoods of future generations. Over the next 50 years, the world population is projected to increase by some 3 billion, primarily in the developing countries. Yet, even today, some 800 million people go hungry daily, and more than a billion live on less than a dollar a day. This food insecurity and poverty affecting one-quarter of the world's population is a sad indictment of the failure to respond adequately in a time of unprecedented scientific progress and economic development. There is no way we can meet food security and poverty concerns without first addressing the issues of sustainable agricultural and rural development.

The methodology and results reported in this study form a first comprehensive and integrated global ecological–economic assessment of the impact of climate change on agro-ecosystems in the context of the world food and agricultural system. The Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) have developed a comprehensive methodology based on environmental principles, referred to as the agro-ecological zones methodology. The GIS-based framework combines crop modeling and environmental matching procedures to identify crop-specific environmental limitations under various levels of inputs and management conditions. This has facilitated comprehensive and geographically detailed assessments of climate-change impacts and agricultural vulnerability.

The sensitivity of agro-ecosystems to climate change, as determined by the FAO/IIASA Agro-ecological Zones (AEZ) model, was assessed within the socio-economic scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions (SRES). For this purpose, IIASA's global linked model of the world food system was used. This modeling framework, referred to as the Basic Linked System (BLS), comprises a representation of all major economic sectors, and views national agricultural systems as embedded in national economies, which in turn interact with each other at the international level.

The BLS is a global general equilibrium model system for analyzing agricultural policies and food system prospects in an international setting. BLS views national agricultural systems as embedded in national economies, which interact with each other through financial flows and trade at the international level. The national models linked in the BLS cover about 80% of the most important attributes

related to the world food system, such as population, land, agricultural production, demand, and trade. The remaining countries of the world are grouped into 14 regional models to provide closure for the world system, both geographically and economically. The national models simulate the behavior of producers, consumers, and the government. They distinguish two broad sectors: agriculture and nonagriculture. Agriculture produces nine aggregate commodities.

The combination of AEZ and BLS provides an integrated ecological–economic framework for the assessment of the impact of climate change. We consider climate scenarios based on experiments with four General Circulation Models (GCM), and we assess the four basic socioeconomic development pathways and emission scenarios as formulated by the IPCC in its Third Assessment Report.

The main results of the study include climate-change impacts on the prevalence of environmental constraints to crop agriculture; climate variability and the variability of rain-fed cereal production; changes in potential agricultural land; changes in crop-production patterns; and the impact of climate change on cereal-production potential. Results of the AEZ-BLS integrated ecological–economic analysis of climate change on the world food system include quantification of scale and location of hunger, international agricultural trade, prices, production, land use, etc. The analysis assesses trends in food production, trade, and consumption, and the impact on poverty and hunger of alternative development pathways and varying levels of climate change.

The methodology and database developed in this study provide a foundation for detailed country studies, incorporating country-level information. The climate change issue is global, long-term, and involves complex interactions between climatic, environmental, economic, political, institutional, social, and technological processes. It has significant international and intergenerational implications in the context of equity and sustainable development. Climate change will impact on social, economic, and environmental systems and shape prospects for sustainable agricultural and rural development. Adaptation to climate change is essential to complement climate-change mitigation, and both have to be central to an integrated strategy to reduce risks and impacts of climate change.

Most of the discussion on climate change has focused on mitigation measures, for example the Kyoto Protocol. Not much attention has been given to climate-change adaptation, which will be critical for many developing countries. The developing world has not yet realized that this issue needs to be on the global agenda and for developed countries this is not a priority, as they have the means and resources to adapt to future climate change.

National governments and the international community must give agriculture and the rural sector the highest priority in terms of resource allocation and adoption of development policies that are locally relevant and globally consistent. Only then can progress be made to eradicate hunger and poverty in the world.

Acknowledgments

This study could not have been carried out without the support of Nitin Desai, Secretary General of the World Summit on Sustainable Development, whose office commissioned this study to the Land Use Change (LUC) Project at IIASA. In particular we appreciate the advice and organizational assistance of Ralph Chipman, Joanne Di Sano, and Nikhil Seth of the United Nations Department of Economic and Social Affairs.

The encouragement and guidance of Walther Lichem of the Austrian Federal Ministry for Foreign Affairs has been invaluable, and his efforts in bringing this study to the attention of a number of countries in Latin America has been pertinent and timely.

This study builds on over twenty years of collaboration between IIASA's LUC project and the Food and Agriculture Organization of the United Nations (FAO), in particular its Agro-ecological Zone Project. We are grateful for guidance and critical data sources that were readily provided by many colleagues at FAO.

We also wish to acknowledge the keen support of Leen Hordijk, Director of IIASA. Many colleagues at IIASA provided valuable insights at various stages of this work and we express our gratitude to them. In addition, we thank our colleagues in IIASA's Publications Department, Ewa Delpos, Lilo Roggenland, and Marie Tweed for their dedicated help in preparing the manuscript.

We appreciate the many insightful and constructive comments and criticisms from members of the Intergovernmental Panel on Climate Change (IPCC). The Task Group for Climate Impact Analysis provided extensive information on the IPCC future development path scenarios. The CRU 0.5 × 0.5 degree latitude/longitude gridded monthly climate data was supplied by the Climate Impact LINK Project (UK Department of the Environment, Contract EPG 1/1/16) on behalf of the Climate Research Unit (CRU), University of East Anglia. In particular we would like to thank David Viner of the CRU for making available the full range of climate projections from the Hadley Centre for Climate Prediction and Research, UK.

The views expressed in this report are solely those of the authors and should not be ascribed to the persons mentioned above or to IIASA or the United Nations. Needless to say, the authors remain solely responsible for any errors and omissions.

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Introduction

At the first World Food Summit (WFS) in 1974, political leaders from around the globe set the goal of eradicating hunger within a decade. Some 22 years later, at the second World Food Summit in 1996, this goal shifted toward a reduction of hunger to 50% of the 1990 levels by 2015. The rate of progress of recent years in reducing the number of hungry people in the world indicates that it may take another 60 years before the WFS target can be reached. Nevertheless, the United Nations Millennium Summit in September 2000 and the third World Food Summit in Rome in June 2002 again endorsed this same goal to halve world hunger levels by 2015. What concrete actions will it take to turn these well-meaning political goals into reality?

Some 780 million people (18% of the population of developing countries and in the case of sub-Saharan Africa some 40%) are chronically undernourished and poor. More than 150 million children under the age of 5 years do not receive the nutrition they need to fully develop mentally and physically. Every minute of every day, 15 adults and 15 children die of starvation in the developing world. This tragic outcome, in a world where more than enough food is produced to provide everyone with an adequate diet, is morally and ethically outrageous.

We live in a world of disparities where a quarter of the world's population lives in degrading poverty. Poverty has received unprecedented international attention in the last two decades, but there has been too little progress in reducing the number affected. In the last ten years, the rate of poverty reduction has been less than a third of what is needed to halve extreme poverty by 2015, as per the 2000 Millennium Summit goal.

The problems of hunger and poverty are interlinked and one cannot be solved without tackling the other. Over 75% of the poor live in rural areas, and are dependent primarily on agriculture. The poor are poor because they lack tangible assets and do not have access to such basic needs as education, clean water, health care, and secure shelter. And the poor are often politically and socially discriminated against.

Agriculture has historically been the foundation of social and economic progress in the developed countries. Today the most powerful political lobbies in support of agriculture are found in Washington, Brussels, and Tokyo, even though less than 3% of the population of the respective countries derives a livelihood directly from agriculture. By contrast, in many developing countries, where as much as two-thirds of the population directly or indirectly earns a living from agriculture, rural and agricultural societies are among the weakest political lobbies. And farming tends to be one of the least respected occupations.

The central challenge of sustainable agriculture is to meet the food demand of the present generation without sacrificing the needs of future generations. This cannot be achieved without the systemic integration of the social, economic, and environmental pillars of agriculture and rural development. Sustainable agricultural development is essential for economic growth, which creates employment opportunities in nonagricultural rural sectors, which in turn reduces poverty.

The agricultural sector is critical to social and economic progress, particularly with regard to the eradication of hunger and poverty, the creation of employment and livelihood-earning opportunities, and the generation of trade and foreign-exchange earnings. Agriculture is also at the core of environmental concerns over the management of natural resources – land degradation, water scarcity, deforestation, and the threat to biodiversity. And yet agriculture has been marginalized, at both national and international levels.

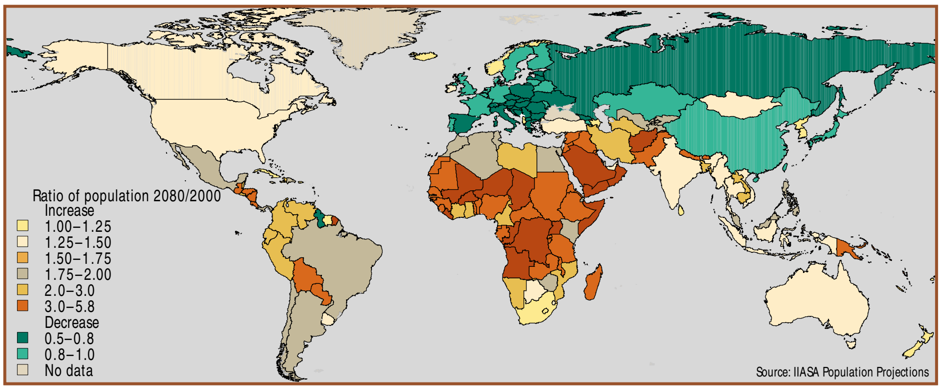
Agriculture essentially concerns the relationship between the natural environment and human society. With rapid population growth, securing the inherent vulnerability of this relationship, whether social, economic, or environmental, has to be central to efforts to achieving sustainable development. The focus on people – their scope, rights, capabilities, limitations, and opportunities – has multiple benefits for individuals and society; yet it is the rural population that has to be central in agricultural development efforts.

1.1 Social Vulnerability

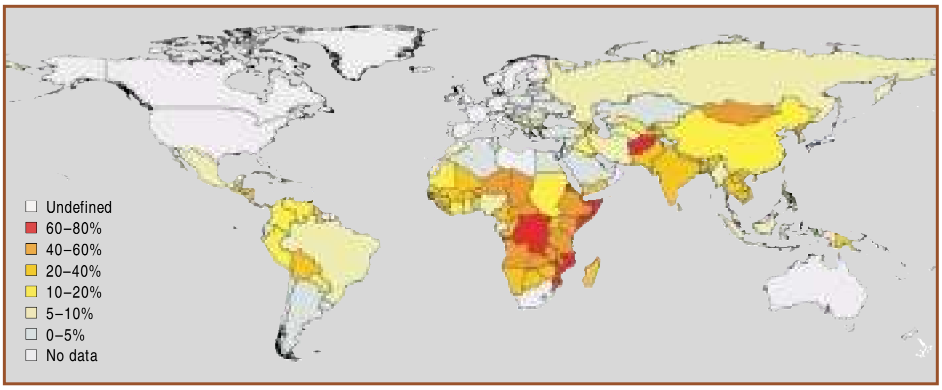
Many factors contribute to *social vulnerability* (*Figure 1.1*), including rapid population growth, poverty and hunger, poor health, low levels of education, gender inequality, fragile and hazardous location, and lack of access to resources and services, including knowledge and technological means. And when people are socially disadvantaged or lack political voice, this vulnerability is exacerbated further.

Over the next 50 years, the world population is projected to increase by some 3 billion, primarily in the developing countries. This increase in population, mainly in sub-Saharan Africa, South Asia, and the Middle East, is expected to be larger than during the period of rapid growth over the last quarter-century. This high rate of growth and agriculture's crucial role in overall rural development mean that in the initial stages this sector will have to absorb many of the new entrants into the rural labor force. Currently half of the world's workforce is employed in agriculture, and the sector dominates the economies of 25% of the world's countries.

Expected population growth and decline between 2000 and 2080



Undernourished population by country



Agricultural population by country

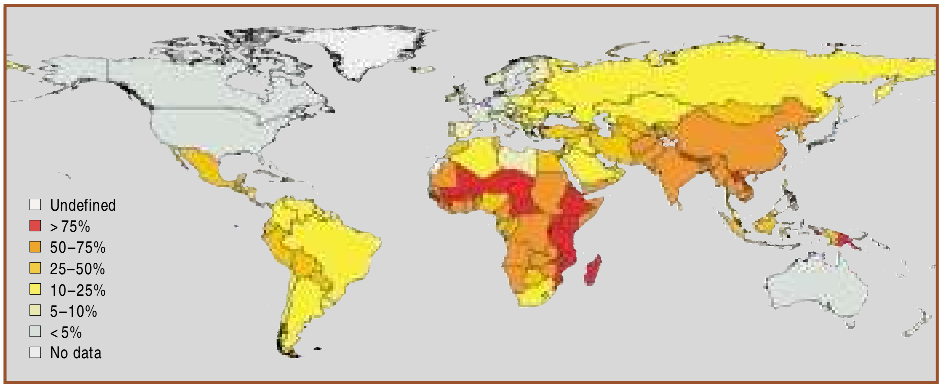


Figure 1.1. Social vulnerability.

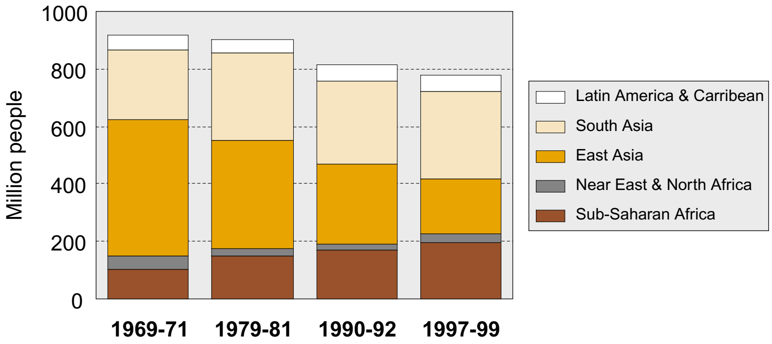


Figure 1.2. Undernourished people by region.

Hunger and poverty are closely related and are the main causes of human vulnerability. While the lack of sufficient income to purchase food is a major factor causing food insecurity, hunger itself contributes to poverty by lowering labor productivity, reducing tolerance to disease, and depressing educational achievements. Most of the 780 million undernourished people (*Figure 1.2*) live in some 84 low-income and poor developing countries, with a current total population of some 4 billion, which is projected to increase to about 7 billion by 2050. The current food gap for this undernourished population is estimated to be in the order of 25 million tons of cereals annually, some 2.5% of total production in these affected countries.

Of serious concern is the group of 46 least developed countries, where domestic per capita food production has declined by 10% in the last 20 years, in sharp contrast to an average increase of some 40% in the developing world. In these least developed countries, which account for 10% of the world's population and less than 1% of the world's income, the number of undernourished has doubled to some 250 million in the past two decades.

Sub-Saharan Africa has the highest percentage of undernourished – some 40% of the total population – and there has been little progress in reducing the hunger in the last three decades. By contrast, the percentage of hungry in Asia has been halved from a level similar to sub-Saharan Africa in the late 1960s.

Some 30 years ago, the world faced a global food shortage that experts predicted would lead to catastrophic famine. That danger was averted as an intensive international research effort enabled the development and farmer adoption of high-yielding varieties of major food crops. This "Green Revolution," driven by investment and knowledge, was most effective where environmental conditions were good, soils were fertile, and water was plentiful. It also involved extensive use of fertilizers and pesticides. Critics of the Green Revolution stress that it benefited resource-rich farmers rather than the millions of small farmers, especially in rainfed areas. That an integrated biological, environmentally sound, and socially viable strategy has to be at the core of the next “precision” green revolution has been one lesson learned.

Vulnerable populations have only limited capacity to protect themselves from environmental hazards, in particular from extreme events such as drought and floods. They also bear the brunt of the consequences of large-scale environmental change, such as land degradation, biodiversity loss, and climate change. In 1998, weather-related economic losses in developing countries amounted to about \$42 billion. Heavy and variable precipitation, heat waves, cyclones, drought, and floods may become more frequent and intense, resulting in more economic shocks. In the short term, policymakers will need to cope with an increased risk of frequent shocks to their economies, which will affect the welfare of their most vulnerable populations. Over the long term, they will need to cope with the effects of climate change on the underlying production structures of the economies, with those countries dependent on agriculture most heavily hit.

The scientific and technological progress made in just the last two decades – the information revolution of the 1980s, and the genetic revolution of the 1990s – offers an unprecedented opportunity to reshape the productivity and sustainability of food and agricultural systems.

The information revolution can facilitate an interactive global agricultural knowledge system. For example, in the past, indigenous knowledge about local varieties, farming techniques, and natural-resource management traditions and practice that have evolved through generations has rarely made its way to researchers, who could incorporate it in their work. The dissemination of agricultural research and farming management experiences from around the world often took considerable time and effort. Today, all of this, and more, can be performed literally instantaneously with the help of the Internet. However, access to these unprecedented tools for acquiring knowledge is growing more disparate. While in the United States and Europe about 50% of the population has access to the Internet, the comparable figure for Africa and South Asia is just 0.5%.

There is also a growing gap between developing and developed countries in scientific and technological capacity. For example, the United States has 70 scientists per 10,000 population, while China has six and sub-Saharan Africa just one. At the same time, science and technology are becoming increasingly proprietary, and owning knowledge has become the order of the day. Does this mean that those who cannot afford it will be denied the fruits of scientific and technological progress? The number of patent applications has grown from 1 million in 1985 to over 7 million today.

An increasing number of agricultural research outcomes are being patented and at the same time traditional crop varieties are disappearing. China, which once had 10,000 landrace varieties of wheat, now has only about 300, and only 14 are grown in 40% of the wheat fields under intensive cultivation. No one knows what genetic traits that lead to insect and disease resistance, stronger plants, higher yields, or even better tasting crops, might have been lost through disappearing varieties.

Genomics, particularly biotechnology, offers a new precision tool to develop new crop varieties with attributes to counter soil toxicity and droughts, resist pests and diseases, and increase nutrient content in crops. These tools are important in targeting biotechnology at those problems and crops that are of relevance to the poor. At the same time the issue of bio-safety has to be at the core of such considerations. The application of biotechnology to food crops of the poor appears to be of little interest to the private sector, while government commitment to agricultural research continues to decline.

The developments in science and technology have the potential to contribute substantively to eradicating hunger and poverty in the rural areas, in which the majority of the world's population resides. But the widening knowledge divides within and across nations threatens the goals of equitable and sustainable development. Only knowledge that is available, accessible, and affordable can drive progress and overcome the increasing social vulnerability in a degrading environment.

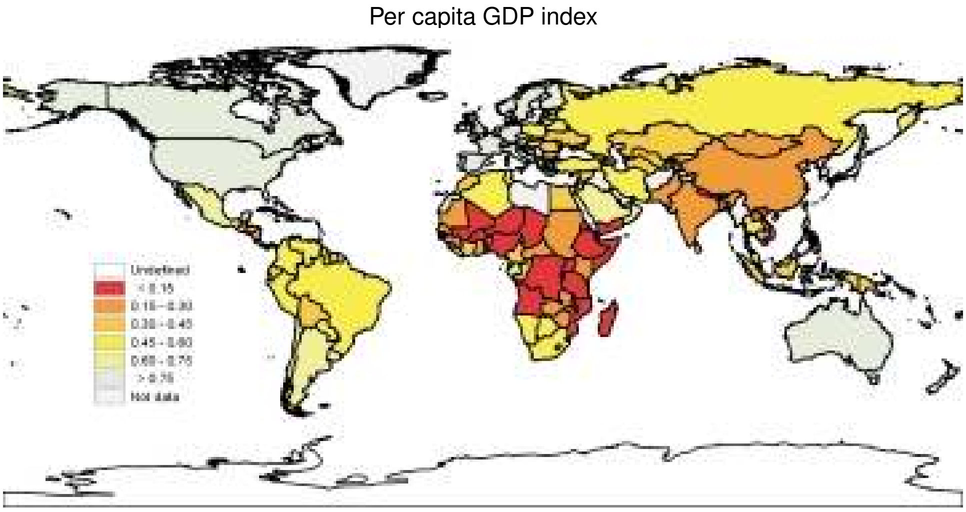
1.2 Economic Vulnerability

The *economic vulnerability* (*Figure 1.3*) of agriculture is related to a number of interacting elements, including its importance in the overall national economy, trade and foreign-exchange earnings, aid and investments, international prices of agricultural commodities and inputs, and production and consumption patterns. All of these factors intensify economic vulnerability, particularly in countries that are poor and have agriculture-based economies.

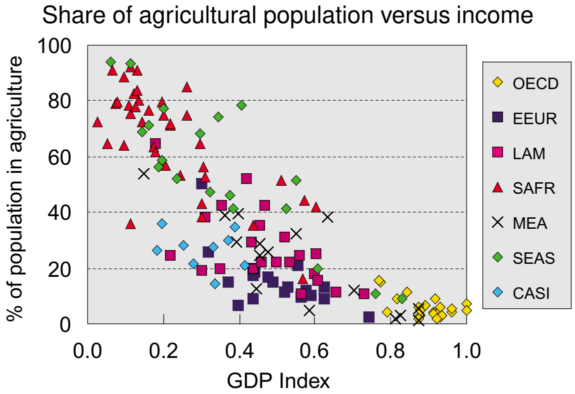
At the world level, the share of agriculture in total gross domestic product (GDP) in developing countries is about 13%, in contrast to 2% in developed countries. For central, eastern, and western Africa, this share is over 31%, and in South Asia it is around 25%. In some 25 developing countries, this share varies from about 40–60%.

During the 1990s, the average growth rate of GDP for all developing countries increased to 4.3%, compared to 2.7% in the 1980s. The growth rate in developed countries was 2.3%, down from 3% in the 1980s. In the case of Africa, there was a marginal improvement in economic growth, but this was eroded by high population growth. The gap in the standard of living between Africa and the other regions widened. It is estimated that the consumption expenditure of the average African household is one-fifth lower than it was a quarter of a century ago.

The richest 20% of the world's population consumes 85% of the world's income, while the poorest 20% lives on about 1% of global income. These disparities



Source: *Human Development Report* (2001)



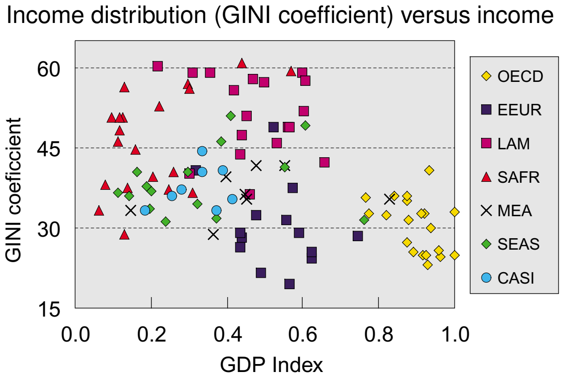


Figure 1.3. Economic vulnerability.

are widening. A generation ago, the richest 20% in the world was 30 times richer than the poorest 20%. Now, they are 70 times as rich.

Official Development Assistance (ODA) flows have fallen during the 1990s, from $58 billion in 1992 to $53 billion in 2000. ODA, as a proportion of GDP, fell from 0.35% in 1992 to 0.22% in 2000. Only five countries – Denmark, Luxembourg, The Netherlands, Norway, and Sweden – met the aid target of 0.7% of GDP in 2000. Most of the least developed countries suffered a decline in ODA of at least 25%, and seven countries in Africa saw ODA reduced by over 50%.

The proportion of ODA going to agriculture, which provides the livelihoods for most people in poverty, declined from 20% in the late 1980s to about 12% in 2000, and in absolute value fell by two-thirds. The share of ODA going to low-income countries, where over 85% of poor people live, has remained roughly constant, at around 63%, but has been declining in real terms.

Most of the ODA originates from the OECD countries, where agricultural subsidies amounting to some $350 billion annually are maintained by import barriers and export subsidies, while the agricultural policies of poorer countries tend to discourage farm production.

In the 1990s, international trade boomed, with world exports growing at a rate of 6.4%. For developing countries an export growth rate of 9.6% was recorded, but again Africa lagged behind, its share of world exports declining from 2.7% in 1990 to 2.1% in 2000. While developed countries have the financial means to provide large subsidies to protect incomes and living standards of under 5% of their population, farmers in developing countries have seen their real incomes go down. The benefits of free trade promised to developing countries in the World Trade Organization (WTO) are a long way from materializing. The real prices on world markets of most agricultural commodities fell in the 1990s.

Total food imports in developing countries amounted to some $60 billion in 2000. Low-income food-insecure countries accounted for about half of this. Agricultural products comprise more than one-fifth of total exports in some 53 developing countries, and some 37 developing countries expend more than a quarter of their total export earnings on food imports. More than half of these countries are in sub-Saharan Africa, a region with the most pervasive hunger and poverty.

World crop production grew by 2.2% per year in the 1990s, of which yield increases contributed three-quarters. The balance came from area expansion and more intense cropping. Increased mineral fertilizer use, mainly in the developing countries, accounted for more than one-third of the growth in cereal production. Fertilizer consumption in developed countries doubled from some 42 kg of nutrients per hectare (ha) during the last four decades. By contrast, in central, eastern, and western Africa, the current level of fertilizer application is less than 10 kg per hectare. The need to intensify production to meet the demands of a growing population, however, must not overlook the threat of chemical pollution, especially of water resources.

The economic challenge for developing countries is to identify specific agricultural and rural development needs and opportunities, and to focus investment in areas where the greatest impact on food security and poverty will be achieved.

The world's land and water resources are critical for human survival. They provide food and other agricultural products, as well as other essential services such as purification of air and water, maintenance of biological diversity, and decomposition and recycling of nutrients.

The growing demand for food for an increasing population is threatening natural resources as people strive to get the most out of land already in production. The damage is increasingly evident: arable lands lost to erosion, salinity, and desertification and urban spread; water shortages; disappearing forests; and threats to biodiversity.

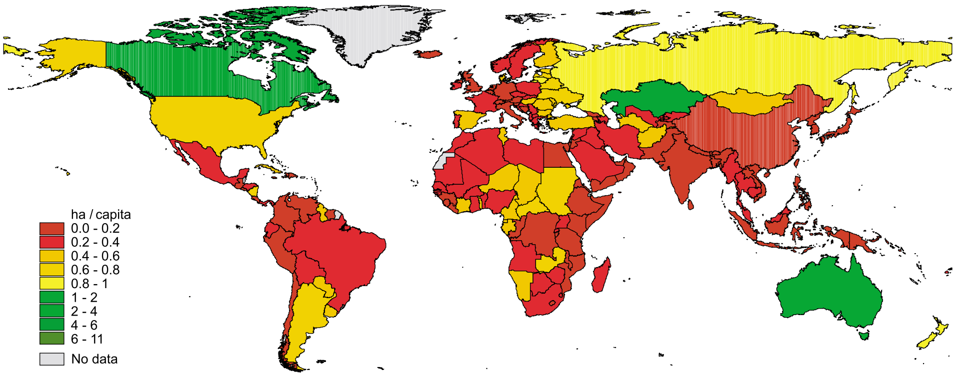
1.3 Environmental Vulnerability

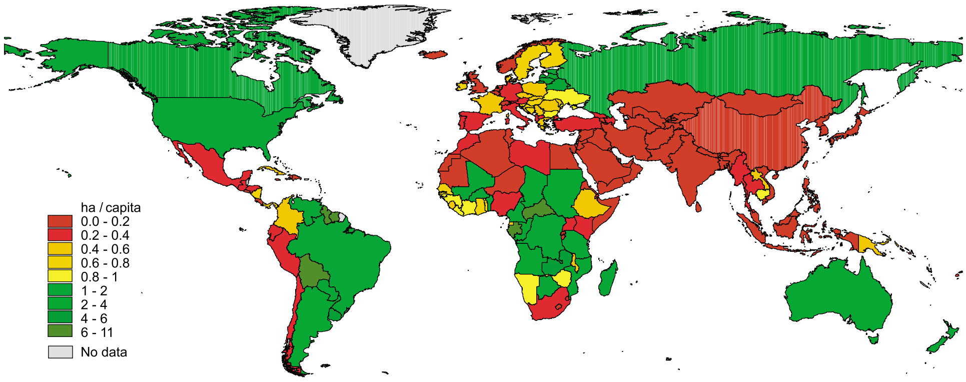
In the 21st century, we now face another, perhaps more devastating, environmental threat, namely global warming and climate change, which could cause irreversible damage to land and water ecosystems and loss of production potential. We cannot be complacent, not when the foundation of human survival, that is, the need for food, may be at risk due to the global-change-induced *environmental vulnerability* of natural ecosystems (*Figure 1.4*).

Combating climate change is vital to the pursuit of sustainable development; equally, the pursuit of sustainable development is integral to lasting climate-change mitigation. And the most pressing challenge is to strengthen the social, economic, and environmental resilience of the poorest and the most vulnerable against climate change and variability.

Environmental change, particularly climate change, will have a disproportionate impact on poor people in rural areas where livelihoods of the majority depend directly on natural resources. Depletion of soil fertility and degradation of forest resources, water resources, pastures, and fisheries is already aggravating poverty in many developing countries. Global warming will affect the agro-ecological suitability of crops. The increasing atmospheric concentration of carbon dioxide will enhance plant photosynthesis and may contribute to improved water-use efficiency. It may also lead to increased pest and disease infestations.

Responses to climate change can be of two broad types. The first employs adaptive measures to reduce the impacts and risks, and maximize the benefits and opportunities, of climate change, whatever its cause. The second involves mitigation measures to reduce human contributions to climate change. Both adaptive


Cultivated land per capita


Potential rain-fed cultivable land per capita

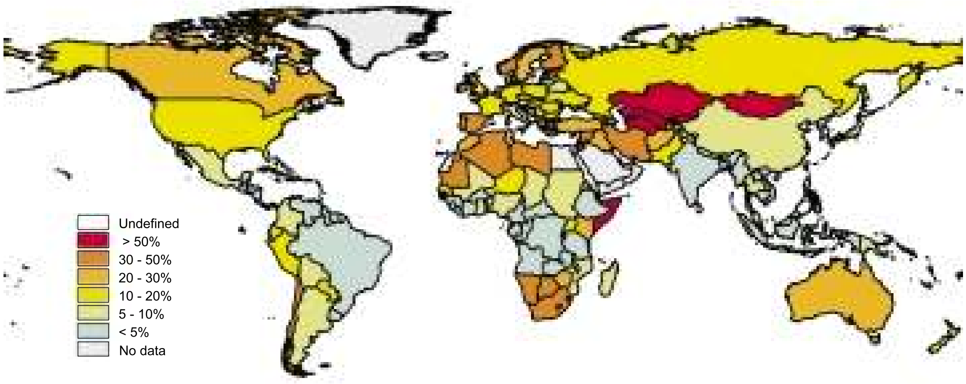

Variability (CV%) of cereal production potential, 1961–1990

Figure 1.4. Environmental vulnerability.

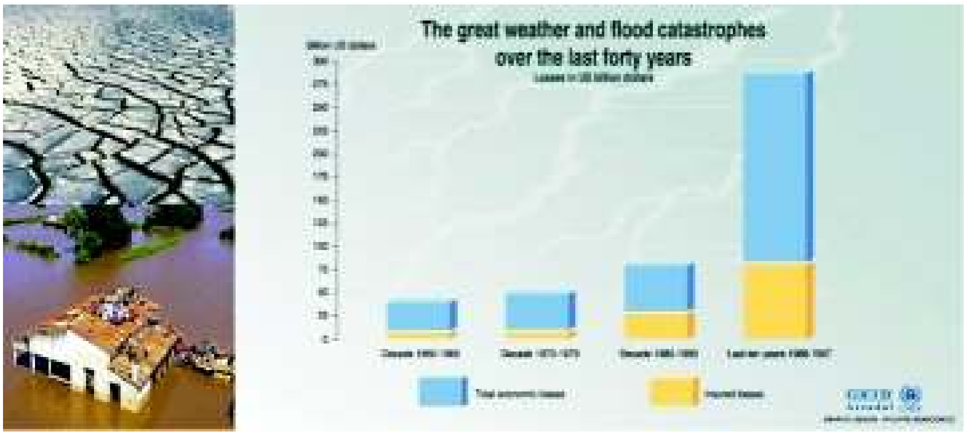


Figure 1.5. The great weather and flood catastrophes over the last forty years.

measures and mitigation measures are necessary elements of a coherent and integrated response to climate change. If future emissions are higher, the impact will be stronger, and vice versa. At the same time, no matter how aggressively emissions are reduced, climate change is a reality for the 21st century, since existing emissions in the atmosphere will remain for decades to come. Thus adaptation to climate change is inevitable.

Reports of increased climate variability and extreme events from around the world are becoming more and more frequent. In the absence of mitigation and response capacities, losses from damage to the infrastructure and the economy, as well as social turmoil and loss of life, will escalate and be substantial (*Figure 1.5*). And this burden will fall on the poorest and in the poorest countries. It is only in poor countries that drought turns to famine, often resulting in population displacement, suffering, and loss of life. The social and economic costs of such occurrences may undo, in just a day or a month, the achievements of years of development efforts.

Global environmental change is expected to have a significant impact on food systems worldwide. The nature and gravity of vulnerabilities of food systems are of utmost importance and the design of adaptive policies to cope with environmental changes is critical.

Global environmental changes pose the following challenges to agricultural research: changes in the flow and storage of materials, ecology of pests and diseases, dynamics of rainfall regimes and water accumulation, plant responses to temperature and CO_2 concentration, reduction of greenhouse-effect gases, plant-salt tolerance affected by intrusion of saltwater due to sea-level rise, conservation of biodiversity, and adaptation of food production systems to extreme weather events.

For agricultural research to respond in a timely manner to these tremendous challenges, a concerted worldwide policy action is necessary. Networking of scientists and researchers, priority-setting, allocation of necessary funding, interregional and inter-country technology transfer, and institutional development and strengthening are among the decisions that world leaders need to make so that humankind as a whole can benefit from the scientific achievements toward adapting world food systems to global environmental change.

Given the expected resilience of the driving forces of global environmental change, even a decisive and drastic global action on mitigation will not subdue the need for an emergent and proactive action toward adapting world food systems to cope with the impacts of global environmental change.

Policymakers and land users face the task of reversing land degradation trends and inefficient water use by improving conditions and re-establishing soil fertility, reducing deforestation, and preventing the degradation of land resources in new development areas through the appropriate allocation and adequate use of resources for sustainable productivity.

Sustainable agricultural land use must be based on sound agronomic principles, but it must also embrace an understanding of the constraints and interactions of other dimensions of agricultural production, including the flexibility to diversify and develop a broad genetic base to ensure the possibility of rapid response to changing conditions. Land management practices, in principal control processes of land degradation and their efficiency in this respect, will largely govern the sustainability of a given land use. Furthermore, sustainability will depend on institutional, political, social, and economic pressures and structures that can exacerbate environmental problems. These considerations must be integral to ensuring sustainable agriculture.

Some 1.5 billion ha of land are used for crop production, with some 960 million ha under cultivation in the developing countries. Over the last 30 years, the world's crop area expanded by some 5 million ha annually, with Latin American countries alone accounting for 35% of this expansion. About 40% of the world's arable land is degraded to some degree. Many of the most degraded soils are found in the world's poorest countries, in densely populated, rain-fed farming areas, where overgrazing, deforestation, and inappropriate use compound problems. When soils become infertile, traditional farmers either let the land lie fallow until it recovers or simply abandon unproductive lands and move on, clearing forests and other fragile land areas as available. And the process is repeated.

Forests play an important environmental role in the production of timber, wood, fuel, and other products, in the conservation of biodiversity and wildlife habitats, as well as in the mitigation of global climate change and the protection of watersheds and against flood risks (*Figure 1.6*). About a fifth of the world's land surface – some 3 billion ha – is under forest ecosystems. Eight countries – Russia, Brazil, Canada,

Figure 1.6. Loss of forest eco-systems and biodiversity.

the United States, China, Australia, Congo, and Indonesia – account for 60% of the world's forestland. During the past decade, some 127 million ha of forests were cleared, while some 36 million ha were replanted. Africa lost some 53 million ha of forest during this period – primarily from expansion of crop cultivation.

Two-thirds of the world's population lives in areas that receive a quarter of the world's annual rainfall, while such sparsely populated areas as the Amazon Basin receive a disproportionate share. About 70% of the world's fresh water goes to agriculture, a figure that approaches 90% in countries that rely on extensive irrigation. Already some 30 developing countries are facing water shortages, and by 2050 this number may increase to over 50 countries, a majority in the developing world. This water scarcity together with degradation of arable land could become the most serious obstacle to increasing food production.

The use that can be made of land for human primary needs is limited by environmental factors such as climate, topography, and soil characteristics, and is to a large extent determined by agronomic viability and the availability of science and technology, as well as demographic, socioeconomic, cultural, and political factors such as land tenure, markets, institutions, and agricultural policies.

Systematic and detailed geographical systems combined with knowledge about natural resources – climate, land, and water resources, land use and land cover, crops and land utilization types – are essential to provide a sound basis for agricultural land-use planning at sub-national and national levels.

1.4 Report Overview

This report comprises four chapters, following this introductory chapter.

Chapter 2 presents details of the ecological–economic analysis based on the FAO/IIASA agro-ecological zones (AEZ) approach for evaluation of biophysical limitations and agricultural production potentials, and IIASA's Basic Linked System (BLS) for analyzing the world's food economy and trade system.

The BLS is a global general equilibrium model system for analyzing agricultural policies and food system prospects in an international setting. BLS views national agricultural systems as embedded in national economies, which interact with each other through trade at the international level.

The combination of AEZ and BLS provides an integrated ecological–economic framework for the assessment of the impact of climate change. We consider climate scenarios based on experiments with four General Circulation Models (GCM), and we assess the four basic socioeconomic development pathways and emission scenarios as formulated by the Intergovernmental Panel on Climate Change (IPCC) in its Third Assessment Report.

Chapter 3 presents the main AEZ results of the impact of climate change on agriculture. Results comprise environmental constraints to crop agriculture; climate variability and the variability of rain-fed cereal production; changes in potential agricultural land; changes in crop-production patterns; and the impact of climate change on cereal-production potential.

Chapter 4 discusses the AEZ-BLS integrated ecological–economic analysis of climate change on the world food system. This includes quantification of scale and location of hunger, international agricultural trade, prices, production, land use, etc. It assesses trends in food production, trade, and consumption, and the impact on poverty and hunger of alternative development pathways and varying levels of climate change.

Chapter 5 presents the main conclusions and policy implications of this study.

2

Methodology of Ecological–Economic Analysis of Climate Change and Agricultural Vulnerability

The sensitivity of agro-ecosystems to climate change, as determined by the FAO/IIASA Agro-ecological Zones (AEZ) model, was assessed within the socio-economic scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions (SRES). For this purpose, IIASA's modeling framework for analyzing the world food system was used. This modeling framework, referred to as the Basic Linked System (BLS), comprises a representation of all major economic sectors, and views national agricultural systems as embedded in national economies, which in turn interact with each other at the international level (see *Figure 2.1*).

The BLS was originally designed to study food policy, but can as well be used to evaluate the effect of climate-induced changes on the world food-trade system. The agro-ecological effects of climate change on food production systems were introduced to the model as changes in the national or regional production relationships per commodity.

2.1 Agro-ecological Zones

2.1.1 Introduction

Land-use and land-cover change are significant to a range of themes and issues central to global environmental change. Alterations in the earth's surface hold major implications for the global radiation balance and energy fluxes, contribute to changes in biogeochemical cycles, alter hydrological cycles, and influence ecological balances and complexity. Through these environmental impacts at local, regional, and global levels, land-use and land-cover changes driven by human activity have the potential to significantly affect food security, renewable fresh-water resources, and the ecological sustainability of the agricultural supply systems.

Increases in the concentration of atmospheric greenhouse gases are leading to future climate change. Of particular interest are the consequences for agriculture and the water sector. Past impact studies have produced a wide range of results, not only because of the uncertainties derived from predicting future climate, but

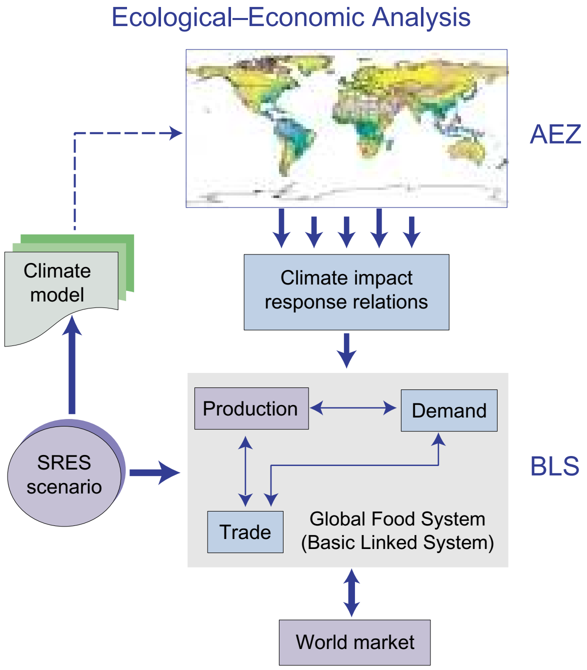


Figure 2.1. Integrated ecological–economic analysis of the impact of climate change on food and agricultural systems.

also due to the vast differences in assumptions and methodologies employed in the analyses. A consensus has emerged that developing countries are more vulnerable to climate change than developed countries, because of the predominance of agriculture in the economies of these countries, the scarcity of capital for adaptation measures, their warmer baseline climates, and their exposure to extreme events.

IIASA has widened the implementation of the FAO/IIASA Agro-ecological Zones (AEZ) methodology to analyze climate change and food systems.

2.1.2 Methodology

The AEZ methodology for land-productivity assessments follows an environmental approach; it provides a framework for establishing a spatial inventory and database of land resources and crop-production potentials. This land-resources inventory is used to assess, for specified management conditions and levels of inputs, the suitability of crops/Land Utilization Types (LUTs) in relation to both rain-fed and irrigated conditions, and to quantify expected production of cropping activities relevant in the specific agro-ecological context. The characterization of land resources includes components of climate, soils, landform, and present land cover.

Crop modeling and environmental matching procedures are used to identify crop-specific environmental limitations, under assumed levels of inputs and management conditions.

Inherent in the methodology is the generation of a climatic inventory to predict agro-climatic yield potentials of crops. The global AEZ study uses a recent global climatic data set compiled by the Climate Research Unit at the University of East Anglia, UK. The database offers a spatial resolution of 30 minutes latitude/longitude and contains climate averages for the period 1961–1990 as well as year-by-year data for the period 1901–1996. These data are used to characterize each half-degree grid-cell in terms of applicable thermal climates, temperature profiles, accumulated temperature sums, length of growing periods, moisture deficits, etc.

Adequate agricultural exploitation of the climatic potentials and maintenance of land productivity largely depend on soil fertility and the management of soils on an ecologically sustained basis. Hence, the climatic inventory was superimposed on the FAO's Digital Soil Map of the World (DSMW). The DSMW is derived from the FAO/UNESCO Soil Map of the World at scale 1:5 million and presents soil associations in grid-cells of 5-minutes latitude/longitude, forming the basis of soil information in Global AEZ. The composition of soil associations is described in terms of percentage occurrence of soil units, soil phases, and textures. Therefore, each 5-minute grid-cell is considered as consisting of several land units.

Terrain slopes were derived from the GTOPO30 database developed at the USGS Eros Data Center, providing digital elevation information in a regular grid of 30 arc-seconds latitude/longitude. At IIASA, rules based on altitude differences of neighboring grid-cells were applied to compile a terrain-slope distribution database (for each 5-minute grid-cell of the FAO's DSMW) in terms of seven average slope range classes).

The individual GIS layers with attribute data and distributions at 5-minutes latitude/longitude constitute the land-resources database. The key components of this database include: the FAO DSMW and linked soil association composition table, a slope distribution database, an ecosystem database derived from the USGS 30 arc-second seasonal land-cover data set providing distributions in terms of 12 aggregate land-cover classes for each 5-minute grid-cell, and a global layer of legally protected areas. The DSMW has been made the reference for constructing a land-surface mask, i.e., a binary layer that distinguishes grid-cells as land or sea, respectively. Also, each 5-minute grid-cell is uniquely assigned to an administrative unit (a country or region).

Methodological Steps of AEZ

The AEZ framework contains the following basic elements:

- Selection of agricultural production systems with defined input and management relationships, and crop-specific environmental requirements and adaptability characteristics. These are termed Land Utilization Types (LUT). AEZ distinguishes between some 154 crop, fodder, and pasture LUTs, each at three generically defined levels of inputs and management, termed high, intermediate, and low levels. In this study a high level of inputs is assumed across the board (see *Box*).
- Geo-referenced climate, soil, and terrain data, which are combined into a land-resources database. The computerized global AEZ database comprises some 2.2 million grid-cells.
- Accounting for spatial land use and land cover, including forests, protected areas, population distribution and density, and land required for habitation and infrastructure.
- Procedures for the calculation of potential agronomically attainable yields and for matching crop and LUT environmental requirements with the respective environmental characteristics contained in the land-resources database, by land unit and grid-cell.
- Assessment of crop suitability and land productivity of cropping systems.
- Applications for the estimation of the land's population-supporting capacity, multiple-criteria optimization considering socio-economics, demography etc., of land-resource use for sustainable agricultural development.

Farming technology assumption used in this study

High-level inputs/advanced management: Production is based on improved high-yielding varieties, efficient combination of labor and mechanization, uses optimum applications of nutrients and chemical pest, disease and weed control, and employs full conservation measures. The farming system is mainly market-oriented.

The FAO/UNESCO Digital Soil Map of the World (DSMW) has been made the reference for constructing a land-surface database comprising more than 2.2 million grid-cells at 5-minutes latitude/longitude within a raster of 2,160 rows and 4,320 columns.

On the input side, the key components of the database applied in AEZ include the FAO DSMW and linked soil association and attribute tables, a global elevation and derived slope distribution database, the global climate data set of the Climate Research Unit of the University of East Anglia consisting of average data (period

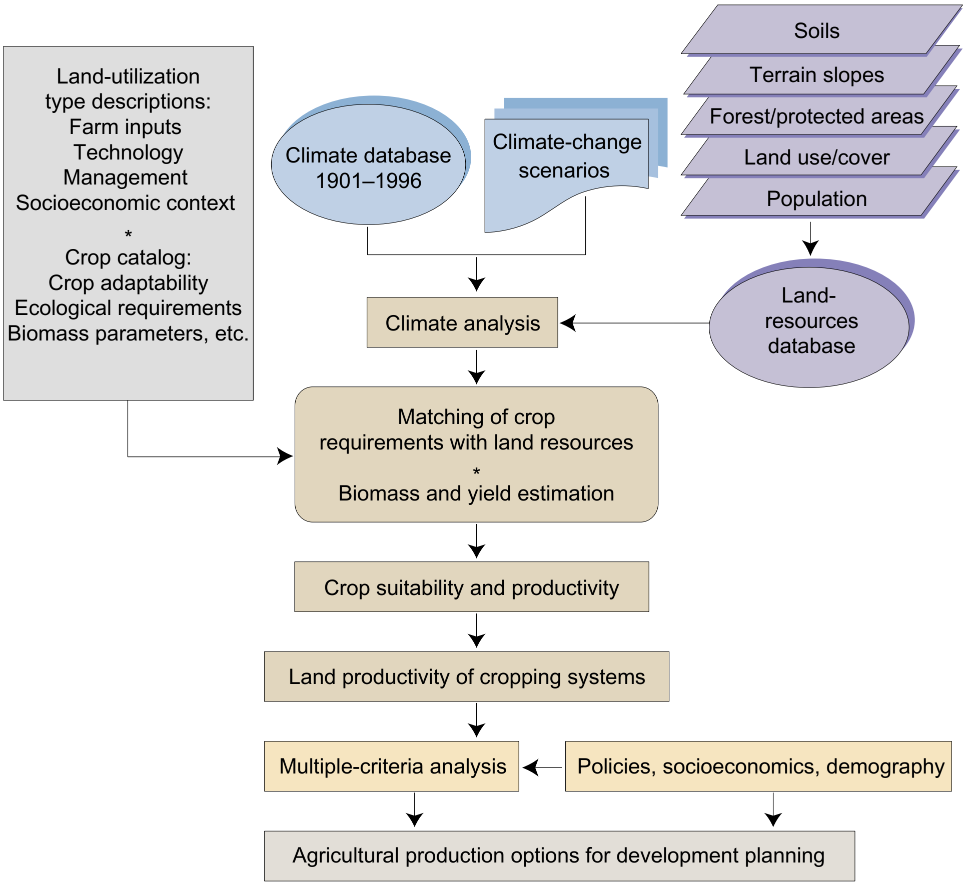


Figure 2.2. AEZ methodology.

