PERGAMON

Global Environmental Change 9 (1999) S51–S67

GLOBAL ENVIRONMENTAL CHANGE

www.elsevier.com/locate/gloenvcha

Climate change and world food security: a new assessment

Martin Parry[a,*], Cynthia Rosenzweig[b], Ana Iglesias[c], Günther Fischer[d], Matthew Livermore[a]

[a]*The Jackson Environment Institute, University of East Anglia, Norwich NR4 7TJ, UK*
[b]*Goddard Institute for Space Studies, New York, 10025, USA*
[c]*Universidad Politecnica de Madrid, 28040 Madrid, Spain*
[d]*International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria*

Abstract

Building on previous work quantitative estimates of climate change impacts on global food production have been made for the UK Hadley Centre's HadCM2 greenhouse gas only ensemble experiment and the more recent HadCM3 experiment (Hulme et al., 1999). The consequences for world food prices and the number of people at risk of hunger as defined by the Food and Agriculture Organisation (FAO, 1988) have also been assessed. Climate change is expected to increase yields at high and mid-latitudes, and lead to decreases at lower latitudes. This pattern becomes more pronounced as time progresses. The food system may be expected to accommodate such regional variations at the global level, with production, prices and the risk of hunger being relatively unaffected by the additional stress of climate change. By the 2080s the additional number of people at risk of hunger due to climate change is about 80 million people ($\pm$ 10 million depending on which of the four HadCM2 ensemble members is selected). However, some regions (particularly the arid and sub-humid tropics) will be adversely affected. A particular example is Africa, which is expected to experience marked reductions in yield, decreases in production, and increases in the risk of hunger as a result of climate change. The continent can expect to have between 55 and 65 million extra people at risk of hunger by the 2080s under the HadCM2 climate scenario. Under the HadCM3 climate scenario the effect is even more severe, producing an estimated additional 70 + million people at risk of hunger in Africa.

Keywords: Climate change; Food security; Crop yields

1. Introduction

The balance of scientific evidence now suggests that over the last century humans have begun to have a discernible influence on the world's climate, causing it to warm (IPCC, 1996,1998). In the coming decades, global agriculture will need to confront this challenge in addition to that of a growing population, which is projected to double its present level by about the 2080s (World Bank, 1995).

This study examines the potential effects of climate change on crop yields, world food supply, and risk of hunger. The responses of crop yield to climate change are estimated from crop growth models. The economic consequences of these potential changes in crop yields are then simulated using a world food trade model. The analysis provides estimates of changes in terms of production and prices of major food crops and the number of people at risk of hunger. The method used has been reported elsewhere (Rosenzweig and Parry, 1994; Fischer et al., 1996). In this paper we show that the use of transient global climate model (GCM) scenarios allows not only the effect of the magnitude of climate change on food production to be assessed but also the effects of rate of change.

Despite technological advances such as improved crop varieties and irrigation systems, weather and climate are still key factors in agricultural productivity. For example, weak monsoon rains in 1987 caused large shortfalls in crop production in India, Bangladesh, and Pakistan, contributing to a reversion to wheat importation by India and Pakistan (World Food Institute, 1988). The last two decades have also witnessed a continuing deterioration of food production in Africa, caused in part by persistent drought and low production potential, and international relief efforts to prevent widespread famine.

* Corresponding author. Tel.: + 44-1603-593-895; fax: +44-1603-593-896.

E-mail address: parryml@aol.com (M. Parry)

0959-3780/99/$ - see front matter
PII: S0959-3780(99)00018-7

At the same time agricultural trade has grown dramatically and now provides significant food supplies for major importing nations and substantial income for exporting nations. These examples emphasise the close links between agriculture and climate, the international nature of food trade and food security, and the need to consider the impacts of climate change in a global context.