1961–1990) and data for each year for the period 1901–1996, and a layer providing distributions in terms of 11 aggregate land-cover classes derived from a global 1 km land-cover data set. The AEZ global land-resource database also incorporates spatial delineation and accounting of forest and protected areas. A global population data set for the year 1995 provides estimates of population distribution and densities at a spatially explicit sub-national level for each country.

On the output side, a range of new data sets has been compiled at grid-cell level and has been tabulated at country and regional level, including agro-climatic characterizations of temperature and moisture profiles, and time-series of attainable crop yields for all major food and fiber crops.

The AEZ assessments were carried out for a range of climatic conditions, including a reference climate, individual historical years, and scenarios of future climate based on various global climate models. Hence, the results quantify the impact of climate change and increased CO_2 concentration on crops, both for historical climate variability as well as for potential future climate change (see *Figure 2.2*).

2.1.3 Effects of climate change and increased atmospheric CO_2 concentrations on crop productivity

Temperature, solar radiation, water, and atmospheric CO_2 concentration are the climate and atmospheric variables of importance to plant productivity. Plant species vary in their response to CO_2 in part because of differing photosynthetic mechanisms. There are important differences in temperature requirements and responses to concentration of atmospheric CO_2 among C_3, C_4, and Crassulacean acid metabolism (CAM) plants. Also, most of the crop plants currently cultivated have been selected and bred into different varieties to produce efficiently high yields under specific environmental and farming-system conditions. Nutrients and water may be augmented via fertilization and irrigation, while radiation and temperature are more difficult to control, particularly in large-scale agricultural operations.

Climate change will most likely result in new combinations of soil, climate, atmospheric constituents, solar radiation, and pests, diseases, and weeds. The responses of plants to climate change have been studied in a large number of experiments and in detailed modeling of basic processes. The results of this research and knowledge of basic physical and biological processes have provided a basic understanding of direct and indirect effects of climate change on agricultural productivity. Some of the interactions of temperature, moisture availability, and increased CO_2 on plant growth have been investigated through crop response models. These models have been widely used to assess yield response to climate change at many different sites around the world, and have produced valuable insights in these interactions (e.g., Rozema, 1993; Rosenzweig and Parry, 1994; IPCC, 1996).

There is generally agreement that an increase of atmospheric CO_2 levels leads to increased crop productivity. In experiments, C_3 plants, such as wheat and soybeans, exhibit an increase in productivity of about 20–30% at doubled CO_2 concentrations. Response, however, depends on crop species as well as soil fertility conditions and other possible limiting factors. C_4 plants, such as maize and sugarcane, show a much less pronounced response than the C_3 crops, increasing productivity on average by 5–10%. In general, higher CO_2 concentrations also lead to improved water-use efficiency of both C_3 and C_4 plants.

Established plant-response trends to increased CO_2 concentrations on the basis of experiments, in terms of plant growth, plant water-use efficiency, and quantity and quality of harvested produce, are summarized below:

i. Plant growth

C_3 plants (temperate and boreal) show a pronounced response to increased CO_2 concentrations. C_4 plants (warm tropical) show only a limited response to increased CO_2 concentrations. C_3 plants with nitrogen-fixing symbionts tend to benefit more from enhanced CO_2 supplies than other C_3 plants. Photosynthesis rate increases occur immediately following exposure to increased CO_2 concentrations. Initial strong response is often reduced under long-term exposure to higher CO_2 levels; experimental evidence suggests that growth responses would be lower for perennials than for annuals. Increased leaf-area production, as a result of the increased rate of photosynthesis, leads to an earlier and more complete light interception and therefore stimulates biomass increases. Higher biomass requires higher energy supply for maintenance, expressed in higher respiration, partly compensated by lower specific respiration. Leaf-turnover rate increases due to self-shading and decrease of specific leaf surface, and both tend to reduce photosynthesis per leaf. At higher CO_2 levels, plant-growth damage inflicted by air pollutants, such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and ozone (O_3), is at least partly limited because of reduced stomatal opening.

ii. Water-use efficiency

Increased CO_2 levels reduce stomatal conductance and transpiration rates. However, water consumption on a ground-area basis, i.e., canopy evapotranspiration, versus consumption on a leaf-area basis is reported to be much less affected. The range in water-use efficiency (WUE) of major crops is fairly wide and most distinct for C_4 crops. Many studies report an increase in the water-use efficiency in terms of dry matter produced per unit of water transpired. As a consequence of reduced transpiration, leaf temperature will rise and may lead to a faster rate of plant development and a considerable increase in leaf-area development, especially in the early crop-growth stages. Reduced transpiration and the resulting higher leaf temperature lead to an accelerated aging of the leaf tissue. Overall effects of leaf-temperature rise will depend upon whether or not optimum temperatures for photosynthesis are approached or exceeded.

iii. Harvest index and quality of produce

Biomass and yield increased in almost all experiments under controlled conditions. Dry-matter allocation patterns to roots, shoots, and leaves have been observed to change differently for C_3 and C_4 crops. Root/shoot ratios often increase under elevated CO_2 levels, favoring root and tuber crops (and also contribute to soil organic matter build-up). Increased CO_2 accelerates crop development due to increased leaf temperature resulting from reduced transpiration, reducing the efficiency of biomass or seed production. The content of non-structural carbohydrates generally increases under high CO_2, while the concentration of mineral nutrients and proteins is reduced. Food quality of leaf tissue may decline, leading to an increased requirement of biomass by herbivores.

Linkage of AEZ Results with BLS

Results of AEZ agricultural production potential assessments, under various climate change/CO_2 emission scenarios and obtained for different GCM-based climate experiments, were input to IIASA's system of national agricultural models to further assess world food system and trade implications.

2.2 Basic Linked System

The ecological–economic simulations in this report use the Basic Linked System (BLS) of models designed by the Food and Agriculture Program of the International Institute for Applied Systems Analysis, Laxenburg, Austria. IIASA's research has provided a framework for analyzing the world food system, viewing national agricultural systems as embedded in national economies, which in turn interact with each other at the international level. The analysis addresses development paradigms as defined by the IPCC Working Group III for the Special Report on Emissions Scenarios (SRES).

The BLS consists of 34 national and/or regional geographical components: 18 single-country national models, two models for regions with close economic cooperation (one for the European Union and one for the countries of Eastern Europe and the former Soviet Union), and 14 models of country groupings. The individual models are linked together by means of a world market, i.e., an international linkage mechanism. The model is formulated as a recursively dynamic system, working in annual steps, the outcome of each step affected by the outcomes of earlier ones. Each individual model covers the whole economy of the respective geographical area. For the purpose of international linkage, production, consumption, and trade are aggregated to nine agricultural sectors and one nonagricultural sector. All physical and financial accounts are balanced and mutually consistent: the production, consumption, and financial ones at the national level, and the trade and financial flows at the global level.

2.2.1 Basic principles underlying the BLS system

The Basic Linked System is a tool for analyzing agricultural policies and food system prospects in an international setting. The BLS has been conceptualized and constructed by IIASA in close cooperation with the Centre for World Food

Studies and with the help of many researchers from around the world. Four books and numerous journal articles have been published about the model system and the results of policy analyses conducted with it. A detailed description of the system is provided in Fischer *et al.* (1988). Results obtained from the system are discussed in Parikh *et al.* (1988) and in Fischer *et al.* (1991, 1994). Several applications of the BLS to climate-change impact analysis have been published, e.g., in Rosenzweig and Parry (1994), Fischer *et al.* (1996), and Parry *et al.* (1999).

The national models linked in the BLS cover about 80% of the most important attributes related to the world food system, such as population, land, agricultural production, demand, and trade. The remaining countries of the world, together accounting for up to 20% of these indicators, are grouped into 14 simplified regional models to provide closure for the world system, both geographically and economically. The groupings are based on country characteristics such as geographical location, income per capita, and the country's position with regard to net food trade. In this way, five regional groups were constructed for Africa, three for Latin America, five for Asia, and one containing the "Rest of the World." Further details are shown in *Annex 2.1*.

The level of commodity aggregation varies between the various components of a model as well as between different types of national models in the BLS (see *Annex 2.2*). This does not, however, apply to the international level where the linkage mechanism requires standardization. In all component models the trade flows adhere to the same commodity classification. A list of commodity aggregates is given in *Annex 2.3*.

The BLS is an applied general equilibrium (AGE) model system. This necessitates that all economic activities are represented in the model. Financial flows as well as commodity flows within a country and at the international level are kept consistent in the sense that they must balance, by imposing a system of budget constraints and market-clearing conditions. Whatever is produced will be demanded, either for human consumption, feed, or as intermediate input. Alternatively, commodities can be exported or put into storage. Consistency of financial flows is imposed at the level of the economic agents in the model (individual income groups, governments, etc.), at the national as well as the international level. This implies that total expenditures cannot exceed total income from economic activities and from abroad, in the form of financial transfers, minus savings. On a global scale, spending cannot exceed earnings.

Linkage of country and country-group models occurs through trade, world market prices, and financial flows. The system is solved in annual increments, simultaneously for all countries in each time period. It is assumed that production does not adjust instantaneously to new economic conditions. Within each one-year time period, only demand changes with price and commodity buffer stocks can be adjusted for short-term supply response. However, production to be marketed in the following year is affected by possible changes in relative prices. This feature makes the BLS a recursively dynamic system. The iterative solution procedure proceeds in three steps:

1. For given prices (either last year's market-clearing solution, or intermediate results from a previous iteration), calculate net exports and imports for all 34 countries and country groups of the BLS.

2. Check market clearance for each commodity, i.e., test whether the sum of exports over countries equals the sum of imports.

3. Revise world market prices according to imbalances calculated in (2). When markets are balanced, accept prices as the world market solution for that particular year and proceed with calculations for next time period; otherwise return to (1).

This process is repeated until the world markets are simultaneously cleared in all commodities. The procedure is sketched in *Figure 2.3*.

It is assumed that goods are marketed in the year following the period in which they are produced. At the beginning of each period, commodity supply is given. The exchange process results in equilibrium prices, i.e., a vector of international prices such that global imports and exports balance for all commodities. These market-clearing prices are then used to determine value added in production and income of households and governments.

Simulations with the BLS generate a variety of outputs for model variables and indicators. At the global level these include world market prices, global population, global production and consumption, and global income. At the country level the information varies with the type of model, including in general the following variables: producer and retail prices, level of production, use of primary production factors (land, labor, and capital), intermediate input use (feed, fertilizer, and other chemicals), human consumption, stock levels and commodity trade, gross domestic product and investment by sector, levels of taxes, tariffs, and income by group and/or sector.

2.2.2 The BLS national models

The national models simulate the behavior of producers, consumers, and the government. The models distinguish two broad sectors: agriculture and nonagriculture. Agriculture produces nine aggregate commodities. All nonagricultural activities are combined into one single aggregate. Domestic disappearance of a commodity is the sum of human consumption, feed use (where appropriate), intermediate consumption, and stock changes. In addition, the nonagricultural commodity is also

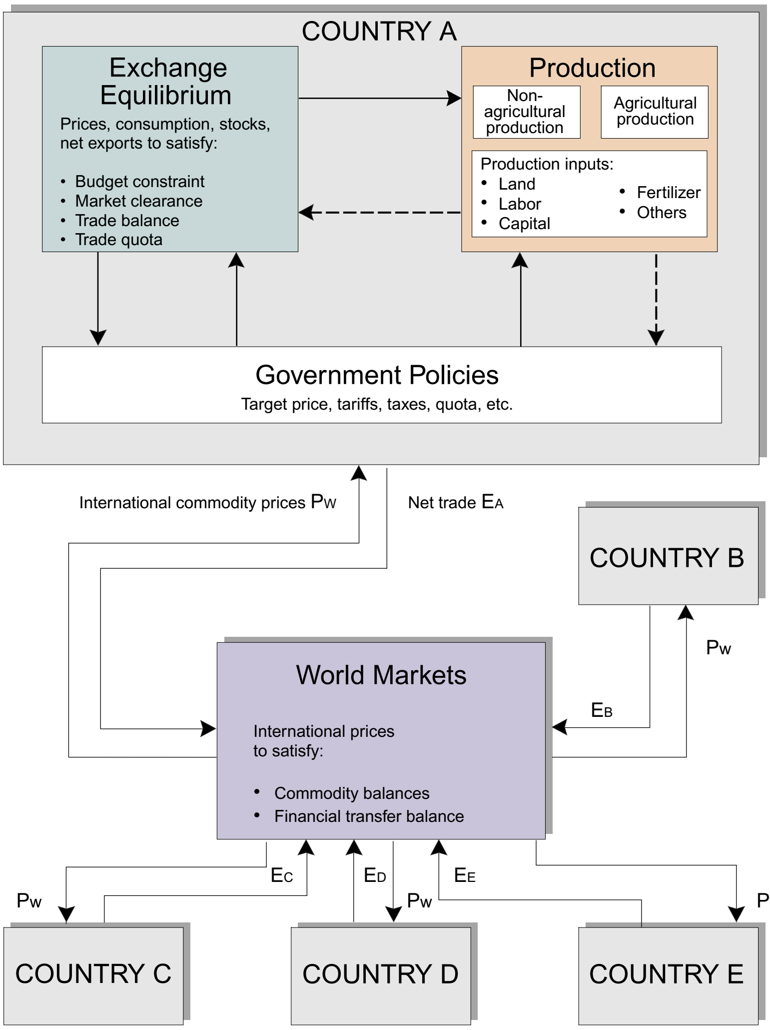


Figure 2.3. The international linkage in the BLS (from Parry *et al.*, 1999).

required as an investment good, and for processing and transporting agricultural goods.

Production in the standard national models is critically dependent on the availability of the primary factors, namely land, labor, and capital. The former is required only in the agricultural sector, while the latter two are determinants of output in both the agricultural and the nonagricultural sectors. Capital stocks are accumulated through investment and depreciation. Once a decision is made on how much to invest in each of the two main sectors, the capital stock generated with this investment is committed to the respective sector. The maximum land available for cropping depends on a country's total extent of land suitable for agriculture and the profitability of agricultural land use, i.e., the economic incentives as expressed by the relative price of agriculture to nonagriculture. The responsiveness of how much land can be cultivated due to changing economic conditions is rather low since both time and investment are needed to bring new land into cultivation.

For each of the agricultural commodities, acreage (or livestock numbers) and yields are determined. Crop yields respond to fertilizer application; animal output increases with feeding intensity. Fertilizer application is sensitive to relative prices. Feed use is adjusted and optimized in each time period so as to obtain least-cost feed rations. This means that variable inputs of fertilizer and animal feeds adjust to changing economic conditions with only a short delay.

Once the yield levels are determined, net revenues per hectare or per livestock unit are calculated. These in turn determine the relative profitability of the various agricultural commodities, a key criterion for allocating land, labor, and capital. These three production factors are required as inputs into the production process and are allocated between the various enterprises in order to maximize net returns subject to the available technology. This allocation process is carried out in each time step.

Technical progress is included in the yield functions of crops and livestock. The rate of technical progress is estimated from past performance. For simulations into the future it is set externally and can be varied according to scenario assumptions.

While it is mainly changing retail prices and incomes that alter consumer demand, producers are most affected by farm-gate prices of outputs and inputs, by their past investment decisions, by technical innovations, and by environmental changes, e.g., projected climate change.

2.2.3 Climate-change impact analysis with the BLS

The evaluation of the potential impacts of the different SRES story lines on production and trade of agricultural commodities, in particular on food staples, was carried out in two steps. First, simulations were undertaken representing "futures" with the BLS, which were consistent with the respective demographic and economic assumptions of the SRES marker scenarios but where current climate and atmospheric conditions would prevail. Second, yield impacts due to temperature and CO_2 changes, as derived from the agro-ecological assessment, were simulated with the BLS and compared to the respective outcomes without climate change.

The primary role of such reference scenarios is to serve as "neutral" points of departure, from which climate-change scenarios with their altered assumptions on crop productivity take off as variants, with the impact of climate change being seen in the deviation of these simulation runs from the respective reference scenario. The simulations are carried out on a yearly basis from 1990 to 2080.

2.2.4 Assumptions about exogenous variables

As a global system of linked national and regional models, and based on general equilibrium principles, the BLS contains only a few variables that are truly exogenous. Among those variables are demographic change and labor participation, technical progress, shifts in lifestyles, and the setting of policy measures, e.g., trade quotas, price subsidies, or tariffs.

Population growth rates were obtained from the projections assumed in the IPCC SRES scenarios, i.e., they are based on three alternative projections prepared by the UN Population Division and by IIASA. Population growth rates have been incorporated for individual countries (Lutz and Goujon, 2002; CIESIN, 2002), and were aggregated to country groups where necessary. Labor participation rates depend on population structure. Thus, trajectories of total labor force in a country are exogenously prescribed and do not change across scenarios of the same family of SRES experiments. Note, however, that the allocation of labor between agriculture and nonagriculture is determined within the model and responds to changing economic conditions.

Technical progress enters the representation of the production processes at different levels in a country model, e.g., yield and mechanization functions of agriculture, feeding efficiency relations, and – important to overall growth performance – technical progress in the nonagricultural sector. Time is used as a proxy variable for phasing in technical progress.

A critical step in the assessment is translating quantified trajectories of key variables from the IPCC SRES scenarios to IIASA's model of the world food and agriculture system. First, the demographic and economic projections of the BLS are calibrated to match the macroeconomic assumptions of the respective IPCC SRES marker scenarios. Second, the climate-change yield component of the BLS is parameterized based on detailed results from global AEZ assessments for climate changes simulated according to alternative SRES assumptions and GCM-based climate scenarios.

The story line formulation and scenario quantifications developed by the SRES analytical teams and several modeling groups includes various "marker" scenarios, i.e., projections of population as well as trajectories of global and regional gross domestic product (GDP), emissions, and energy consumption. A high degree of correspondence with the BLS in key variables for modeling the economy makes it feasible to harmonize the scenario analysis undertaken in IPCC SRES and with the BLS. One possible approach would have been to directly impose projections of GDP and other variables from SRES marker scenarios as exogenous inputs to the BLS. This would have constrained the BLS in a very rigid manner, in effect bypassing its representation of the interdependencies between agricultural and nonagricultural sectors.

To keep these interdependencies intact, the approach chosen was to harmonize rates of economic growth generated in the BLS with those projected in the IPCC SRES marker scenarios through adjustment of production factors and of assumed rates of technical progress. Growth rates in the national models of the BLS are endogenously generated based on three elements: (a) capital accumulation through investment and depreciation, related to a savings function that depends on lagged GDP levels as well as balance of trade and financial aid flows; (b) dynamics of the labor force as a result of demographic changes; and (c) (exogenous) technical progress. For calibrating economic growth to SRES story lines, the 34 geographical model components of the BLS were aggregated into ten broad regions (EMF14, 1995). The harmonization of production factors and GDP for the period 1990–2080 was then carried out on a region-by-region basis. The relationship between the BLS geographical entities and the regions used in the calibration process is shown in *Annex 2.4*. It also indicates the mapping of BLS entities to broad SRES regions defined in the IPCC special report.

With population predetermined and economic growth calibrated to SRES story lines, important factors determining food requirements and demand are specified exogenously. The other factors that influence human consumption, e.g., prices and incomes, are endogenous to the model. All demand components, i.e., human consumption, feed use, other intermediate consumption, buffer stock levels, and seed and waste, are endogenous in the models. The flexibility to adjust to price and income changes varies significantly, among commodities as well as for different kinds of utilization.

2.2.5 Assessing impacts of climate change on agriculture

Most models included in the BLS distinguish between yield and acreage functions. Yield impacts caused by climate change have been assessed outside the BLS, using the FAO/IIASA global agro-ecological zones methodology. They enter the various BLS yield functions by means of multiplicative adjustment factors, i.e., yield changes suggested by agronomic research were translated into altered parameterizations of BLS yield functions. It is important to note that we bend or shift yield functions in accordance with experimental results, rather than changing yields directly; this leaves room in the model for economic adaptation in response to climate change.

Acreage allocation is indirectly affected through changes in the economic performance of the competing crop-production activities. The BLS is also equipped to handle explicit acreage constraints in the factor allocation module of the agricultural production component; this feature has not been activated in the current analysis.

The assessment of the impacts of climate change on agriculture is carried out relative to four baselines, modeled according to the IPCC SRES marker scenarios termed A1, A2, B1, and B2. These base scenarios represent alternative extrapolations of the world system into the future. The system is simulated for the period 1990–2080. Simulation is carried out in one-year increments. All scenarios of climate-change impact start in 1990 and are taken relative to a reference climate of the period 1961–1990. Climate impacts on yields were phased in with piecewise linear functions, i.e., the yield change multipliers incorporated into the yield response functions were built up gradually with time so as to reach the respective impacts as determined by the AEZ analysis for the years 2020, 2050, and 2080.

The BLS offers a range of variables and indicators for assessing the simulation results. The most important among them are those that are indicative of changes in welfare, such as cost of consumption comparisons, gross domestic product, calorie consumption, estimates of the number of people at risk of hunger, and income parity between agriculture and the other sectors of the economy. In addition, there are several commodity-specific indicators available, such as production, yield and acreage, consumption and trade, as well as prices.

2.3 Climate Scenarios

Scenarios of climate change were developed in order to estimate their effects on crop yields, extents of land with cultivation potential, and the number and type of crop combinations that can be cultivated. A climate-change scenario is defined as a physically consistent set of changes in meteorological variables, based on generally accepted projections of CO_2 (and other trace gases) levels.

The IPCC published a Special Report on Emissions Scenarios (SRES) in 2000 (Nakicenovic and Swart (eds.), 2000). This report describes the new set of emissions scenarios used in the IPCC Third Assessment Report (IPCC, 2001). The SRES scenarios have been constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. All the SRES scenarios are “non-mitigation” scenarios with respect to climate change.

The range of scenarios analyzed in this study addresses development paradigms as defined by the IPCC Working Group III for the SRES. The AEZ model has been applied to results of General Circulation Models (GCM), which were available for the IPCC SRES emission scenarios A1FI, A1B, A2, B1, and B2. Outputs from GCM experiments were obtained through the IPCC Data Distribution Centre (DDC) and the Climate Research Unit (CRU) at the University of East Anglia (http://ipcc-ddc.cru.ac.uk). For use in AEZ, the outputs of the climate model experiments, with various spatial resolutions, have been interpolated to a grid of

0.5 × 0.5 degrees latitude/longitude and applied to reference a climatology of 1961–1990, which has been compiled by the CRU (New *et al.*, 1998). Results of the following coupled atmosphere-ocean general circulation models were included in the analysis for this report:

Hadley Centre for Climate Prediction and Research: HadCM3 is a coupled atmosphere-ocean GCM developed at the Hadley Centre and described by Gordon *et al.* (2000) and Pope *et al.* (2000). The model has a stable control climatology and does not use flux adjustment. The atmospheric component of the model has 19 levels with a horizontal resolution of 2.5 degrees of latitude by 3.75 degrees of longitude, which produces a global grid of 96 × 73 grid-cells. This is equivalent to a surface resolution of about 417 km × 278 km at the equator, reducing to 295 km × 278 km at 45 degrees of latitude. The oceanic component of the model has 20 levels with a horizontal resolution of 1.25 × 1.25 degrees of latitude/longitude. At this resolution it is possible to represent important details in oceanic current structures. Annual results of monthly weather variables of HadCM3 simulations were available from DDC for simulations using the IPCC SRES A2 and B2 emission scenarios; additionally, results for A1FI and B1 scenarios were provided by CRU.

Commonwealth Scientific and Industrial Research Organisation (CSIRO): The CSIRO Climate Change Research Program is Australia's largest and most comprehensive program investigating the greenhouse effect and global climate change. The CSIRO coupled model involves global atmospheric, oceanic, sea-ice, and biospheric sub-models (Gordon and O'Farrell, 1997; Hirst *et al.*, 1997). The atmospheric, biospheric, and sea-ice sub-models are the same as those used in the CSIRO Mark 2 GCM, as detailed in McGregor *et al.* (1993) and Kowalczyk *et al.* (1994). Atmospheric and oceanic components use a spectral horizontal grid, each grid-cell measuring about 625 km by 350 km, with nine vertical levels in the atmosphere and 21 levels in the ocean. Annual results of monthly weather variables of CSIRO experiments were available from DDC for simulations using the IPCC SRES A1b, A2, B1, and B2 emission scenarios.

Canadian Centre for Climate Modelling and Analysis (CCCma): For SRES emission scenarios, results were obtained with the second version of the Canadian Global Coupled Model (CGCM2). It is based on the earlier CGCM1, but with some improvements, in particular, regarding the ocean mixing parameterization and sea-ice dynamics (Flato and Hibler, 1992). A description of CGCM2 and a comparison, relative to CGCM1, of its response to increasing greenhouse-gas forcing is available in Flato and Boer (2001). The CGCM1 model and its control climate are described by Flato *et al.* (2000). It is a spectral model with a surface grid resolution of roughly 3.7 by 3.7 degrees latitude/longitude and ten vertical levels. The ocean component has a resolution of roughly 1.8 by 1.8 degrees and 29 vertical levels. A multi-century control simulation with the coupled model has been performed using the present-day CO_2 concentration to evaluate the stability of the coupled model's climate, and to compare the modeled climate and its variability to that observed. The IPCC DDC provides annual time-series of monthly climate variables for SRES A2 and B2 scenarios.

National Center for Atmospheric Research (NCAR): The Parallel Climate Model (DOE-PCM) is a joint effort, sponsored by the US Department of Energy (DOE), to develop a parallel climate model between Los Alamos National Laboratory (LANL), the Naval Postgraduate School, the US Army Corps of Engineers' Cold Regions Research and Engineering Lab, and the National Center for Atmospheric Research. Version 1 of the PCM couples the NCAR Community Climate Model version 3, the LANL Parallel Ocean Program, and a sea-ice model from the Naval Postgraduate School. Further details of the PCM control run are described in Washington *et al.* (2000). Results provided by the IPCC DDC are annual time-series of monthly climate variables for a grid of 68 by 128 grid-cells for IPCC SRES emission scenarios A2 and B2.

2.3.1 Comparison of outputs of the four GCMs

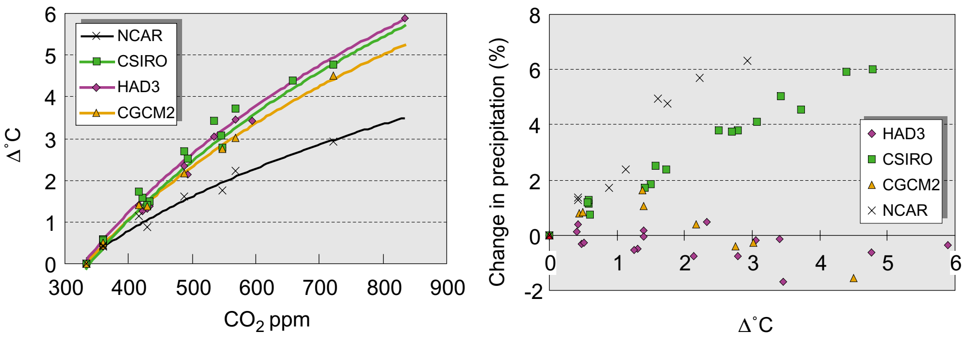
Comparisons of results from HadCM3, CSIRO, CGCM2, and NCAR have been made for all land and for current agricultural land separately in terms of "Temperature change (°C) versus CO_2 concentration levels (ppm)" and for "Temperature change (°C) versus precipitation change (%)."

Relationships between CO_2 concentration levels and predicted temperature responses show a close correlation. Results for HadCM3, CSIRO, and CGCM2 are similar. Temperature response to increased CO_2 is, however, systematically lower in the case of NCAR's PCM model.

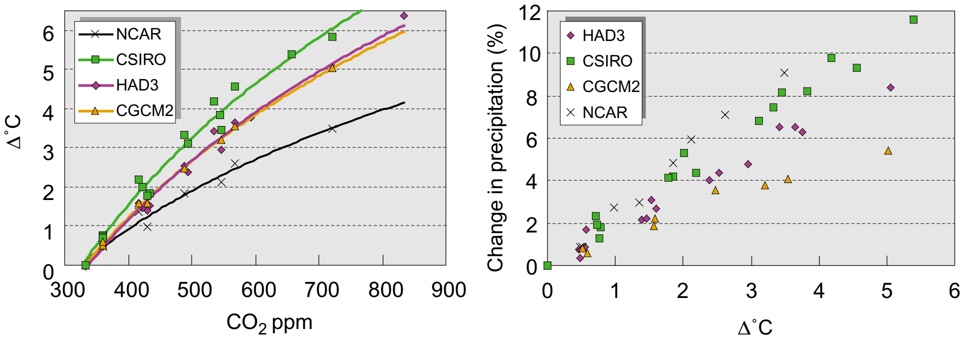
Relationships between temperature change and change in precipitation levels are far less distinct; rather large regional differences exist, both in terms of correlation among different climate models and even direction of change.

Figure 2.4 and *Table 2.1* present for the four GCMs the implied responses of temperature to increasing CO_2 concentrations, compiled from the GCM outputs obtained for different SRES emission scenarios, and the correlations between modeled temperature increase and precipitation change, considering all land grid-cells for the world and for developed and developing nations separately. *Annex 2.1* provides correlations for individual regions.

(a) World



(b) Developed world



(c) Developing world

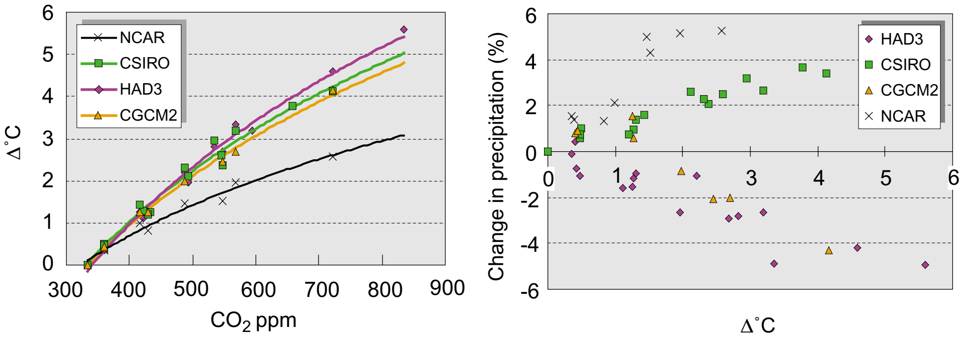


Figure 2.4. Responses of temperature to increasing CO_2 concentrations and correlations between temperature increase and precipitation change.

Table 2.1. Overall correlations between temperature increase and precipitation change.

Regions	HadCM3	CSIRO	CGCM2	NCAR
World	+/–	+	+/–	–
Developed	+	+	+	+
Developing	–	+	–	+
North America	+	+	+	+
Central America	–	0	–	+/–
South America	–	0	–	+
Oceania	+/–	+/–	+	+
East Asia	+	+	0	+
South Asia	+	+	+	+
Southeast Asia	+	+	–	+
Northern Africa	–	–	+/–	–
Eastern Africa	–	+	+/–	+
Western Africa	+/–	–	+	+
Central Africa	–	0	+/–	+
Southern Africa	–	–	+/–	+/–
Northern Europe	+	+	+	+
Western Europe	–	+	+/–	0
Eastern Europe	+/–	+/–	+/–	+
Southern Europe	–	–	–	–
Russia	+	+	+	+
Central Asia	+	+/–	0	+
West Asia	–	–	+/–	+

+ positive correlation, – negative correlation, +/– mixed and 0 constant precipitation.

2.4 IPCC SRES Scenarios

The climate issue is part of the larger question of how complex social, economic, and environmental subsystems interact and shape development pathways, thereby strongly affecting emissions and consequently the extent and pace of resulting climate change, as well as the capacity to mitigate and adapt to climate change. The long-term nature and uncertainty of climate change and its driving forces require scenarios that extend to the 21st century (IPCC, 2000). In response to a 1994 evaluation of the earlier IPCC IS92 emission scenarios, the 1996 Plenary of the IPCC requested a Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000).

The SRES scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments, but exclude policies that would explicitly address climate change. The SRES scenarios include the range of emissions of all relevant species of greenhouse gases and sulfur and their driving forces.

Four different narrative story lines were developed to describe consistently the relationships between driving forces and their evolution, and to add context for the scenario quantification. Each story line represents different demographic, social, economic, technological, and environmental developments (IPCC, 2000). The story lines, termed A1, A2, B1, and B2, are briefly summarized here.

SRES A1: A future world of very rapid economic growth, low population growth, and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity-building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

- World economy grows at 3.3% over the period 1990–2080. The per capita GDP in 2080 amounts to \$76,000 in the developed world and \$42,000 in the developing world. The average income ratio between currently developed and developing countries was 13.8 in 1990 and this reduces to 1.8 in 2080. Thus it is an equitable world where current distinctions between poor and rich countries eventually dissolve.

- Demographic transition to low mortality and fertility; the world sees an end to population growth. The total population for developing countries reaches 7,100 million in 2050 and then declines to 6,600 million in 2080, whereas the population in the developed world stabilizes at 1,250 million in 2050.

- Environmental quality is achieved through active measures emphasizing "conservation" of nature changes towards active "management" – and marketing – of natural and environmental services.

- Final energy intensity decreases at an average annual rate of 1.3%; transport systems evolve to high car ownership, sprawling sub-urbanization, and dense transport networks, nationally and internationally; large regional differences in future GHG emission levels.

SRES A2: A very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.

- World economy grows at 2.3% over the period 1990–2080. The per capita GDP in 2080 amounts to \$37,000 in the developed world and \$7,300 in the developing world. The average income ratio between currently developed and developing countries was 13.8 in 1990 and this reduces to 5.1 in 2080. Thus it is a world where income disparities have been reduced by about two-thirds of current levels.

- Rapid population growth continues, reaching a world total of 11 billion in 2050 and almost 14 billion in 2080. The total population of developing countries reaches 9.4 billion in 2050 and 11.7 billion in 2080, whereas the population in the developed world reaches 1.4 billion in 2050 and 1.6 billion in 2080. Social and political structures diversify, with some regions moving toward stronger welfare systems.

- Environmental concerns are relatively weak, although some attention is paid to bringing local pollution under control and maintaining local environmental amenities.

- The fuel mix in different regions is determined primarily by resource availability; technological change is rapid in some regions and slow in others; high energy and carbon intensity, and correspondingly high GHG emissions.

SRES B1: A convergent world with rapid change in economic structures, "dematerialization," and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability, including concerted efforts for rapid technology development, dematerialization of the economy, and improving equity.

- World economy grows at 2.9% over the period 1990–2080. The per capita GDP in 2080 amounts to \$55,000 in the developed world and \$29,000 in the developing world. The average income ratio between currently developed and developing countries was 13.8 in 1990 and this reduces to 2.0 in 2080. Thus it is an equitable world where current distinctions between poor and rich countries eventually dissolve.

- Demographic transition to low mortality and fertility; the world sees an end to population growth. The total population for developing countries reaches 7,100 million in 2050 and than declines to 6,600 million in 2080, whereas the population in the developed world stabilizes at 1,250 million in 2050. High level of environmental and social consciousness combines with a globally coherent approach to sustainable development.

- Environmental consciousness and institutional effectiveness; high environmental quality is high; increasing resource efficiency; reduction of material wastage, maximizing reuse and recycling.
- Smooth transition to alternative energy systems as conventional oil resources decline; high levels of material and energy saving as well as reductions in pollution; transboundary air pollution is basically eliminated in the long term; low GHG emissions.

SRES B2: A world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid and more diverse technological change, but a strong emphasis on community initiative and social innovation to find local, rather than global solutions.

- World economy grows at 2.7% over the period 1990–2080. The per capita GDP in 2080 amounts to $47,000 in the developed world and $18,000 in the developing world. The average income ratio between currently developed and developing countries was 13.8 in 1990 and this reduces to 2.6 in 2080. Thus it is a world where income disparities have been reduced by over four-fifths of current levels.
- Population growth continues, reaching a world total of 9.3 billion in 2050 and almost 10.1 billion in 2080. The total population for developing countries reaches 7.9 billion in 2050 and 8.7 billion in 2080, whereas the population in the developed world reaches 1.2 billion in 2050 and then declines to 1.1 billion in 2080. Social and political structures diversify, with some regions moving toward stronger welfare systems; increased concern for environmental and social sustainability.
- Environmental protection is an international priority; improved management of some transboundary environmental problems.
- Energy systems differ from region to region, depending on the availability of natural resources; energy intensity of GDP declines by about 1% per year; technical change across regions is uneven; low level of car dependence and less urban sprawl; transition away from fossil resources; development of less carbon-intensive technology in some regions.

A comparison of some key characteristics, such as population development, economic wealth, emissions and the resulting atmospheric CO_2 abundance, is presented in *Figure 2.5*.

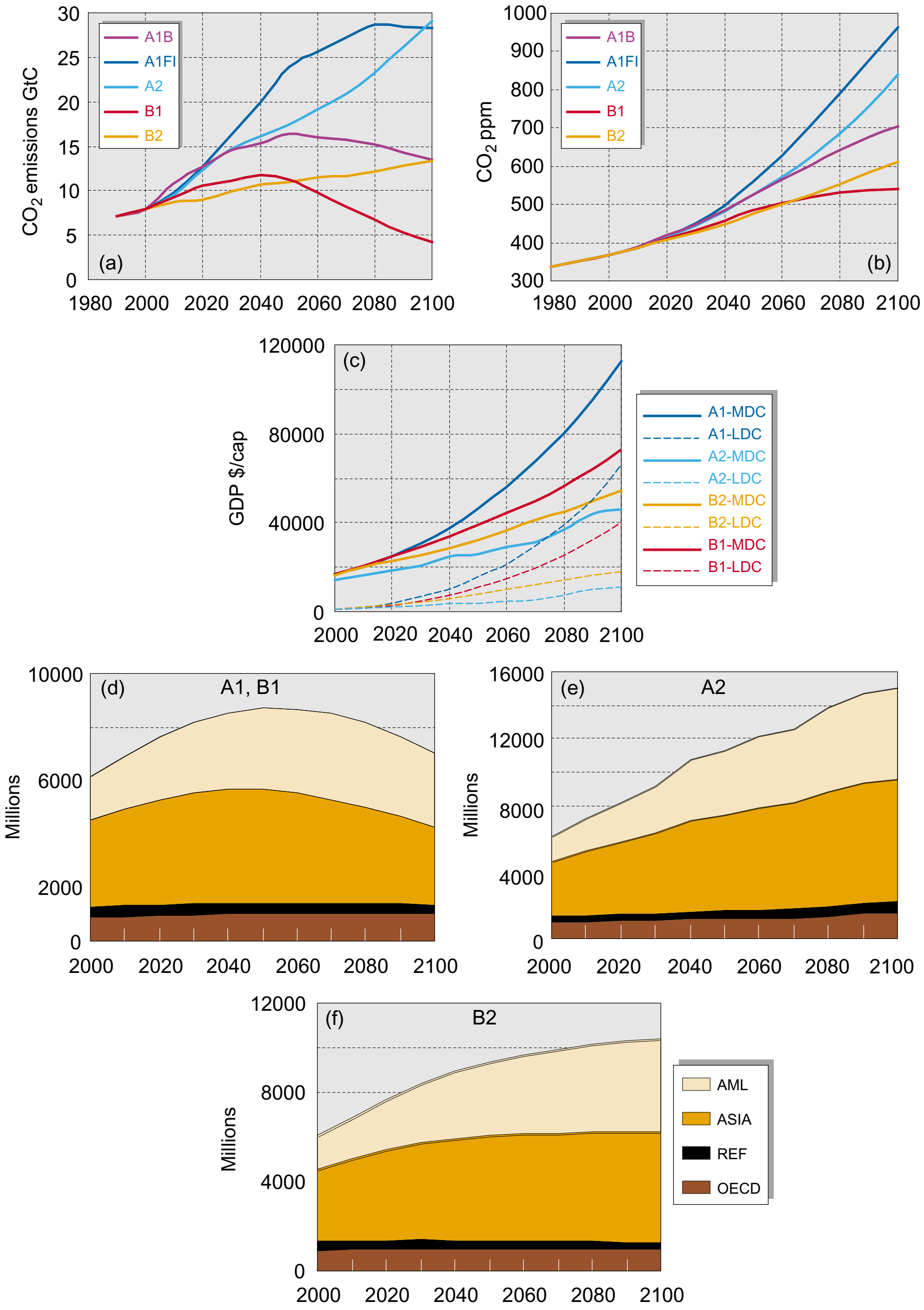


Figure 2.5. IPCC SRES scenarios to 2100. (a) CO$_2$ emissions to 2100. (b) CO$_2$ concentration. (c) GDP per capita. (d)–(f) Population projections.

3

Impacts of Climate Change on Agro-ecology

3.1 Introduction

Human activities are changing the Earth's climate, and this is having an impact on all ecosystems. The expected changes in climate will alter regional agricultural systems, with consequences for food production. The specifics of the impact will depend on how the effects of climate change translate into factors that determine the viability and utility of ecosystems.

Article 2 of the United Nations Framework Convention on Climate Change (1992) states that the impact on world food supply should be key when considering at which point greenhouse gas emissions might imply dangerous anthropogenic interference with the climate system. The AEZ methodology and the spatial database with global coverage provide a comprehensive basis for ecological assessments and quantification of the impact of climate variability and climate change on regional and national crop production.

During the past few years, case studies on the potential impacts of climate change have been compiled for a number of countries, including Australia, Egypt, Finland, Indonesia, Malaysia, the Netherlands, Norway, Thailand, the UK, the USA, and Vietnam. The majority of these studies have been based on climate-change experiments with General Circulation Models (GCMs), but they differ markedly in their baseline data, methods of analysis, and scenarios of climate change.

In the context of the present debate over international agreements such as the Kyoto Protocol and the outcome of the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC), it is important that uniform assessments be carried out to compare and evaluate national, regional, and global impacts of climate change on food and agricultural production. Such quantified and spatial information provides important inputs that can underpin national and regional adaptive polices to mitigate the consequences of climate change and also facilitate international negotiations on climate change, taking into account the relative impacts in the context of their specific development needs and priorities.

The effects of global warming and increased atmospheric carbon concentrations will result in improved growing conditions in some areas, and thus crop production may increase. Elevated atmospheric CO_2 levels are expected to augment crop productivity because of increased photosynthetic activity and improved water-use efficiency. At the same time, however, higher temperatures may intensify pest and disease problems, which in turn would lead to crop losses. Crop yields in some countries may also be affected by drier conditions and increased water stress.

As a first step in the ecological-economic assessment of climate change and agricultural vulnerability, climate-change scenarios were developed in order to estimate their effects on crop yields, amounts of land with cultivation potential, and the number and type of crop combinations that can be cultivated. The range of scenarios analyzed in this study addresses development trajectories as defined by the Working Group III for the IPCC TAR (IPCC, 2001). The AEZ model has been applied to results of various recent GCM experiments, which are available from the IPCC DDC for the IPCC SRES emission scenarios A1FI, A1B, A2, B1, and B2. A total of 12 climate runs from four GCM groups in Australia, Europe, and North America were compiled and assessed to cover a wide range of possible future developments, to cater for uncertainties regarding future greenhouse gas emissions, and to obtain robust conclusions vis-à-vis apparent differences among climate models.

This chapter presents the main AEZ results and findings of the impact of climate change on agriculture. Results comprise environmental constraints to crop agriculture; climate variability and the variability of rain-fed cereal production; changes in the characteristics and extent of potential agricultural land; changes in crop suitability and multi-cropping; and the impact of climate change on cereal-production potential. The economic implications of these changes in agroecology and the consequences for regional and global food systems are explored in Chapter 4.

3.2 Climatic Resources under Climate Change

Agricultural crop distribution and production is largely dependent on the geographical distribution of thermal and moisture regimes. Global warming is significantly increasing the area with temperature regimes conducive to growth and production of agricultural crops. As an example, *Plates 3.1* and *3.2* present the distribution of thermal climates for reference conditions (period 1961–1990) and for the HadCM3-A1FI climate projections in the 2080s. The northward shift in thermal regimes due to global warming implies a significant reduction of boreal and arctic ecosystems, and a large expansion of areas with temperate climate conditions in Siberia and Canada. In the Southern hemisphere, however, the temperate zones of Argentina and Chile disappear almost completely. The subtropics, apart from a general shift

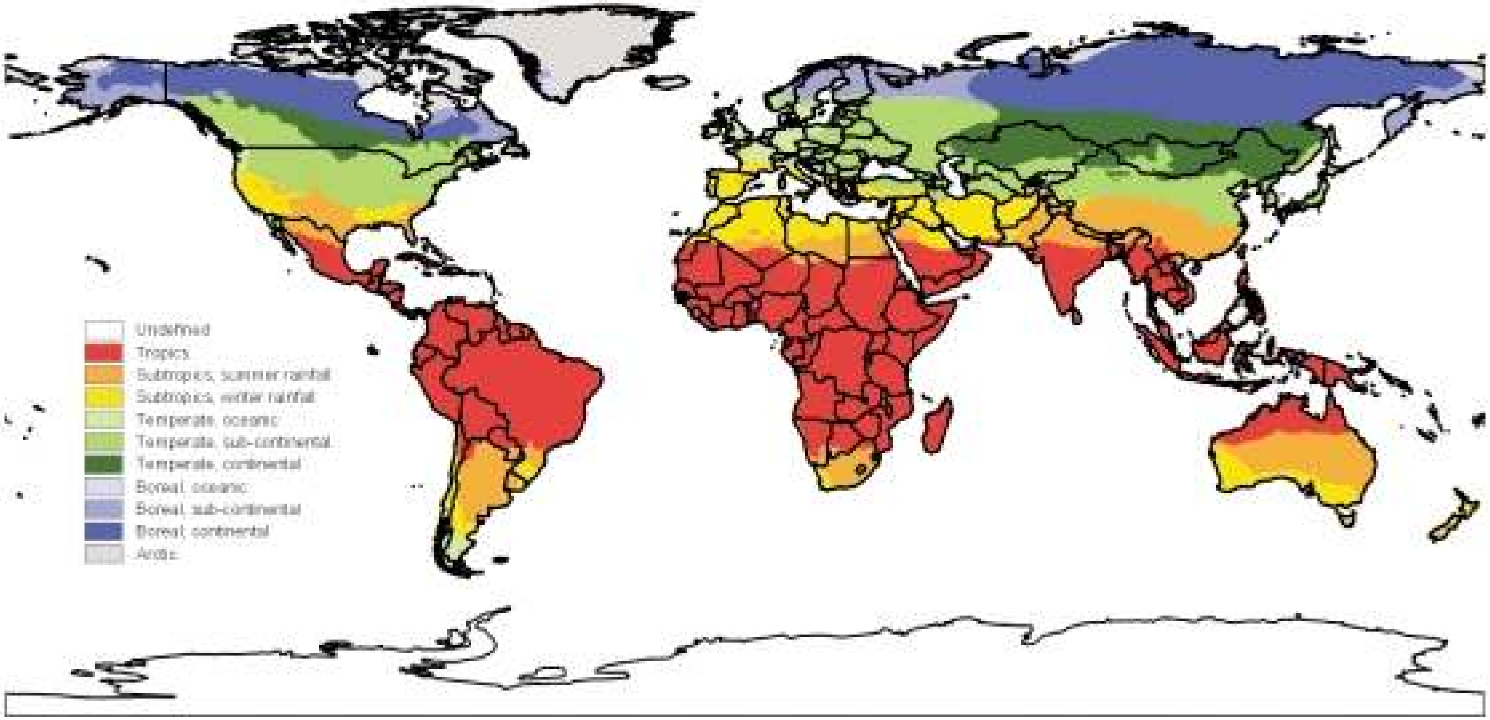


Plate 3.1. Thermal climates (reference climate, 1961–1990).

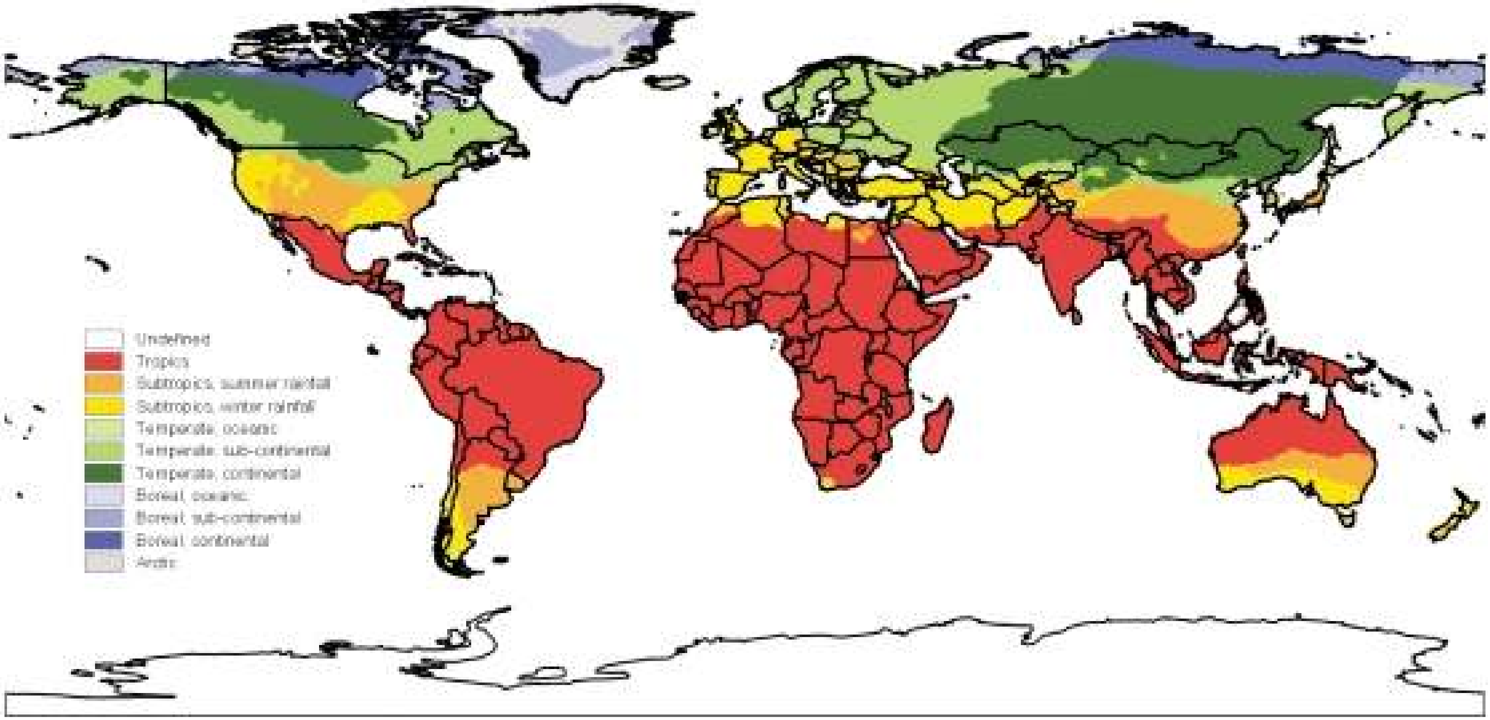


Plate 3.2. Thermal climates (HadCM3-A1F1, 2080s).

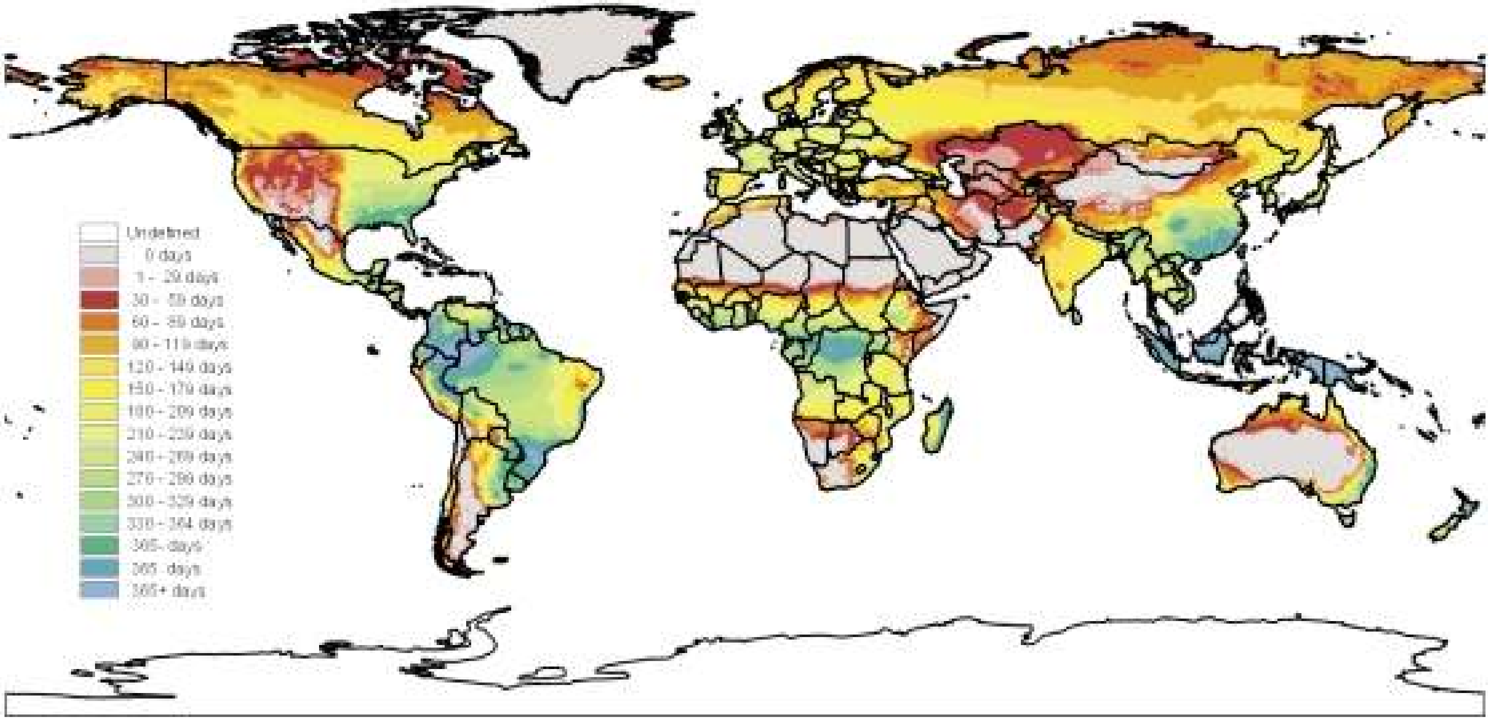


Plate 3.3. Length of growing periods (reference climate, 1961–1990).

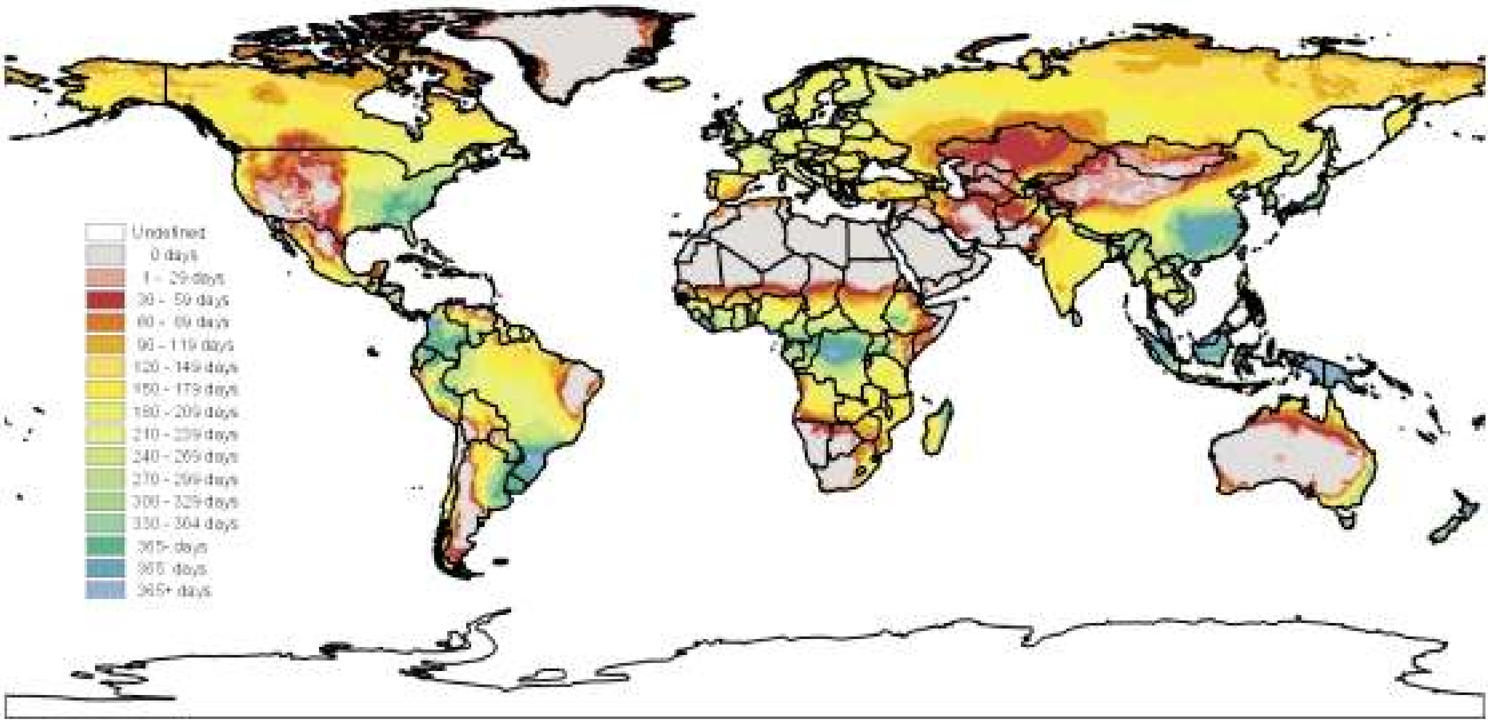


Plate 3.4. Length of growing periods (HadCM3-A1F1, 2080s).

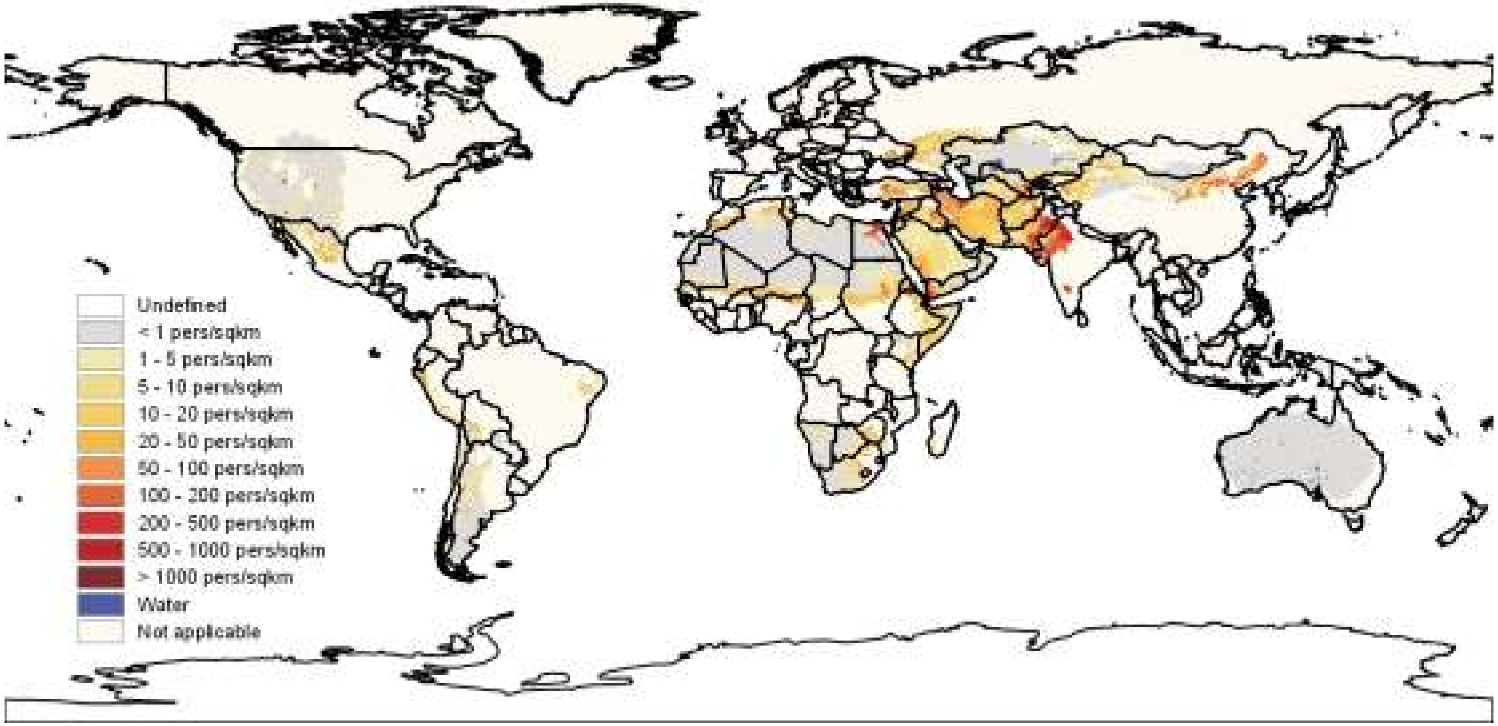


Plate 3.5. Population density (1995) in hyper-arid, arid, and semi-arid areas (LGP < 120 days) for reference climate (1961–1990).

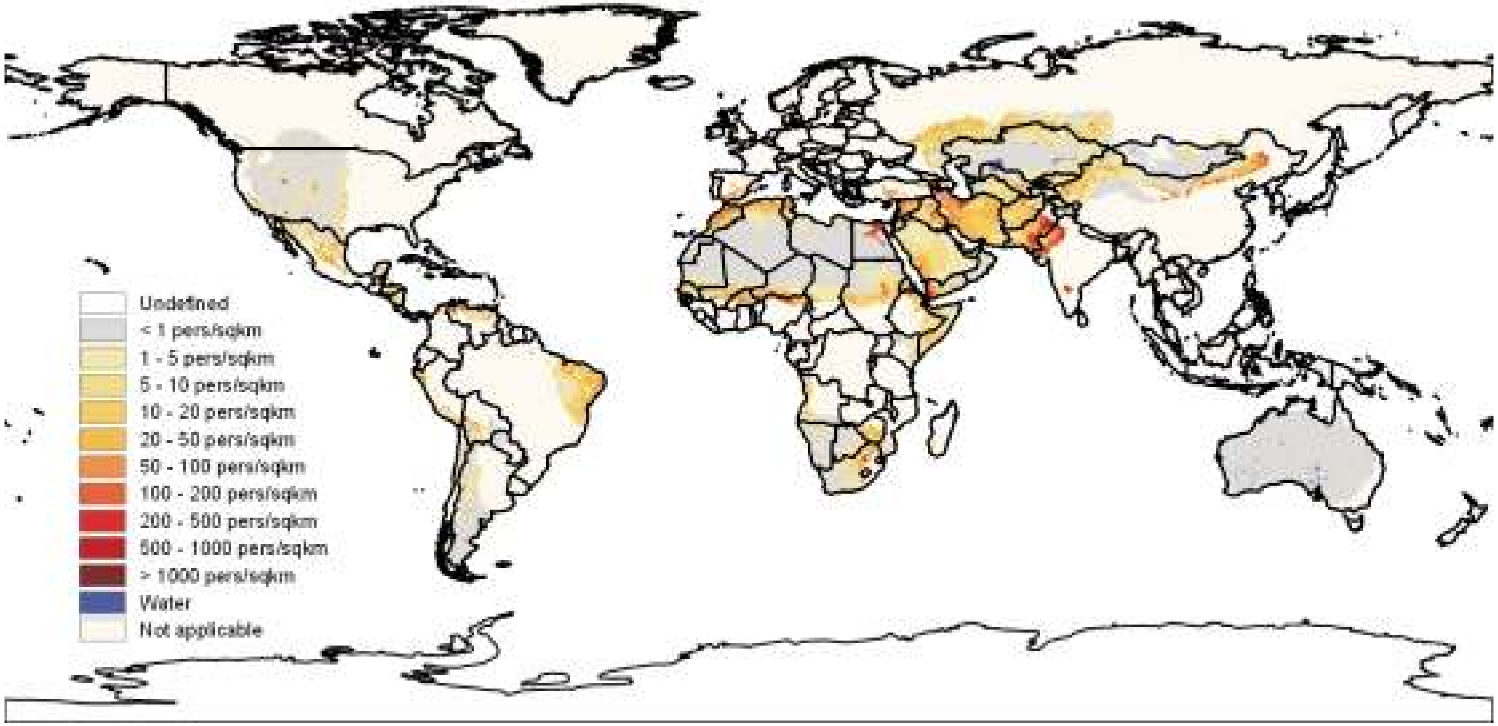


Plate 3.6. Population density (1995) in hyper-arid, arid, and semi-arid areas (LGP < 120 days) for projected climate of scenario HadCM3-A1FI in the 2080s.

to higher latitudes, remain by and large of a similar extent. A major expansion of tropical zones occurs, which apart from a very small stretch in South Africa and a narrow fringe along the Mediterranean coast, will cover almost all of Africa.

Changes in rainfall patterns, in addition to shifts in thermal regimes, influence local seasonal and annual water balances, and in turn affect the distribution of periods during which temperature and moisture conditions permit agricultural crop production. Such characteristics are well reflected by the so-called length of growing period (LGP), which has been calculated by grid-cell for reference conditions and for the 12 GCM climate-change projections considered in this study. *Plates 3.3* and *3.4* present an example of the global distribution of LGP for reference conditions and again for the 2080s using the HadCM3-A1FI scenario.

Mainly due to the influence of higher temperatures, large increases of LGP are found in current temperate, boreal, and arctic regions. For developed countries and the group of developing countries in temperate Central and East Asia, the zones with LGP of less than 120 days calculated for reference climate (1961–1990) amount to some 37.1 million km^2, i.e., 55% of total area. Under the conditions of the SRES B2 climate projections for the 2080s, this area with short LGP would be reduced by 4.2–9.2 million km^2 for the range of GCMs assessed in this study. The average reduction across models, of these areas with very limited growing conditions, under the SRES B2 scenario is 6.3 million km^2, about 17% of current extents. For even larger climate changes, as would result from greenhouse-gas emissions in the SRES A2 scenario, the average decrease of areas with LGP of less than 120 days would amount to 8.1 million km^2, a decline of 21% compared to current conditions.

Decreases of LGP, on the other hand, are found in areas with diminishing amounts or deteriorating distribution of rainfall as, for example, in Northern Africa and northeast Brazil. Another remarkable trend in the projections of the Hadley Centre model is an apparent decrease of excess wetness in the Amazon area. For tropical and sub-tropical regions, an LGP of less than 120 days indicates hyper-arid, arid, and dry semi-arid lands with unsuitable or highly variable and unreliable conditions for crop agriculture. Nearly 1 billion people worldwide and more than 180 million people in Africa alone are presently living in these vulnerable environments, relying to a large extent on agriculture for their livelihood (*Plates 3.5* and *3.6*). Climate change will cause a deterioration of growing conditions for crops and natural ecosystems in developing countries (excluding temperate Central and East Asia) where some 27.4 million km^2, i.e., just over 40% of total area in these countries, currently have an LGP of less than 120 days. Calculations with climate projections from three of the four GCMs (excluding NCAR-PCM) produce consistent increases of arid areas in developing countries, on average of 0.9 million km^2 (or 3.4%) and 1.5 million km^2 (5.5%) respectively for simulations of SRES B2 and A2 emission scenarios in the 2080s.

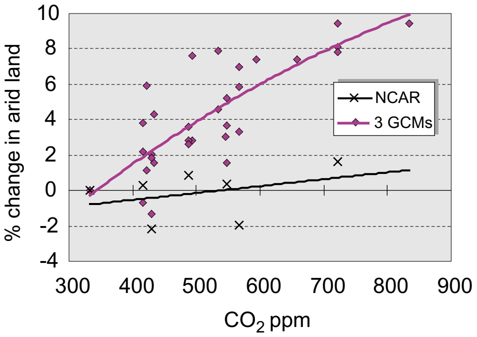


Figure 3.1. Impact of climate change on extents of arid and dry semi-arid lands in sub-Saharan Africa.

More than 60% of the negative outcomes occur in sub-Saharan Africa, where AEZ estimates for the reference climate (1961–1990) amount to some 10.8 million km^2 of land with an LGP of less than 120 days. Climate changes, as projected by GCMs for the SRES B2 and A2 emission scenarios in the 2080s, would result in another 580,000 km^2 (scenario B2, with a range of 360,000–760,000 km^2) and 920,000 km^2 (scenario A2, with a range of 850,000–1,025,000 km^2) of arid and dry semi-arid lands, an increase of 5.4% and 8.5% over current conditions respectively. This outcome is mirrored by a decrease of areas with favorable growing conditions, such as the moist semi-arid and sub-humid zones with an LGP of 120–270 days. For these areas, average reductions of their extents in the 2080s amount to 310,000 and 510,000 km^2 for the SRES B2 and A2 climate scenarios respectively, a decrease of 3.3% and 5.5% of these zones compared to current conditions. The results for sub-Saharan Africa are presented in *Figure 3.1*, which shows percentage changes in extents of land with an LGP of less than 120 days relative to the level of atmospheric CO_2 concentrations occurring in different SRES scenarios.

3.3 Environmental Constraints to Crop Agriculture

3.3.1 Land constraints under current climate

The AEZ land-resources inventory allows a characterization of various regions according to the prevailing environmental constraints. A soil and terrain constraint classification has been formulated and has been applied to each grid-cell of the land-resources inventory, covering all land excluding Antarctica. The constraints considered include: terrain-slope, soil depth, soil fertility, soil drainage, soil texture, and soil salinity/sodicity. Climate constraints are classified according to the length of periods with cold temperatures and moisture limitations.

Table 3.1. Severe environmental constraints for rain-fed crop production (reference climate, 1961–1990).

		Land with severe constraints for rain-fed cultivation of crops						
Region	Total extents (10^6 ha)	Total with constraints (10^6 ha)	Total with constraints (%)	Too cold (%)	Too dry (%)	Too wet (%)	Too steep (%)	Poor soils (%)
North America	2,139	1,529	71.5	35.9	14.0	0.0	3.2	18.5
Eastern Europe	171	31	18.0	0.0	0.0	0.0	3.0	15.0
Northern Europe	173	78	45.2	18.0	0.0	0.0	2.5	24.6
Southern Europe	132	58	44.1	0.7	0.2	0.0	20.2	23.1
Western Europe	110	32	28.9	0.6	0.0	0.0	10.3	18.1
Russian Federation	1,677	1,140	68.0	44.5	1.9	0.0	1.9	19.7
Central America & Caribbean	271	140	51.7	0.0	27.7	0.4	15.0	8.7
South America	1,778	1,101	61.9	0.5	10.6	6.6	3.2	41.0
Oceania & Polynesia	848	630	74.3	0.1	58.6	3.9	1.2	10.5
Eastern Africa	888	462	52.1	0.0	27.0	0.0	3.1	22.0
Middle Africa	657	387	58.9	0.0	12.9	0.2	0.5	45.3
Northern Africa	547	500	91.3	0.0	88.0	0.0	2.2	1.0
Southern Africa	266	200	75.3	0.0	58.7	0.0	6.5	10.1
Western Africa	632	464	73.3	0.0	50.6	0.0	0.1	22.7
Western Asia	433	364	84.2	0.0	74.2	0.0	6.2	3.7
Southeast Asia	445	234	52.6	0.0	0.0	25.0	11.5	16.1
South Asia	668	361	54.1	2.0	34.7	0.0	10.6	6.8
East Asia & Japan	1,152	776	67.4	16.3	26.4	0.2	12.0	12.4
Central Asia	414	372	89.8	2.5	75.7	0.0	4.8	6.7
Developed	5,231	3,478	66.5	29.6	15.8	0.1	3.1	17.9
Developing	8,168	5,381	65.9	2.7	33.3	3.2	5.6	21.0
World	13,400	8,859	66.1	13.2	26.5	2.0	4.6	19.8

Note: Columns are mutually exclusive and the order in which constraints are listed defines a priority ranking for areas where multiple severe constraints apply. For instance, land with very poor soil conditions in the arctic region is shown as “too cold” and is not listed as having severe soil constraints.

On the basis of available global soil, terrain, and climatic data, the AEZ assessment estimates that under current climate conditions, some 8.9 billion hectares of land – about two-thirds of the Earth’s surface – suffer severe constraints for rain-fed crop cultivation. An estimated 13% is too cold, 27% is too dry, 2% is too wet, 5% is too steep, and 20% has very poor soils. *Table 3.1* presents the regional distribution of different types of severe constraints to rain-fed crop production. Please note that columns in *Table 3.1* are mutually exclusive and that the order in which constraints are listed defines a priority ranking for areas where multiple severe constraints apply. For instance, land with very poor soil conditions in the arctic region is shown as “too cold” and is not listed as having severe soil constraints.

3.3.2 Land constraints under climate change

The AEZ assessment estimates, for climate scenario HadCM3-A1FI in the 2080s, that the amount of land with severe environmental constraints for rain-fed crop cultivation will slightly decrease from 88.6 million km^2 to 87.7 million km^2 of land. For developed countries, the net decrease in extent of land with severe constraints amounts to 1.6 million km^2, while the net extent in developing countries increases by 0.7 million km^2. However, these aggregate net totals hide many important changes.

In the warmer world of scenario HadCM3-A1FI, only an estimated 5% will suffer from severe cold temperature constraints in the 2080s, a major change from some 13% under current climate conditions. Too-dry conditions occur in 29% of land, and 1% is too wet. As climate change alters the prevalence of climate limitations, terrain and soil become limiting factors in respectively 6% (i.e., too steep) and 25% (poor soil conditions) of land. *Table 3.2* presents the regional distribution of different types of severe constraints to rain-fed crop production under the Hadley Centre climate-change experiment.

Plates 3.7 and *3.8* present, for current conditions and for scenario HadCM3-A1FI in the 2080s, the spatial distribution of areas with overall no constraints, slight and moderate constraints, and areas with severe temperature, moisture stress, excess wetness, terrain or soil constraints. *Plate 3.9* highlights areas where improvements with regard to environmental constraints to crop production can be expected, as well as areas where climate change would result in harsher environments for crop agriculturalists.

Table 3.3 presents a transition matrix for extents of grid-cells as classified for reference climate (1961–1990) and for conditions according to scenario HadCM3-A1FI in the 2080s. Current conditions are summarized by the row totals shown in the first numeric column. Column totals, in the last row of the matrix, denote class extents calculated for future climate. The transition matrix captures underlying dynamics of changes better than the aggregate class totals alone. For instance, while the extent of land classified as posing no constraint for rain-fed crop agriculture increases from 4,153,000 to 4,338,000 km^2, the full matrix reveals that only 3,413,000 km^2, about 80% of the area without constraints under current conditions, would remain in that class.

3.3.3 Convergence of scenario results for environmental constraints

On the positive side, according to all 12 GCM climate projections for the 2080s, the results suggest that, for the world as a whole, land with severe constraints that essentially prohibit crop agriculture may decrease slightly by 0.7–2.2% of total

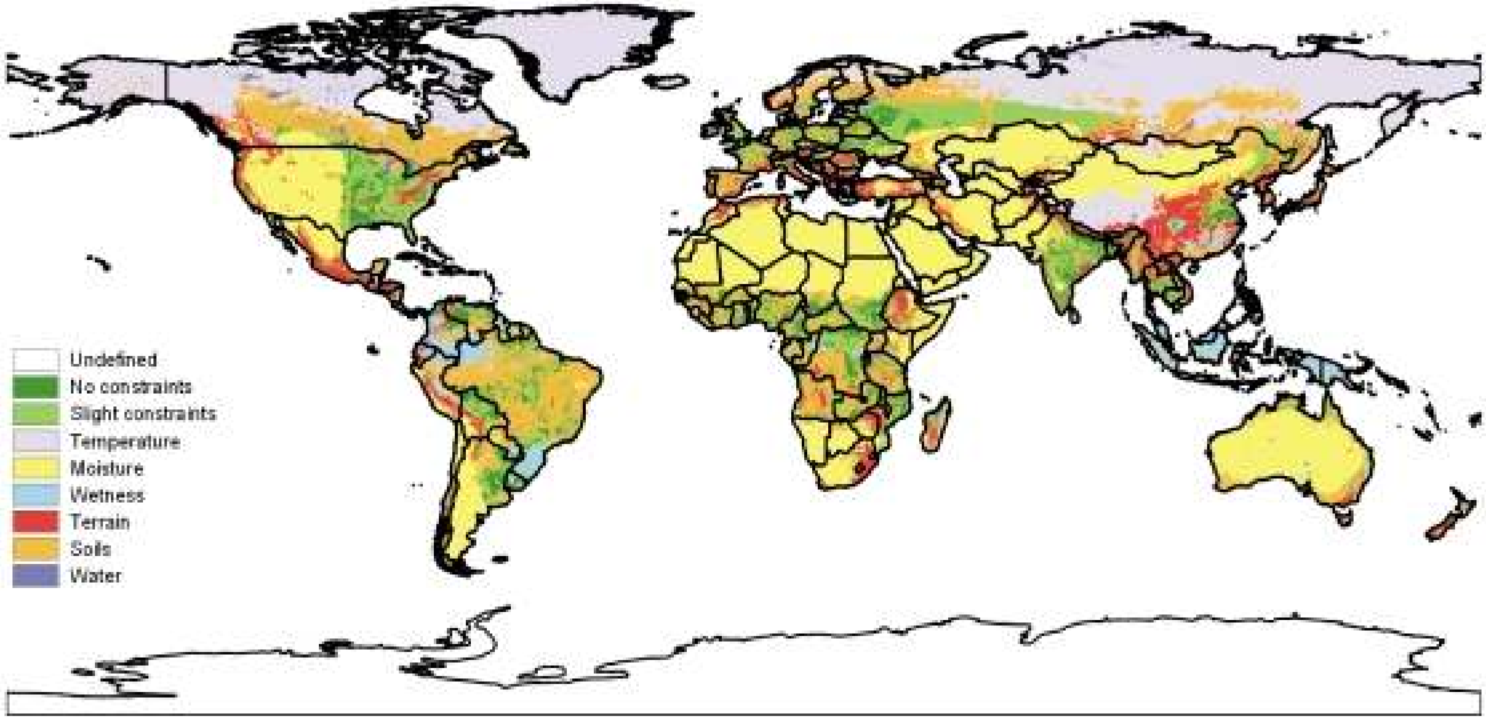


Plate 3.7. Environmental constraints to rain-fed crop agriculture under current conditions (reference climate, 1961–1990).

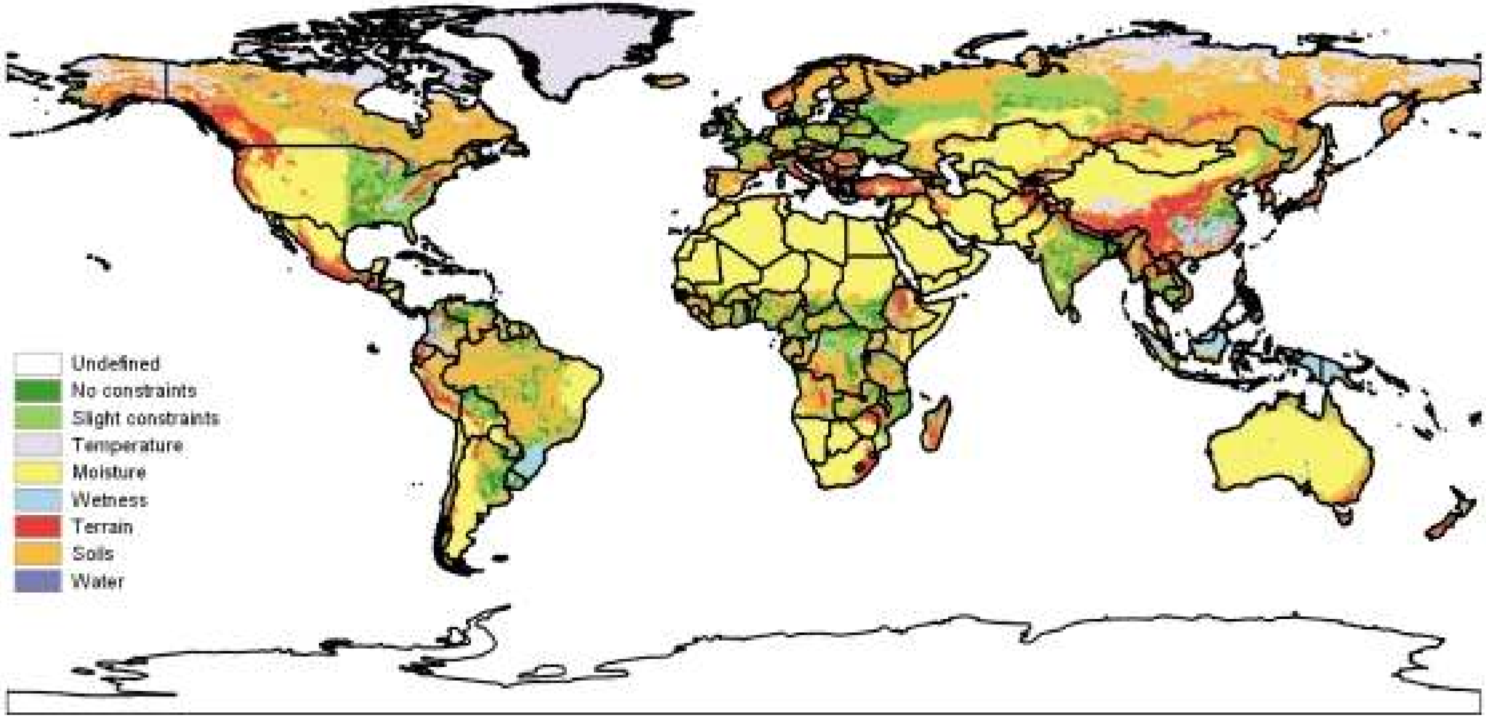


Plate 3.8. Environmental constraints to rain-fed crop agriculture under future climate (HadCM3-A1FI, 2080s).

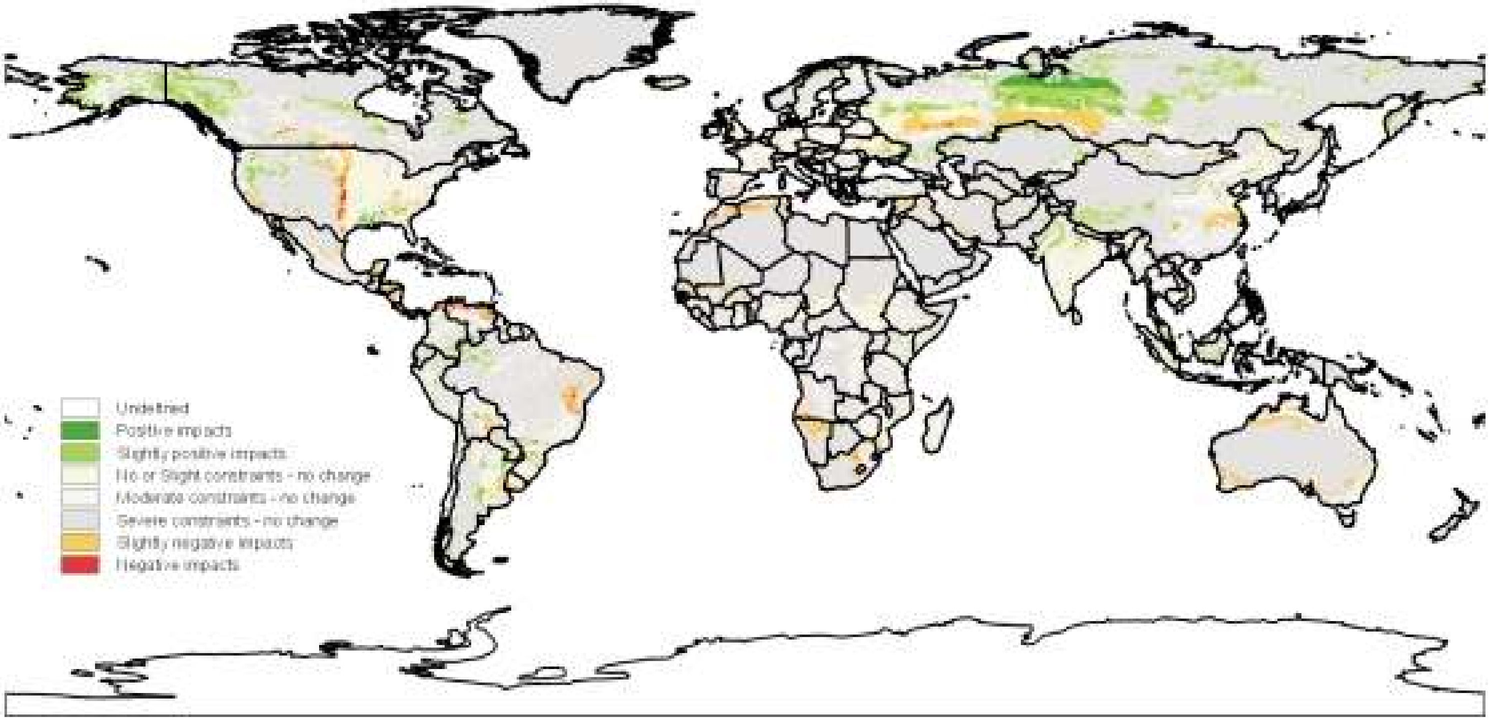


Plate 3.9. Change in environmental constraints to rain-fed crop agriculture due to climate change (HadCM3-A1FI, 2080s).

Table 3.2. Severe environmental constraints for rain-fed crop production (scenario HadCM3-A1FI in 2080s).

		Land with severe constraints for rain-fed cultivation of crops						
Region	Total extents (10^6 ha)	Total with constraints (10^6 ha)	(%)	Too cold (%)	Too dry (%)	Too wet (%)	Too steep (%)	Poor soils (%)
North America	2,139	1,451	67.8	21.2	13.9	0.0	4.9	27.9
Eastern Europe	171	31	18.0	0.0	0.0	0.0	3.0	15.0
Northern Europe	173	66	38.3	0.5	0.0	0.4	4.5	32.9
Southern Europe	132	60	45.5	0.0	2.4	0.0	20.4	22.6
Western Europe	110	32	28.9	0.0	0.0	0.0	10.8	18.1
Russian Federation	1,677	1,018	60.7	12.3	0.2	0.0	5.0	43.2
Central America & Caribbean	271	160	58.8	0.0	37.9	0.0	14.1	6.9
South America	1,778	1,128	63.4	0.0	18.3	1.2	3.1	40.7
Oceania & Polynesia	848	678	79.9	0.1	66.3	4.0	1.2	8.3
Eastern Africa	888	466	52.5	0.0	27.3	0.0	3.1	22.0
Middle Africa	657	397	60.3	0.0	14.4	0.8	0.4	44.8
Northern Africa	547	530	96.8	0.0	95.4	0.0	1.2	0.2
Southern Africa	266	235	88.4	0.0	78.8	0.0	5.7	4.0
Western Africa	632	473	74.8	0.0	54.3	0.0	0.1	20.5
Western Asia	433	372	86.0	0.0	77.1	0.0	6.2	2.7
Southeast Asia	445	211	47.3	0.0	0.0	17.3	12.0	18.0
South Asia	668	362	54.1	0.1	35.0	0.0	11.7	7.3
East Asia & Japan	1,152	753	65.4	3.0	31.4	0.7	15.2	15.1
Central Asia	414	350	84.4	0.0	60.1	0.0	6.8	17.4
Developed	5,231	3,320	63.5	12.6	16.6	0.2	4.8	29.2
Developing	8,168	5,449	66.7	0.4	37.0	1.7	6.2	21.5
World total	13,400	8,769	65.4	5.2	29.0	1.1	5.7	24.5

Table 3.3. Transition matrix of global changes in environmental constraints to crop agriculture (scenario HadCM3-A1FI in 2080s).

Reference		HadCM3-A1FI, 2080s			
climate	1,000 km^2	No constraint	Slight	Moderate	Severe
No constraints	4,153	**3,413**	464	206	69
Slight	12,054	607	**8,985**	2,172	289
Moderate	29,203	316	2,607	**23,554**	2,726
Severe	88,585	0	547	3,434	**84,605**
		4,338	12,603	29,366	87,688

Table 3.4. Distribution of constraints across all 12 climate projections for the 2080s compared to reference climate of 1961–1990.

Constraints	1961–	HadCM3				CSIRO				CGCM2		NCAR	
(%)	1990	A1FI	A2	B1	B2	A1B	A2	B1	B2	A2	B2	A2	B2
None	3.1	3.2	3.1	3.3	3.1	3.0	3.0	3.0	3.1	3.4	3.3	3.6	3.5
Slight	9.0	9.4	9.4	9.0	9.0	9.5	9.3	9.2	9.3	9.6	9.3	9.5	9.4
Moderate	21.8	21.9	22.3	22.3	22.6	23.3	23.5	23.3	23.2	22.8	22.9	23.0	22.5
Severe, of which:	66.1	65.4	65.2	65.3	65.2	64.2	64.3	64.4	64.5	64.2	64.5	63.9	64.5
Temperature	13.2	5.2	6.7	8.7	8.4	3.9	3.5	5.2	4.6	6.5	8.3	8.8	10.1
Moisture	26.5	29.0	28.1	27.7	27.7	26.7	27.0	27.0	27.1	26.8	26.6	25.0	25.7
Wetness	2.0	1.1	1.1	1.2	1.0	1.8	1.7	1.7	1.8	1.1	1.2	2.0	1.8
Terrain	4.6	5.7	5.6	5.4	5,4	6.0	6.0	5.8	5.9	5.8	5.5	5.4	5.2
Soil	19.8	24.5	23.7	22.3	22.7	25.8	26.1	24.6	25.0	23.9	23.0	22.7	21.8

land,[1] i.e., by some 1–3 million km^2. In developed countries this decrease is rather pronounced, namely 2.3–4.8% of a total land area of some 52 million km^2. In the developing world the emerging picture is mixed. *Table 3.4* compares the distributions of the environmental constraint classification across all 12 GCM-based climate scenarios with their occurrence under current reference climate conditions.

Table 3.5 presents the range of estimates of land with severe, slight, and no constraints across four GCM outputs for the 2080s based on the emission trajectories of the SRES A2 scenario in comparison to values obtained for the reference climate of 1961–1990. Regions of the developed world that are seeing improvements, i.e., a reduction of land with severe environmental constraints, mainly due to the removal of cold-temperature constraints, are in particular the regions of Northern Europe (5.5–6.8% of total area), Russia (5.3–8.0% of total area), and Central Asia (5.0–8.3% of total area). Also North America (3.3–5.6% of total area) and East Asia & Japan (1.4–2.6% of total area) are consistently experiencing an improvement with regard to land constraints for crop agriculture.

On the negative side, also consistently according to the four GCM climate projections of SRES A2 scenario for the 2080s, the following regions may experience an increase of land with severe constraints: Central America & Caribbean (1.2–2.9% of total area), Oceania & Polynesia (0.3–4.3% of total area), Northern Africa (1.9–3.4% of total area), and Western Asia (0.1–1.0% of total area). In Southern Africa, as much as an additional 11% of total land may suffer from severe constraints.

When looking at the other end of the environmental spectrum, i.e., as to changes of land with no or with only slight constraints, thereby indicating "good" land for

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[1] Note that these percentages here and in the following paragraphs refer to total land rather than class extents.

Table 3.5. Percentage of land with severe versus slight or no constraints for reference climate (1961–1990) and maximum and minimum values[a] occurring in four GCM climate projections for the 2080s based on SRES A2 emission scenario.

	Severe constraints % of total land			Slight or no constraints % of total land		
	Ref	Min	Max	Ref	Min	Max
North America	71.5	65.9	68.2	11.7	11.2	13.3
Eastern Europe	18.0	18.0	18.0	49.9	46.6	53.4
Northern Europe	45.2	38.3	39.7	25.9	16.6	23.5
Southern Europe	44.1	44.1	44.4	17.0	15.9	16.6
Western Europe	28.9	28.9	28.9	45.2	35.5	45.7
Russian Federation	68.0	60.0	62.7	14.9	19.4	21.2
Central America & Caribbean	51.7	52.1	54.6	10.5	10.3	10.9
South America	61.9	60.6	61.7	11.1	11.3	12.7
Oceania & Polynesia	74.3	74.4	78.6	5.0	3.6	4.9
Eastern Africa	52.1	50.5	54.5	18.9	16.7	18.9
Middle Africa	58.9	58.8	60.1	12.2	11.3	11.8
Northern Africa	91.3	93.2	94.7	1.8	0.4	0.9
Southern Africa	75.3	74.6	86.2	1.6	0.1	0.6
Western Africa	73.3	72.6	75.0	11.3	9.7	11.1
Western Asia	84.2	84.3	85.2	2.9	2.1	2.7
Southeast Asia	52.6	47.3	51.5	11.3	11.4	13.6
South Asia	54.1	50.1	53.9	22.6	21.0	24.7
East Asia & Japan	67.4	64.8	66.0	8.7	5.9	8.1
Central Asia	89.8	81.5	84.8	0.9	2.2	2.9
Developed	66.5	61.7	63.6	14.3	15.2	16.8
Developing	65.9	64.7	66.2	10.7	10.3	10.7
World	66.1	63.9	65.2	12.1	12.2	13.1

[a] Maximum and minimum values across constraints do generally not add up to 100%, since values are not necessarily from the same scenario.

agriculture, a somewhat different picture emerges. It must be noted that decreases in land with severe constraints for agriculture do not necessarily imply increases in prime land, as in North America, Northern Europe, and East Asia & Japan. The decreases of severe constraints result in these regions merely in more marginal agricultural land. Improvements are found consistently in Russia, South America, Southeast Asia, and Central Asia.

According to all four GCM projections for the 2080s, the total extent of potentially good agricultural land systematically decreases in Northern Europe, Southern Europe, all five African regions, Western Asia, East Asia & Japan, and Oceania & Polynesia.

Table 3.6. Transition matrix of changes in environmental constraints to crop agriculture of land in sub-Saharan Africa (scenario HadCM3-A1FI, 2080s).

Reference climate	1,000 km^2	HadCM3-A1FI, 2080s No constraint	Slight	Moderate	Severe
No constraint	535	**457**	66	6	6
Slight	2,704	11	**2,395**	262	36
Moderate	6,061	3	67	**5,379**	612
Severe	15,128	0	0	80	**15,048**
		471	2,528	5,727	15,702

3.3.4 The case of sub-Saharan Africa

Considering 12 climate projections of SRES scenarios simulated by four GCM groups (at Hadley Centre, CSIRO, Canadian Climate Centre, and NCAR), the following overall picture emerges for sub-Saharan Africa: constraint-free prime land decreases, land with moisture stress increases, land with extreme wet conditions decreases slightly. Altogether, land with no or only slight constraints decreases for 11 of 12 GCM climate projections. For the SRES scenario A2, a decrease of good land occurs for all four GCM climate projections, by an average of 204,000 km^2, i.e., 6.3% of total sub-Saharan prime land; results range from 82,000 km^2 (NCAR-PCM) to 273,000 km^2 (CSIRO). Land with severe climate, soil, or terrain constraints, prohibiting use for rain-fed agriculture, increases according to 10 of the 12 climate projections, by 260,000–610,000 km^2. Only for the NCAR-PCM model, which differs markedly from the results of other GCM experiments and paints a somewhat benign future, the extent of sub-Saharan land with severe environmental constraints to crop agriculture declines by about 150,000 km^2 for both the simulated A2 and B2 scenarios (see *Figures 3.2* and *3.3*).