2. Study method

The structure and research methods for the world food supply study are illustrated in Fig. 1. There are two main components: Estimation of potential changes in crop yield and estimation of world food trade responses. All climate change, technology and socio-economic scenarios used in this study are based on an IS92a future (for

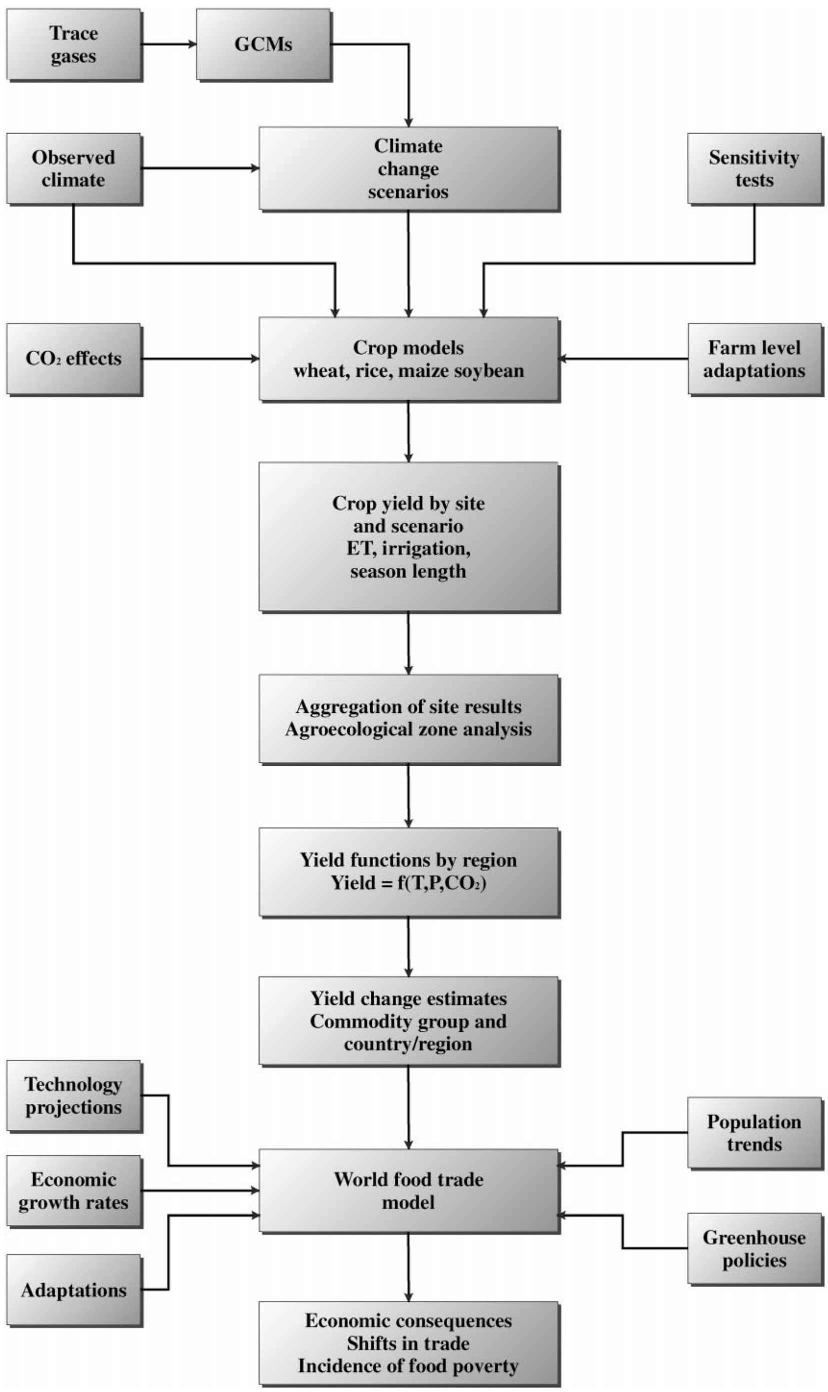


Fig. 1. Key elements of the crop yield and world food trade study (from Rosenzweig et al., 1993).

an explanation, see Hulme et al., 1999). The methodological elements of each of the two components are described below.