A detailed picture of the changes in environmental constraint classification is presented in *Table 3.6*, showing the transition matrix from current reference climate conditions to a climate of the 2080s for projections of scenario HadCM3-A1FI for land in sub-Saharan Africa, classified according to four broad groups: no constraints, slight, moderate, and severe constraints.

As discussed before, current conditions are summarized in the transition matrix by the row totals shown in the first numeric column. Column totals, in the last row of the matrix, denote class extents calculated for future climate. The values in each row of the transition matrix indicate for different classes the fate of extents classified under current conditions. The table indicates that only 80,000 km^2 with currently severe environmental constraints, out of more than 15.1 million km^2, are expected to improve with climate change, whereas more than 600,000 km^2 currently classified as moderately constrained would migrate to the class of severe environmental limitations.

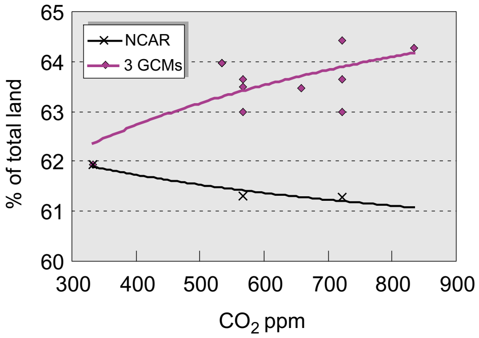

Figure 3.2. Changes in sub-Saharan land with severe environmental constraints versus increasing atmospheric CO_2 concentrations.

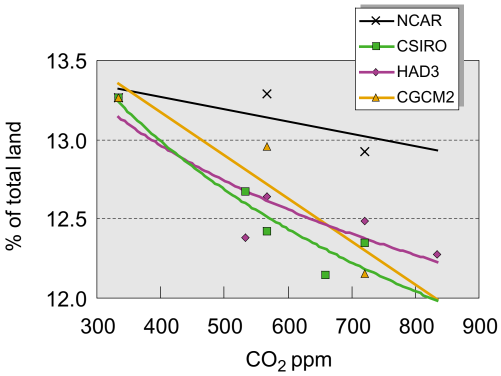

Figure 3.3. Changes in sub-Saharan land with no or slight environmental constraints versus increasing atmospheric CO_2 concentrations.

3.4 Climate Variability and Variability of Rain-fed Cereal Yields and Production

3.4.1 Climate variability

On the basis of historical annual time-series of climate data for the period 1901–1995, for each individual year the length of growing period (LGP) was calculated, and standard deviation of LGP (SD in days) and coefficients of variation (CV in %) were determined. For instance, *Plate 3.10* shows the simulated standard deviation of LGP for the period 1901–1995, highlighting areas of unreliable growing periods. Areas with particular high variability in year-by-year growing conditions are found in the mid-west of the USA, northeast Brazil, northeast Argentina and Uruguay,

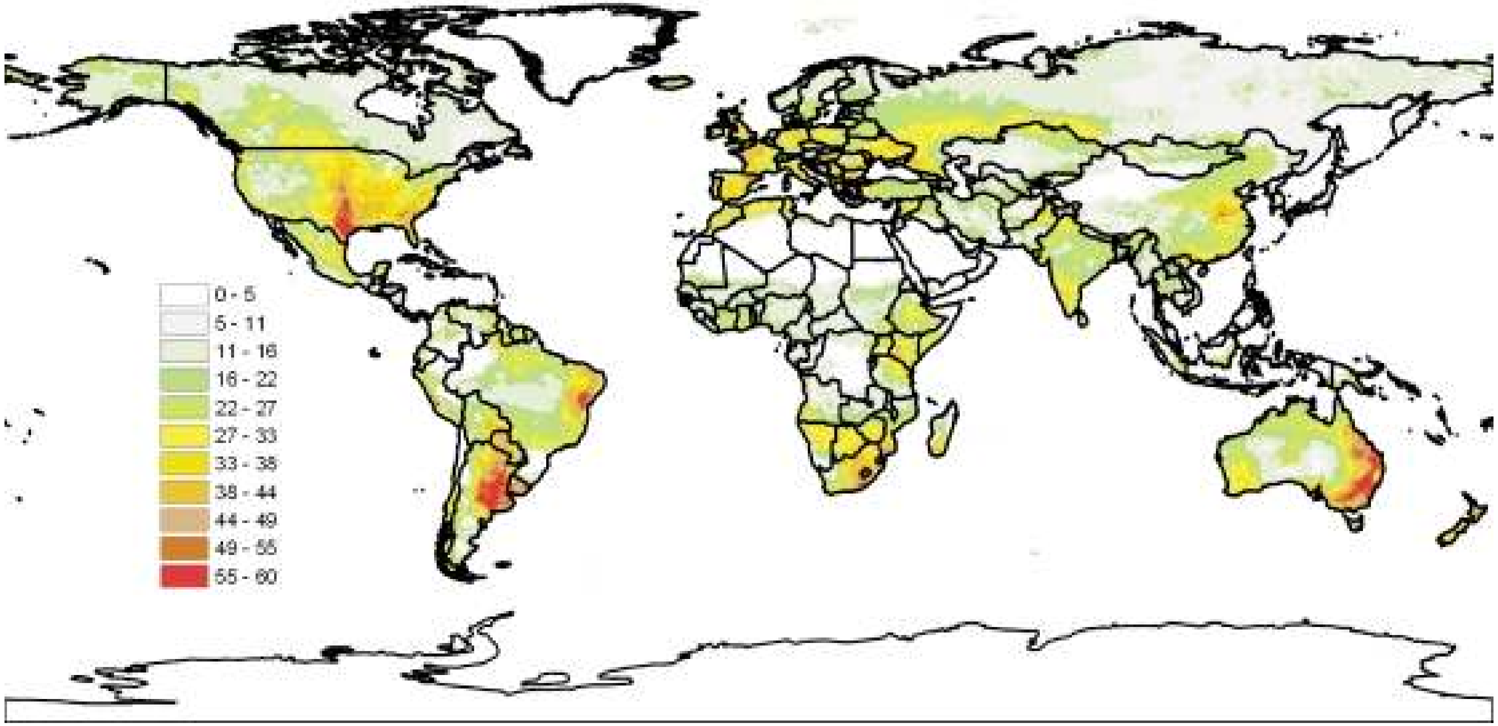

Plate 3.10. Standard deviation of length of growing period (SD in days).

Southern Africa, Southern Mozambique, and the southeast of Australia. In all these areas, the SD of LGP exceeds 40 days and the CV is larger than 45%.

3.4.2 Variability of rain-fed cereal production

Historical climate data for individual years has also been used to calculate a time-series of production potentials for cereals. Of a total of 83 cereal types, consisting of cultivars of wheat, rice, barley, rye, sorghum, millet, and setaria, AEZ tests and selects for each grid-cell and each year the cereal type that results in the highest production. Results were obtained for individual years, and means and standard deviations were calculated separately for the periods 1901–1930, 1931–1960, and 1961–1990. The grid-cell results in terms of average annual total production potential and its annual variations were subsequently aggregated at country and regional levels. The assessment was carried out for areas classified as being in cultivation in 1992–1993 according to interpretation of remotely sensed data, as well as for all land with rain-fed cereal-production potential, regardless of current use. The data set used to mask areas with current cultivation is shown in *Plate 3.11*. Furthermore, for comparison with average climate conditions, calculations were also performed with average climate data of the reference period 1961–1990.

During the 20th century, the global cereal-production potential on currently cultivated land (for fixed technology level), as simulated with AEZ year by year, improved steadily, by some 6%, between the periods of 1901–1930 and 1961–1990. It is also interesting to compare the average cereal output calculated on a year-by-year basis with output that would result from an averaged reference climate. Over the period 1961–1990, the calculations using average climate data are more than 10% higher than the average over individual years, providing a rough estimate of the losses being incurred due to climate variability.

The picture becomes more diverse when looking at regional and country levels (see *Table 3.7*). Most regions have been experiencing some improvements in attainable production potential during the last century. In the developed nations as a whole, potential cereal output increased by more than 8% due to changing climate, while simulated output variability decreased. Improvements range from little change in potential cereal output in Southern Europe to an increase of more than 20% in Russia.

In the developing countries as a whole, simulated potential cereal output increased somewhat, only by less than 3%. Yet variability increased as well. No improvements were found for sub-Saharan Africa. Some regions, for instance in Southern Africa, even lost average potential cereal output and at the same time saw a considerable increase in the variability of cereal outputs.

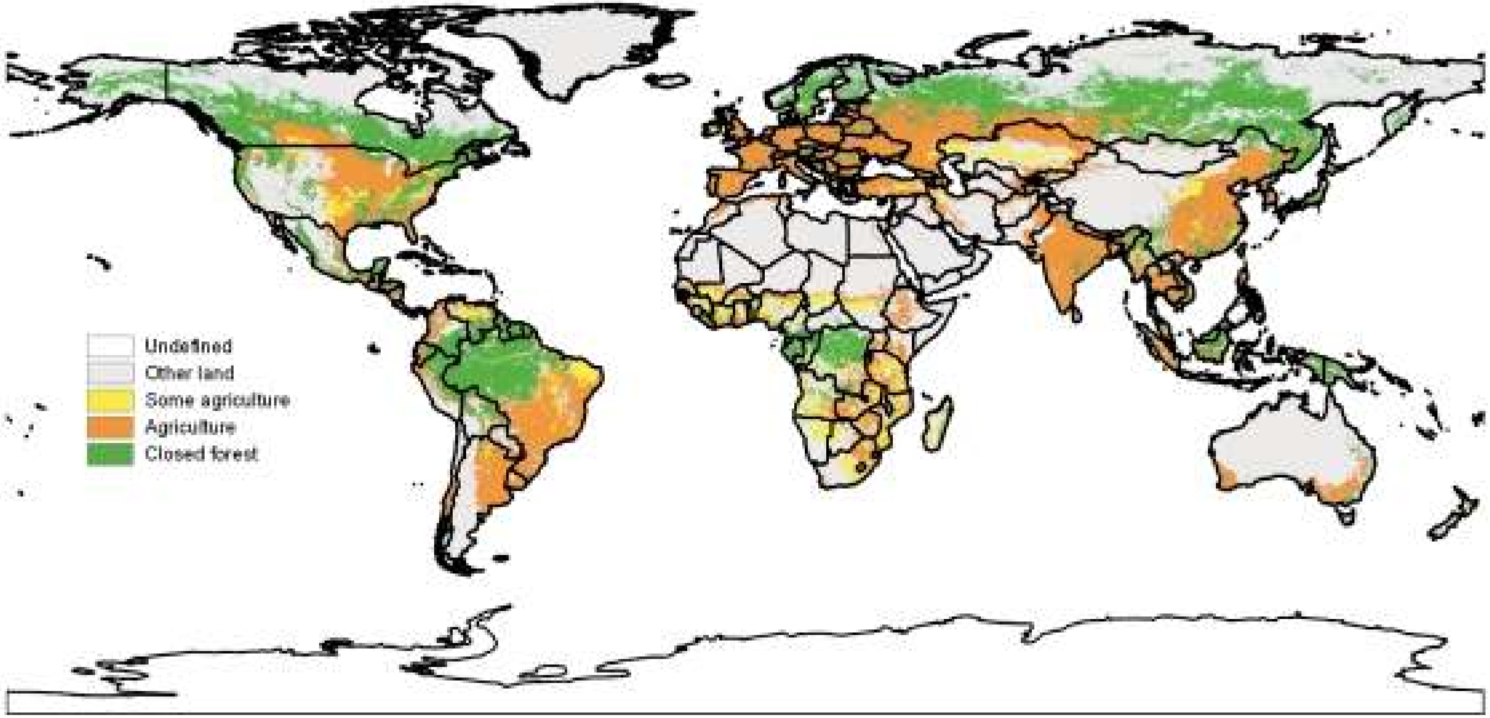

Plate 3.11. Distribution of current cultivated land and closed forests in 1992–1993.

Table 3.7. Variability and level of cereal-production potential for the periods 1901–1930, 1931–1960, 1961–1990 compared to reference climatic conditions of 1961–1990, on current cultivated land.

	Individual years						Average climate
	1901–1930		1931–1960		1961–1990		1961–1990
Region	Average potential production (mill. tons)	Coefficient of variation (%)	Average potential production (mill. tons)	Coefficient of variation (%)	Average potential production (mill. tons)	Coefficient of variation (%)	Average potential production (mill. tons)
North America	993	16.6	1006	18.0	1060	14.4	1189
Eastern Europe	473	17.0	460	20.5	499	17.0	613
Northern Europe	111	25.7	125	22.0	122	17.2	154
Southern Europe	149	14.4	148	14.2	150	10.0	170
Western Europe	272	19.9	274	16.3	278	19.8	345
Russian Federation	408	27.0	402	23.3	495	26.5	629
Central America & Caribbean	96	3.2	97	6.1	98	5.9	101
South America	469	7.8	464	6.0	487	7.1	543
Oceania & Polynesia	49	32.3	50	29.0	54	26.3	55
Eastern Africa	326	3.5	324	3.0	327	5.6	344
Middle Africa	81	2.6	79	3.1	80	2.0	82
Northern Africa	22	18.0	22	20.4	23	22.4	25
Southern Africa	43	33.2	42	29.8	41	36.7	38
Western Africa	134	5.5	135	5.7	133	7.6	139
Western Asia	73	22.2	60	33.7	66	23.3	79
Southeast Asia	220	2.6	221	1.9	219	2.4	220
South Asia	711	9.7	736	6.0	739	6.5	783
East Asia & Japan	391	9.4	410	10.7	420	10.1	448
Central Asia	28	19.7	30	21.8	31	23.0	26
Developed	2477	10.1	2489	10.8	2681	8.1	3178
Developing	2579	3.4	2606	3.3	2650	3.8	2815
World	5055	5.3	5095	5.3	5330	4.7	5993

3.5 Changes in Rain-fed Crop Production Potentials

There are various ways of estimating the extent and production potential of land for rain-fed crops. Any quantification depends on a variety of assumptions concerning the range of crops and crop cultivars considered; the definition of what level of output qualifies as acceptable; the social acceptance of land-cover conversions (of forest in particular); and what land constraints may be alleviated with farming technology. The results of extents of land suitable for the production of crop groups and the potential production from these extents are presented in two sets: (i) considering all land, and (ii) considering current cultivated land. *Table 3.8* shows the results of the estimation for five crop groups, cereals, roots and tubers, pulses, oil crops, and sugar crops, which are assessed at an assumed high level of inputs and management level, respectively for very suitable and suitable areas (VS+S), and very suitable and suitable and moderately suitable areas (VS+S+MS). For details of assessments of crops under various level of inputs circumstances, reference can be made to an IIASA Research Report and CD-ROM "Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results" (Fischer *et al.*, 2002).

Results (see *Tables 3.8a* and *3.8b*) show that in both cases, i.e., all land and current cultivated land, cereals as a group have the widest adaptation to prevailing ecological conditions. About 22% of the global total land area (excluding Antarctica) is suitable (VS+S+MS) for cereals. Sugar crops, due to more specific ecological requirements, are suitable in about 11%. Pulses, suitable in about 14% of the total land area, have, due to relative low yield levels, a relative low production potential.

It should be emphasized that these results indicate the potential area suitable for each of these individual crop groups. In reality, the demand mix for domestic consumption and trade will drive the allocation of land to particular crops.

The values presented in *Table 3.8* are used as a reference for comparison with results of climate-change scenarios.

3.5.1 Cereals

Figure 3.4 offers a graphical representation of the change of cereal production potential in relation to changes in atmospheric CO_2 concentrations and related global warming, as predicted by the various GCM experiments for IPCC SRES scenarios. The production change is expressed as a percentage change in relation to the reference climate (1961–1990). The results are plotted for, respectively, all land and current cultivated land, separately for developed and developing countries.

The figure shows that with increasing CO_2 concentrations when considering all land, production of cereals will increase according to all scenarios. The strongest increase is found in developed nations, mainly due to the expansion of suitable areas at higher latitudes. When considering current cultivated land only, the results

Table 3.8a. Extents of rain-fed land with cultivation potential for major crop groups (million ha), reference climate (1961–1990).

Suitability	Cereals	Roots & tubers	Pulses	Oil crops	Sugar crops
All land					
VS+S land	1,980	1,422	1,237	1,812	729
VS+S+MS land	2,959	2,186	1,901	2,585	1,418
Current cultivated land					
VS+S land	992	686	665	825	408
VS+S+MS land	1,368	1,016	968	1,137	671

Table 3.8b. Production potentials of rain-fed land with cultivation potential for major crop groups (million tons), reference climate (1961–1990).

Suitability	Cereals	Roots & tubers	Pulses	Oil crops	Sugar crops
All land					
VS+S land	13,959	11,649	3,260	6,485	5,220
VS+S+MS land	17,857	15,616	4,517	8,203	9,246
Current cultivated land					
VS+S land	7,450	5,107	1,774	2,651	2,233
VS+S+MS land	9,036	6,664	2,274	3,302	3,429

Note: The suitability assessment for the crop groups has been based on assessments of individual crops and crop cultivars. The cereal group is made up of wheat, barley, rye, rice, grain maize, sorghum, millet, and setaria cultivars; roots and tubers of cassava, sweet potato and white potato; pulses of phaseolus bean, chickpea and cowpea; oil crops of soybean, rape, groundnut, sunflower, oil palm and olive, and for sugar crops both sugarcane and sugarbeet cultivars have been used.

are far less spectacular, except for the NCAR-PCM climate projections, which predict substantive potential production gains even on current cultivated land for both developed and developing countries. The other scenarios predict little change for the developed nations. Hadley Centre (shown as HAD3 in graphs) and Canadian Climate Center (CGCM2) projections show, after an initial increase, a decline of production potential with climate changes for developing nations, owing to CO_2 concentrations above 600–700 ppm. Please note that results account for yield improvements due to so-called CO_2 fertilization, i.e., enhanced photosynthesis due to CO_2 enrichment of the atmosphere.

The regional aggregation of results, based on HadCM3 A1FI scenario (see *Tables 3.9* and *3.10*), shows for both suitable land extents and production potential of cereals a significant decrease in Northern and Southern Africa in both cases when considering all land or current cultivated land. Substantial increases in suitable areas and production potentials in all land as well as in current cultivated land are

Table 3.9. Impact of climate change on suitable land for cereals.

	All land					Current cultivated land				
	Reference 1961–1990	HadCM3-A1FI (relative to reference)				Reference 1961–1990	HadCM3-A1FI (relative to reference)			
Region	(1,000 ha)	1990	2020	2050	2080	(1,000 ha)	1990	2020	2050	2080
North America	358,202	102	110	121	141	235,416	99	103	99	102
Eastern Europe	124,935	103	101	96	96	121,017	103	101	96	96
Northern Europe	45,462	101	109	113	116	33,149	103	105	103	103
Southern Europe	38,524	98	94	94	91	33,761	98	94	94	90
Western Europe	63,267	100	98	98	97	61,514	100	98	98	96
Russian Federation	243,898	105	124	148	164	167,828	101	105	104	101
Central America & Caribbean	51,505	99	105	109	99	23,309	100	104	113	96
South America	653,060	102	104	105	102	113,416	102	103	100	94
Oceania & Polynesia	115,310	102	102	102	88	18,844	102	100	100	75
Eastern Africa	316,282	99	98	100	96	76,855	100	101	101	97
Middle Africa	254,500	102	104	106	102	20,931	103	105	109	103
Northern Africa	11,782	106	97	62	25	7,172	104	100	75	35
Southern Africa	31,316	88	55	48	54	10,477	93	62	57	64
Western Africa	178,095	99	101	100	96	36,544	100	99	96	89
Western Asia	23,561	105	112	94	101	20,461	103	112	94	100
Southeast Asia	97,831	100	98	103	104	71,654	100	99	104	105
South Asia	189,132	101	101	99	97	174,284	101	100	97	95
East Asia & Japan	149,694	102	99	108	110	130,975	101	95	100	97
Central Asia	12,908	111	117	147	153	10,450	107	116	142	151
Developed	993,529	102	110	119	128	675,582	100	102	100	99
Developing	1,965,735	101	101	103	100	692,475	101	100	100	97
World	2,959,264	101	104	108	109	1,368,057	101	101	100	98

Table 3.10. Impact of climate change on cereal production potentials.

	All land					Current cultivated land				
	Reference 1961–1990	HadCM3-A1FI (relative to reference)				Reference 1961–1990	HadCM3-A1FI (relative to reference)			
Region	(1,000 tons)	1990	2020	2050	2080	(1,000 tons)	1990	2020	2050	2080
North America	2,579,314	101	109	114	128	1,760,002	99	106	99	96
Eastern Europe	952,308	104	99	92	91	925,596	104	99	92	91
Northern Europe	298,436	98	111	114	118	239,877	98	107	98	98
Southern Europe	248,701	97	92	90	82	223,471	97	92	89	80
Western Europe	498,449	98	89	88	80	486,705	98	89	88	79
Russian Federation	1,257,656	110	127	165	191	953,060	105	106	113	106
Central America & Caribbean	284,772	99	109	117	105	137,143	99	107	119	94
South America	3,592,333	104	109	115	113	699,762	105	108	107	106
Oceania & Polynesia	644,053	101	96	97	87	81,652	102	100	110	92
Eastern Africa	2,126,133	100	100	102	98	514,856	100	102	103	101
Middle Africa	1,321,918	102	104	107	102	123,308	103	105	110	103
Northern Africa	56,824	107	93	59	24	34,167	106	97	72	34
Southern Africa	145,724	88	53	56	59	51,928	93	58	67	72
Western Africa	1,050,120	99	99	98	94	207,466	99	98	95	86
Western Asia	121,028	102	112	88	99	106,551	101	111	87	99
Southeast Asia	487,360	103	104	110	109	368,162	103	105	111	111
South Asia	1,377,772	103	99	101	97	1,283,493	103	99	100	96
East Asia & Japan	881,479	102	99	108	113	788,031	101	95	101	102
Central Asia	61,297	114	123	143	148	50,460	112	121	138	145
Developed	6,517,580	103	107	116	124	4,701,290	101	102	99	94
Developing	11,468,097	102	103	107	104	4,334,400	102	101	103	100
World	17,985,677	102	105	110	111	9,035,690	102	101	101	97

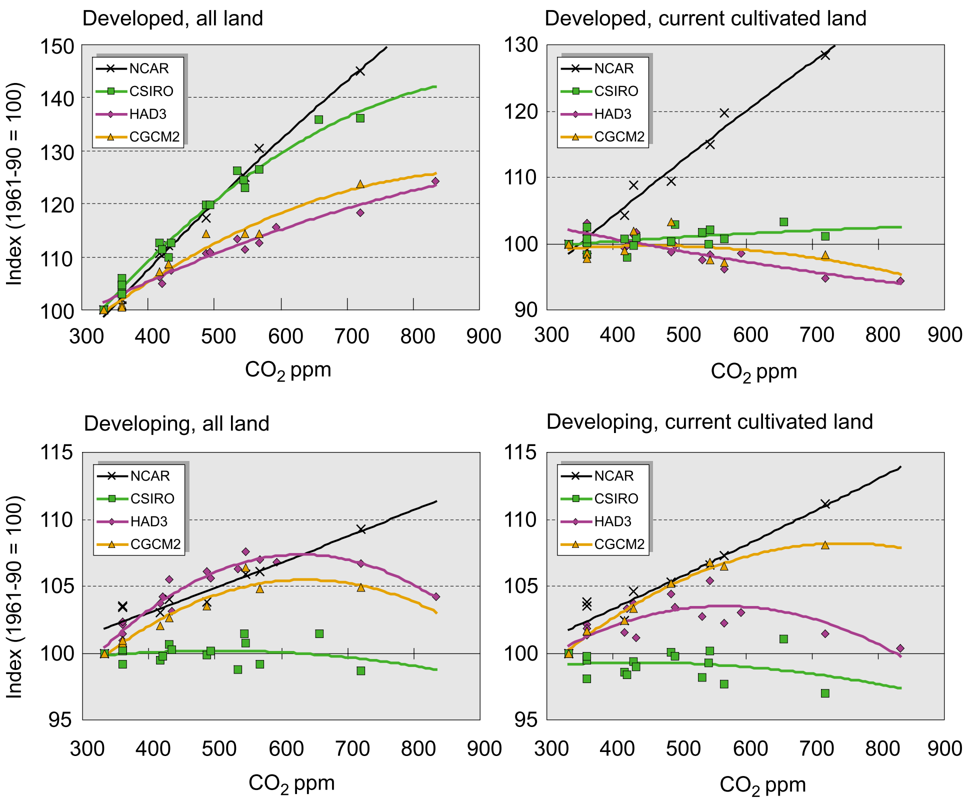

Figure 3.4. Changes in cereal production potential versus increased atmospheric CO_2 concentrations and related global warming as predicted by GCMs.

found in Central Asia. Increases in suitable land extents and production potentials for cereals on all land are found in North America, Northern Europe, the Russian Federation, and East Asia & Japan. This is a clear indication of the northward shift of agricultural zones. Due to the increases in the high-latitude regions, the developed nations will see a considerable expansion of suitable land extents and increased production potential for cereals only when considering the use of this "new land" at high latitudes.

Plates 3.12a and *3.12b* present respectively a map showing suitability distribution of cereals for the reference climate and a map showing changes to this distribution for the HadCM3-A1FI 2080s scenario. Suitability results were calculated for each of the approximately 2.2 million grid-cells of the database. The outcome was mapped by means of a suitability index (SI). This reflects the suitability makeup of a particular grid-cell. In this index VS represents the portion of the grid-cell with attainable yields that are 80% or more of the maximum potential yield. Similarly, S, MS, and mS represent portions of the grid-cell with attainable yields 60–80%, 40–60%, and 20–40% of the maximum potential yield, respectively. SI is calculated using the following equation: SI = VS*0.9 + S*0.7 + MS*0.5 + mS* 0.3. Positive changes are to be noted in the Northern hemisphere at high latitudes (removal of cold-temperature constraints), in the Amazon area, and parts of Central Africa (reduced excess wetness). Decreases are concentrated in parts of the USA, Western and Eastern Europe, Southern Africa, parts of East Asia, and parts of Australia. In particular, northeast Brazil is predicted to see a further reduction in soil-moisture conditions and consequently a substantial reduction in the suitability for cereals.

3.5.2 Wheat

Figure 3.5 shows that with increasing CO_2 concentrations when considering all land, production of wheat will increase in the developed nations according to all scenarios. The developing countries, however, face a substantial decrease of wheat-production potential, consistently according to all scenarios, when considering all land or only current cultivated land.

Plates 3.13a and *3.13b* present respectively a map showing suitability distribution of wheat for the reference climate and a map showing changes to this distribution for the HadCM3-A1FI 2080s scenario. The wheat crop is strongly affected by changes in temperature regime, which is reflected in a clear shift to higher latitudes in the Northern hemisphere. On the other hand, wheat is virtually disappearing from Africa and suitability is decreasing in parts of the USA, large portions of Europe and South Asia, the Southern part of East Asia, and the Northern part of the wheat-growing areas of Brazil and Paraguay.

3.5.3 Other crops

A distinct downward trend for production potentials for rain-fed sugar crops emerges from the analysis. On all land and current cultivated land, for developing nations substantial decreases in potential productivity are predicted by all scenarios. In developed countries the results for all land are showing increases for CSIRO, CGCM2, and NCAR, and a slight decrease for the HadCM3 scenarios. In case of current cultivated land, the results are mixed; NCAR shows a steady increase with increasing atmospheric CO_2 concentrations; CGCM2 shows, after an initial increase, a gradual decrease for CO_2 concentrations over 600 ppm; CSIRO shows a moderate linear decrease, and HAD3 an almost linear strong decrease.

Changes in production potentials, for rain-fed sugar crops, roots and tubers, pulses, and oil crops, as well as for rain-fed/irrigated wetland rice and other rain-fed cereals are charted in *Annex 3.1*.

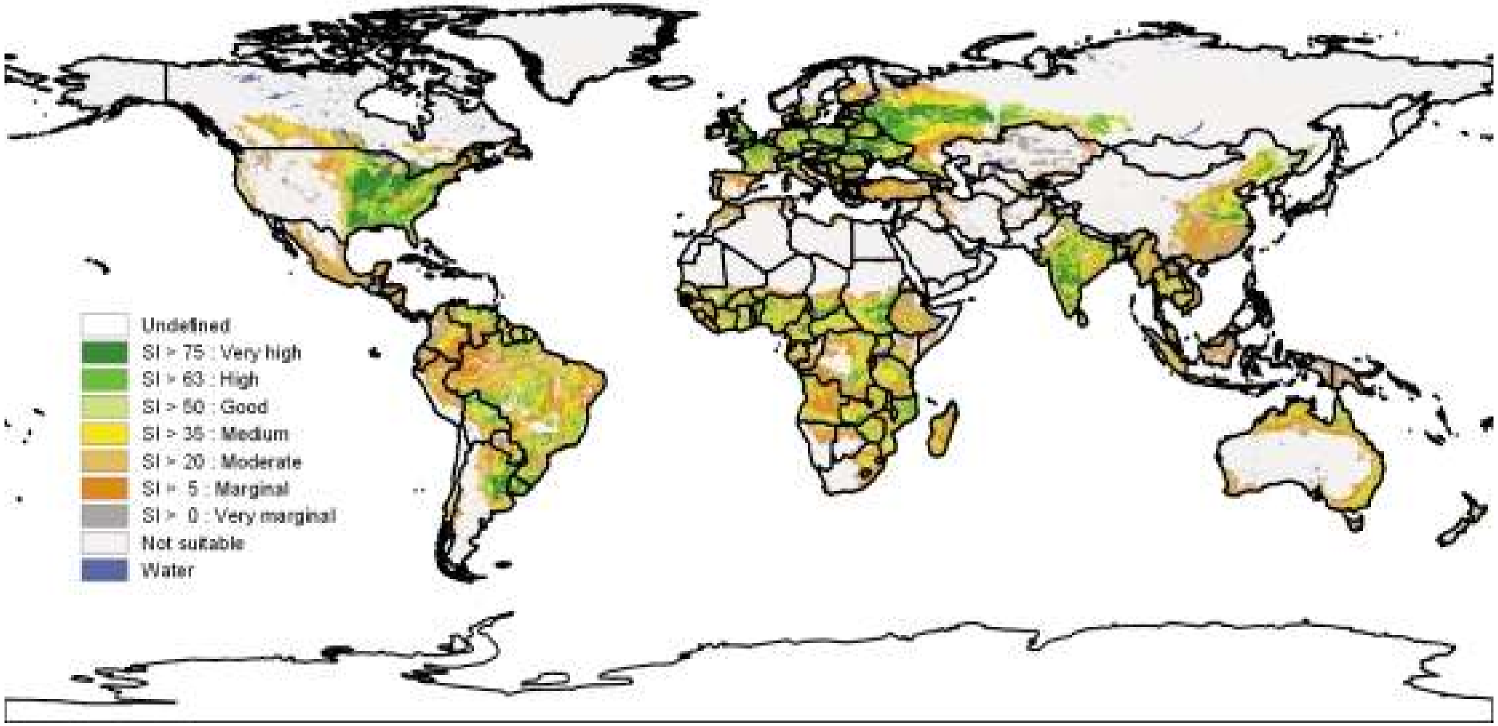

Plate 3.12a. Suitability for rain-fed cereals (reference climate, 1961–1990).

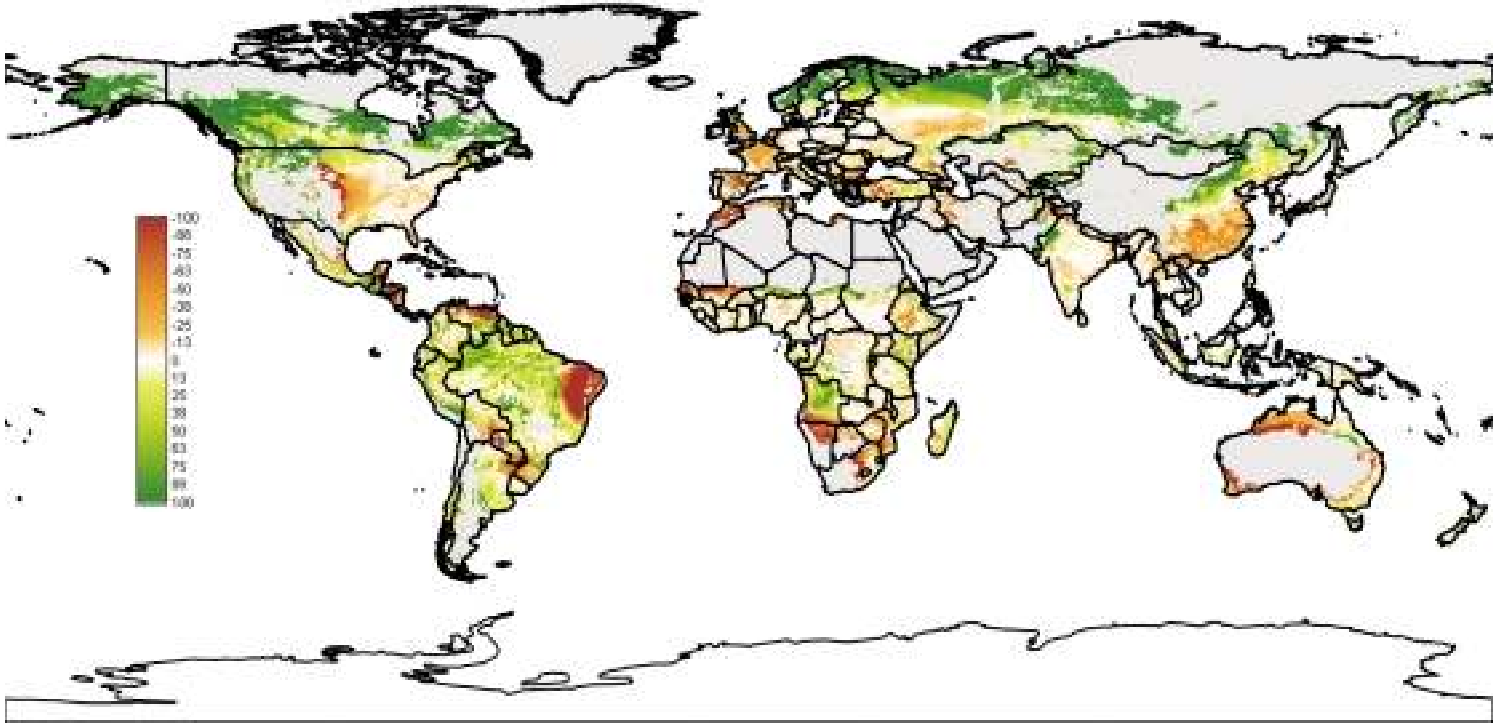

Plate 3.12b. Change in suitability for rain-fed cereals (Had3-A1FI, 2080s).

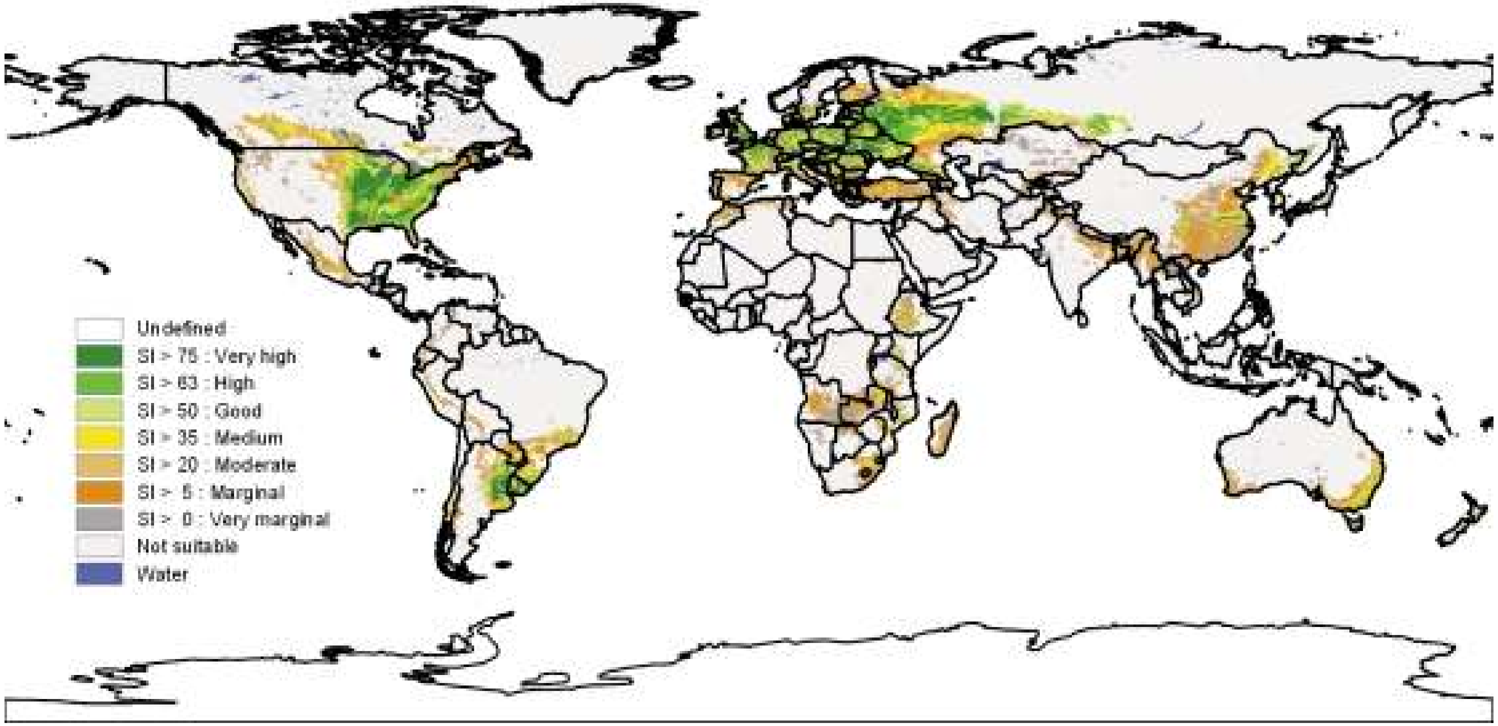

Plate 3.13a. Suitability for rain-fed wheat (reference climate, 1961–1990).

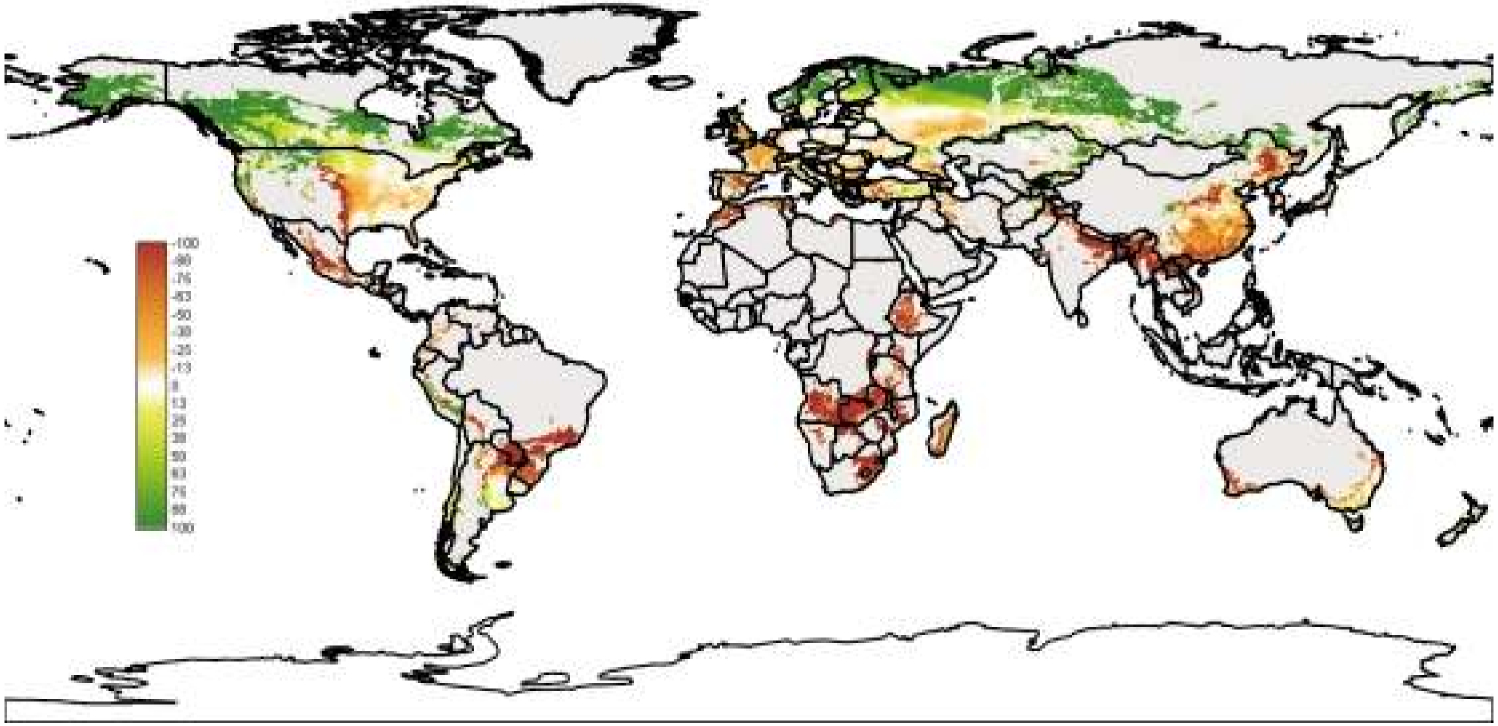

Plate 3.13b. Change in suitability for rain-fed wheat (HadCM3-A1FI, 2080s).

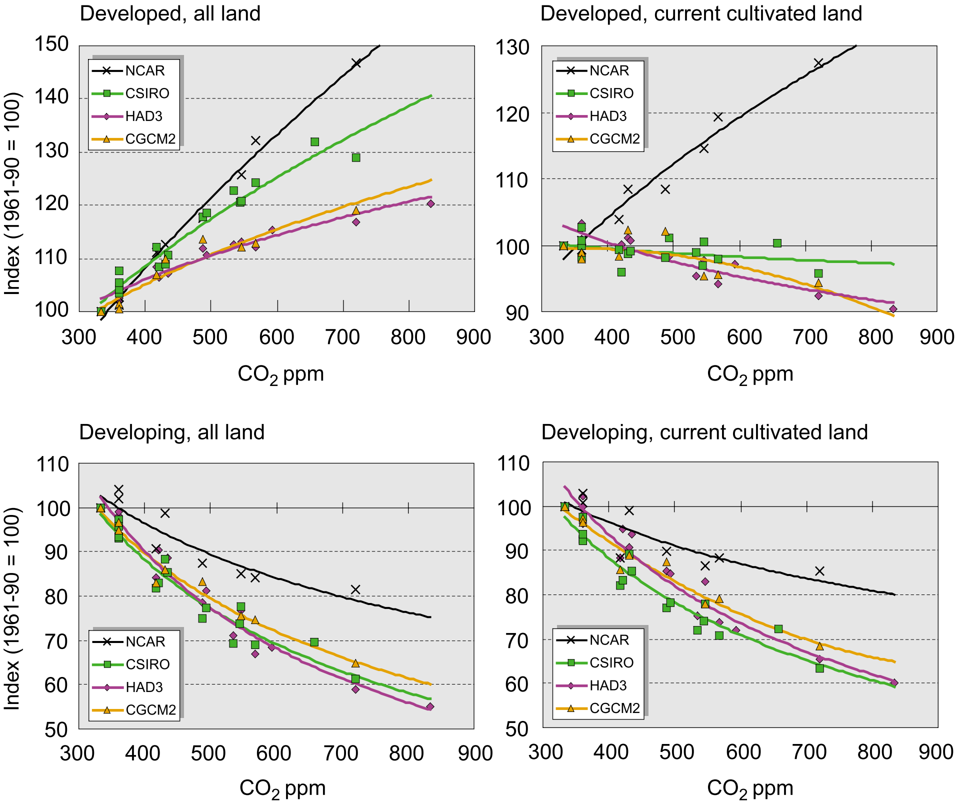

Figure 3.5. Changes in wheat-production potential versus increase in atmospheric CO_2 concentrations and related global warming as predicted by GCMs.

3.6 Changes in Potential Agricultural Land

3.6.1 Potential agricultural land under current and future climates

The total extent of potential rain-fed land is estimated for each grid-cell. With no restrictions for land-cover conversion, the results show that about one-quarter of the global land surface, excluding Antarctica, can be regarded as potentially suitable for crop cultivation. About 25% of the total potential suitable land is currently located in closed forest (FAO, 2001) and highly protected areas (UNEP-WCMC, 2001). About 2 billion hectares are potentially good or prime land for agricultural crops (VS+S); this excludes land under closed forest and highly protected areas.

More than 70% of the remaining balance between potential land and land currently in use for agriculture is found in just seven countries in Latin America and

Africa – Argentina, Bolivia, Brazil, Colombia, Angola, Democratic Republic of Congo, and Sudan. In these two continents there is clearly still scope for further expansion of current agricultural land, even if closed forest and legally protected areas remain untouched. [Despite the fact that currently reported cultivated land in official statistics is likely to underestimate actual use in several developing countries, this does not affect the conclusion that there is still significant potential for expansion of cultivated land in Africa and South America.]

Agronomic suitability will by no means be the only determinant of future land development. The expansion of cultivable land will be limited due to constraints of ecological fragility, degradation, toxicity, incidences of diseases, and lack of finance and infrastructure. These issues will need to be explicitly considered in country-level agricultural development.

Table 3.11 presents extents of total land with cultivation of annual or permanent crops in 1994–1996 (this includes irrigated land shown separately), and rain-fed cultivation potential for major food and fiber crops for the reference climate and the HadCM3-A1FI 2080s scenario for net total land (excluding land under closed forest and in highly protected areas) and separately for land under closed forest and highly protected areas. A comparison of current net land potential with the land potential derived from the HadCM3-A1FI 2080s climate projections at the global level highlights a slight decrease in good and prime agricultural land (VS+S), but a modest increase in total potential land (VS+S+MS) of about 2%. This indicates that much of the additional land becoming available according to this scenario is of only moderate quality.

All 12 GCM climate projections predict gains in potential agricultural land globally. Strong gains are predicted for the developed nations as a whole, but especially for North America and the Russian Federation. For the developing nations the picture is mixed. Gains are predicted by all 12 scenarios for Central Asia. Decreases are mainly confined to developing nations; in Africa, South America, Oceania & Polynesia, and Southeast Asia. In 10 of the 12 GCM climate projections, substantial losses are predicted for sub-Saharan Africa. Nevertheless, note that for Africa and South America the decrease of suitable land is relatively small in comparison to the remaining balance of unused potential cultivable land.

To compare estimates of land with cultivation potential across scenarios, we use a suitability index SI, which accounts for changes in area extents as well as changes in suitability make-up of grid-cells (see Section 3.5.1).

This SI index is also particularly useful when comparing land estimates across regions as it adjusts for differences in land quality and provides a more realistic estimate of land-resource availability.

Table 3.11. Cultivated land 1994–1996, and rain-fed cultivation potential for major food and fiber crops, high inputs (million ha) for reference climate and HadCM3-A1FI 2080 scenario for net total land and land under closed forest and protected areas (F+H).

		Cultivated land FAOSTAT (1994–1996)		Land with cultivation potential							
				Reference climate (1961–1990)				HadCM3-A1FI 2080s			
				VS+S		VS+S+MS		VS+S		VS+S+MS	
Region	Total land	Total	Irrigation	Net total	F+P	Net total	F+P	Net total	F+P	Net total	F+P
North America	2,139	225	22	216	87	267	117	277	161	354	201
Eastern Europe	171	82	7	93	12	111	15	95	11	112	15
Northern Europe	173	22	1	29	10	36	16	28	12	39	17
Southern Europe	132	46	9	30	2	42	3	34	2	45	3
Western Europe	110	35	3	50	4	57	6	46	4	56	6
Russian Federation	1,674	130	5	125	80	163	99	169	144	254	193
Central America & Caribbean	272	44	8	34	10	44	14	31	10	43	16
South America	1,778	115	10	393	325	473	371	320	214	419	345
Oceania & Polynesia	850	53	3	87	20	121	25	71	18	101	24
Eastern Africa	640	46	4	253	10	333	13	231	9	315	12
Middle Africa	657	25	0	173	75	243	109	162	56	228	92
Northern Africa	794	44	6	13	0	18	0	1	0	4	0
Southern Africa	266	17	1	21	0	38	0	9	0	20	0
Western Africa	633	65	1	135	14	169	19	124	13	162	19
Western Asia	433	46	11	16	0	29	0	20	0	31	0
Southeast Asia	445	90	15	93	24	115	34	85	23	107	32
South Asia	672	232	86	156	4	178	5	150	3	177	5
East Asia & Japan	1,150	144	56	106	5	147	7	115	6	159	10
Central Asia	414	45	12	5	0	14	0	10	0	23	0
Developed	5,228	596	53	630	207	798	274	718	345	960	450
Developing	8,172	910	208	1,396	473	1,800	581	1,261	343	1,689	540
World	13,400	1,505	260	2,027	681	2,598	855	1,979	688	2,649	990

Note: Net total land excludes land under closed forest and highly protected areas, also areas required for habitation and infrastructure have been accounted for using 1995 population distribution.

On the basis of SI, changes in the extent of land with cultivation potential, aggregated by region, for the reference climate and the 12 GCM climate projections for the 2080s considered in this study, are presented in *Table 3.12*.

Plates 3.14 and *3.15* present the distribution of cultivable land for the reference climate (1961–1990) and the HadCM3-A1FI 2080s scenario respectively. The quality of the potential rain-fed cultivable land is reflected by different classes of the suitability index (SI), as described above. An SI value of 100 indicates that the entire grid-cell is very suitable for crop cultivation. Lower values mean that grid-cells are at least partly limited by slope, soil, or climate conditions.

A comparison of the two plates demonstrates a remarkable expansion of potential cultivable land to higher latitudes of the Northern hemisphere, in particular benefiting the Russian Federation, Northern Europe, and Canada.

Changes are very noticeable in South America. In Northern Africa, decreases are substantial; approximately three-quarters of the potential rain-fed cultivable land are lost as compared to the reference climate, leaving just a narrow strip of potential rain-fed cultivable land along the Mediterranean coast. Decreases are also visible in Southern Africa, mainly affecting Mozambique, Botswana, Namibia, Zimbabwe, and South Africa.

For each of the approximately 2.2 million grid-cells of the database, the rain-fed agricultural production potentials were mapped by means of a normalized suitability index (SI). This index reflects the suitability make-up of a particular grid-cell. A value of 100 indicates that an entire grid-cell is very suitable for crop cultivation; values of less than 100 mean that parts of the grid-cell are of lower quality due to slope, soil, or climatic constraints.

Figure 3.6 shows three basic sets of information for Asia, Africa, Latin America, Oceania, the Russian Federation combined with Europe, and North America, namely: (i) current cultivated land (rain-fed and irrigated) in use in 1994–1996; (ii) potential cultivable land under the reference climate; and (iii) potential cultivable land for the HadCM3-A1FI climate projections in the 2080s. The potential is shown for very suitable and suitable land (VS+S), moderately suitable land (MS), and separately for potentially suitable land (VS+S+MS) under closed forest or in protected areas.

3.6.2 Multiple cropping

Most cultivated land in the developed world belongs to the single-cropping zone. Under the current climate, the extent of land allowing double or triple cropping of rain-fed cereals in these countries is rather small, at only some 16% of the total. In contrast, in the developing world, about 55% of land with cultivation potential for rain-fed cereals is suitable for double or triple cropping. In South and Central

Table 3.12. Suitability Index (SI) for the reference climate and changes for 12 scenarios, aggregated by region.

Region	SI units	H3 A1FI Δ%	H3 A2 Δ%	H3 B2 Δ%	H3 B1 Δ%	CS A1B Δ%	CS A2 Δ%	CS B2 Δ%	CS B1 Δ%	C2 A2 Δ%	C2 B2 Δ%	NC A2 Δ%	NC B2 Δ%
North America	228	27	18	11	7	32	32	23	24	16	5	26	16
Eastern Europe	87	1	–5	–9	–2	1	1	5	3	–11	–10	8	10
Northern Europe	29	2	0	4	–1	3	–1	–1	1	1	1	0	–1
Southern Europe	32	7	9	9	5	14	13	12	11	10	6	10	5
Western Europe	46	–5	–8	–5	–6	–4	–5	–5	–3	–4	–4	–3	–2
Russian Federation	132	44	39	25	29	56	49	45	45	43	29	50	38
Central America & Caribbean	35	–3	2	4	3	–4	–3	–1	–1	–7	–5	–1	–1
South America	374	–14	–9	–7	–5	1	1	0	1	2	0	3	2
Oceania & Polynesia	99	–19	–17	–11	–9	3	–7	–13	0	–4	1	2	1
Eastern Africa	256	–7	–6	–3	–2	–8	–11	–7	–7	–2	–1	1	0
Middle Africa	183	–5	–3	0	2	–3	–4	–3	–1	0	–2	–1	–1
Northern Africa	14	–76	–54	–40	–36	–24	–45	–27	–25	–31	–30	–25	–35
Southern Africa	29	–45	–41	–55	–43	–25	–33	–25	–34	–44	–8	13	–4
Western Africa	133	–7	–7	–3	–1	–8	–10	–5	–3	–4	0	7	5
Western Asia	22	3	6	9	2	16	4	10	5	–1	2	–1	3
Southeast Asia	90	–7	–5	–3	–3	–4	–4	–3	–3	2	2	–2	–1
South Asia	147	–4	–3	–3	1	2	–2	–2	–1	5	5	1	0
East Asia & Japan	115	6	8	7	3	–1	–2	–2	–6	22	20	16	8
Central Asia	13	60	42	48	46	121	86	64	55	9	11	74	43
Developed	651	15	11	6	6	24	20	16	18	13	7	21	15
Developing	1,411	–8	–5	–3	–2	–2	–4	–3	–3	1	2	4	1
World	2,062	0	0	0	1	6	4	3	4	5	3	9	6
Sub-Saharan Africa	602	–7.9	–6.8	–4.5	–2.4	–7.3	–9.6	–6.1	–5.8	–3.8	–1.3	2.4	0.6

Note: The estimate for the reference climate includes all cultivable land excluding closed forests and legally protected areas. Also, areas required for habitation and infrastructure have been deducted based on levels and distribution of population in 1995.

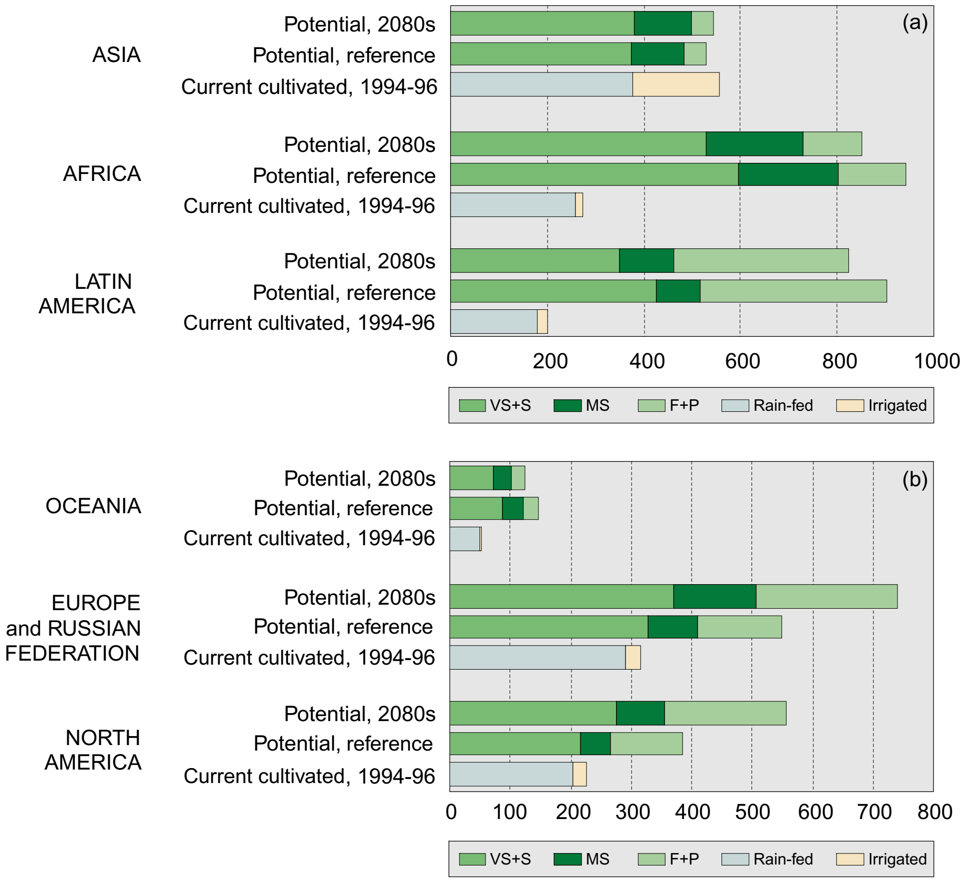

Figure 3.6. Comparison of land with rain-fed crop production potential for current climate, for future climate projected by HadCM3-A1FI scenario in the 2080s, and land in use for cultivation in 1994–1996 (million ha).

America, this figure exceeds 80%, with 65% for double and about 17% for rain-fed triple cropping (Fischer *et al.*, 2002).

The multiple-cropping zone classification applied in *Plates 3.16* and *3.17* (defined by climate conditions only), for the reference climate and HadCM3-A1FI scenario in the 2080s, indicates a major expansion of areas with single cropping. Shifts in double- and triple-cropping areas are minor and differ in direction depending on changes in moisture conditions.

Table 3.13 shows the occurrence of multiple-cropping zones for the reference climate of 1961–1990 and the percentage changes in each class according to estimates for the 12 GCM climate projections in the 2080s.

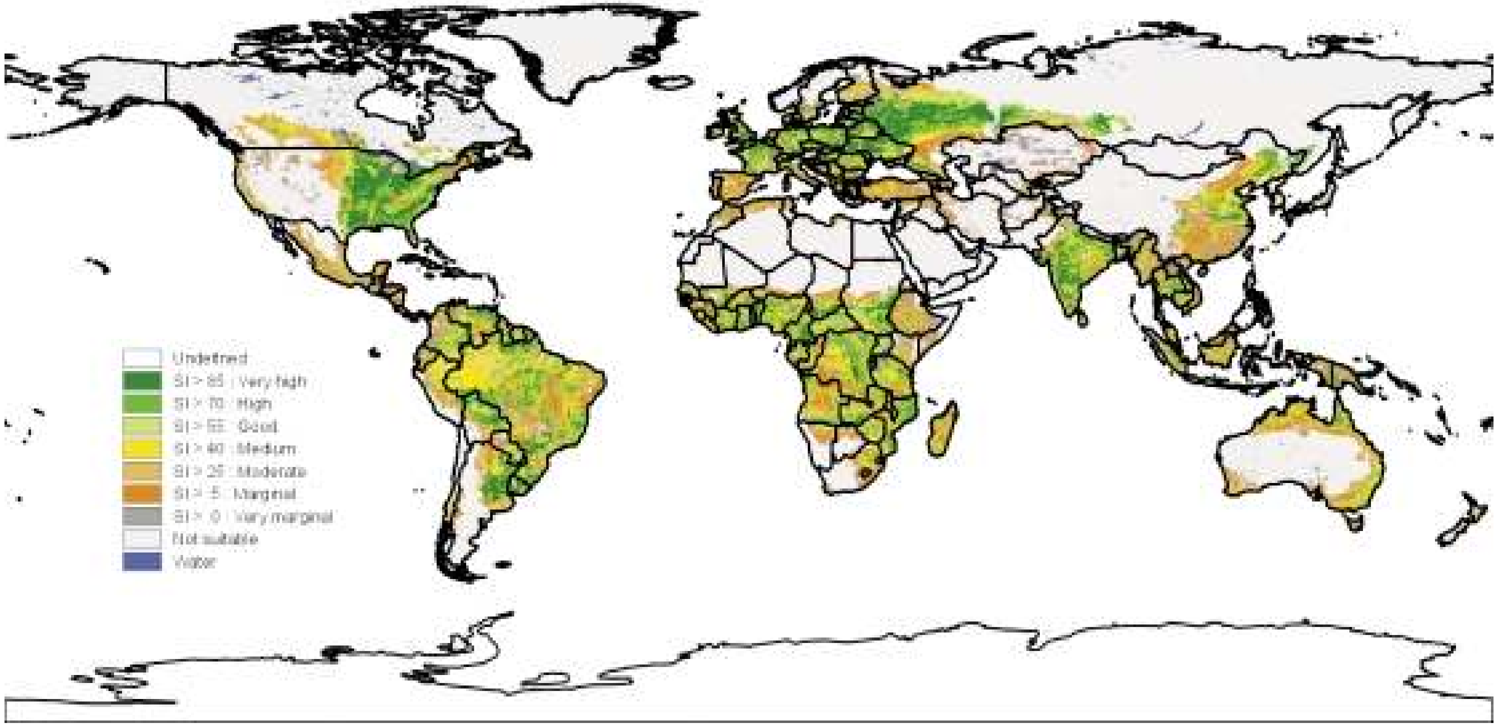

Plate 3.14. Land with rain-fed cultivation potential (reference climate, 1961–1990).

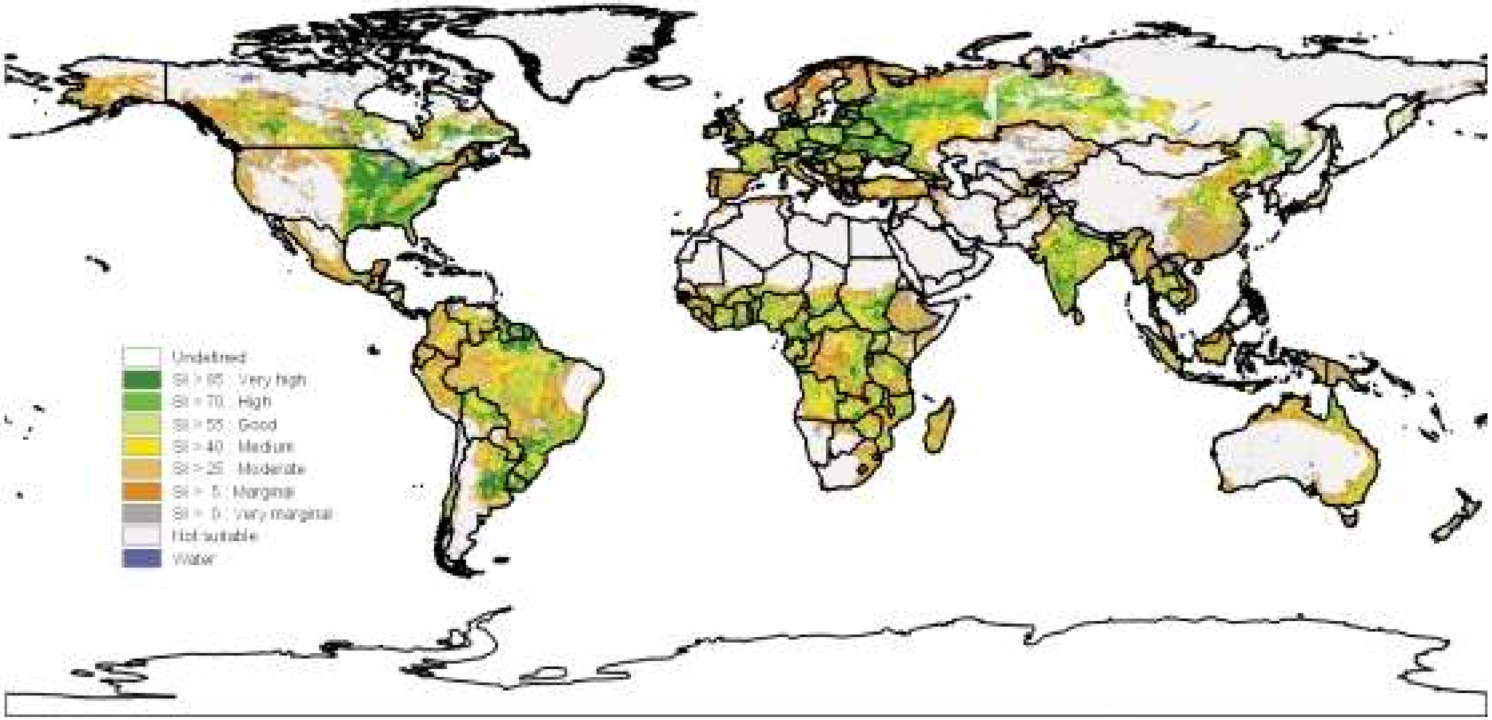

Plate 3.15. Land with rain-fed cultivation potential (HadCM3-A1FI, 2080s).

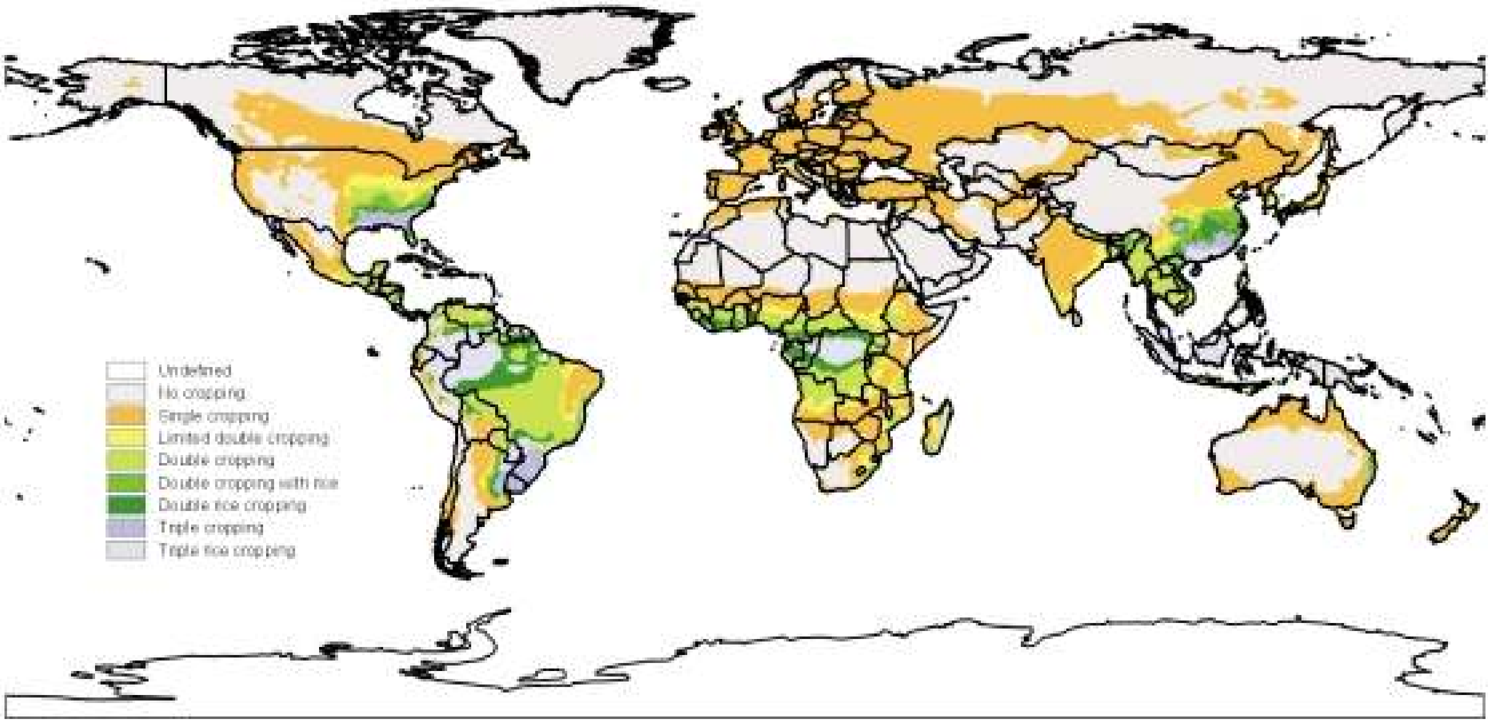

Plate 3.16. Multiple-cropping zones for rain-fed crop production (reference climate, 1961–1990).

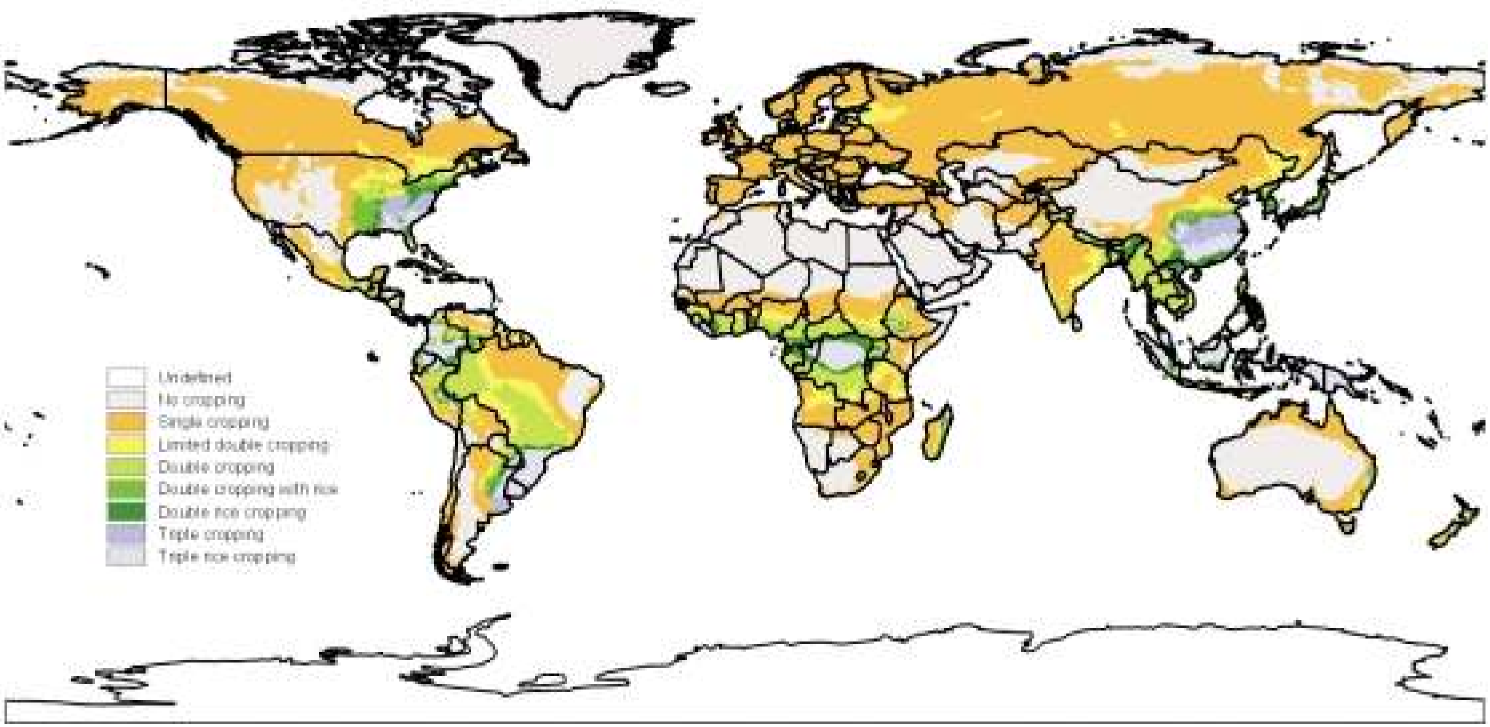

Plate 3.17. Multiple-cropping zones for rain-fed crop production (HadCM3-A1FI, 2080s).

Table 3.13. Extents of single-, double-, and triple-cropping zones for reference climate and percent change for 12 GCM climate projections for the 2080s.

(a) World and developed nations

Reference climate &	World				Developed nations			
GCM climate projections for the 2080s	Single cropping	Double cropping	Triple cropping	Total	Single cropping	Double cropping	Triple cropping	Total
Reference climate (million ha)	2,820	1,088	422	4,331	1,656	227	83	1,966
	% changes							
CGCM2 A2	14.6	–2.8	10.0	9.8	21.9	–0.3	57.8	20.9
CGCM2 B2	9.7	–0.9	16.5	7.7	14.3	–2.9	78.9	15.0
CSIRO A1B	12.3	–0.7	17.9	9.6	20.6	–4.1	124.5	22.2
CSIRO A2	11.3	0.5	22.0	9.6	20.2	–3.0	140.4	22.6
CSIRO B1	10.2	–1.0	21.4	8.5	18.0	–8.0	122.5	19.4
CSIRO B2	11.9	–4.5	17.3	8.3	19.0	–17.0	120.5	19.2
HadCM3 A1FI	14.6	–16.7	7.0	6.0	16.0	–5.5	124.2	18.1
HadCM3 A2	15.0	–12.8	–3.3	6.2	16.6	–9.2	78.5	16.3
HadCM3 B1	9.4	–6.4	3.8	4.9	11.0	–2.7	79.1	12.3
HadMC3 B2	12.4	–7.8	–4.6	5.7	12.6	2.4	69.6	13.8
NCAR A2	9.9	0.5	22.1	8.8	14.6	8.5	70.4	16.3
NCAR B2	6.2	2.9	15.4	6.2	9.9	6.1	53.8	11.3

(b) Developing nations and sub-Saharan Africa

Reference climate &	Developing nations				Sub-Saharan Africa			
GCM climate projections for the 2080s	Single cropping	Double cropping	Triple cropping	Total	Single cropping	Double cropping	Triple cropping	Total
Reference climate (million ha)	1,164	862	339	2,364	573	300	57	930
	% changes							
CGCM2 A2	4.2	–3.4	–1.7	0.6	–3.0	–11.1	–5.9	–5.8
CGCM2 B2	3.1	–0.4	1.1	1.5	–2.2	–6.2	9.6	–2.8
CSIRO A1B	0.4	0.2	–8.3	–0.9	–5.1	–2.1	–4.0	–4.1
CSIRO A2	–1.4	1.4	–7.0	–1.2	–8.5	–0.6	–0.3	–5.4
CSIRO B1	–0.9	0.8	–3.5	–0.7	–5.5	–1.7	–2.9	–4.1
CSIRO B2	1.8	–1.2	–8.1	–0.7	–4.5	–5.0	–1.3	–4.5
HadCM3 A1FI	12.7	–19.7	–21.8	–4.1	0.7	–19.0	–7.7	–6.2
HadCM3 A2	12.7	–13.8	–23.4	–2.1	–2.1	–14.3	–10.7	–6.6
HadCM3 B1	7.0	–7.4	–14.7	–1.3	–1.0	–13.5	–6.7	–5.4
HadMC3 B2	12.2	–10.5	–22.8	–1.1	–1.9	–11.1	–3.8	–5.0
NCAR A2	3.3	–1.6	10.2	2.5	0.0	0.3	26.3	1.7
NCAR B2	0.9	2.0	6.0	2.0	–0.8	1.3	27.8	1.6

Note: Extents for reference climate and percent changes due to climate changes shown in Table 3.13 are based on a climate classification procedure as detailed in Fischer *et al*. (2002). They exclude grid-cells with dominantly severe constraints, such as steep slopes and very poor soil conditions.

Globally, the major share of the increase of potential cultivatable land involves single-cropping areas. In 10 of the 12 climate scenarios, triple-cropping areas also increase, while double-cropping areas change little or decrease.

For developing nations, in particular sub-Saharan Africa, the overall losses in potential cultivatable areas are mainly at the expense of double- and triple-cropping areas, for which losses are above-average. Unlike the other three GCMs used in the study, the NCAR climate projections present a fairly positive picture, also for sub-Saharan Africa, with increases in both double- and triple-cropping areas.

3.7 Heterogeneity of Climate-Change Impacts on Cereal Production

In this study, the AEZ climate impact assessment for all developed and developing countries is based on the projections of four GCMs, including the HadCM3 model of the Hadley Centre for Climate Prediction and Research, the CGCM2 model of the Canadian Centre for Climate Modeling, the CSIRO Model of Australia's Scientific and Industrial Research Organization, and the NCAR PCM model of the United States National Center for Atmospheric Research.

The AEZ framework allows an assessment of the spatial diversity of impacts and to explore the robustness of conclusions regarding the climate projections of different GCM groups as well as the wide range of IPCC emission scenarios.

3.7.1 Results at global level

The heterogeneity of results are illustrated with the impacts on rain-fed cereal production of the HadCM3 climate-change projections. For this analysis, an advanced level of inputs and management for currently cultivated areas is assumed. The cereal-production potential for the 1961–1990 reference climate and for four different climate projections for the 2080s is assessed, based on the range of IPCC SRES emission scenarios. The resulting atmospheric CO_2 concentrations, starting with 330 parts per million (ppm) (average of 1961–1990), reach in the mid-2080s respectively 534 ppm (scenario B1), 568 ppm (scenario B2), 721 ppm (scenario A2), and 834 ppm (scenario A1FI).

The detailed and spatially explicit results of AEZ obtained for grid-cells at 5 arc-minutes latitude/longitude can be summarized, for instance, by drawing distributions of climate impacts on production potential in currently cultivated areas. *Figure 3.7* provides some examples. In each graph, the central bar represents areas where projected climate change results in minor productivity changes of between –5% and +5%. Bars to the right of the center represent areas where impacts are increasingly positive, i.e., between +5% and +15%, +15% and +25%, respectively,

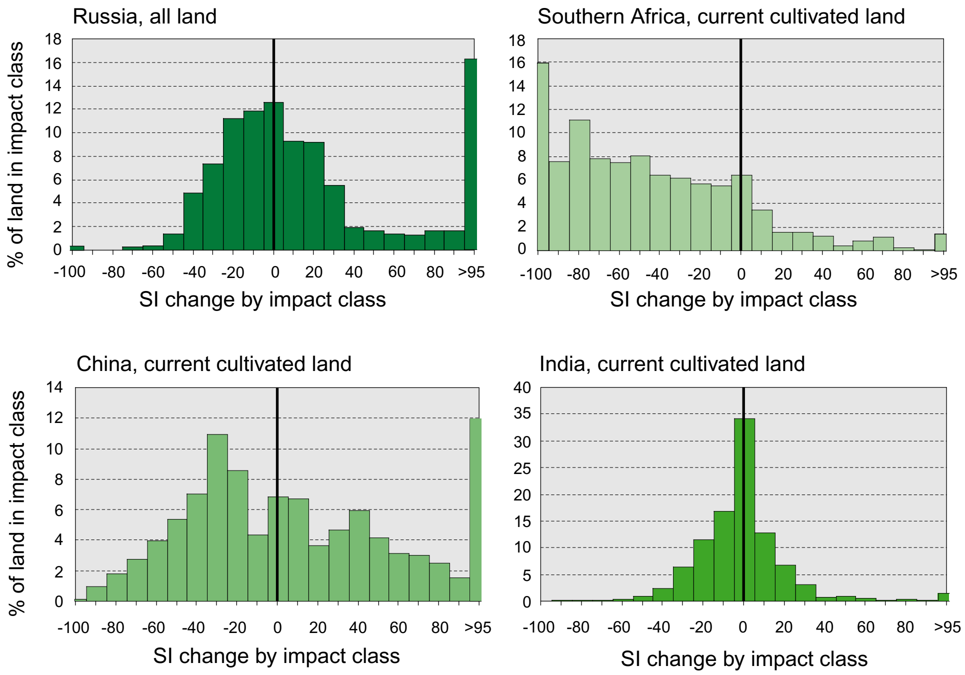

Figure 3.7. Distribution of cultivable land in terms of climate impact on cereal productivity, HadCM3-A1FI climate projections, in the 2080s.

etc. To the left of the central bar, climate-change impacts are increasingly negative, between –5% and –15%, –15% and –25%, respectively, etc.

Figure 3.7 illustrates the variety and complexity of climate-change outcomes. For instance, while Russia generally gains production capacity under a climate change as projected by the HadCM3 model, SRES scenario A1FI for the 2080s, even in this country some areas (and hence farmers) will lose. Note the bar on the extreme right of the graph for Russia, which represents gains due to expansion of agricultural potentials into “new” areas. Another gaining country is China, although impact distribution is widely spread and most cultivated land experiences significant change. By contrast, India shows a rather narrow distribution, with a pronounced median of impacts in the –5% to +5% range, indicating that agricultural conditions in India under this scenario would change little, with limited negative overall impacts, as can be seen from the somewhat larger area of the distribution to the left of the center line.

Understanding these outcomes, it is not surprising that in the past, site-specific climate-impact studies have come to a wide range of seemingly contradicting results. While differences in assumptions and methodologies may account for some of the differences, the results obtained in this study clearly demonstrate that a wide

Table 3.14. Estimated impacts on rain-fed cereal-production potential of gaining and losing countries, for currently cultivated land, HadCM3 projections, in the 2080s.

	Number of countries			Projected population, 2080 (billions)			Change in cereal-production potential (% of global potential)			
Scenario	G	N	L	G	N	L	G	N	L	Total
A1FI	54	23	73	3.0	2.2	3.3	5.5	–0.4	–7.9	–2.8
A2	61	32	57	3.3	1.4	3.8	4.1	0.5	–6.8	–2.1
B2	71	36	43	3.8	2.0	2.7	4.2	–0.9	–4.3	–1.0
B1	67	41	42	2.3	4.5	1.6	3.6	–0.6	–3.0	0.0

G = countries gaining 5% or more; N = small change of –5% to +5%; L = countries losing 5% or more.

range of outcomes is to be expected for many countries, and that a full and reliable picture requires a spatially comprehensive approach and analysis such as AEZ.

Table 3.14 summarizes for four HadCM3 climate-change scenarios the estimated impacts on cereal-production potential in current cultivated land under rainfed conditions. It shows that the projected year 2080 population in 42–73 countries, with potential cereal-productivity declines of more than 5% (“losing” countries), ranges between 1.6 billion and 3.8 billion people. In these countries, cereal-production losses vary between 3% and 8% of the global potential, a grim outlook for the already poor among these losing countries despite the substantial increases in some 54–71 gaining countries.

Hence, while aggregate global changes are usually rather small, large negative and positive shifts in productivity can be expected. This polarity of outcomes increases with higher levels of CO_2 concentration and the resulting climate change.

Scenario A1FI: The results for the HadCM3 climate projections show that at the global level, 54 countries with 36% of the world’s projected population in 2080s would gain as much as an equivalent 5.5% share of the global cereal-production potential due to climate change, while 73 countries, accounting for 39% of the world’s population in the 2080s, would lose 7.9%. The resulting global net loss on current cultivated land for scenario HadCM3-A1FI amounts to 2.8%.

Scenario A2: The results for HadCM3 show that 61 countries with 38% of the world’s projected population in the 2080s would gain an equivalent 4.1% share of the global cereal-production potential due to climate change. However, 57 countries, with 45% of the world’s population in the 2080s, lose together 6.8%. The global net loss for scenario HadCM3-A2 amounts to 2.1%.

Scenario B2: In the case of this lower emission scenario, there are 71 gaining countries with a combined increase equivalent to 4.2% of global cereal potential on currently cultivated land, and 43 countries, with about a third of the world's 2080s population, losing 4.3% of the global cereal potential.

Scenario B1: For this scenario global cereal-production potential is not changing. Yet, there are still 42 losing countries, 41 countries with only small changes, and 67 countries gaining.

3.7.2 Developing world results

Figure 3.8 summarizes results for developing countries in terms of changes in cereal-production potential for gaining and losing countries, i.e., for three broad groups of countries where (i) production capacity increases by more than 5%, (ii) production capacity is only somewhat affected, in the range of 5% losses to 5% gains (not shown in graphs), and (iii) production capacity decreases by more than 5%.

Scenario A1FI: The results under HadCM3 show that 42 developing countries may benefit from substantial increases in cereal-production potential averaging more than 17% of their potential, which represents 6.2% of developing-world cereal-production potential. At the same time, some 52 countries may lose on average 19% of their current potential, a loss of 5% of developing-world potential.

Scenario A2: Some 50 developing countries, with 45% of the developing world's projected population in the 2080s, would gain 6% of developing-world cereal-production potential (over 16% of their own potential) due to climate change, while 40 countries may lose 12% of their production potential. For the CSIRO model, 48 developing countries gain 20% production potential (i.e., 3.5% of the total potential in developing countries), while 35 countries lose 17%, some 6.5% of developing-world cereal-production potential. Thus, there would be an overall 3% net loss according to CSIRO climate projections. The results for Canadian CGCM2 and the NCAR climate models indicate gains for the developing world as a whole, in the range of 8% (for CGCM2) to 11% (for NCAR-PCM).

Scenario B2: For this lower emission scenario, the net balance of changes in cereal-production potential of developing countries for the HadCM3 projections shows a 2.2% increase. There are 59 developing countries that gain 12% cereal potential (6.1% of regional total) and 29 countries that lose an average 10% (3.8% of regional total) of the cereal-production potential. The results of the CSIRO model show 43 countries gaining and 30 countries losing cereal potential, with a net regional loss of 2.3%. For the CGCM2 and the NCAR model, developing countries may gain 6–7% of potential production due to climate changes in the 2080s.

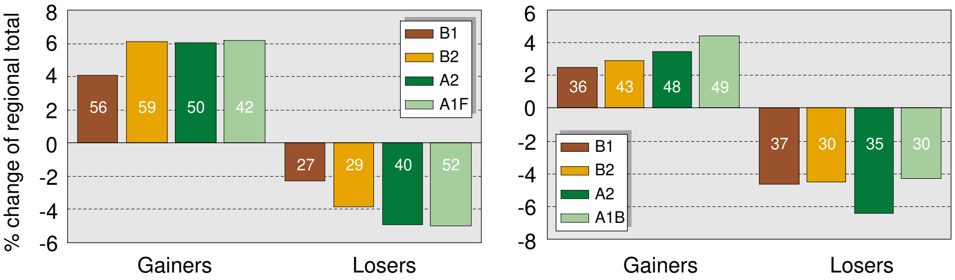

Figure 3.8. Impacts of climate change on rain-fed cereal-production potential of developing countries, for currently cultivated land in the 2080s, according to HadCM3 and CSIRO climate projections.

Country Results Highlights

In the case of the major developing-country cereal producers, 14 countries account for 80% of current cereal production in the developing world. China, the world's largest cereal producer, gains substantially, in the 5–23% range for all climate models except for the CSIRO model, where there is a loss of 5–7%. For India, the second-largest cereal producer, Brazil, and Thailand, results vary according to climate model. Argentina gains production potential by 7–24% for the HadCM3 and NCAR models, and loses 10–30% production potential for the CSIRO and CGCM2 models. South Africa substantively loses production potential for all climate models and scenarios, except for NCAR's projection of scenario A2, where a small gain occurs.

Examples of the impacts of climate change for individual countries, calculated for the higher emission scenarios A1FI and A2 using the HadCM3 and CSIRO climate projections, are shown in map form in *Plates 3.18* and *3.19*.

3.7.3 Current food-insecure countries

The FAO has estimated the total number of undernourished people in 99 developing countries at 780 million (FAO, 2001). Fifteen of these countries, mainly in the Middle East, North Africa, and South America, have relatively high levels of gross domestic product per capita of more than US$3,000. These countries, accounting for about 1% of the total undernourished, are not discussed here.

The total population of the remaining 84 food-insecure countries at present amounts to some 4.2 billion, equivalent to 74% of the current world population. Some 18% of the 4.2 billion are undernourished. By the 2080s, the UN projects the total population of these countries to increase to 6.8 billion (United Nations, 2001), equivalent to 80% of the world population.

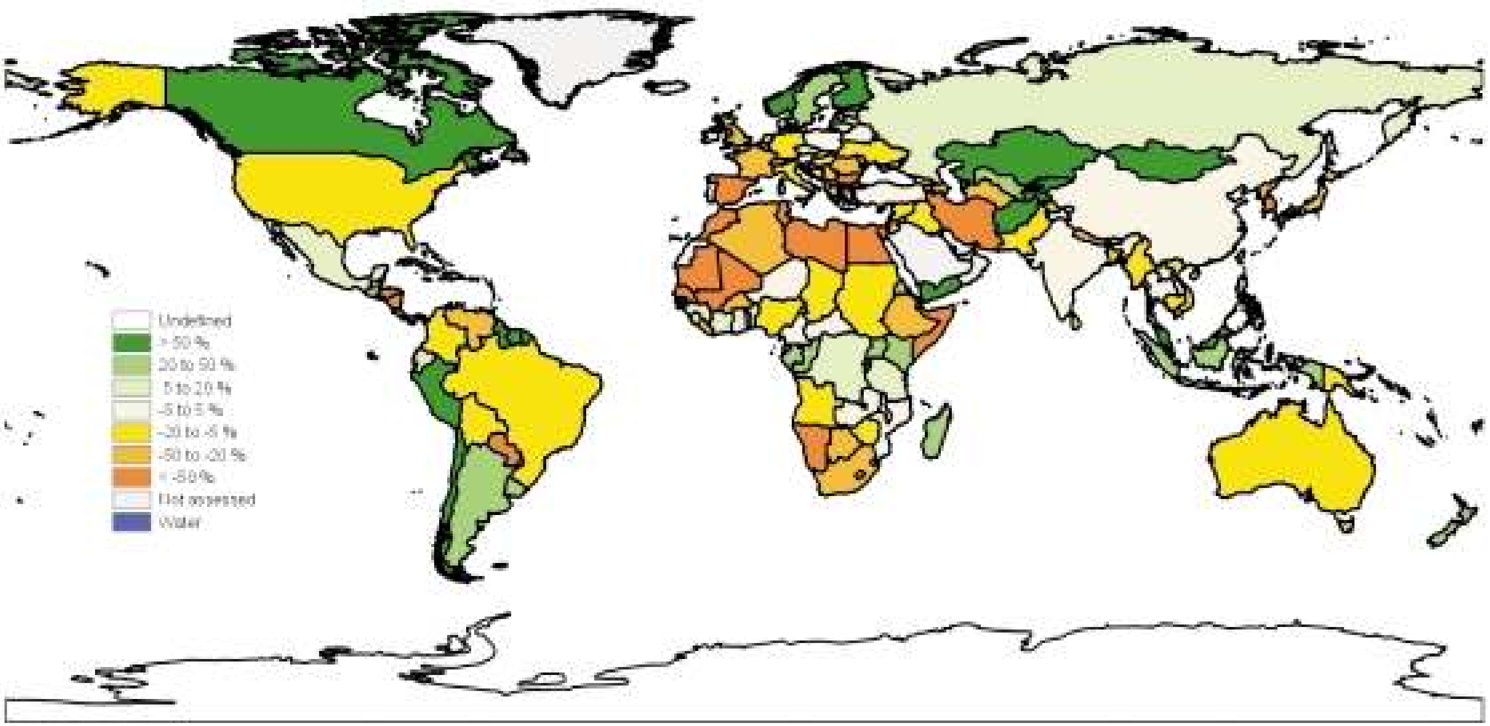

Plate 3.18. Country-level climate-change impacts on rain-fed cereal-production potential on currently cultivated land (HadCM3-A1FI, 2080s).

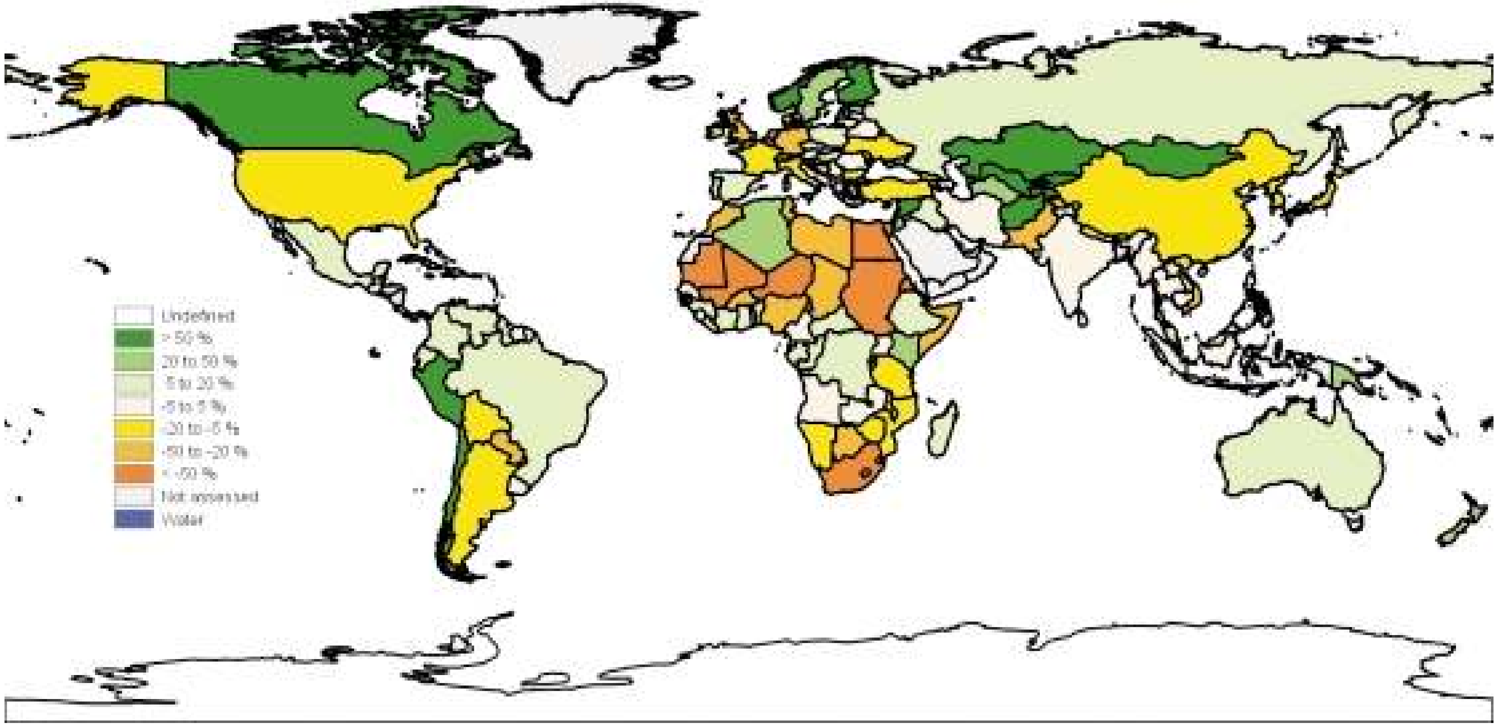

Plate 3.19. Country-level climate-change impacts on rain-fed cereal-production potential on currently cultivated land (CSIRO-A2, 2080s).

The results for this group of food-insecure countries, depending on the level of CO_2 emissions and rate of climate change, show a net loss of up to 2% in four of the 12 scenarios, namely for HadCM3 and CSIRO. Despite these relatively small changes for the group as a whole, the individual country results are reason for concern in that up to 40 countries, with a total population in the range of 1–3 billion, may lose on average 10–20 % of their cereal production potential in the 2080s due to climate change.

Food-insecure Countries in Sub-Saharan Africa

With the exception of the results for the NCAR-PCM model, Sudan, Nigeria, Senegal, Mali, Burkina Faso, Somalia, Ethiopia, Zimbabwe, Chad, Sierra Leone, Angola, Mozambique, and Niger lose cereal production potential in the 2080s for the other three climate models and across all the emission scenarios. These countries currently have 87 million undernourished, equivalent to 45% of the total undernourished in sub-Saharan Africa. In contrast, Zaire, Tanzania, Kenya, Uganda, Madagascar, Côte d'Ivoire, Benin, Togo, Ghana, and Guinea all gain cereal production potential in the 2080s. These eight gaining countries currently have 73 million undernourished, equivalent to 38% of the undernourished population in sub-Saharan Africa.