Adaptation was considered and incorporated in the evaluations made by the two components of the climate change study. *Farm-level adaptations* were tested by the crop models which result in yield changes, and *economic adjustments* to the yield changes were tested by the BLS world food trade model which result in national and regional production changes and price responses. Farm-level adaptations tested in the crop models include planting date shifts, more climatically adapted varieties, irrigation and fertiliser application. Economic adjustments represented by the BLS include: increased agricultural investment, reallocation of agricultural resources according to economic returns (including crop switching), and reclamation of additional arable land as a response to higher cereal prices. It is assumed that these economic adjustments do not to feed back to the yield levels predicted by the crop modelling study.

2.1. Estimation of potential changes in crop yield

The IBSNAT-ICASA dynamic crop growth models for the major grain cereals and soybean (see Fig. 2) were specified and validated 124 sites in 18 countries (see Fig. 3) representing major agricultural regions of the world (Rosenzweig and Iglesias, 1994, 1999; Fig. 2). The IBSNAT-ICASA models were developed by the US Agency for International Development's International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT, 1989). Crop model simulation results were aggregated and extrapolated to regional level based on agroclimatic zone analysis. Aggregated crop model results under different climate and management conditions were then used to specify appropriate functional forms for regional yield response to climate parameters (temperature and precipitation), and environmental modifications (atmospheric CO_2 concentration). The resulting functions were then linked to a geographically explicit database for the evaluation of spatial yield changes under the climate and CO_2 scenarios predicted by Hadley

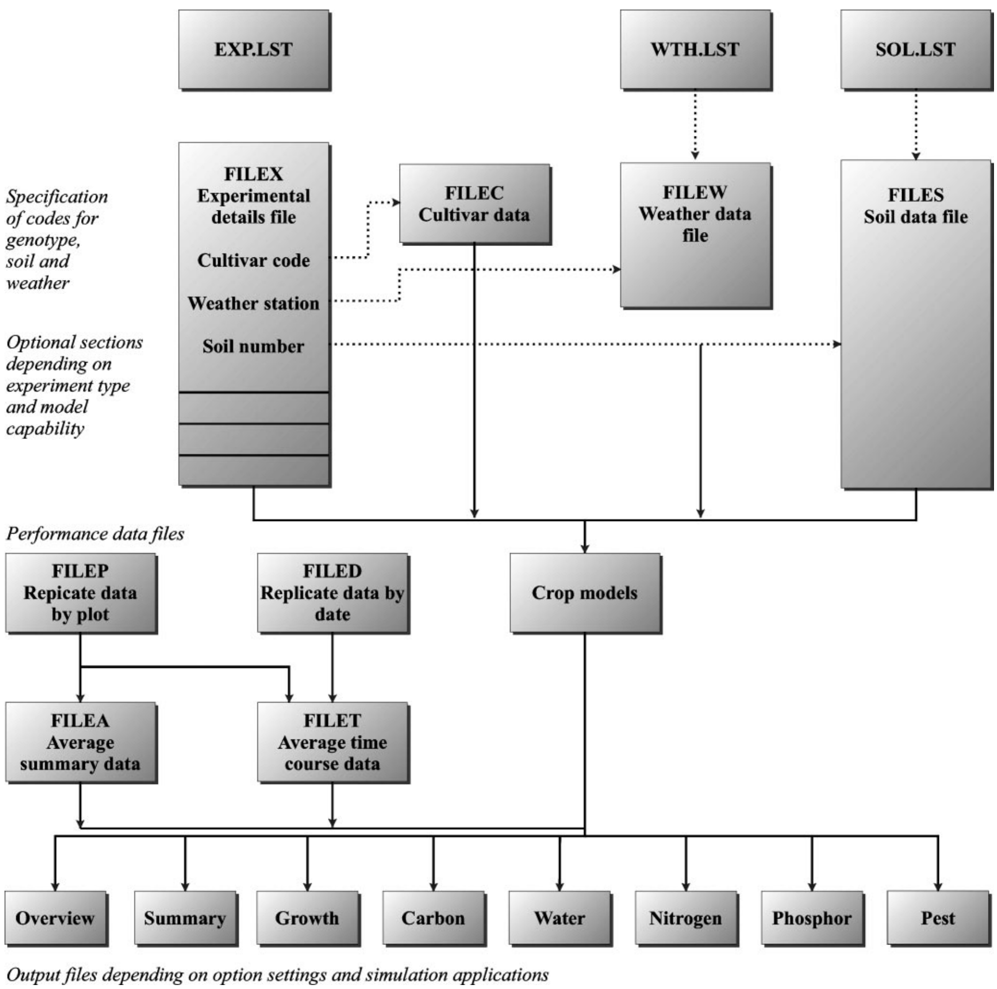


Fig. 2. The IBSNAT crop models.

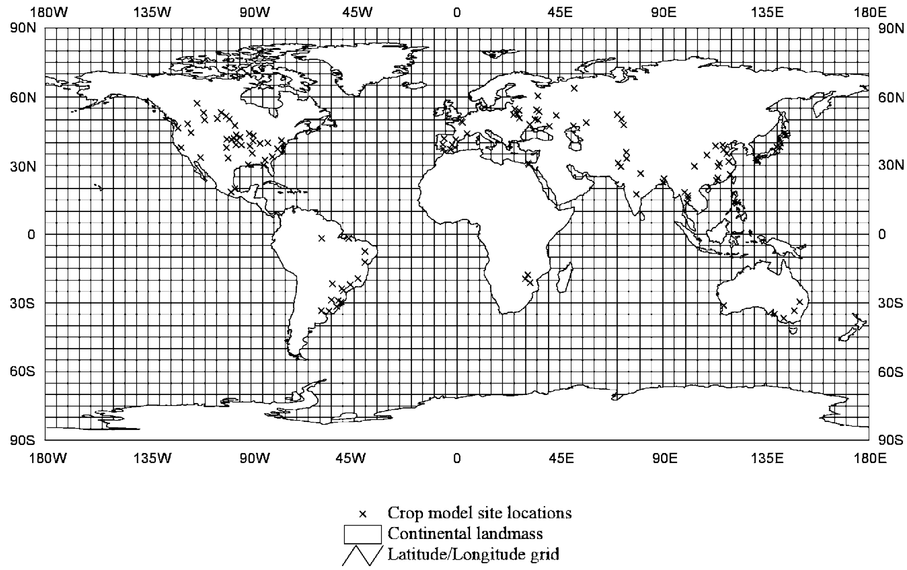


Fig. 3. The locations of the IBSNAT crop model sites.

Table 1
Current world crop yield, area, production, and percent world production aggregated for countries participating in study

	Yield t/ha	Area ha × 1000	Production t × 1000	Study countries %
Wheat	2.1	230,839	481,811	73
Rice	3.0	143,603	431,585	48
Maize	3.5	127,393	449,364	71
Soybeans	1.8	51,357	91,887	76

Centre's GCMs known as HadCM2 (Mitchell et al., 1995) and HadCM3 (Hulme et al., 1999). Explicit links were created between analyses and simulations conducted at the validated site level and at the country/regional level.

The crops simulated (main grain cereals and soybean) account for 85% of the world cereal exports. Table 1 shows the current percentages of world production of wheat, rice, maize, and soybean for the countries in which simulations were conducted. Simulations were carried out in regions representing 70–76% of the current world production of wheat, maize, and soybean production. Rice production was less well represented in the model simulations than the other crops, because India, Indonesia and Vietnam have significant production areas not included in the study. Further research is needed in these key countries in order to improve the reliability of the projections of climate change impacts on rice production.