The balance of gaining and losing countries in *Tables 3.15* to *3.17* demonstrates two important factors. First, the net balance of changes in cereal-production potential for sub-Saharan Africa will very likely be negative, with net losses of up to 12% of the region's current production potential. Second, there will be large variations in outcomes, with up to 40% of sub-Saharan countries losing a rather substantial share of their agricultural resources.

Most of the food-insecure countries in sub-Saharan Africa are also poor. They lack the resources to produce enough food and often do not have access to foreign exchange for financing food imports. Production losses resulting from climate change could further worsen the prevalence and depth of hunger. This burden will undoubtedly fall disproportionately on the poorest and the most vulnerable.

Climate-change impacts highlight the urgent need to intensify agricultural land management and expand agricultural land area, both of which will lead to additional greenhouse-gas emissions and increasing environmental pressures. Moreover, agricultural land expansion will unavoidably lead to losses of natural ecosystems and biodiversity, especially through clearance of forests. Such considerations must be central in mitigating the impacts of climate change on food and agricultural production.

Table 3.15. Estimated impacts on rain-fed cereal-production potential, for currently cultivated land of sub-Saharan African countries, HadCM3 projections, in the 2080s.

	Number of countries			Projected population, 2080 (billions)			Change in cereal-production potential (% of region's potential)			
Scenario	G	N	L	G	N	L	G	N	L	Total
A1FI	17	8	16	0.62	0.43	0.55	5.1	–0.6	–8.6	–4.1
A2	14	11	16	0.58	0.23	0.78	5.3	0.7	–7.9	–1.9
B2	13	15	13	0.56	0.57	0.46	4.4	0.1	–7.1	–2.6
B1	17	10	14	0.65	0.22	0.72	5.0	0.1	–6.4	–1.3

G = countries gaining 5% or more; N = small change of –5% to +5%; L = countries losing 5% or more.

Table 3.16. Estimated impacts on rain-fed cereal-production potential, for currently cultivated land of sub-Saharan African countries, CSIRO projections, in the 2080s.

	Number of countries			Projected population, 2080 (billions)			Change in cereal-production potential (% of region's potential)			
Scenario	G	N	L	G	N	L	G	N	L	Total
A1B	18	8	15	0.67	0.24	0.69	3.7	0.5	–12.3	–8.1
A2	16	8	17	0.63	0.24	0.73	3.3	0.1	–15.1	–11.7
B2	16	11	14	0.71	0.27	0.62	2.6	0.5	–10.1	–6.7
B1	12	13	16	0.59	0.31	0.69	2.2	0.1	–9.3	–7.1

G = countries gaining 5% or more; N = small change of –5% to +5%; L = countries losing 5% or more.

Table 3.17. Estimated impacts on rain-fed cereal-production potential, for currently cultivated land of sub-Saharan African countries, for IPCC scenario A2, in the 2080s.

	Number of countries			Projected population, 2080 (billions)			Change in cereal-production potential (% of region's potential)			
Scenario	G	N	L	G	N	L	G	N	L	Total
HadCM3	14	11	16	0.58	0.23	0.78	5.3	0.7	–7.9	–1.9
CSIRO	16	8	17	0.63	0.24	0.73	3.3	0.1	–15.1	–11.7
CGCM2	13	14	14	0.79	0.32	0.49	6.0	0.0	–8.7	–2.7
NCAR	25	13	3	1.07	0.39	0.13	8.2	0.4	–0.8	7.8

G = countries gaining 5% or more; N = small change of –5% to +5%; L = countries losing 5% or more.

4

Climate Change: Impacts on Food Systems

The climate-change impact on agricultural production potential, discussed in the previous chapter, allows consideration of not only the spatial (local, national, regional, and global) and temporal (current and future generations) dimension of climate change, but also its linkage with the economic and social dimension of sustainable development. The vulnerability of agricultural systems varies with geographic location, time, socioeconomic conditions, and environmental resources.

The capacity to mitigate and to adapt to climate-change impacts is strongly related to the future development paths. The socioeconomic and, even more so, the technological characteristics of different futures strongly affect emissions, hence the extent and pace of the impacts of climate change, as well as the capability of societies to adapt to and mitigate climate change.

The combination of the agro-ecological zones (AEZ) approach and IIASA's linked system of national agricultural models (BLS) provides an integrated ecological-economic framework for the assessment of the impact of climate change. We consider climate scenarios based on experiments with four General Circulation Models (GCM), and we assess the four basic socioeconomic development pathways and emission scenarios as formulated by the Intergovernmental Panel on Climate Change (IPCC) in its Third Assessment Report.

This chapter presents the results of an integrated spatial ecological and economic assessment of climate-change impacts, evaluated in the context of the world food economy.

4.1 World Food System – Baseline Simulations under IPCC Future Development Paths

In addition to CO_2 emissions and energy technologies, two principal driving forces in the SRES scenarios are population and economic growth. We have formulated two additional scenarios, A2s and B2s, alongside the four IPCC scenario families, A1, A2, B1, and B2, in order to test in particular the robustness and sensitivity of main conclusions with regard to assumptions on economic growth.

In scenario A1, the world economy grows at 3.3% over the period 1990–2080. The per capita GDP in 2080 amounts to a gigantic $76,000 in the developed world and $42,000 in the developing world. The average income ratio between developed and developing countries is reduced from 13.8 in 1990 to about 1.8 in 2080. Thus, it is a rich and equitable world where current distinctions between poor and rich countries eventually dissolve. Over the period 1990–2080, the annual per capita GDP growth rate is 2% for developed countries and around 4.3% for developing countries. This compares with the historical 1975–1990 growth rates of 2.0% and 1.7% respectively. Here the issue is whether developed countries can achieve such growth "forever", and whether the assumed high growth rate for the developing world, at more than twice the level of the developed world, can be sustained for a period of 100 years.

There is also a continued demographic transition to low mortality and fertility; in this scenario, the world sees an end to population growth. The total population for developing countries reaches 7.1 billion in 2050 and then starts declining to 6.6 million in 2080. The population in the developed world peaks at 1.5 billion (including the "Rest of World" region) in the 2050s and then decreases slowly. Two regions, namely Africa and Western Asia, are projected to see a three-fold increase in their populations over the next 100 years, in comparison to an average overall increase of two-thirds for the developing world as a whole over the period 1990–2080 (see *Table 4.1*).

Scenario B1 assumes the same population projections as scenario A1. The world economy grows at 2.9% over the period 1990–2080. The per capita GDP in 2080 amounts to $55,000 in the developed world and $29,000 in the developing world. The average income ratio between currently developed and developing countries reduces from 13.8 in 1990 to 2.0 in 2080. As in A1, this scenario results in an equitable world where current distinctions between poor and rich countries eventually dissolve.

Although the economic growth rate in scenario B1 is assumed to be some 10% and 20% lower for the developing and developed countries respectively, in comparison to the high growth assumptions in scenario A1, this still results in a high per capita GDP annual growth rate of 3.9% for the developing countries averaged over the period 1990–2080.

In scenario B2, the world economy grows at 2.7% over the period 1990–2080. The per capita GDP in 2080 amounts to $18,000 in the developing world. The average income ratio between currently developed and developing countries reduces to 2.6 in 2080. Thus it is a world where income disparities have been reduced by over four-fifths from current levels. Population growth continues, reaching a world total of 9.3 billion in 2050 and then about 10 billion in 2080. The total population for developing countries reaches 7.9 billion in 2050 and 8.7 billion in 2080.

In scenario A2, the world economy grows at 2.3% over the period 1990–2080. The per capita GDP in 2080 amounts to $37,000 in the developed world and $7,300 in the developing world. The average income ratio between currently developed

Table 4.1. BLS reference projections for IPCC future development path scenarios: Population (in millions).

	Scenario A1				Scenario B1			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	5194	7531	8634	8086	5194	7531	8634	8086
OECD	689	794	852	880	689	794	852	880
EFSU	400	420	410	364	400	420	410	364
MDCs	1089	1214	1262	1244	1089	1214	1262	1244
AFR	611	1278	1770	1869	611	1278	1770	1869
LAM	434	649	747	696	434	649	747	696
WAS	194	400	591	598	194	400	591	598
CPA	1247	1517	1422	1092	1247	1517	1422	1092
SEA	1442	2246	2603	2341	1442	2246	2603	2341
LDCs	3927	6089	7132	6596	3927	6089	7132	6596
ROW	178	228	241	246	178	228	241	246
	Scenario A2				Scenario B2			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	5194	8028	11094	13656	5194	7607	9323	10135
OECD	689	805	892	1035	689	776	764	731
EFSU	400	439	503	611	400	408	396	374
MDCs	1089	1243	1395	1646	1089	1184	1159	1105
AFR	611	1330	2111	2609	611	1292	2021	2510
LAM	434	713	1056	1417	434	656	808	870
WAS	194	431	811	1134	194	390	560	645
CPA	1247	1707	2219	2805	1247	1599	1705	1718
SEA	1442	2369	3223	3708	1442	2246	2789	2975
LDCs	3927	6550	9420	11672	3927	6183	7883	8717
ROW	178	234	280	338	178	240	280	313

and developing countries reduces to 5.1 in 2080. Thus it is a world where income disparities still exist but have been reduced by about two-thirds from current levels. The average annual GDP growth rates for developing and developed countries over the period 1990–2080 are the lowest in this scenario (in comparison to the other SRES scenarios), at 1.2% and 2.3% respectively.

Scenario A2 assumes a high level of demographic growth, with the world population increasing to 13.7 billion in 2080. The total population of developing countries reaches 9.4 billion in 2050 and 11.7 billion in 2080 (see *Table 4.1*).

In addition to the above four SRES scenarios, we consider two more scenarios, which we call A2s and B2s. They use the same basic assumptions as A2 and B2, except for economic growth: the annual economic growth rate over the period 1990–2080 in A2s and B2s is assumed to be some 45% lower than the corresponding values in A2 and B2.

In scenario A2s, the world economy grows at 2.0% over the period 1990–2080. The per capita GDP in 2080 amounts to \$35,000 in the developed world and \$3,000 in the developing world. The average income ratio between developed and developing countries is reduced only by about 15% from current levels, indicating a largely inequitable world still in 2080.

In scenario B2s, the world economy grows at 1.7% over the period 1990–2080. The per capita GDP in 2080 amounts to \$43,000 in the developed world and \$4,600 in the developing world. Here, the average income disparity ratio between developed and developing countries declines to about 9.3 in 2080.

The BLS results of the above six scenarios, without climate change, provide the baseline assessment, against which the climate-change impact results for the four GCMs and the various IPCC scenarios will be compared to quantify the impact of climate change on specific agricultural measures.

4.1.1 Baseline assessment

Tables 4.2–4.7 show the results of the baseline assessment for the six scenarios.

Cereal Production

In 1990, world cereal production amounted to 1.8 billion tons,[1] divided roughly equally between developed and developing countries. The simulated world cereal production in 2080 ranges from 3.7 billion tons in scenario B1 to 4.8 billion tons in scenario A2. The developed world production ranges from 1.4 billion tons in scenario B1 to 1.6 billion tons in scenario A2s. The developing countries achieve up to a three-fold increase in production from the 1990 levels, with Africa alone increasing production five-fold or more in all of the six scenarios.

At the world level, the developed countries, particularly OECD countries, form the major cereal exporter, with total net exports in 2080 ranging from 240 million tons in scenario B1 to some 380 million tons in scenario A2 (see *Table 4.4*). Africa (including Northern Africa) is projected to import some 20–30%, in all of the six scenarios, of its cereal demand in 2080. In the case of Western Asia, cereal demand is met through imports equivalent to some 50–60% of the region's demand in the six scenarios. The Centrally Planned Asia region, which includes China, becomes a net cereal exporter in the 2080s in scenarios A1 and B1, and an importer in the other four scenarios due to (perhaps unrealistic) high population growth assumed in the region. For Southeast Asia, net cereal trade is less than 5% of the cereal demand in this region. Latin America is a net exporter in all scenarios, except for some imports in scenario B2s.

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[1] Rice is included as milled equivalent. A factor of 0.67 was used to convert paddy rice to milled equivalent.

Table 4.2. BLS reference projections for IPCC future development path scenarios: Cereal production (in million tons).

	Scenario A1				Scenario B1			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1801	2673	3406	3884	1801	2641	3334	3729
OECD	590	785	915	956	590	781	912	941
EFSU	307	361	421	488	307	359	410	468
MDCs	897	1147	1336	1445	897	1139	1322	1410
AFR	73	163	265	331	73	162	265	322
LAM	102	202	253	243	102	197	230	211
WAS	50	84	108	103	50	84	108	106
CPA	362	539	693	841	362	536	687	827
SEA	250	446	639	800	250	431	612	735
LDCs	837	1434	1957	2318	837	1410	1901	2202
ROW	67	92	113	121	67	91	110	117
	Scenario A2				Scenario B2			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1801	2736	3764	4791	1801	2682	3474	4115
OECD	590	787	944	1053	590	781	905	970
EFSU	307	370	471	593	307	367	438	542
MDCs	897	1157	1415	1645	897	1148	1343	1512
AFR	73	167	298	438	73	167	284	382
LAM	102	217	361	507	102	204	270	286
WAS	50	84	116	165	50	84	109	115
CPA	362	542	711	890	362	538	697	855
SEA	250	472	737	998	250	446	653	833
LDCs	837	1483	2223	2998	837	1439	2013	2470
ROW	67	97	126	147	67	96	119	133
	Scenario A2s				Scenario B2s			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1801	2712	3695	4642	1801	2659	3377	3850
OECD	590	785	947	1023	590	778	906	936
EFSU	307	367	465	617	307	365	420	508
MDCs	897	1153	1412	1640	897	1143	1327	1443
AFR	73	166	292	439	73	166	268	361
LAM	102	214	355	498	102	201	254	248
WAS	50	84	109	129	50	84	112	127
CPA	362	539	702	876	362	535	684	830
SEA	250	460	704	917	250	437	619	717
LDCs	837	1464	2161	2859	837	1422	1937	2283
ROW	67	96	122	143	67	95	113	124

Note: Rice is included as milled equivalent; conversion factor from paddy rice to milled is 0.67.

Table 4.3. BLS reference projections for IPCC future development path scenarios: Cereal demand (in million tons).

	Scenario A1				Scenario B1			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1796	2669	3403	3877	1796	2639	3330	3721
OECD	434	562	665	719	434	557	648	702
EFSU	339	378	432	505	339	376	433	510
MDCs	773	940	1096	1224	773	933	1082	1212
AFR	109	242	391	456	109	242	387	462
LAM	112	198	248	248	112	198	242	237
WAS	76	153	235	261	76	153	235	262
CPA	388	568	646	636	388	566	644	641
SEA	257	450	655	916	257	430	608	770
LDCs	941	1612	2175	2517	941	1589	2117	2373
ROW	81	117	132	136	81	117	132	137
	Scenario A2				Scenario B2			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1796	2736	3764	4790	1796	2680	3471	4112
OECD	434	536	591	670	434	553	594	607
EFSU	339	373	435	525	339	369	423	499
MDCs	773	909	1026	1195	773	922	1017	1106
AFR	109	250	425	551	109	242	427	568
LAM	112	199	303	411	112	190	250	277
WAS	76	161	289	412	76	151	229	277
CPA	388	619	888	1214	388	595	737	872
SEA	257	479	687	836	257	459	665	851
LDCs	941	1708	2593	3425	941	1637	2308	2843
ROW	81	119	145	170	81	122	147	162
	Scenario A2s				Scenario B2s			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1796	2711	3694	4640	1796	2656	3375	3846
OECD	434	532	587	661	434	549	579	576
EFSU	339	372	436	531	339	369	420	506
MDCs	773	904	1023	1192	773	918	999	1082
AFR	109	245	408	526	109	235	405	524
LAM	112	198	300	400	112	189	247	263
WAS	76	160	284	387	76	150	223	261
CPA	388	620	888	1211	388	597	736	872
SEA	257	465	648	754	257	446	618	680
LDCs	941	1688	2527	3278	941	1617	2229	2601
ROW	81	119	144	170	81	122	147	163

Note: Rice is included as milled equivalent; conversion factor from paddy rice to milled is 0.67.

Table 4.4. BLS reference projections for IPCC future development path scenarios: Net cereal exports (in million tons).

	Scenario A1				Scenario B1			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	6	4	4	4	6	2	4	7
OECD	156	223	250	250	156	224	263	240
EFSU	–32	–17	–11	–11	–32	–18	–23	–42
MDCs	123	206	240	240	123	207	240	198
AFR	–36	–79	–126	–126	–36	–80	–122	–140
LAM	–9	4	5	5	–9	0	–12	–26
WAS	–26	–69	–127	–127	–26	–69	–127	–156
CPA	–26	–30	46	46	–26	–30	42	186
SEA	–7	–4	–16	–16	–7	0	4	–35
LDCs	–104	–178	–217	–217	–104	–179	–215	–171
ROW	–14	–25	–19	–19	–14	–26	–21	–19
	Scenario A2				Scenario B2			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	6	0	0	0	6	1	3	3
OECD	156	251	352	383	156	227	311	363
EFSU	–32	–3	36	67	–32	–2	15	42
MDCs	124	248	389	450	124	225	326	405
AFR	–36	–82	–127	–113	–36	–76	–142	–185
LAM	–10	19	58	96	–10	14	19	9
WAS	–26	–77	–173	–248	–26	–67	–120	–162
CPA	–26	–77	–177	–324	–26	–57	–39	–17
SEA	–7	–7	50	162	–7	–13	–12	–18
LDCs	–105	–225	–369	–427	–105	–198	–295	–373
ROW	–14	–22	–19	–23	–14	–26	–28	–30
	Scenario A2s				Scenario B2s			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	6	1	2	2	6	3	2	5
OECD	156	254	361	363	156	229	327	360
EFSU	–32	–5	29	86	–32	–4	1	1
MDCs	124	249	390	448	124	225	328	361
AFR	–36	–78	–116	–87	–36	–69	–137	–163
LAM	–10	16	55	98	–10	11	7	–15
WAS	–26	–76	–175	–258	–26	–66	–111	–134
CPA	–26	–80	–186	–334	–26	–62	–52	–42
SEA	–7	–5	56	163	–7	–9	1	38
LDCs	–105	–224	–365	–419	–105	–195	–292	–318
ROW	–14	–23	–23	–27	–14	–27	–34	–39

Note: Rice is included as milled equivalent; conversion factor from paddy rice to milled is 0.67.

Table 4.5. BLS reference projections for IPCC future development path scenarios: Cultivated land (in million ha).

	Scenario A1				Scenario B1			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1521	1616	1651	1599	1521	1611	1638	1581
OECD	343	340	339	341	343	339	337	338
EFSU	263	260	257	259	263	260	256	257
MDCs	606	600	596	600	606	599	593	595
AFR	232	280	311	290	232	279	309	287
LAM	160	200	201	185	160	198	194	177
WAS	70	68	71	67	70	68	71	67
CPA	147	144	141	135	147	144	141	135
SEA	264	284	294	289	264	284	294	288
LDCs	872	976	1018	966	872	972	1008	953
ROW	43	40	36	33	43	40	36	33
	Scenario A2				Scenario B2			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1521	1636	1746	1794	1521	1623	1692	1693
OECD	343	340	341	346	343	340	339	340
EFSU	263	262	259	262	263	262	260	261
MDCs	606	602	600	608	606	602	598	601
AFR	232	282	333	345	232	281	332	345
LAM	160	212	257	285	160	204	218	209
WAS	70	68	71	71	70	68	70	69
CPA	147	146	146	145	147	145	143	139
SEA	264	286	303	306	264	283	295	296
LDCs	872	994	1109	1153	872	981	1057	1059
ROW	43	40	37	33	43	40	37	33
	Scenario A2s				Scenario B2s			
	1990	2020	2050	2080	1990	2020	2050	2080
WORLD	1521	1633	1743	1792	1521	1620	1685	1669
OECD	343	339	338	343	343	339	341	333
EFSU	263	262	260	262	263	262	260	261
MDCs	606	601	598	604	606	601	601	594
AFR	232	281	331	342	232	280	326	337
LAM	160	212	259	292	160	204	215	204
WAS	70	68	71	70	70	68	70	69
CPA	147	146	145	145	147	145	143	139
SEA	264	286	302	306	264	283	294	294
LDCs	872	992	1108	1155	872	979	1048	1043
ROW	43	40	37	33	43	40	36	33

Table 4.6. BLS reference projections for IPCC future development path scenarios: People at risk of hunger (in millions).

	Scenario A1				Scenario B1			
	1990	2020	2050	2080	1990	2020	2050	2080
LDCs	824	663	208	108	824	749	239	91
ASIA	527	342	41	24	527	432	53	22
CPA	172	81	3	4	172	92	4	0
SEA	355	261	38	21	355	340	49	22
OTHER LDCs	297	321	167	84	297	317	187	69
AFR	207	251	102	42	207	250	127	34
LAM	58	22	13	9	58	21	11	7
WAS	32	48	52	32	32	46	49	27
	Scenario A2				Scenario B2			
	1990	2020	2050	2080	1990	2020	2050	2080
LDCs	824	782	721	768	824	630	348	233
ASIA	527	387	209	195	527	246	85	54
CPA	172	136	110	110	172	98	42	20
SEA	355	251	99	85	355	148	42	33
OTHER LDCs	297	395	512	573	297	384	263	180
AFR	207	271	297	287	207	283	181	113
LAM	58	64	79	90	58	51	26	16
WAS	32	60	136	197	32	50	57	51
	Scenario A2s				Scenario B2s			
	1990	2020	2050	2080	1990	2020	2050	2080
LDCs	824	925	988	1065	824	773	502	458
ASIA	527	477	323	274	527	315	90	54
CPA	172	133	103	105	172	94	27	3
SEA	355	343	220	170	355	221	63	51
OTHER LDCs	297	448	665	790	297	458	412	405
AFR	207	317	431	475	207	345	323	331
LAM	58	70	89	101	58	58	26	14
WAS	32	62	145	214	32	54	63	60

The world cereal prices are highest in scenario A2 in the 2080s, reaching a value more than 2.7 times the 1990 prices. Only in scenario B2s, the world cereal price in the 2080s falls some 17% below the 1990 price level owing to a low effective demand for food due to low population growth and lack of purchasing power in developing countries. *Table 4.7* also shows that world market prices for all crops increase by 30–110% in five of the scenarios, except for scenario B2s, where the price in 2080 would be 25% lower than in the 1990s.

Table 4.7. BLS reference projections for IPCC future development path scenarios: Index of agricultural world market prices (1990=100).

	SRES A1				SRES B1			
	2010	2020	2050	2080	2010	2020	2050	2080
All crops	94	115	157	172	89	103	132	132
Cereals	98	120	156	161	93	109	131	113
Other crops	91	112	157	178	87	101	133	141
Production	99	120	162	172	95	109	140	137
Exports	99	120	162	172	96	112	145	141
	SRES A2				SRES B2			
	2010	2020	2050	2080	2010	2020	2050	2080
All crops	97	106	152	209	97	102	135	147
Cereals	103	118	184	267	100	108	138	150
Other crops	94	100	135	181	95	99	134	147
Production	99	107	145	189	99	103	132	140
Exports	100	109	154	211	99	104	135	144
	SRES A2s				SRES B2s			
	2010	2020	2050	2080	2010	2020	2050	2080
All crops	92	96	118	143	92	92	89	75
Cereals	98	106	144	195	94	97	95	83
Other crops	89	91	104	118	90	89	86	72
Production	94	97	115	131	94	93	90	75
Exports	96	100	123	149	95	95	93	81

Cultivated Land

Total cultivated land in developed countries in 1994–1996 amounted to about 600 million hectares (ha). As discussed previously in Chapter 3, there is additional potential land that can be cultivated. The results of all the four scenarios, A1, B1, A2, and B2, show, however, that land under cultivation is likely to stay close to the 1990 level and that additional production in various scenarios comes mainly from increased productivity (see *Table 4.5*). For developing countries total land in 1994–1996 amounted to 870 million ha, with Southeast Asia accounting for about 30% of this. In scenarios A1 and B1, the land under cultivation in 2080 in the developing countries increases by about 10% compared to 1990, whereas in scenario A2 and B2 this increase is higher, at about 30% and 20% respectively. Most of the new crop land is cultivated in Africa and Latin America. In Southeast Asia, some 30–40 million ha of additional land are brought under cultivation in the four scenarios. For 2050 and 2080, the lowest level of total world cultivated land results in scenario B1, respectively 1.64 billion ha and 1.58 billion ha; the highest demand for land occurs in scenario A2, with some 1.75 billion ha in 2050 and almost 1.8 billion ha in 2080. Note that in scenarios A1 and B1, the land under cultivation in the 2050s is higher than in the 2080s; this occurs in line with the peak in projected population that also occurs around the middle of the century.

Hunger

The results in *Table 4.6* show that in scenarios A1, B1, A2, and B2, in spite of relatively high levels of economic growth, there is little progress in reducing hunger to 2020. The results to 2020 imply that specific targeted programs for hunger reduction will be necessary to meet the millennium goals of reducing hunger by half in 2015.

In the period 2020–2050, considerable progress is made and hunger is substantially reduced in scenarios A1, B1, and B2. In the case of scenario A2, hunger persists and the number of undernourished in 2080 amounts to 768 million compared to roughly 800 million undernourished in 2000.

In scenario A2s, the number of hungry increases to some 1.1 billion in the 2080s, equivalent to almost 10% of the projected population. The situation is worse in Africa, where the number of hungry would more than double, to 475 million people in 2080, equivalent to around 20% of the total population.

In the case of Asia, there is a reduction of the number of hungry in all scenarios.

These results indicate that "trickle down" of development, under relatively very high levels of economic growth and with moderate population increases, can reduce the number of hungry in the world in the 2050s and 2080s. It is worrying, however, that this does not appear to have a sufficient impact in the next 20 years. If population growth is high, as in scenario A2, progress on eradicating hunger will be difficult, with the total number of hungry remaining at about the same level in the 2080s as in the 1990s.

The above baseline results provide a frame for assessing the climate-change impact of various climate models and emission scenarios, which follows in the next section.

4.2 Impact of Climate Change on Food Production, Consumption, and Trade

The evaluation of the impact of climate change on production, consumption, and trade of agricultural commodities, in particular on food staples, was carried out by comparing the results of a range of IPCC climate-change scenarios to reference projections of the world food system simulated without imposing climatic change. These reference projections were presented in the previous section.

The climate-change scenarios devised within the project involve a large number of experiments that relate to four aspects:

- climate impacts for different future socioeconomic and technical development paths;
- uncertainty of results in view of differences in climate projections of different GCM groups;
- robustness of results with regard to altered economic growth assumptions; and
- sensitivity of results to different assumptions with regard to physiological effects of atmospheric CO_2 enrichment on yields.

Some 50 simulation experiments have been carried out with the ecological-economic framework provided by AEZ and BLS. The simulation experiments cover the following aspects:

1. Simulations for the four basic IPCC demographic and economic future development paths were described as scenarios A1, A2, B1, and B2.
2. In addition, two development scenarios with lowered economic growth rates and based on IPCC scenarios A2 and B2 were simulated.
3. Simulations for these development paths were carried out separately without considering climate-change impacts on yields and for climate-change projections of four GCM groups.
4. The socioeconomic development paths scenarios A2 and B2 were simulated super-imposing the full range of climate projections to analyze their sensitivity with regard to the magnitude of climate change.
5. Additional simulations were carried out without considering physiological effects of increased atmospheric CO_2 concentrations on crop growth and yield.

Data on crop yield changes were estimated with AEZ, as detailed in the previous chapter, for different scenarios of climate change, and were compiled to provide yield-impact parameterizations for the 34 countries or major regions covering the world in the BLS. Yield variations caused by climate change were introduced into the yield response functions by means of a multiplicative factor impacting upon the relevant parameters in the mathematical representation.

Exogenous variables, population growth and technical progress, were left at the levels specified in the respective reference projections. No specific adjustment policies to counteract altered performance of agriculture were assumed beyond the farm-level adaptations resulting from economic adjustments of the individual actors in the national models. The adjustment processes taking place in the different scenarios are the outcome of the imposed yield changes causing distortions in national production levels and costs, leading to changes of agricultural prices in the international and national markets; this in turn affects investment allocation and labor migration between sectors as well as reallocation of resources within agriculture. Time is an important aspect in this adjustment process: the yield modifications due to climate change begin in 1990. Three separate snapshots of climatic change are provided referring to the 2020s, 2050s, and 2080s, respectively. This allows the economic actors in the national and international food system to adjust their decisions over a 90-year period. AEZ model simulations were conducted separately for these three time points. Climate-change yield impacts were phased in linearly between the climate "snapshots" provided by the respective climate scenario; i.e., the yield change multiplier terms incorporated in the yield response functions of the BLS were built up gradually as a function of time for the periods 1990–2020, 2020–2050, and 2050–2080, so as to fully reach the impact levels derived with AEZ respectively in 2020, 2050, and 2080.

4.2.1 Climate-change yield impacts without economic adjustments

Before assessing the dynamic impacts of climate-change-induced yield modifications through simulation with the BLS, we may ask what magnitude of distortion the change in agricultural productivity of a particular scenario would imply for the world food system. This measure of distortion indicates the production changes that would occur due to yield changes without adjustments of the economic system, which will take place over time due to market-price changes among agricultural commodities, in response to demand-supply imbalances of commodity markets, as well as adjustments of agricultural prices relative to other sectors. It refers to a state of the system that would not be in equilibrium, in the sense of meeting commodity supply-demand balances. As such it is only of theoretical interest, but it helps to understand and quantify the nature and magnitude of adjustments taking place in the food system due to changing economic conditions.

To obtain for any particular year t an estimate of the climate-change yield impact without economic adjustment, $\Lambda(t)$, for any particular scenario, we apply the crop-wise productivity changes obtained in the AEZ assessment, $\lambda_i^j(t)$, to the production levels determined in the respective BLS reference projection (without climate change) in year t. For cereals these impacts can be added up without weighting. To arrive at estimates of climate-change impacts (without economic adjustment) for other groups of crops and the entire sector, world market prices of year t as simulated in the respective reference projection are used. In mathematical notation,

Table 4.8. Climate-change impacts on crop production, without economic adjustment, year 2080 (% change).

	HadCM3			CSIRO			CGCM2			NCAR-PCM		
Scenario	Cereals	Other crops	All crops	Cereals	Other crops	All crops	Cereals	Other crops	All crops	Cereals	Other crops	All crops
World												
A2	–0.7	–2.2	–1.6	–1.2	–1.5	–1.3	–0.4	5.0	2.7	3.4	7.3	5.6
B2	–0.1	–0.4	–0.2	–1.7	–0.9	–1.2	1.3	6.0	4.0	2.4	5.4	4.1
Developed												
A2	2.1	–3.0	–0.0	5.1	1.3	3.5	1.5	3.7	2.4	10.2	16.4	12.8
B2	1.7	–2.4	–0.1	3.2	0.1	1.9	3.7	7.0	5.1	7.4	12.0	9.3
Developing												
A2	–2.1	–2.1	–2.1	–4.3	–2.1	–3.0	–1.4	5.4	2.8	–0.1	5.2	3.2
B2	–1.0	0.1	–0.3	–4.2	–1.1	–2.3	0.1	5.8	3.6	–0.2	3.9	2.4

Note: For aggregation, production distortions due to climate change were weighted with world market prices of the scenario A2 reference projection without climate change.

$$\Lambda_R(t) = \left(\sum_{j\in R}\sum_{i\in C} P_{it}^W \cdot Q_{it}^j \cdot \lambda_i^j(t)\right) \Big/ \left(\sum_{j\in R}\sum_{i\in C} P_{it}^W \cdot Q_{it}^j\right) ,$$

where $\Lambda_R(t)$ is climate-change production impact, without economic adjustment, on region R in year t; $\lambda_i^j(t)$ is climate-change yield impact for crop i, in country j, in year t; P_{it}^W is world market price of commodity i in year t of BLS reference projection simulated without considering climate change; Q_{it}^j is production of commodity i, in country j, in year t of BLS reference projection simulated without considering climate change.

Table 4.8 shows impacts of climate change on production estimated for the global and regional levels for the IPCC A2 and B2 development path scenarios.

The magnitude and even direction of the aggregate impact at world level varies with climate projections of different GCM groups. Scenarios based on HadCM3 and CSIRO projections result in a small negative net impact at global level. For instance, for climate projections using emission scenario A2, the global impact on cereals ranges from –0.7% to –1.2%, i.e., a gap of about 60 million tons in 2080. When aggregating all crops, and using the production levels of the A2 reference projection as weights, the net impact amounts to –1.3% to –1.6%. Climate projections by the Canadian CGCM2 model and NCAR-PCM model imply moderate positive global crop-production changes of 2.7–5.6%. In *Figures 4.1* and *4.2*, the time path of production impacts of different climate projections is shown for IPCC scenario A2.

However, as demonstrated in *Table 4.9* for scenario A2, the impacts of climate change on crop production are geographically quite unevenly distributed, with

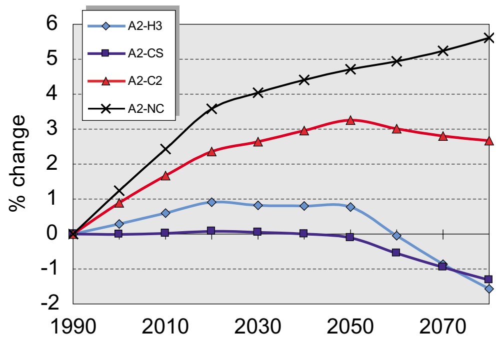
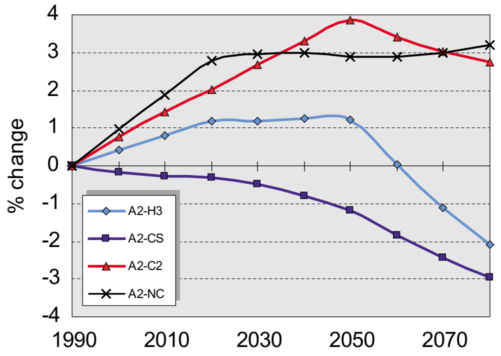


Figure 4.1. Climate-change impacts on global crop production for projections of IPCC scenario A2, without economic adjustment.

(a) Developing countries



(b) Developed countries

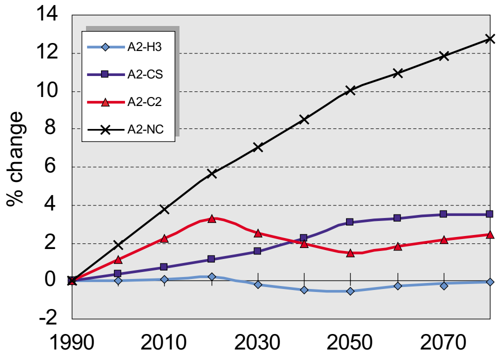


Figure 4.2. Climate-change impacts on aggregate crop production in developing and developed regions for projections of IPCC scenario A2, without economic adjustment.
Note: H3 = HadCM3; CS = CSIRO; C2 = CGCM2; NC = NCAR-PCM.

Table 4.9. Climate-change impacts on crop production for IPCC scenario A2, by region, without economic adjustment, year 2080 (% change).

	HadCM3		CSIRO		CGCM2		NCAR-PCM	
Region	Cereals	All crops	Cereals	All crops	Cereals	All crops	Cereals	All crops
World	–0.7	–1.6	–1.2	–1.3	1.4	4.0	2.4	4.1
Developed	2.1	0.0	5.1	3.5	3.7	5.1	7.4	9.3
North America	2.5	0.8	9.8	8.3	3.2	2.4	8.3	8.4
Western Europe	–2.6	–5.8	–5.0	–3.9	–1.5	–2.8	0.6	0.3
Former Soviet Union	2.9	–0.3	3.9	0.8	6.1	9.5	9.6	14.1
Developing	–2.1	–2.1	–4.3	–3.0	–1.4	2.8	–0.2	2.4
Africa	–2.2	–1.9	–3.1	–4.6	–1.9	0.5	0.1	4.3
Latin America	4.6	0.6	0.8	2.5	0.4	1.0	2.1	2.3
Centrally Planned Asia	–0.8	–4.5	–3.4	–5.8	2.2	4.8	4.3	5.7
South Asia	–13.5	–10.7	–11.6	–7.6	–5.4	0.2	–7.4	–2.0

Note: For aggregation, production distortions due to climate change were weighted with world market prices of the scenario A2 reference projection without climate change.

many much larger positive and negative distortions for different regions. At the aggregate level, developed countries experience for all variants of the A2 scenario an increase in productivity. In contrast, developing regions suffer a loss in cereal productivity in all estimates presented here; for aggregate crop production the outcome is mixed. Within the group of developed countries, gains of 2.5–9.8% in cereal productivity occur for North America, and similar for the Former Soviet Union. Western Europe suffers losses of up to 6%, except for minor gains when using NCAR-PCM projections.

Impacts on developing regions are mostly negative for South Asia and Africa, mixed for Centrally Planned Asia (including China), and overall positive for Latin America.

4.2.2 Climate-change impacts with economic adjustments

The calculations above discuss an effect that would result if climate-induced yield changes were to occur without agronomic and economic adjustment. However, when simulating with the BLS, in scenarios with shortfalls in food production caused by climate-change yield impacts, market imbalances push international prices upwards and provide incentives for reallocation of capital and human resources. At the same time, consumers react to price changes and adjust their patterns of consumption accordingly. Let us first discuss the simulated changes on the world market.

Table 4.10. Impact of climate change on world market prices, year 2080 (% changes relative to reference projection).

	Cereals				All crops			
Scenario	HadCM3	CSIRO	CGCM2	NCAR	HadCM3	CSIRO	CGCM2	NCAR
A2	14.4	8.9	3.3	–10.6	11.3	6.9	–2.9	–12.9
B2	2.1	6.8	–6.7	–11.8	0.0	3.6	–10.3	–14.8
B1	3.1	4.7	n.a.	n.a.	2.5	2.0	n.a.	n.a.
A1FI	19.5	n.a.	n.a.	n.a.	10.5	n.a.	n.a.	n.a.
A1B	n.a.	4.2	n.a.	n.a.	n.a.	0.5	n.a.	n.a.

Table 4.10 contains changes in world market prices, for cereals and an overall crop price index, as simulated in the respective yield impact scenarios relative to the respective reference projection.

In the case of HadCM3 climate projections, cereal prices increase by 2–20% relative to the respective reference projection. For CSIRO the increase is 4–10%. For NCAR-PCM, as global production capacity increases relative to reference conditions, cereal prices drop by 10–12%, and the crop price index decreases by 13–15%. The simulated crop-price changes in response to climate change are quite moderate due to the relatively small net global impact on crop-production potential.

Impact of Climate Change on Agriculture

The dynamic simulation of climate-change impacts with the BLS result in complex interactions among commodity markets, regions, as well in manifold responses by consumers and producers. In order to estimate the aggregate impacts caused by both the climate-change-induced productivity changes and the economic adjustments of actors, we compare value added in agriculture (at constant world market prices of the base year 1990) obtained in a climate scenario simulation to the outcome in the respective reference projection simulated without climate change. Results are summarized in *Table 4.11*.

The results re-emphasize the general findings that: (i) impacts at aggregate global level are small, ranging from –1.5% (in HadCM3-A1FI scenario) to 2.6% (in NCAR-A2 scenario) – this compares to a global GDP of agriculture, obtained in the reference projections, ranging in 2080 from US$2.9 trillion (scenario B1) to US$3.6 trillion (scenario A2) at 1990 prices; (ii) agriculture in developed countries as a group will likely benefit from climate change; and (iii) developing regions, with the exception of Latin America, are confronted with negative impacts on GDP of agriculture. For Asia the loss in value added of agriculture amounts to some 4% in the case of the higher emission scenarios for HadCM3 and CSIRO, equivalent to some US$500 billion. Outcomes differ by less than 1% from the respective reference scenarios for CGCM2 and NCAR climate projections. Aggregate outcomes

Table 4.11. Impact of climate change on GDP of agriculture, by region and climate model projections, in 2080 (% changes from respective reference projection).

	HadCM3				CSIRO			CGCM2		NCAR	
	A1FI	A2	B2	B1	A2	B2	B1	A2	B2	A2	B2
World	–1.5	–0.9	–0.4	–0.5	–0.8	–0.9	–0.3	1.1	1.0	2.6	2.4
Developed	–0.5	0.2	–0.7	1.1	3.9	2.6	5.1	2.8	5.1	12.9	9.6
North America	7.5	3.1	2.7	7.7	10.5	8.6	11.2	2.8	5.4	12.6	5.4
Europe	–14.7	–18.0	–16.9	–8.1	–10.9	–11.8	–7.0	–14.0	–16.9	–6.2	–8.2
Soviet Union	–4.9	–0.5	1.9	–0.9	0.5	2.0	3.5	3.5	11.9	22.7	17.0
Developing	–1.9	–1.2	–0.3	–0.9	–2.4	–2.2	–2.4	0.6	–0.3	–0.5	0.1
Africa	–4.9	–3.7	–1.6	–7.0	–9.2	–6.8	–7.1	–1.9	–8.2	–2.0	1.4
Latin America	3.7	1.4	1.8	4.1	3.6	1.7	0.4	–1.8	–4.3	–2.4	–2.5
Southeast Asia	–3.7	–5.0	–3.5	–0.8	–4.4	–4.3	–4.1	–0.4	1.0	–0.9	–1.1
Centrally Planned Asia	–6.4	–2.1	–0.8	–2.0	–4.0	–3.9	–4.1	–1.1	–0.1	2.2	1.6
Asia	–4.3	–4.2	–2.8	–1.1	–4.3	–4.2	–4.1	–0.6	0.7	–0.1	–0.4

Table 4.12. Impact of climate change on cereal production, by region and climate model projections, in 2080 (% changes from respective reference projection).

	HadCM3				CSIRO			CGCM2		NCAR	
	A1FI	A2	B2	B1	A2	B2	B1	A2	B2	A2	B2
World	–1.4	–0.9	–0.4	–0.7	–1.2	–1.3	–1.1	–0.5	0.4	1.7	1.2
Developed	2.8	–0.4	2.8	2.2	5.5	5.5	6.3	1.8	4.7	11.2	8.4
North America	1.3	–5.6	–0.1	1.5	7.4	5.9	7.2	–0.5	1.5	9.6	9.0
Western Europe	–3.4	2.1	2.0	–1.6	–5.4	–5.5	–4.8	–2.1	2.2	0.3	0.2
Former Soviet Union	7.0	5.4	7.2	4.9	7.3	8.7	9.2	5.1	9.4	18.7	10.9
Developing	–3.9	–1.1	–2.2	–2.4	–4.8	–5.3	–5.8	–1.7	–2.1	–3.4	–3.0
Africa	–0.6	–0.3	–0.5	–0.2	1.3	–0.4	–0.2	2.7	–1.5	1.1	–1.0
Latin America	15.9	11.5	4.9	8.2	3.7	0.8	–0.7	–1.6	–1.2	–2.4	–1.1
Southeast Asia	–10.2	–10.7	–8.8	–5.9	–12.7	–11.3	–10.7	–6.2	–6.7	–13.0	–10.4
Centrally Planned Asia	–7.1	–0.6	–0.4	–2.7	–5.5	–4.9	–5.2	–1.4	–0.1	3.9	2.6
Asia	–8.6	–5.9	–4.6	–4.2	–9.3	–8.0	–7.8	–4.0	–3.4	–5.0	–3.8

for Africa are generally negative as well, a loss of 2–8% for HadCM3 and CGCM2 simulations, and decreases of 7–9% for CSIRO projections, implying a loss at 1990 prices of US$10–60 billion. Among developed regions, North America gains substantially in all simulated scenarios; Western Europe loses agriculture value added in all scenarios, and the Former Soviet Union mostly benefits from climate-induced changes in production conditions.

Impact of Climate Change on Cereal Production

The dynamic impact of climate change on the production of cereals, resulting both from changes in land productivity as well as economic responses of actors in the system, is summarized in *Table 4.12*.

Table 4.13. Impact of climate change on direct human cereal consumption, by developing region and climate model projections, in 2080 (% changes from respective reference projection).

	HadCM3				CSIRO			CGCM2		NCAR	
	A1FI	A2	B2	B1	A2	B2	B1	A2	B2	A2	B2
World	–3.4	–2.4	–1.4	–1.6	–2.5	–2.5	–2.4	–1.5	–0.4	0.7	0.7
Developing	–3.7	–2.6	–1.5	–1.8	–2.8	–2.7	–2.7	–1.6	–0.5	0.7	0.8
Africa	–2.8	–3.0	–1.1	–1.1	–1.8	–1.2	–1.1	–1.2	–0.1	0.0	0.9
Latin America	–2.0	–2.1	–0.5	–0.6	–1.2	–0.9	–0.5	–0.6	0.5	0.5	1.1
Southeast Asia	–3.9	–4.2	–3.0	–2.7	–2.5	–3.1	–3.3	–1.5	–1.2	–0.4	–0.6
Centrally Planned Asia	–4.8	–0.7	–0.2	–1.3	–4.3	–4.0	–4.2	–2.5	–0.2	2.4	2.4
Asia	–4.2	–2.5	–1.8	–2.2	–3.4	–3.5	–3.6	–2.0	–0.8	1.0	0.7

The model results present a fairly consistent pattern of response in regional cereal production to climate change. At global level, taking into account economic adjustment of actors and markets, cereal production falls within 2% of the results for the respective reference simulations without climate change. Again, aggregation produces deceivingly small numbers. Developing countries consistently experience reductions in cereal production in all climate scenarios. Negative changes of 5–6% are most pronounced in simulations based on CSIRO climate projections. In this case, production moves to developed regions, notably North America and the Former Soviet Union, where increases of 6–9% are observed. The most significant negative changes occur in Asian developing countries, where production declines in all scenarios, ranging from about 4% decreases for CGCM2 and NCAR climate projections to reductions of 6–10% for HadCM3 and CSIRO.

Impact of Climate Change on Cereal Consumption and Net Trade

In the SRES worlds of the 2080s, consumers are assumed to be much richer than today and are largely separated from agricultural production processes. They earn their incomes mainly in the nonagricultural sector. Therefore, changes in consumption depend more on food prices and income differences than on local agricultural production. *Table 4.13* summarizes the changes in direct human food consumption of cereals (i.e., excluding feed consumption) occurring in the world food system simulations in response to climate change.

Table 4.13 shows a fairly uniform decline in direct human consumption of cereals across models and scenarios, with the exception of simulations based on NCAR climate projections. For HadCM3, direct human cereal consumption in developing countries declines by 2–4%, i.e., equivalent to 40–80 million tons, compared to direct human consumption of cereals in developing countries for the respective reference simulations ranging from 1.6 billion tons (scenario B1) to 2.1 billion tons (scenario A2). Consumption in Asian developing countries accounts for two-thirds of this amount. Consumers in Latin America are least affected.

Demand and supply for commodities meet in the market. The simulations of the IPCC development path scenarios without climate change result in a growing dependence of developing countries on net cereal imports of between 170 million tons (scenario B1) and 430 million tons (scenario A2), as shown in Section 4.1 (*Table 4.4*). Climate change will add to this dependence, increasing net cereal imports of developing regions in the order of 10–40%, varying with development path scenario and GCM climate projections. Even in the case of NCAR projections, resulting in overall positive impacts on agricultural productivity, the comparative advantage for producing cereals shifts to developed countries, and net imports of developing countries increase by about 25%, equivalent to an additional 110 million tons in scenario A2 and about 90 million tons of additional imports in scenario B2.

It is important to note that these changes in comparative advantage between developed and developing regions are likely to accentuate the magnitude of the impacts suggested by the assessment, i.e., "winners" are likely to gain more, "losers" will lose more than projected here without full economic impacts and adjustment in nonagricultural sectors.

4.3 Impact of Climate Change on the Number of People at Risk of Hunger

Section 4.1 has highlighted that estimates of the number of *people at risk of hunger* vary greatly according to socioeconomic development trajectories, in particular assumed income levels and income distribution, and population numbers.