2.2. Crop models

The study simulated the main grain crops with the IBSNAT-ICASA models for wheat (CERES-Wheat, Godwin et al., 1990), rice (CERES-Rice, Godwin et al., 1993), maize (Jones and Kiniry, 1986; Ritchie et al., 1989), and soybean (SOYGRO, Jones et al., 1989). The IBSNAT models are comprised of parameterisations of important physiological processes responsible for plant growth and development, evapotranspiration, and partitioning of photosynthate to produce economic yield. The simplified functions enable prediction of the growth of crops as influenced by the major factors that affect yields, i.e. genetics, climate (daily solar radiation, maximum and minimum temperatures, and precipitation), soils, and management practices. The models include a soil moisture balance sub-model so that they can be used to predict both rainfed and irrigated crop yields. The models simulate the effects of nitrogen fertiliser on crop growth, and these were analysed in several sites in the context of climatic change (for example, Argentina and Uruguay, see Rosenzweig and Iglesias, 1994). For the most part, however, the results of this study assume optimum nutrient levels.

The IBSNAT models were selected for use in this study because they have been validated over a wide range of environments (e.g. Otter-Nacke et al., 1986) and are not specific to any particular location or soil type. They are better suited for large-area studies, in which crop-growing and soil conditions differ greatly, than more detailed physiological models that have not been as widely tested. The validation of the crop models over different environments also improves the ability to estimate effects of changes in climate. Because the crop models have been tested over essentially the full range of temperature and precipitation regimes where crops are grown in today's climate, and to the extent that future climate change brings temperature and precipitation regimes within these ranges, the models may be considered useful tools for assessment of potential climate change impacts. Furthermore, because management practices, such as the choice of varieties, the planting date, fertiliser application, and irrigation, may be varied in the models, they permit experiments that simulate adaptation by farmers to climatic change.

2.3. Simulation of the direct effects of CO_2 on crop growth

Most plants growing in experimental environments with increased levels of atmospheric CO_2 exhibit increased rates of net photosynthesis (i.e. total photosynthesis minus respiration) and reduced stomatal openings. (Experimental effects of CO_2 on crops have been reviewed by Cure and Acock (1986).) Partial stomatal closure leads to reduced transpiration per unit leaf area and, combined with enhanced photosynthesis, often improves water-use efficiency (the ratio of crop biomass accumulation or yield to the amount of water used in evapotranspiration). Thus, by itself, increased CO_2 can increase yield and reduce water use (per unit biomass).

The crop models used in this study account for the beneficial physiological effects of increased atmospheric CO_2 concentrations on crop growth and water use (Peart et al., 1989). As simulated in this study, the direct effects of CO_2 may bias yield changes in a positive direction, since there is uncertainty regarding whether experimental results will be observed in the open field under conditions likely to be operative when farmers are managing crops. Plants growing in experimental settings are often subject to fewer environmental stresses and less competition from weeds and pests than are likely to be encountered in farmers' fields. However, recent field free-air release studies have found overall positive CO_2 effects under current climate conditions (Hendry, 1993).

2.4. Yield simulations at the site level

Crop modelling simulation experiments included in the study were performed for: the baseline climate; step changes in temperature, precipitation and CO_2 levels; and GCM climate change scenarios with and without the physiological effects of CO_2. This involved the following tasks:

- Definition of the representative crop management (e.g. crop variety, fertiliser inputs, rainfed and/or irrigated production, number of crops grown per year) and soils.
- Definition of the baseline daily climate data for the period 1961–90, or for as many years of daily data as were available.
- Validation of the crop models under current climate with experimental data from field trials, to the extent possible.
- Simulations of crop responses with the climate modified scenarios.
- Testing of farm level adaptations: shifts in planting date ($\pm$ 1 month); additional application of irrigation water to crops already under irrigation; and changes in crop variety assuming only the range that exists today.

2.4.1. Aggregation of site results to agroclimatic regions

Crop model results for wheat, rice, maize and soybean from the 124 sites were aggregated to agroclimatic regions by weighting their representative contribution to current regional production. The aggregations were calculated jointly with agricultural scientist from 18 countries (see Rosenzweig and Iglesias, 1994) and with production data sources included the United Nations Food and Agriculture Organisation (FAO, 1995), the US Department of Agriculture (USDA) Crop Production Statistical Division, and the USDA International Service. The regional yield estimates represent the current mix of rainfed and irrigated production and the current crop varieties, nitrogen management and soils.