The BLS estimate is based on FAO data (FAO, 2001) and relies on a strong empirical correlation between the share of undernourished in the total population and the ratio of average national food supply relative to aggregate national food requirements. This correlation is plotted in *Figure 4.3*. The horizontal axis represents an aggregate measure of food availability. For instance, the curve suggests that the share of undernourished in the total population will fall below 20% for an index value of 130, i.e., when aggregate food supply exceeds aggregate national food requirements by 30%. Hunger is completely eliminated for index values of food supply over requirements of above 170.

The impact of climate change on the number of people at risk of hunger is estimated in the BLS, using the relationship shown in *Figure 4.3*. Hence, the impact of climate change on the number of undernourished is measured via changes in the ratio of aggregate national human food consumption to food requirements. This ratio is affected by the direct impact of climate change on domestic food production, as well as by the indirect effects related to income changes and the prices

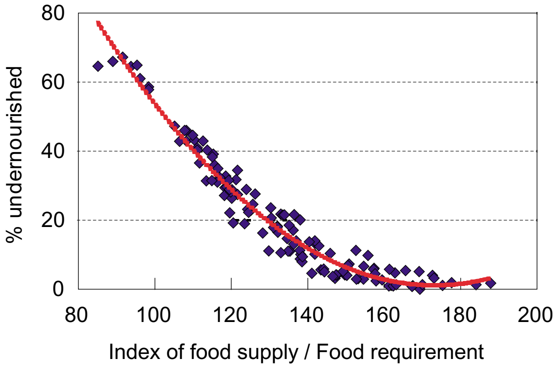


Figure 4.3. The share of undernourished in the total population.

of food imports, which depend on the global availability of food. Therefore, on the one hand the trade system will mitigate negative local climate-change impacts when consumers can afford to buy food on the international market. On the other hand, food prices rising due to climate change may put an extra burden on those consumers who depend on imports, even without a region experiencing direct local climate-change impacts on production conditions. Overall, the trade system helps somewhat to disperse the impacts of climate change by providing access to food for consumers that can pay for it and by providing additional incentives to producers to mobilize additional production capacities where available.

Based on more than 40 simulation experiments with the BLS, some fairly robust conclusions emerge from our analysis of climate-change impacts. First, climate change will most likely increase the number of people at risk of hunger. The impact of climate change reduced the number of undernourished only in one scenario, namely the benign climate projected by the NCAR-PCM model. Second, the significance of any climate-change impact on the number of undernourished depends entirely on the level of economic development assumed in the SRES scenarios.

In scenario A1, where the number of undernourished decreases to about 200 million by 2050, and is further reduced to about 100 million people by 2080, i.e., one-eighth of the current level, the impact of climate change in 2080 is large only in relative terms, an increase of 26% from 108 million to 136 million, but relatively small in absolute terms when the magnitude of the current hunger problem is considered. According to the underlying assumptions of scenario A1, consumers worldwide are economically well-off and agriculture provides only a marginal contribution of around 1% to national incomes. Under such assumptions, trade can compensate for regional shortfalls in production, and due to generally high levels of consumption reductions in food supply will cause only moderate changes in the number of undernourished. To put it very bluntly, for the wealthy societies of scenario A1 – even the currently poor regions are assumed to reach economic levels exceeding in per capita terms current average OECD incomes – hunger is a marginal issue and remains so even with climate change; a desirable vision but perhaps overly optimistic in comparison to actual achievements of the last 30 years.

The conclusions obtained for SRES scenario B1 are similar to those for scenario A1. For B1, without climate change, we estimate that the number of people at risk of hunger would fall from currently about 800 million people to below 100 million by the 2080s, i.e., a number even slightly lower than in scenario A1. As there is more moderate climate change in scenario B1, due to lower CO_2 emissions than in scenario A1, the negative impact on the number of undernourished is small both in relative and absolute terms. HadCM3-B1 results show an increase of 8%, from 91 to 99 million people; for climate projections of the CSIRO model the impact is even less, at some 4%.

The outcome of BLS simulation experiments regarding the number of people at risk of hunger is quite different under the high-population SRES scenario A2. Under this set of assumptions, the number of undernourished, even without considering climate change, remains high throughout the simulation period to 2080. Again, climate change increases the number of hungry, but this time absolute numbers do matter. In the reference case, without considering climate change, the number of undernourished estimated for 2050 amounts to 721 million people; for 2080 it is 768 million. This number increases by nearly 120 million, by some 15%, in both HadCM3 and CSIRO climate projection scenarios. Climate projections of the Canadian CGCM2 model result in 817 million people at risk of hunger, equivalent to an additional 50 million undernourished due to climate change. The situation reverses only in the simulations with projections of NCAR-PCM for emission scenario A2. Here the number of undernourished decreases by 5% due to improved agricultural conditions worldwide, with mitigated moisture stress in many regions and the lowest temperature increase of all the models considered in this study.

To explore further the relationship between different levels of climate change and the prevalence of hunger in a socioeconomic setting as defined by the SRES scenarios A2 and B2, several additional simulation experiments were undertaken. The full range of climate-change impacts on crop yields as projected in AEZ were imposed on the socioeconomic development paths of the two scenarios. *Figure 4.4* summarizes the simulation results, showing for the demographic and socioeconomic development assumed in SRES scenario A2, the *additional* number of people at risk of hunger in 2080 plotted against different levels of atmospheric CO_2 concentrations and associated climate changes. Note that the number of undernourished grows faster than linear with the level of climate change. For climate change according to scenario HadCM3-A1FI, the additional number of undernourished is about 175 million people, more than 22% above the reference projection without climate change.

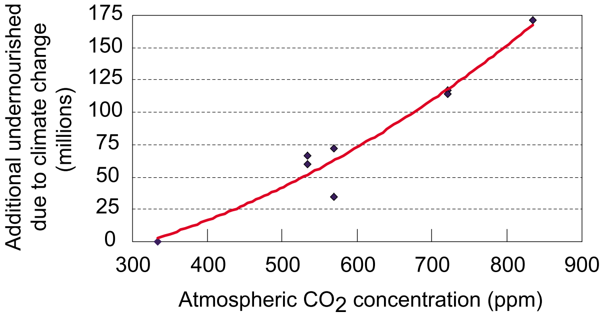


Figure 4.4. Increase in undernourished due to climate change, for socioeconomic conditions of the SRES A2 scenario in the 2080s.

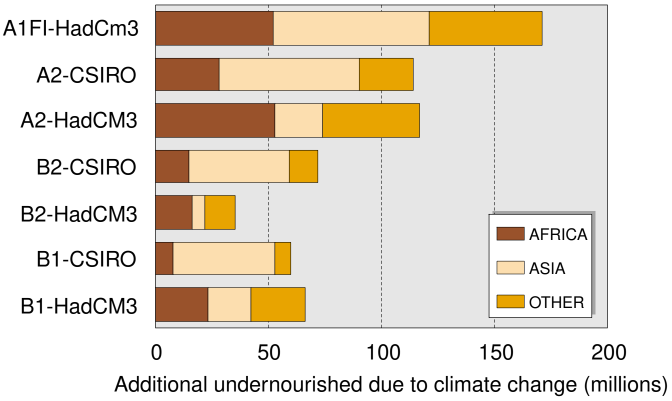


Figure 4.5. Additional number of undernourished due to climate change, by region, for socioeconomic conditions of the SRES A2 scenario in the 2080s.

Figure 4.5 indicates that the overall impact of climate change on the level of undernourishment is comparable for the simulations with climate projections from the HadCM3 and the CSIRO models. However, the regional distribution of the occurrence of additional undernourished differs. CSIRO results show increased hunger in Asian countries, while HadCM3 results show increased hunger in Africa and Latin America.

Scenario B2, with regard to demographic and socioeconomic development, falls inbetween the results obtained for scenario A2 on the one side and scenarios A1 and B1 on the other. Regarding greenhouse-gas emissions and projected levels of climate change, scenario B2 falls inbetween the lower scenario B1 and the higher emission scenarios A2 and A1. Concerning people at risk of hunger, there is a substantial improvement observed in scenario B2, from more than 800 million currently to an estimated 350 million people in 2050 and down further to about

230 million in 2080. This number is quite sensitive to long-term economic performance, as is illustrated by the results obtained for sensitivity scenario B2s discussed earlier. For both the HadCM3 and CSIRO climate projections, the estimated number of people at risk of hunger in the 2080s increases by about 5%. For climate projections of the Canadian model and the NCAR-PCM, hunger even decreases due to much improved growing conditions in many developed and developing countries, mainly in the temperate climate zones. Several sensitivity simulation experiments for the full range of climate projections with HadCM3 and CSIRO models were completed for the demographic and socioeconomic development stipulated in SRES scenario B2. The resulting estimates of the number of undernourished range from 208 million (an improvement of 10% obtained with the NCAR-PCM climate projections) to 268 million (with HadCM3 climate for emissions of A1FI). The latter number is some 15% higher than in the reference simulation of scenario B2 without climate change.

In summary, climate-change impacts on agriculture will increase the number of people at risk of hunger. This impact would be of global significance if imposed on an already high level of undernourishment, as is the case in the assumed development of scenario A2. In all other scenarios, with rapid economic growth and a transition to stable population levels, poverty, and with it hunger – though negatively affected by climate change – would become a much less prevalent phenomenon than it is today.

5

Conclusions

5.1 Climate Change and Agricultural Vulnerability

Combating climate change is vital to the pursuit of sustainable development; equally, the pursuit of sustainable development is integral to lasting climate-change mitigation and adaptation. The climate-change issue is global, long-term, and involves complex interaction between climatic, social, environmental, economic, technological, institutional, and political processes. It has significant international and intergenerational implications in the context of equity and sustainable development.

The ability of agriculture to adapt to and cope with climate change depends on such factors as population growth, poverty and hunger, arable-land and water resources, farming technology and access to inputs, crop varieties adapted to local conditions, access to knowledge, infrastructure, agricultural extension services, marketing and storage systems, rural financial markets, and economic status and wealth. The livelihoods of populations and communities are highly dependent on these factors, and the developing countries, particularly the least developed countries, are most vulnerable. As a result of this dependency, the developing countries are less able to adapt and are susceptible to climate-change damage, just as they are vulnerable to other social, environmental, and economic stresses.

Vulnerable populations have only limited capacity to protect themselves from environmental hazards, in particular from extreme events such as drought and floods. They also bear the brunt of the consequences of large-scale environmental damage, such as land degradation, biodiversity loss, and climate change. Heavy and variable precipitation, heat waves, cyclones, drought, and floods may become more frequent and intense, resulting in more economic shocks. In the short term, policymakers will need to cope with an increased risk of frequent shocks to their economies, which will affect the welfare of their most vulnerable populations. Over the long term, they will need to manage the effects of climate change on the underlying production structures of the economies, with those countries dependent on agriculture most heavily hit.

The central challenge of sustainable agriculture is to meet the food demand of the present generation without sacrificing the needs of future generations. This cannot be achieved without the systemic integration of the social, economic, and environmental pillars of agriculture and rural development. Sustainable agricultural development is essential for economic growth, which creates employment opportunities in nonagricultural rural sectors, which in turn reduce poverty.

Policies that reduce pressure on resources, improve management of environmental risks, and increase the welfare of the poorest members of society can simultaneously advance sustainable development and equity, and enhance adaptive capacity and coping mechanisms. The inclusion of climate-change impacts in the design and implementation of national and international development initiatives can reduce vulnerability to climate change.

Many factors contribute to *social vulnerability*, including rapid population growth, poverty and hunger, poor health, low levels of education, gender inequality, fragile and hazardous location, and lack of access to resources and services, including knowledge and technological means. And when people are socially disadvantaged or lack political voice, their vulnerability is exacerbated further.

The *economic vulnerability* of agriculture is related to a number of interacting elements, including its importance in the overall national economy, trade and foreign-exchange earnings, aid and investments, international prices of agricultural commodities and inputs, and production and consumption patterns. All of these factors intensify economic vulnerability, particularly in countries that are poor and have agriculture-based economies.

Agriculture is at the core of *environmental vulnerability* and concerns the management of natural resources – land degradation, water scarcity, deforestation, and the threat to biodiversity. Climate change could cause irreversible damage to land and water ecosystems, and lead to loss of production potential. In this report the agro-ecological impact of climate change has been quantified for all countries, developed and developing. These results have been integrated in an ecological–economic framework, embedded in the world food economy. The main results of these assessments are summarized below.

5.2 Summary of Results

5.2.1 Impacts of climate change on agro-ecology

Human activities are changing the Earth’s climate, and this is having an impact on all ecosystems. The expected changes in climate will alter regional agricultural systems, with consequences for food production. The specifics of the impact will depend on how the effects of climate change translate into factors that determine the viability and utility of ecosystems.

Climatic Resources

The results of an agro-climatic assessment using climate projections of Global Circulation Models (GCM) show a northward shift in thermal regimes due to global warming, with a significant reduction of boreal and arctic ecosystems [62% reduction of the current total of 2,122 million hectares (ha)]. A major expansion of the tropical zones occurs, which, apart from a very small stretch in South Africa and a narrow fringe along the Mediterranean coast, will cover almost all of Africa.

Calculations using outputs from three of four major GCMs produce consistent increases of arid areas in developing countries. At present, there are 1,080 million ha of land in Africa with a length of growing period (LGP) of less than 120 days. Climate change in the 2080s would result in an expansion of such land by about 5–8%, equivalent to 58 million ha and 92 million ha respectively. This expansion of arid areas would be mirrored by a contraction of 31–51 million ha of the favorable growing zones of 120–270 days. Nearly 1 billion people worldwide and more than 180 million people in Africa alone are presently living in these vulnerable environments, relying mainly on agriculture for their livelihoods.

Environmental Constraints to Crop Agriculture

In the 2080s, the following regions may experience an increase of land with severe constraints: Central America & Caribbean (1.2–2.9% of a total area of 271 million ha), Oceania & Polynesia (0.3–4.3% of a total area of 848 million ha), Northern Africa (1.9–3.4% of a total area of 547 million ha), and Western Asia (0.1–1.0% of a total area of 433 million ha). In Southern Africa, as much as an additional 11% of a total land area of 266 million ha may suffer from severe constraints.

In the 2080s, the total extent of potentially good agricultural land systematically decreases in Northern Europe (by 1.5–9.6%), in particular in the UK and Ireland; Southern Europe (0.7–7.7%), in particular in Spain; Eastern Europe (0.2–5.9%), in particular in Ukraine; Northern Africa (0.5–1.3%), in particular in Algeria, Morocco, and Tunisia; Southern Africa (0.1–1.5%), in particular in South Africa; and in East Asia & Japan (0.9–2.5%), in particular in China and Japan. Individual countries with decreasing, potentially good agricultural land not reflected in regional totals are: Venezuela, New Zealand, Mozambique, Sudan, and Uganda.

Considering projections of SRES scenarios simulated by four GCMs, constraint-free prime land decreases for sub-Saharan Africa, while land with moisture stress increases. In addition, land with severe climate, soil, or terrain constraints, prohibiting use for rain-fed agriculture, increases according to 10 of the 12 climate projections, by 26–61 million ha, compared to 1,513 million ha in the reference climate scenario.

Climate Variability and Variability of Rain-fed Cereal Production

Areas with a particularly high variability of year-by-year growing conditions are found in the mid-west of the USA, northeast Brazil, northeast Argentina and Uruguay, Southern Africa, southern Mozambique, and the southeast of Australia.

In the developed nations as a whole, potential rain-fed cereal output increased between the periods of 1901–1930 and 1961–1990 by more than 8%, equivalent to about 200 million tons, due to the changing climate, while output variability decreased. In the developing countries as a whole, potential cereal output increased somewhat, by just under 3%, equivalent to about 70 million tons. Yet variability increased as well. No improvements were found for sub-Saharan Africa. Some regions, for instance in Southern Africa, lost average potential cereal production as compared to the beginning of the 20th century, and at the same time saw a considerable increase in the variability of cereal outputs.

Crop-production Potentials

The regional aggregation of results, based on the HadCM3-A1FI 2080s scenario, shows for both suitable rain-fed land extents and production potential of cereals a significant decrease in Northern and Southern Africa.

The developed nations, however, will see a considerable potential for expansion of suitable land extents and increased production potential for cereals only when considering the use of this "new land" at high latitudes. These potential increases are mainly located in North America (40% increase over reference climate estimate of 358 million ha), in Northern Europe (16% increase over reference climate estimate of 45 million ha), in the Russian Federation (64% increase over reference climate estimate of 244 million ha), and in East Asia & Japan (10% increase over reference climate estimate of 150 million ha).

Developing countries consistently face a substantial decrease of wheat-production potential, according to all scenarios for the 2080s (in the order of 15–45%); wheat is virtually disappearing from Africa. Wheat-production potential is decreasing in South Asia (20–75%), Southeast Asia (10–95%), and South America (12–27%).

A distinct downward trend for the production potential of rain-fed sugar crops emerges from the analysis. Developing countries lose some 6–38% of their rain-fed production potential on currently cultivated land. For developed countries the outcome is mixed.

For roots and tubers, the change in rain-fed production potential varies, from a loss of 13% to a gain of 4% in all model scenarios, except for the NCAR where there is a gain in production potential of 23–29%. In the case of the developing countries the change ranges from a loss of 23% to a gain of 20%.

Potential Agricultural Land

All 12 GCM climate projections predict gains in potential agricultural land globally. Strong gains are predicted especially for North America (20–50%) and in the Russian Federation (40–70%). However, significant losses are predicted in particular in Northern and Southern Africa. In 10 of the 12 GCM climate projections, substantial losses (up to 9%) are predicted for the sub-Saharan African region.

In developing nations and in particular sub-Saharan Africa, the overall contractions in potential cultivatable areas are mainly at the cost of double- and triple-cropping areas, where losses are above average. Although the area for single cropping increased in sub-Saharan Africa at the expense of double- and triple-cropping areas, considerably more is lost to the category where cropping is not possible.

The land suitability index (SI) accounts for changes in area extents as well as changes in productivity. This SI index is useful when comparing land productivity estimates across regions, as it adjusts for differences in land quality and provides a more realistic estimate of land-resource availability. The HadCM3-A1F1 scenario results show a remarkable increase of effective land resources, as expressed by SI, in higher latitudes of the northern hemisphere, in particular benefiting the Russian Federation, Northern Europe, and Canada. In Northern Africa, three-quarters of suitable rain-fed land is lost as compared to reference climate conditions. Decreases are also noted in Southern Africa, mainly affecting Mozambique, Botswana, Namibia, Zimbabwe, and South Africa. In all 12 scenarios, developed countries gain 6–24%, while for developing countries there is a loss of 2–8% for HadCM3 and CSIRO climate projections and gains of 1–4% when applying the CGCM2 and NCAR model results.

Climate-change Impacts on Cereal Production

Site-specific climate-impact studies have come to a wide range of seemingly contradicting results. While variations in assumptions and methodologies may account for some of the differences, the results obtained in this study clearly demonstrate that a wide range of outcomes is to be expected for many countries, and that a full and reliable picture requires a spatially comprehensive approach and analysis such as AEZ.

For four HadCM3 climate-change scenarios, the estimated impacts on rain-fed cereal-production potential on current cultivated land imply that there are 42–73 countries with potential cereal-productivity declines of more than 5% (“losing” countries). The population in 2080 of these countries ranges between 1.6 billion and 3.8 billion people. In these countries, cereal-production losses amount to 3–8% of the global potential; a grim outlook for the already poor among these losing countries despite substantial increases in some 54–71 gaining countries.

Some 14 developing countries account for 80% of current cereal production in the developing world. China, the world's largest cereal producer, gains substantially, in the 5–23% range for all climate models except for the CSIRO model, where there is a loss of 5–7%. For India, the second-largest cereal producer, Brazil, and Thailand, results vary according to climate model. Argentina gains production potential by 7–24% for the HadCM3 and NCAR models, and loses 10–30% production potential for the CSIRO and CGCM2 models. South Africa substantively loses production potential for all climate models and scenarios, except for NCAR's projection of scenario A2, where a small gain occurs.

Current Food-insecure Countries

The total population of the 84 poor food-insecure countries at present amounts to some 4.2 billion, equivalent to 74% of the current world population. Some 18% of the 4.2 billion are undernourished. By the 2080s, the UN projects the total population of these countries to increase to 6.8 billion (United Nations, 2001), equivalent to 80% of the world population.

Individual country results are reason for concern. For example, in the results of the HadCM3 scenarios, 20–40 poor and food-insecure countries, with a projected total population in 2080 in the range of 1–3 billion, may lose on average 10–20% of their cereal-production potential due to climate change.

With the exception of the results for the NCAR-PCM model, Sudan, Nigeria, Senegal, Mali, Burkina Faso, Somalia, Ethiopia, Zimbabwe, Chad, Sierra Leone, Angola, Mozambique, and Niger lose cereal-production potential in the 2080s for the other three climate models, across all the emission scenarios. These countries currently have 87 million undernourished, equivalent to 45% of the total undernourished in sub-Saharan Africa. By contrast, Zaire, Tanzania, Kenya, Uganda, Madagascar, Côte d'Ivoire, Benin, Togo, Ghana, and Guinea all gain cereal-production potential in the 2080s. These eight gaining countries currently have 73 million undernourished, equivalent to 38% of the undernourished population in sub-Saharan Africa.

Most of the food-insecure countries in sub-Saharan Africa are also poor. They lack the resources to produce enough food and often do not have access to foreign exchange for financing food imports. Production losses as a result of climate change could further worsen the prevalence and depth of hunger. This burden will undoubtedly fall disproportionately on the poorest and the most vulnerable.

Climate-change impacts highlight the urgent need to intensify agricultural land management and expand agricultural land area, both of which will lead to additional greenhouse-gas emissions and increasing environmental pressures. Moreover, agricultural land expansion will unavoidably lead to losses of natural ecosystems and biodiversity, especially through the clearance of forests. Such considerations must be central in mitigating the impacts of climate change on agricultural production.

5.2.2 Impacts of climate change on food systems

The evaluation of the impact of climate change on production, consumption, and trade of agricultural commodities, in particular on food staples, was carried out with a large number of experiments that relate to four aspects: magnitude of climate change for different future socioeconomic and technical development paths; uncertainty of results in view of differences in climate projections of different GCM groups; robustness of results with regard to altered economic growth assumptions; and sensitivity of results to different assumptions with regard to physiological effects of atmospheric CO_2 enrichment on yields. Some 50 simulation experiments were carried out with the integrated ecological-economic framework provided by the agro-ecological zones (AEZ) model and databases, and IIASA's linked system of national agricultural models (BLS). Yield modifications due to climate change start in the base year 1990. Three separate snapshots of climatic change are provided referring to the 2020s, 2050s, and 2080s, respectively.

Impacts of Climate Change on Crop Production without Economic Adjustments

The magnitude and even direction of the aggregate climate-change impact at world level varies with climate projections of different GCM groups. We estimated the magnitude of distortions that result from applying climate-induced productivity changes to each country's agricultural production pattern in a reference projection without climate change, thus measuring the impact without economic adjustment. Scenarios based on HadCM3 and CSIRO projections result in a small negative net impact at global level. For climate projections using emission scenario A2, the global impact on cereals ranges from –0.7% to –1.2%, i.e., a gap of about 60 million tons in 2080. When aggregating all crops, the net impact amounts to –1.3% to –1.6%. Climate projections by the Canadian CGCM2 model and the NCAR-PCM model imply moderate positive global crop-production changes of 2.7–5.6%.

However, the impacts of climate change on crop production are geographically unevenly distributed. Developed countries experience for all variants of the A2 scenario an increase in productivity. In contrast, developing regions suffer a loss in cereal productivity in all estimates. Within the group of developed countries, gains of 3–10% in cereal productivity occur for North America, and similar for the Former Soviet Union. Western Europe suffers losses in most projections of up to 6%.

Impacts on developing regions are mostly negative for South Asia (–8% to –17% for scenario A2) and Africa (–3.5% to +0.5%), mixed for Centrally Planned Asia (–6% to +1%), and overall positive for Latin America.

Impacts of Climate Change with Economic Adjustments

Shortfalls in food production, caused by climate change, create market imbalances, which push international prices upwards and provide incentives for reallocation of capital and human resources, thus mitigating climate-change impacts by economic adjustments.

In the case of HadCM3 climate projections, cereal prices increase by 2–20% relative to the reference projection; for CSIRO the increase is 4–10%. Generally, the simulated crop-price changes in response to climate change are moderate due to a relatively small net global impact on crop-production potential.

Impact of climate change on agricultural GDP. The results underline three general findings. First, the impact of climate change on GDP of the agriculture sector is relatively small for the aggregate global level, between –1.5% (in HadCM3-A1FI scenario) and +2.6% (in NCAR-A2 scenario); this refers to total global GDP of agriculture in the reference projections ranging from US$2.9–3.6 trillion (at 1990 prices). Second, agriculture in developed countries as a group will likely benefit from climate change. Third, developing regions, with the exception of Latin America, are confronted with negative impacts on agricultural GDP.

For Asia, the loss in value added of agriculture in 2080 amounts to some 4% in the case of A1 and A2 emission scenarios for HadCM3 and CSIRO (total agricultural GDP of US$1.1–1.3 trillion in the reference projections). Aggregate outcomes for Africa are generally negative, a loss of 2–8% for HadCM3 and CGCM2 simulations, and decreases of 7–9% for CSIRO projections (total agricultural GDP of US$0.6–0.7 trillion in reference projections). Among developed regions, North America gains substantially in all simulated scenarios (3–13% for scenario A2); Western Europe loses agriculture value added in all scenarios (loss of 6–18% in scenario A2), and the Former Soviet Union mostly gains value added (some 0–23% in scenario A2) in response to climate change.

Impact of climate change on cereal sectors. The model results present a fairly consistent response pattern of regional cereal production to climate change. At global level, taking into account economic adjustments of actors and markets, cereal-production changes fall within 2% of the results for the reference simulations without climate change. However, aggregation produces deceivingly small numbers. Developing countries consistently experience reductions in cereal production in all climate scenarios. Negative changes of 5–6% are most pronounced in simulations based on CSIRO climate projections. In this case, production moves to developed regions, notably North America and the Former Soviet Union, where increases of 6–9% are observed. The most significant negative changes occur in Asian developing countries, where production declines in all scenarios, ranging from about 4% decreases for CGCM2 and NCAR climate projections to reductions of 6–10% for HadCM3 and CSIRO.

Impact of climate change on cereal consumption and net trade. In the SRES worlds of the 2080s, consumers are assumed much richer than they are today, and are largely separated from agricultural production processes. Consumption levels depend foremost on food prices and incomes rather than on changes in local agricultural production.

A fairly uniform decline in direct human consumption of cereals (i.e., excluding feed consumption) in developing countries occurs in response to climate change across all climate models and emission scenarios (with the exception of simulations based on NCAR climate projections). For HadCM3, direct human cereal consumption in developing countries declines by 2–4%, i.e., in the order of 40–80 million tons, compared to total consumption in the range of 1.6 billion tons (scenario B1) to 2.1 billion tons (scenario A2) in the reference projections. Consumption changes in Asian developing countries account for two-thirds of this amount, albeit consumption declines from relatively high levels due to fast economic growth. Consumers in Latin America are least affected.

The simulations of the IPCC development path scenarios without climate change result in a growing dependence of developing countries on net cereal imports of between 170 million tons (scenario B1) and 430 million tons (scenario A2). Climate change will add to this dependence, increasing net cereal imports of developing regions by 10–40% according to development path scenario and GCM climate projections. Even in the case of NCAR projections, resulting in overall positive impacts on agricultural productivity, the comparative advantage for producing cereals shifts to developed countries, and net imports of developing countries increase by about 25%, an additional 110 million tons in scenario A2 and around 90 million tons of additional cereal imports in scenario B2.

It is important to note that these changes in comparative advantage between developed and developing regions are likely to accentuate the magnitude of the impacts suggested by this agricultural assessment, i.e., “winners” are likely to gain more, “losers” will lose more than projected without accounting fully for impacts and adjustments in nonagricultural sectors.

Impact of Climate Change on the Number of People at Risk of Hunger

Based on more than 50 simulation experiments with the BLS model, fairly robust conclusions emerge from the analysis of climate-change impacts. First, climate change will most likely increase the number of people at risk of hunger. Second, the importance and significance of the climate-change impact on the level of undernourishment depends entirely on the level of economic development assumed in the SRES scenarios.

For the wealthy societies of IPCC development path scenario A1 – even the currently poor regions are assumed to reach economic levels exceeding in per capita terms current average OECD incomes – hunger is a marginal issue and remains so even with climate change; a desirable vision, but perhaps overly optimistic in view of the actual achievements of the last 30 years.

The outcome of BLS simulation experiments regarding the number of people at risk of hunger is quite different for the high-population SRES scenario A2. Under this set of assumptions, the level of undernourished, even without considering climate change, remains at a high level in the 2080s. In the reference case, without considering climate change, the number of undernourished estimated for 2080 is 768 million. This number increases by nearly 120 million, equivalent to some 15%, in both experiments with HadCM3 and CSIRO climate projections. Climate projections of the Canadian CGCM2 model result in an additional 50 million undernourished due to climate change. For even larger climate changes, such as projected by HadCM3-A1FI scenario for the 2080s, additional undernourished people amount to 175 million. This indicates that under socioeconomic conditions of development path A2, the number of undernourished is likely to increase more than linear with the level of climate change.

Climate change will affect the number of people at risk of hunger. This impact will be of global significance only if super-imposed in a situation with an already high level of undernourishment, as in development path A2 and to a lesser extent in scenario B2. In all other cases, with stabilizing population levels and rapid economic growth, poverty, and with it hunger – though negatively affected by climate change – would become much less prevalent than it is today.

The results of this study provide a methodology and database for country-level assessments of climate and agricultural vulnerability. In the context of the present debate over international agreements, such as the Kyoto Protocol and the outcome of the Third Assessment of the International Panel on Climate Change (IPCC), it is important that uniform assessments be carried out to compare and evaluate national, regional, and global impacts of climate change on food and agricultural production systems. Such quantified and spatial information provides important inputs that can underpin national and regional adaptive policies to mitigate the consequences of climate change and also facilitate international negotiations on climate change, taking into account the contributions of various countries to global warming as well as their specific development needs and priorities.

The nature and gravity of vulnerabilities of food systems to climate change and variability, and the design of policies to adapt them to cope are of utmost importance, and agricultural research has a central role in this.

The challenges of climate change and variability for agricultural research now relate to elucidate the changes in the flow and storage of materials, the ecology of pests and diseases, the dynamics of rainfall regimes and water accumulation, the plant responses to temperature and CO_2 concentration, the reduction of greenhouse gases in animal production, the plant tolerance to salty water due to sea-level increase in many coastal areas, the conservation of biodiversity, the adaptation of food production systems to extreme weather events, among other important issues that need to be tackled.

For agricultural research to respond in a timely manner, a worldwide concerted policy action is necessary. Networking of researchers, priority setting, allocation of necessary funding, inter-regional and inter-country technology transfer, institutional development and strengthening are among the decisions that need to be made so that agricultural research can contribute toward mitigation and adaptation of agriculture to climate change.

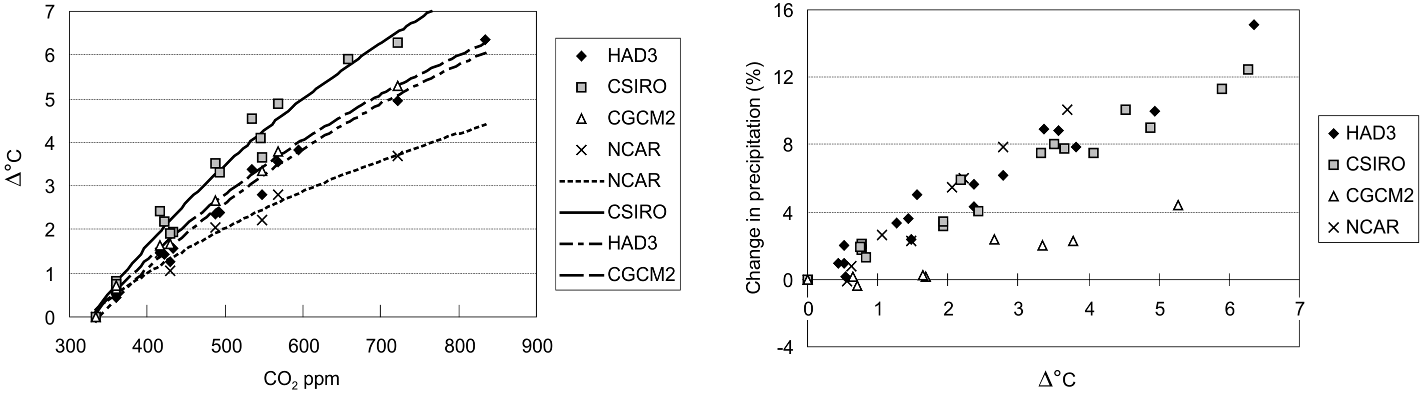
Most of the discussion on climate change has focused on mitigation measures, for example the Kyoto Protocol. Not much attention has been given to climate-change adaptation, which will be critical for many developing countries. For developed countries, the issue of adaptation to future climate change is not a priority, as they already have the means and resources to respond. In contrast, the developing world must recognize the urgency to put this issue of adaptation to climate change on the global agenda.

Annex 2.1

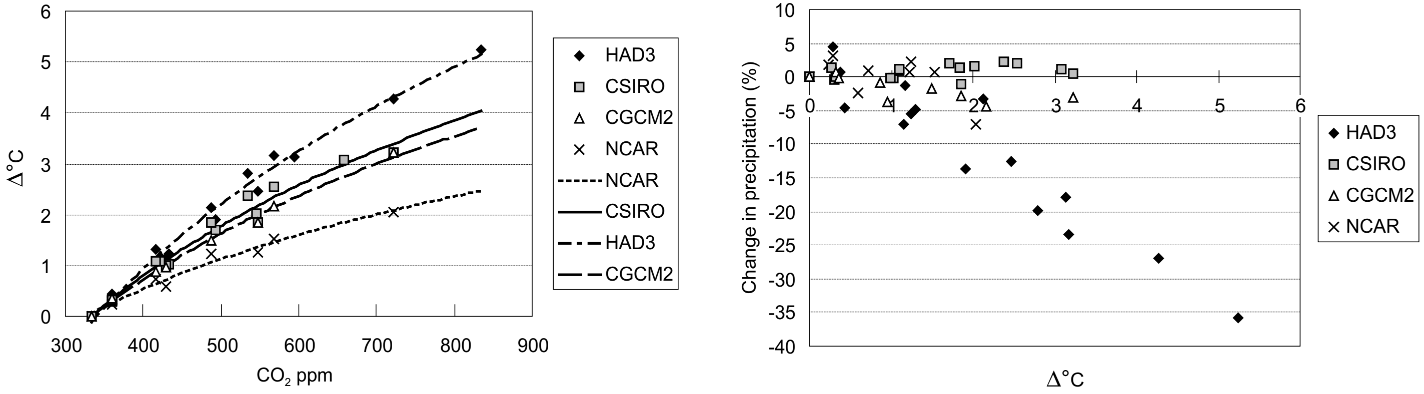
Responses of Temperature to Increasing CO_2 Concentrations and Correlations Between Temperature Increase and Precipitation Change by Region

Comparisons of results from four General Circulation Models (GCM), the HadCM3, CSIRO, CGCM2, and NCAR model, have been made separately for *all land* and for *current cultivated land* in terms of "Temperature change (°C) versus CO_2 concentration levels (ppm)" and for "Temperature change (°C) versus precipitation change (%)." The figures in this Annex present for the four GCMs the implied responses of temperature to increasing CO_2 concentrations, compiled from the GCM outputs obtained for different SRES emission scenarios and combined with AEZ data layers. It also shows the correlations between projected temperature increases and precipitation changes, considering all land grid-cells for individual regions (excluding Antarctica).

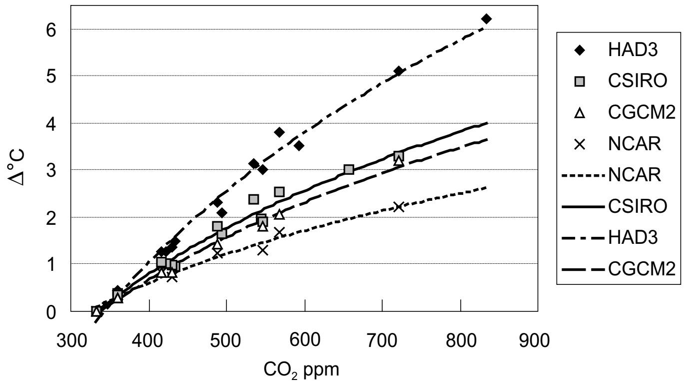
North America

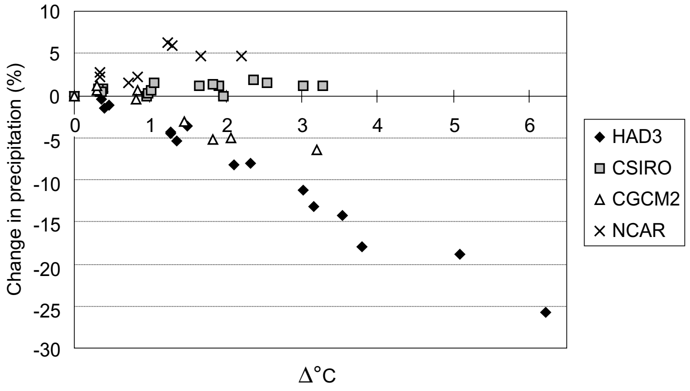


Central America

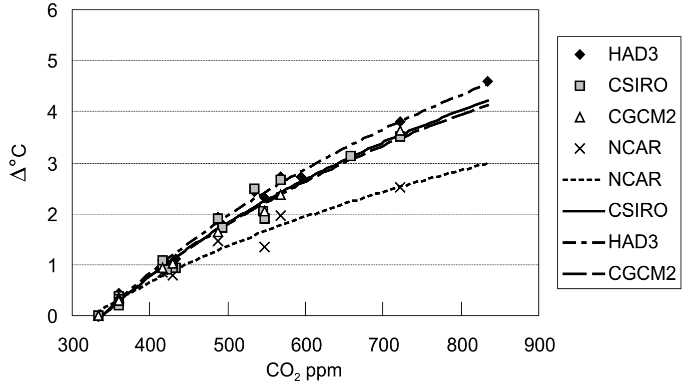


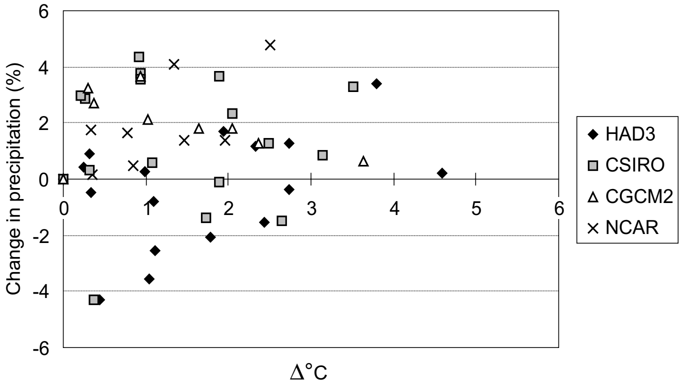
South America



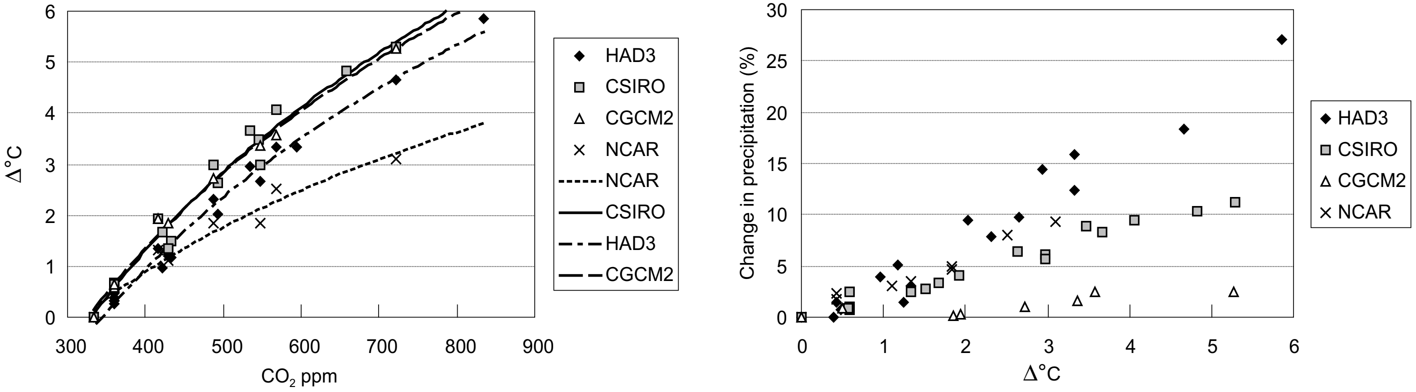


Oceania

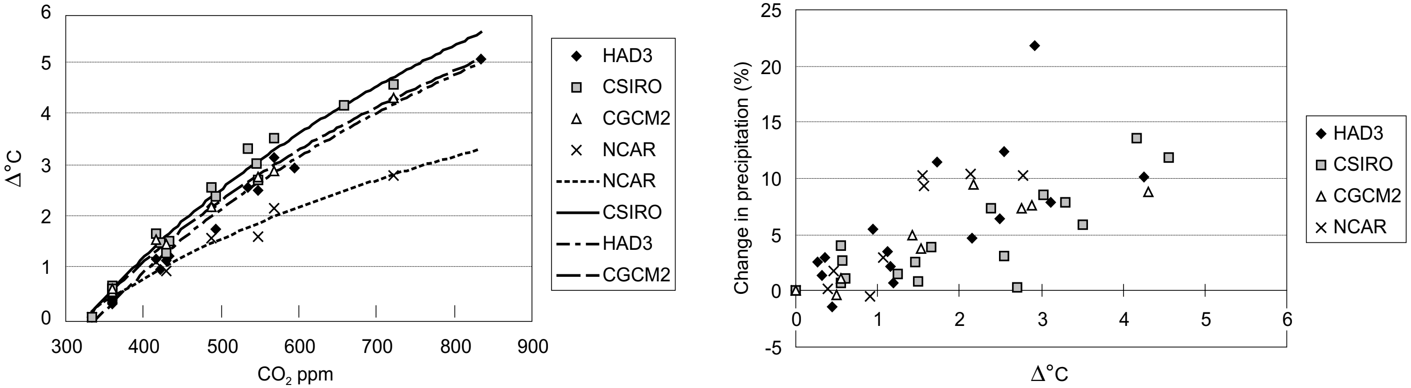




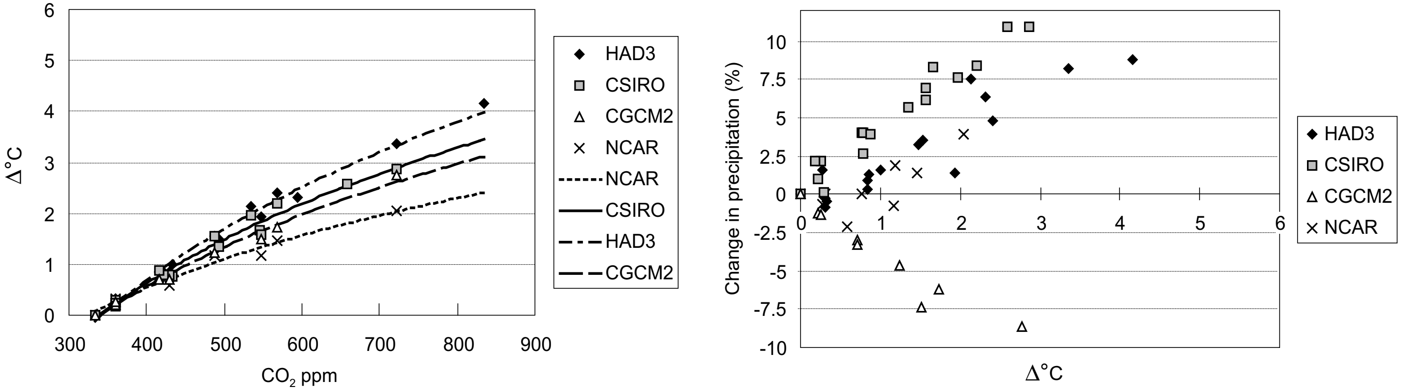
East Asia



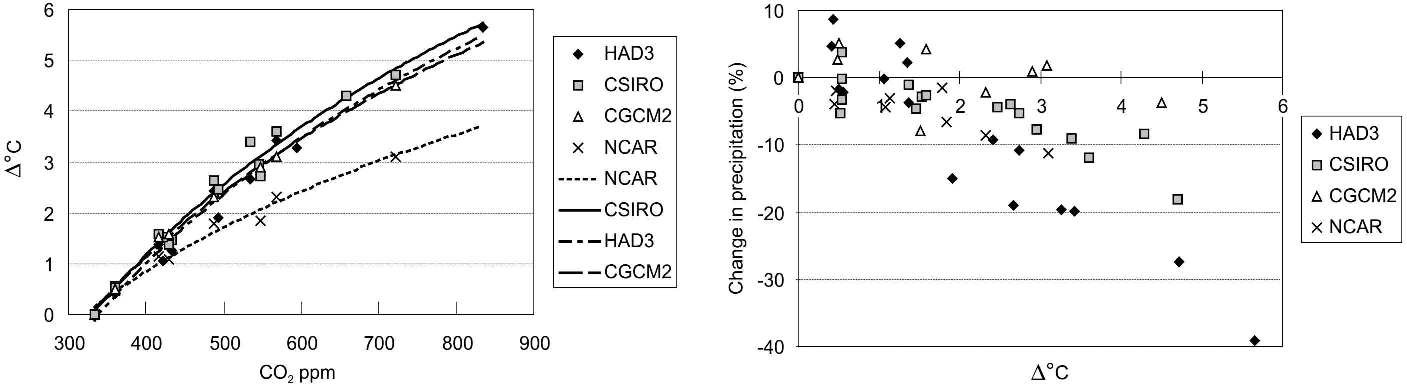
South Asia



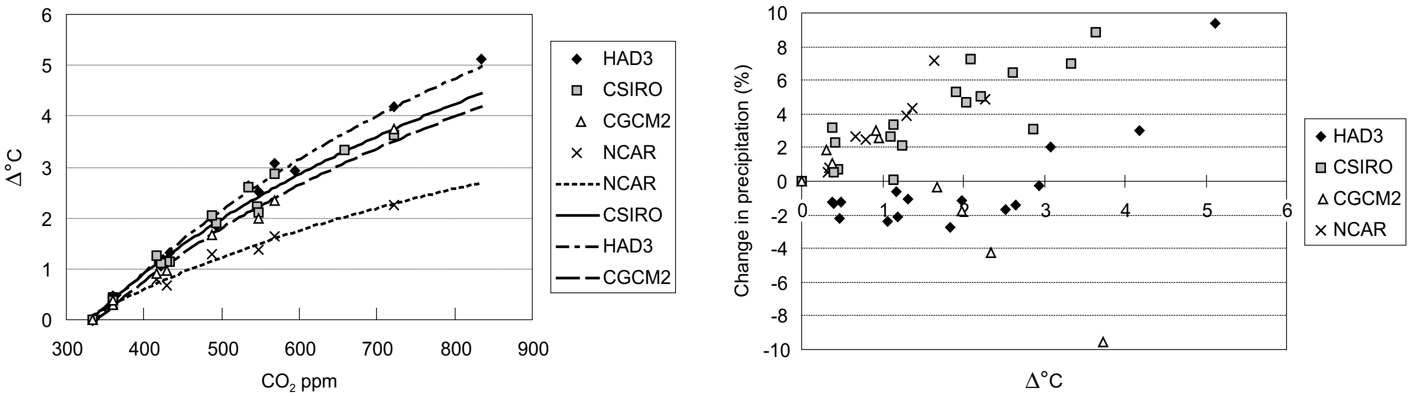
Southeast Asia



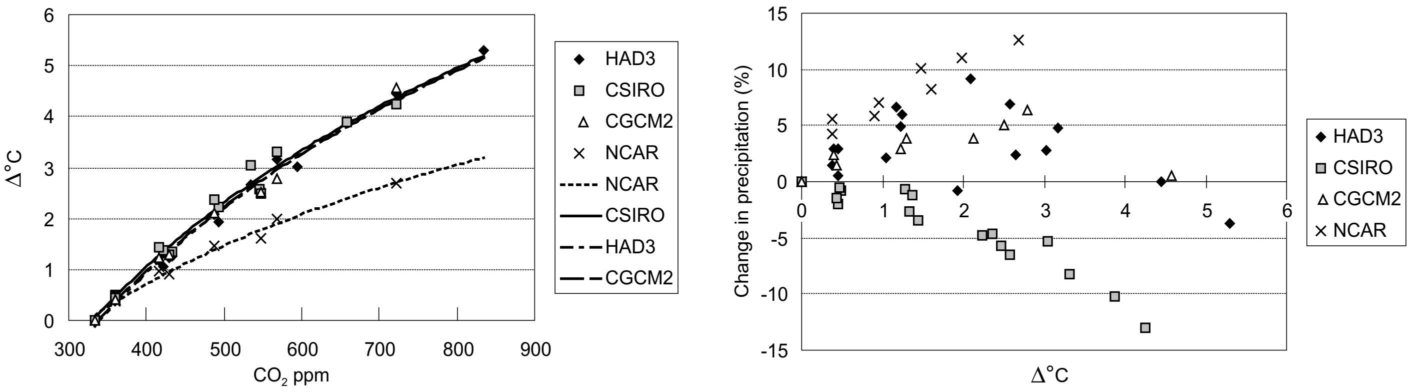
North Africa

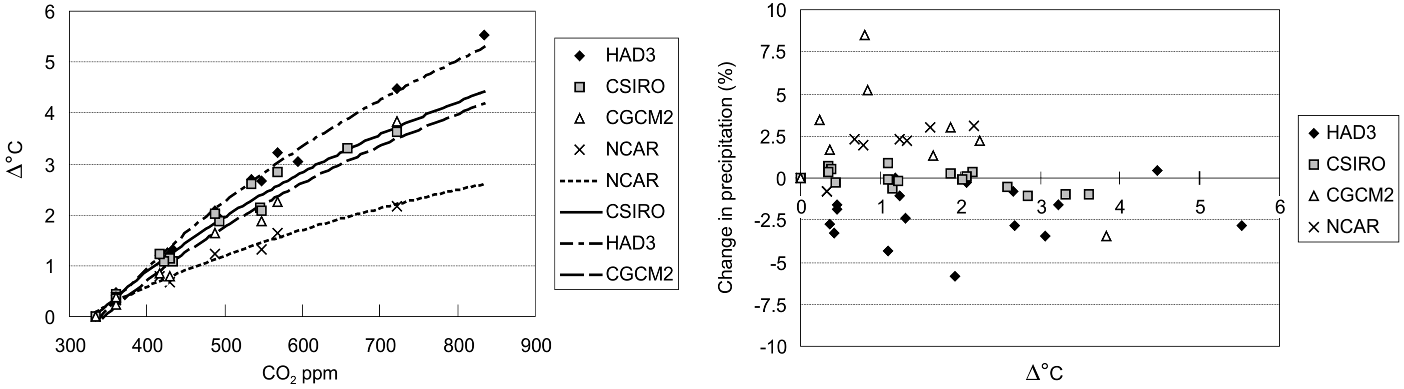


East Africa

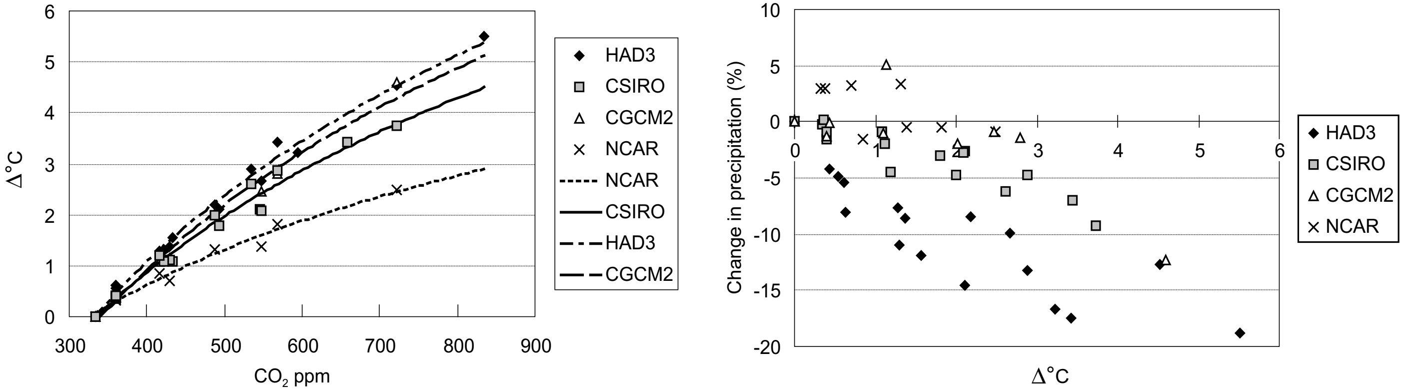


West Africa



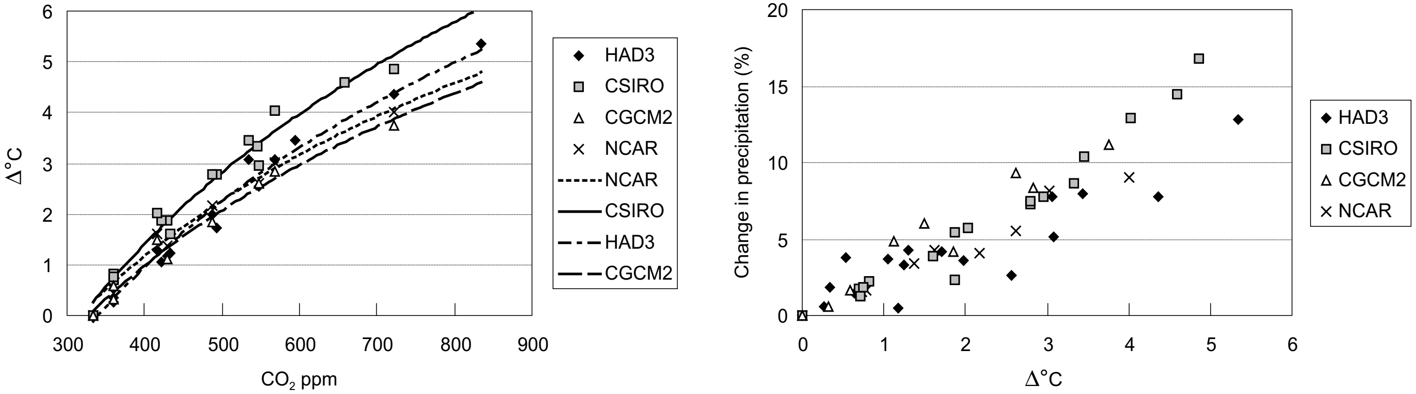


Central Africa

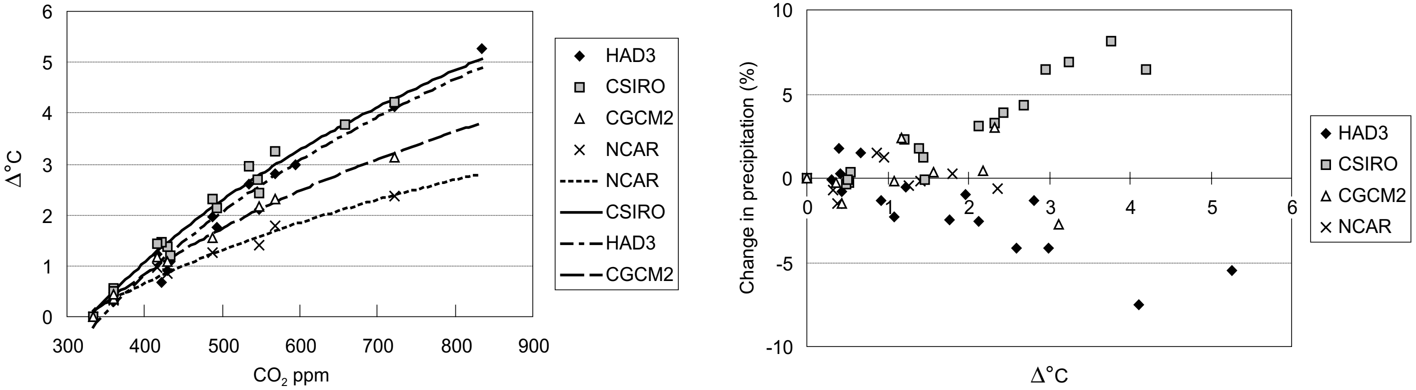


South Africa

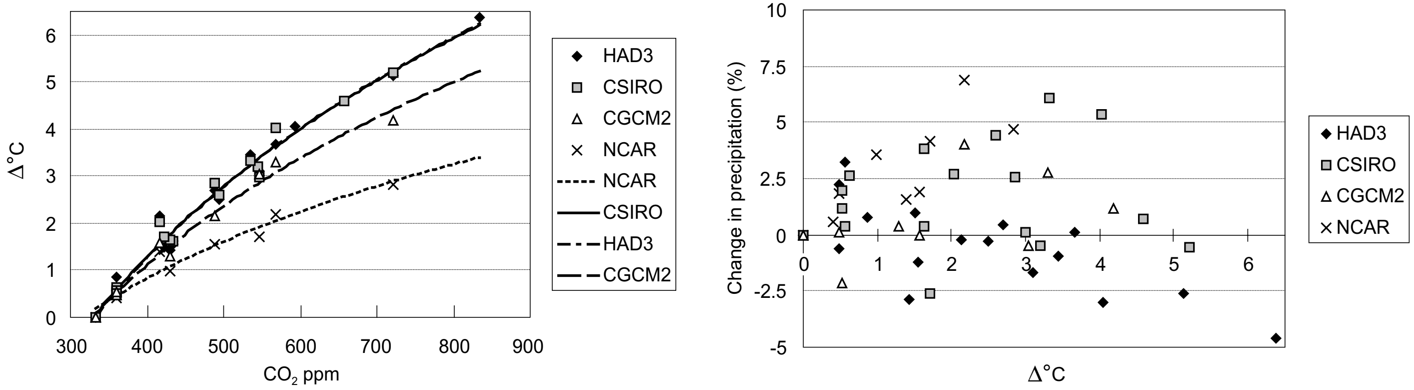
Northern Europe



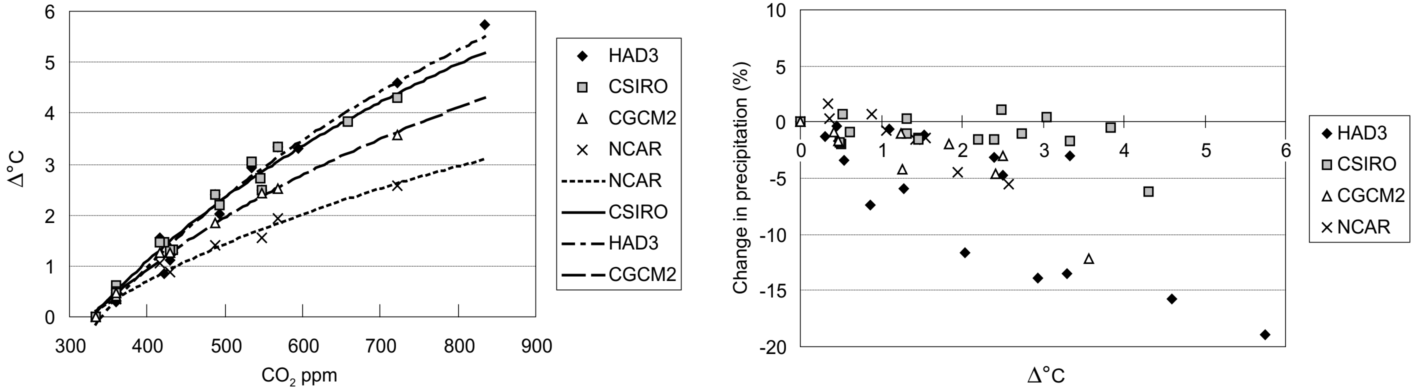
Western Europe

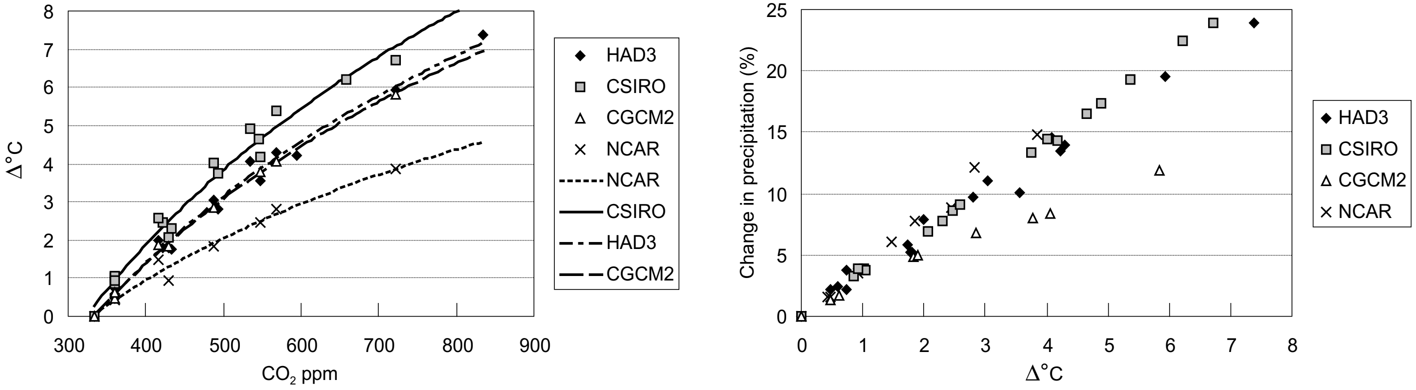


Eastern Europe

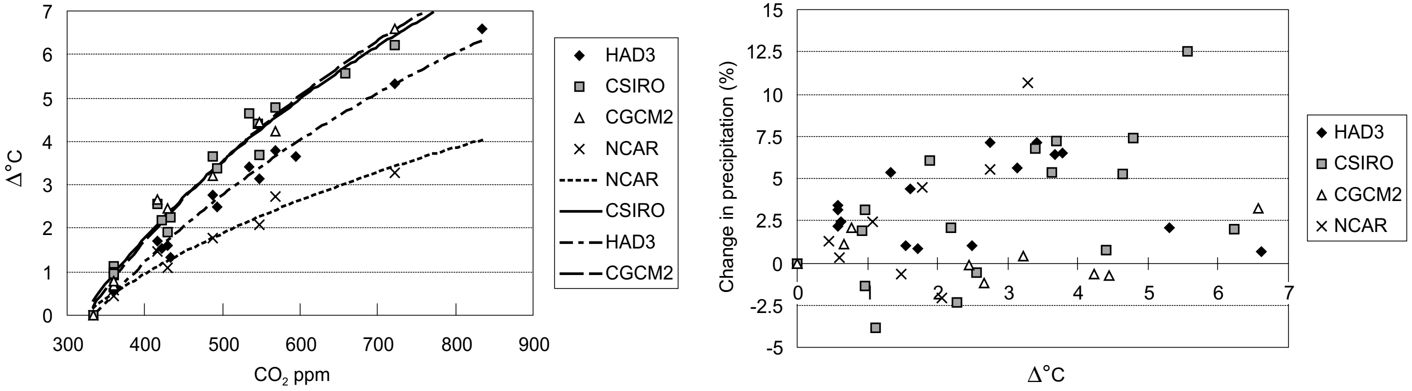


Southern Europe

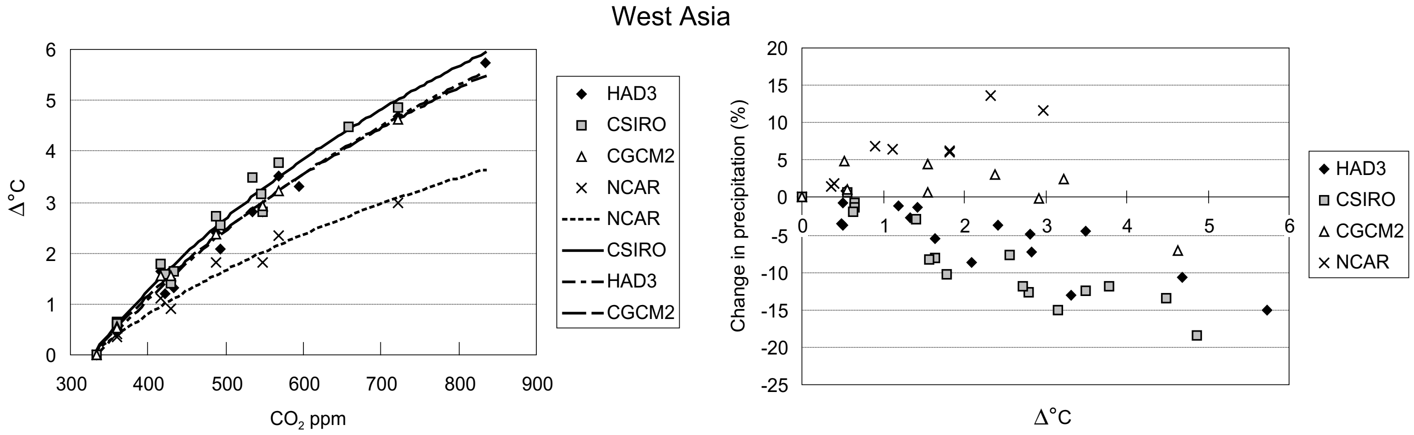




Russia



Central Asia



West Asia

Δ°C
CO2 ppm
0
1
2
3
4
5
6
300
400
500
600
700
800
900
HAD3
CSIRO
CGCM2
NCAR
NCAR
CSIRO
HAD3
CGCM2
Change in precipitation (%)
Δ°C
20
15
10
5
0
-5
-10
-15
-20
-25
0
1
2
3
4
5
6
HAD3
CSIRO
CGCM2
NCAR

Annex 2.2

National and Regional Models in the BLS

National Models

Argentina, Australia, Austria, Brazil, Canada, China, Egypt, India, Indonesia, Japan, Kenya, Mexico, New Zealand, Nigeria, Pakistan, Thailand, Turkey, United States; EU-9, Eastern Europe, and Former USSR.

Aggregate Regional Country Group Models

African Oil Exporters: Algeria, Angola, Congo, Gabon.

Africa, Medium Income, Food Exporters: Ghana, Côte d'Ivoire, Senegal, Cameroon, Mauritius, Zimbabwe.

Africa, Medium Income, Food Importers: Morocco, Tunisia, Liberia, Mauritania, Zambia.

Africa, Low Income, Food Exporters: Benin, Gambia, Togo, Ethiopia, Malawi, Mozambique, Uganda, Sudan.

Africa, Low Income, Food Importers: Guinea, Mali, Niger, Sierra Leone, Burkina Faso, Central African Republic, Chad, Zaire, Burundi, Madagascar, Rwanda, Somalia, Tanzania.

Latin America, High Income, Food Exporters: Costa Rica, Panama, Cuba, Dominican Republic, Ecuador, Suriname, Uruguay.

Latin America, High Income, Food Importers: Jamaica, Trinidad and Tobago, Chile, Peru, Venezuela.

Latin America, Medium Income: El Salvador, Guatemala, Honduras, Nicaragua, Colombia, Guyana, Paraguay, Haiti, Bolivia.

Southeast Asia, High-Medium Income, Food Exporters: Malaysia, Philippines.

Southeast Asia, High-Medium Income, Food Importers: Republic of Korea, Democratic People's Republic Korea, Laos, Vietnam, Cambodia.

Asia, Low Income: Bangladesh, Myanmar, Nepal, Sri Lanka.

Near/Middle East, Oil Exporters: Libya, Iran, Iraq, Saudi Arabia, Cyprus, Lebanon, Syria.

Near/Middle East, Medium-Low Income: Jordan, Yemen, Afghanistan.

Rest of the World: All other countries not specified above.

Annex 2.3

Commodity Classification in the BLS

Commodity classifications as used in the national models of the BLS are given below. Table A2.3.1 shows the ten commodities used at the world market level, i.e., the level of commodity aggregation employed to clear the international markets. Table A2.3.2 presents the more detailed commodity list as used to describe human demand. Finally, Table A2.3.3 gives the classification used in the agricultural supply module that allocates production inputs, i.e., land, capital and labor, to the agricultural production activities.

Table A2.3.1. Classification at the world market level.

No.	Commodity	Unit of measurement
I.	Wheat	1,000 mt
II.	Rice, milled	1,000 mt milled equivalent
III.	Coarse grains	1,000 mt
IV.	Bovine & ovine meat	1,000 mt carcass weight
V.	Dairy product	1,000 mt whole milk equivalent
VI.	Other meat & fish	1,000 mt protein equivalent
VII.	Protein feeds	1,000 mt protein equivalent
VIII.	Other food	US$ million, 1970
IX.	Nonfood agriculture	US$ million, 1970
X.	Nonagriculture	US$ million, 1970

Table A2.3.2. Human demand in standard national models.

No.	Commodity	Unit of measurement	Index
1.	Wheat	1,000 mt	I
2.	Rice, milled	1,000 mt milled equivalent	II
3.	Coarse grains	1,000 mt	III
4.	Oils & fats	1,000 mt oil equivalent	VIII
5.	Protein feeds	1,000 mt protein equivalent	VII
6.	Sugar products	1,000 mt sugar refined	VIII
7.	Bovine & ovine meat	1,000 mt carcass weight	IV
8.	Pork	1,000 mt carcass weight	VI
9.	Poultry & eggs	1,000 mt protein equivalent	VI
10.	Dairy products	1,000 mt whole milk equivalent	V
11.	Roots & vegetables	US$ million, 1970	VIII
12.	Fruits & nuts	US$ million, 1970	VIII
13.	Fishery products	1,000 mt protein equivalent	VI
14.	Coffee	1,000 mt	VIII
15.	Cocoa & tea	US$ million, 1970	VIII
16.	Clothing fibers	US$ million, 1970	IX
17.	Industrial crops	US$ million, 1970	IX
18.	Nonagriculture	US$ million, 1970	X

Table A2.3.3. Agricultural production in standard national models.

No.	Commodity	Unit of measurement
1.	Wheat	1,000 mt
2.	Rice, milled	1,000 mt milled equivalent
3.	Coarse grains	1,000 mt
4.	Protein feed, crop origin	1,000 mt protein equivalent
5.	Other food, crop origin	US$ million, 1970
6.	Nonfood, crop origin	US$ million, 1970
7.	Roughage (not used)	(not used)
8.	Pork, poultry, eggs	1,000 mt protein equivalent
9.	Bovine & ovine meat	1,000 mt carcass weight
10.	Dairy products	1,000 mt whole milk equivalent
11.	Fruits & nuts	US$ million, 1970

Annex 2.4

Aggregation of BLS Country Modules to World Regions

Economic group	SRES region	Region	BLS component[a]
MDC = More developed countries	OECD	NAM	Canada, United States
		WEU	Austria, EC-9
		PAO	Australia, Japan, New Zealand
	EFSU	FSU+EEU	Eastern Europe & Former USSR
LDC = Less developed countries	ALM	AFR	Egypt, Kenya, Nigeria, Africa oil exporters, Africa medium income/food exporters, Africa medium income/food importers, Africa low income/food exporters, Africa low income/food importers
		LAM	Argentina, Brazil, Mexico, Latin America high income/food exporters, Latin America high income/food importers, Latin America medium income
		WAS	Turkey, Near/Middle East oil exporters, Near/Middle East medium-low income countries
	ASIA	CPA	China, Far East Asia high-medium income/food importers
		SEA	India, Pakistan, Asia low income countries Indonesia, Thailand, Far East Asia high-medium income/food exporters
Rest of world	ROW	ROW	Rest of the world

[a] For details of country grouping in the BLS, see Fischer *et al.* (1988).

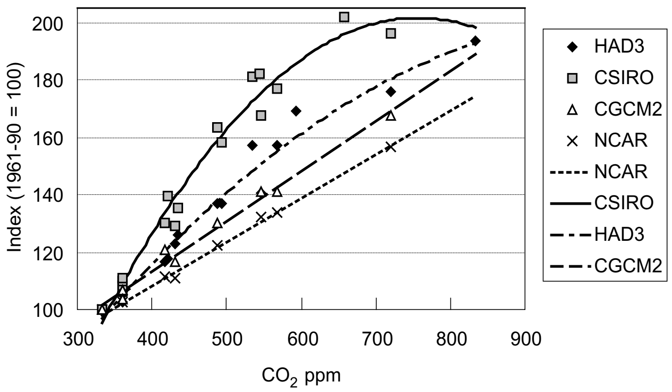
Note: The *Rest of the World* aggregate includes both more and less developed countries. Although the aggregate variables in ROW are dominated by more developed countries of the OECD, these are not included with the respective regional aggregates, MDC and LDC. The table above provides the closest possible match between BLS geographic components and the regions considered by the SRES story lines.

Annex 3.1

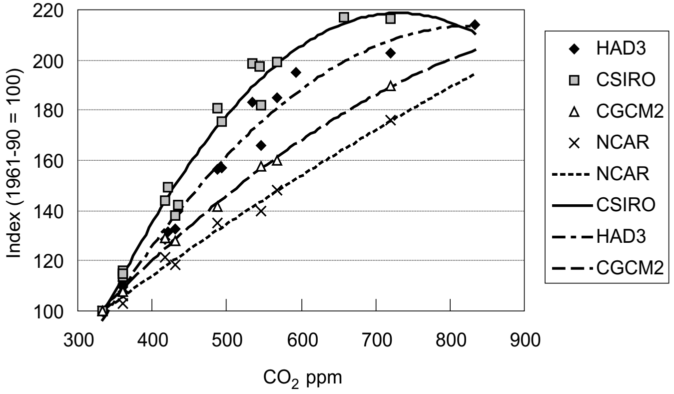
Changes in Crop-production Potential Versus Increase in Atmospheric CO_2 Concentrations and Related Global Warming as Predicted by GCMs

Comparisons of results from four General Circulation Models (GCM), the HadCM3, CSIRO, CGCM2, and NCAR model, have been made for the change of crop-production potential in relation to changes in atmospheric CO_2 concentrations and related global warming. The figures presented in this Annex offer a graphical representation of production change of rain-fed/irrigated *rice* and the following rain-fed crop groups: *other grains* (including maize, sorghum, millet, barley, rye, and setaria); *roots & tubers, pulses, oil crops*, and *sugar crops*. The production change is expressed as a percentage change in relation to the reference climate (1961–1990). The results are plotted for, respectively, *all land* and *current cultivated land*, separately for developed and developing countries.

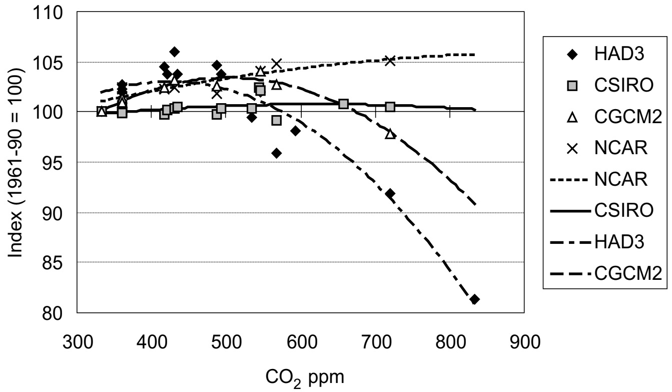
Rice (ir+rf), developed, all land



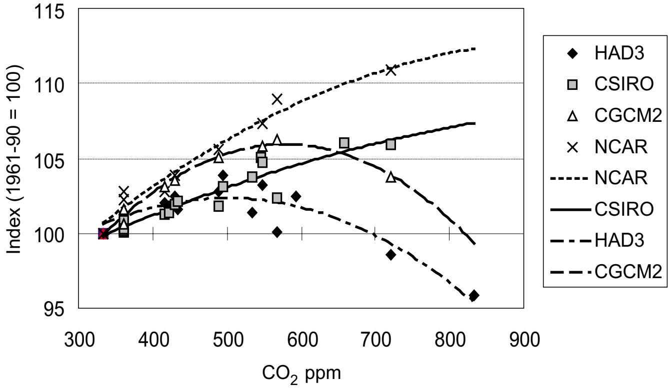
Rice (ir+rf), developed, current cultivated land

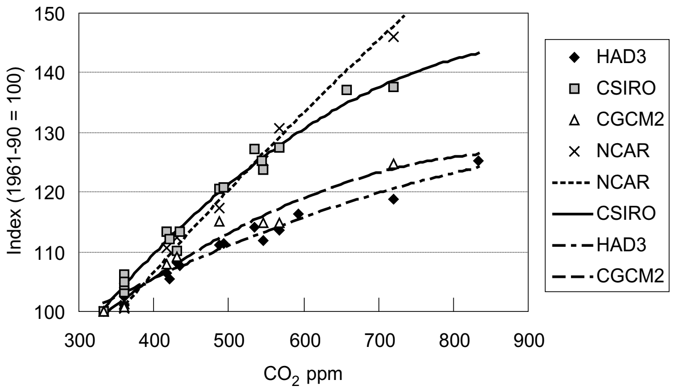


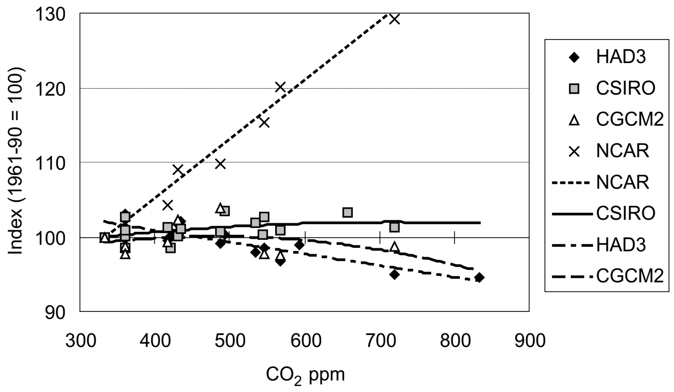
Rice (ir+rf), developing, all land

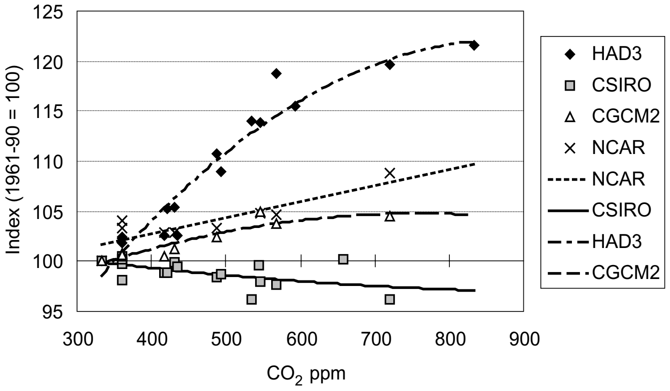


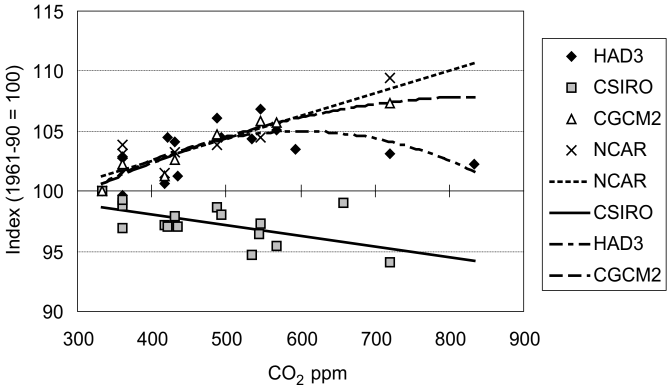
Rice (ir+rf), developing, current cultivated land

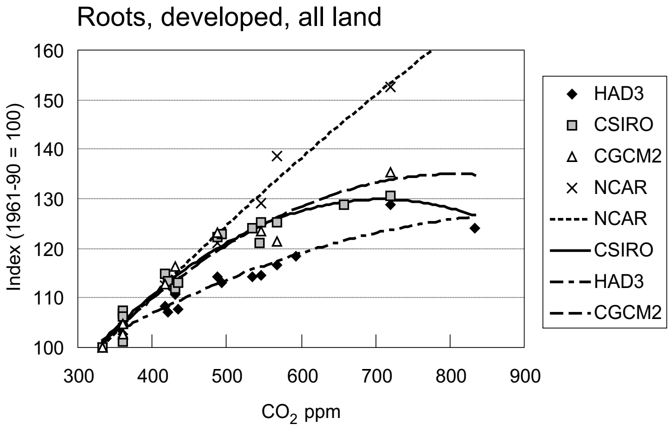


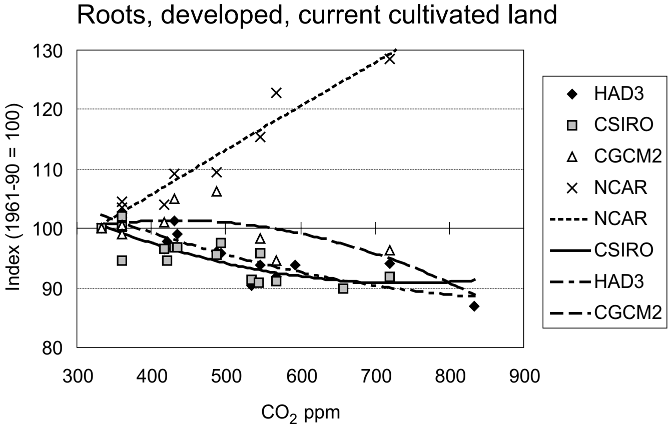

Other grains, developed, all land

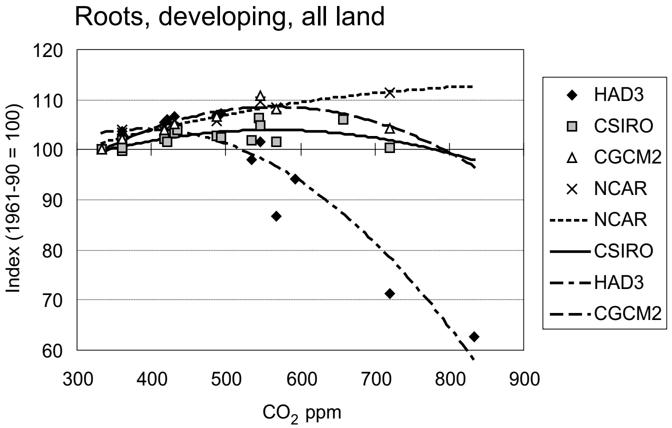

Other grains, developed, current cultivated land

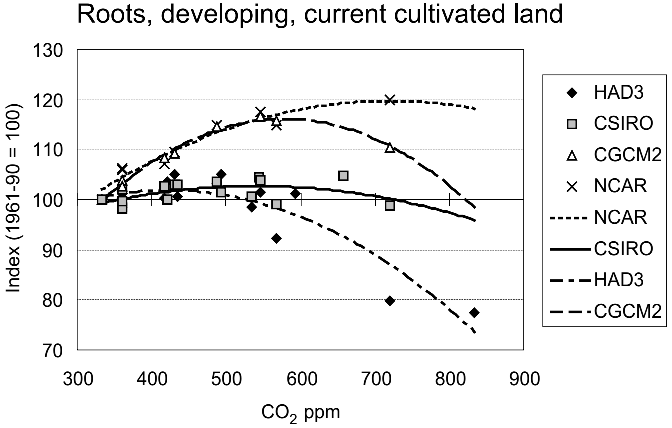

Other grains, developing, all land


Other grains, developing, current cultivated land

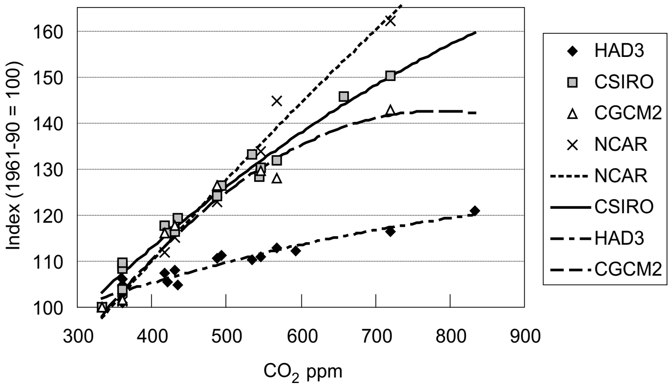

Roots, developed, all land


Roots, developed, current cultivated land

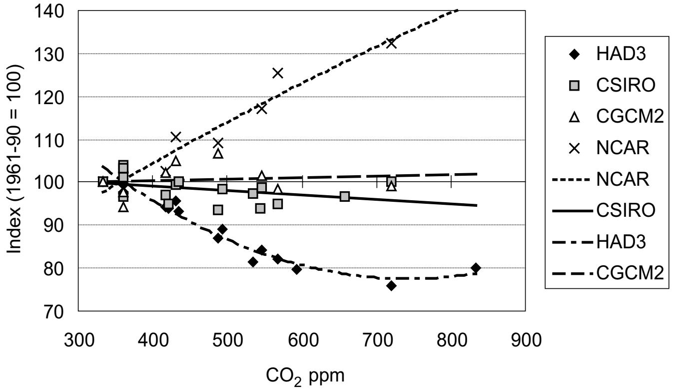

Roots, developing, all land


Roots, developing, current cultivated land

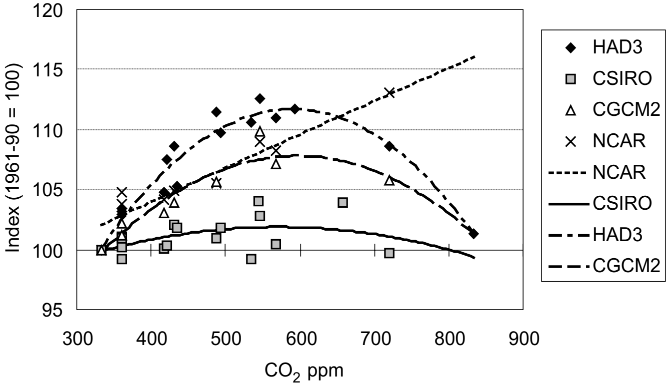
Pulses, developed, all land



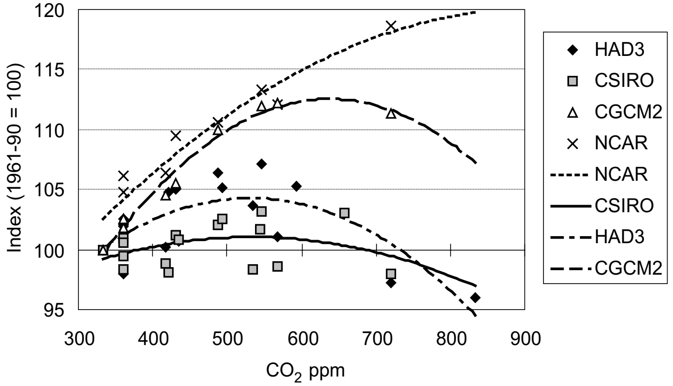
Pulses, developed, current cultivated land

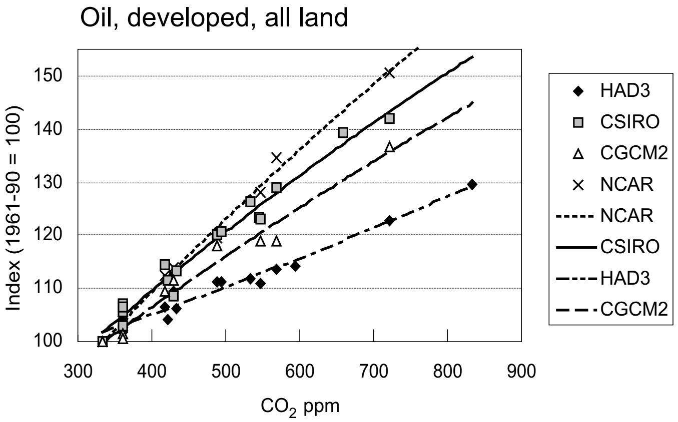


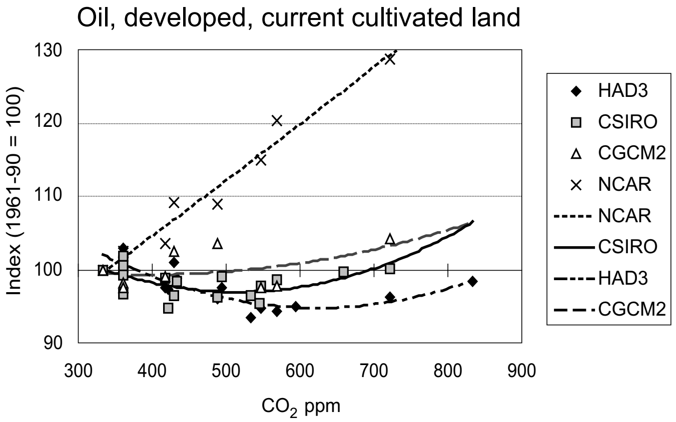
Pulses, developing, all land

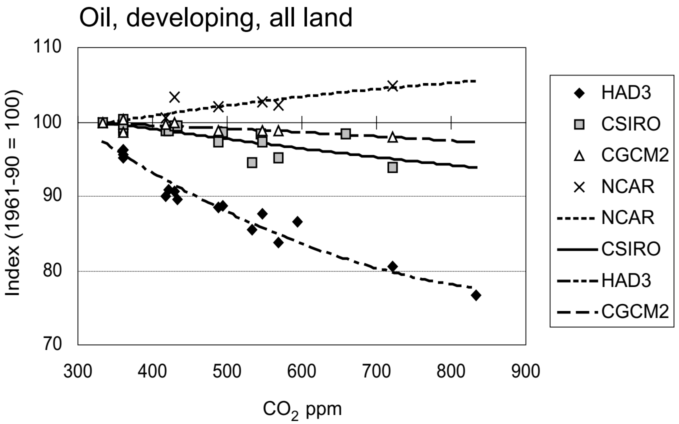


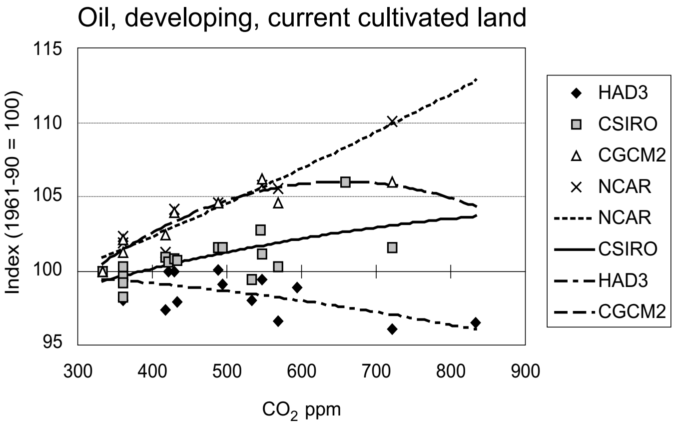
Pulses, developing, current cultivated land

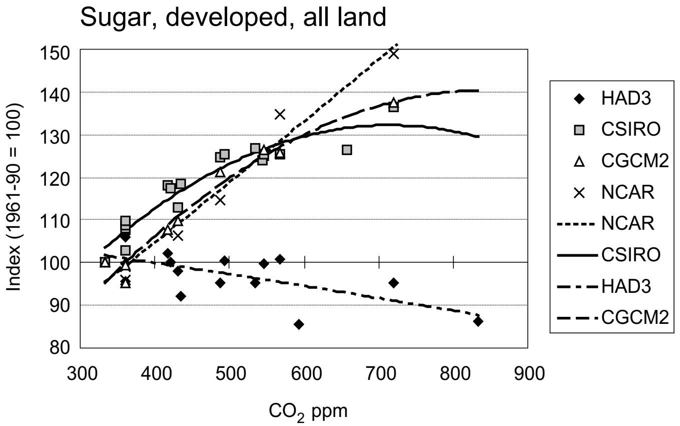


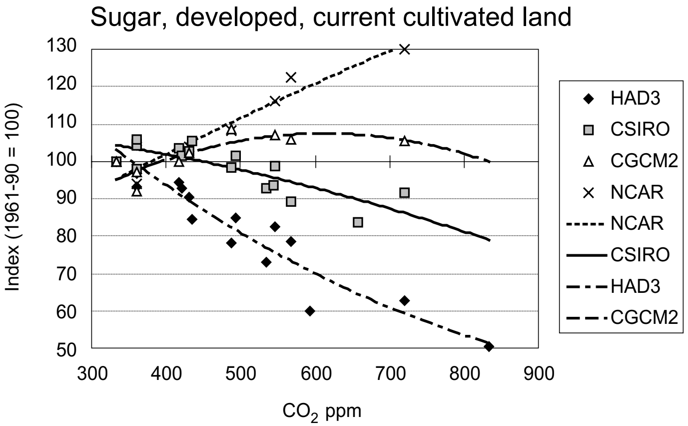

Oil, developed, all land
Index (1961-90 = 100)
100
110
120
130
140
150
300
400
500
600
700
800
900
CO$_2$ ppm
HAD3
CSIRO
CGCM2
NCAR
NCAR
CSIRO
HAD3
CGCM2

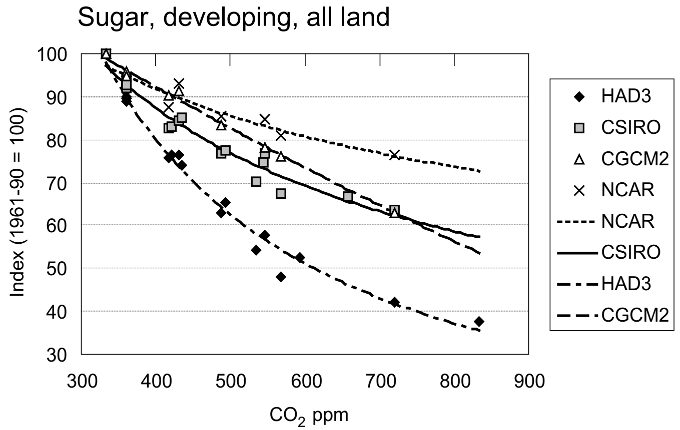

Oil, developed, current cultivated land
Index (1961-90 = 100)
90
100
110
120
130
300
400
500
600
700
800
900
CO$_2$ ppm
HAD3
CSIRO
CGCM2
NCAR
NCAR
CSIRO
HAD3
CGCM2

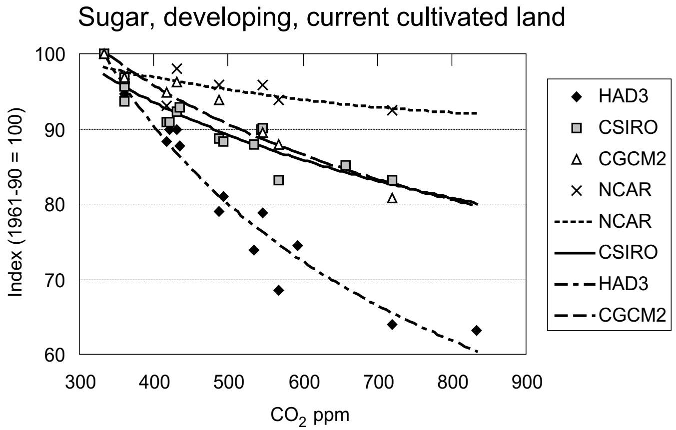

Oil, developing, all land
Index (1961-90 = 100)
70
80
90
100
110
300
400
500
600
700
800
900
CO$_2$ ppm
HAD3
CSIRO
CGCM2
NCAR
NCAR
CSIRO
HAD3
CGCM2


Oil, developing, current cultivated land
Index (1961-90 = 100)
95
100
105
110
115
300
400
500
600
700
800
900
CO$_2$ ppm
HAD3
CSIRO
CGCM2
NCAR
NCAR
CSIRO
HAD3
CGCM2


Sugar, developed, all land


Sugar, developed, current cultivated land


Sugar, developing, all land


Sugar, developing, current cultivated land

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