2.4.2. Development of the regional yield functional forms

Statistical analyses were used to derive regional yield response functions from the site results. First, relationships between crop yield and temperature and precipitation anomalies over the entire growing period and atmospheric CO_2 levels were analysed independently using the Pearson product moment correlation coefficient, as calculated by the SPSS statistical programme. This exploratory analysis served to identify those variables, which explained a significant proportion of the observed yield variance.

The yield response to combined changes in temperature, precipitation and CO_2 concentration (between 10 and 200 simulations per crop and agroclimatic region) was then statistically analysed. The multiple linear and quadratic regression models were tested as possible yield functions. For each function, the agreement between simulated "observed" yields (the term "observed" is used here to designate the results of the crop model simulations) and yields predicted by the functions was measured using the adjusted R^2, representing the fraction of variation in simulated yield explained by the fitted yield values. The significance of the estimated models was also assessed by screening the values obtained using the F-test criteria of F values being less than 0.0001 at the 95% significance level. Function parameters, their significance, and predicted yields were calculated using the SPSS statistical programme.

These yield functions were then applied to the spatial climate change data (scenario changes in the temperature, precipitation, and CO_2 levels) to derive scenario yield change estimates for individual crops.

2.4.3. Yield change estimates for crops and regions not simulated

The regional crop yield changes were extrapolated:

- To provide estimates of yield changes for the other crops and commodity groups included in the food trade analysis using a blend of expert judgement and historical analogues.
- To the specific countries and regions considered in the BLS that do not represent agroclimatic homogeneous regions (see Table 2).

The extrapolation was estimated based on three criteria:

- similarities to growing conditions for modelling crops;
- results from over 50 previously published and unpublished regional climate change impact studies; and
- projected temperature and precipitation changes (and hence soil moisture availability for crop growth) from the four HadCM2 ensemble member and single HadCM3 climate change scenarios (Hulme et al., 1999).

2.4.4. Limitations of crop yield change estimates

The yield change estimates include different sources of uncertainty. At the site level, the main source of uncertainty is inherent to the use of crop models. The crop models embody a number of simplifications. For example, weeds, diseases, and insect pests are assumed to be controlled; there are no problem soil conditions (e.g. salinity or acidity); and there are no extreme weather events such as droughts or severe storms. The models are calibrated to experimental field data, which often have yields higher than those currently typical under farming conditions. Thus, the absolute effects of climatic change on yields in farmers' fields may be different from those simulated by the crop models. The crop models simulate the current range of agricultural technologies available around the world, including the use of high-yielding varieties that are responsive to technological inputs, but by the 2080s agricultural technology is likely to be very different. The models may be used to test the effects of some potential improvements in agricultural production, such as varieties with higher thermal requirements and installation of irrigation systems, but do not include possible future improvements. (The BLS economic model used in the study does include future trends in yield improvement, but not technological developments induced by negative climate change impacts.)

At the regional level, the primary source of uncertainty in the estimates lies in the sparseness of the crop modelling sites to derive regional yield functions and the fact that the sites may not adequately represent the variability of agricultural regions within countries, the variability of agricultural systems within similar agro-ecological zones, or dissimilar agricultural regions. However, since the site results relate to regions that account for about 70% of world grain production, the conclusions concerning

Table 2
Models in the Basic Linked System

National models	
Argentina	Kenya
Australia	Mexico
Austria	New Zealand
Brazil	Nigeria
Canada	Pakistan
Egypt	Thailand
Indonesia	Turkey
Japan	
Models with country specific structure	
China	United States
India	
Models with close economic-co-operation	
Eastern Europe & former USSR	EU
Regional group models	
Africa oil exporters	Latin American medium-income
Africa medium-income exporters	South-East Asia high–medium exporters
Africa medium-income importers	South-East Asia high–medium importers
Africa low-income exporters	Asia low-income
Africa low-income importers	South-West Asia oil exporters
Latin American high-income exporters	South-West Asia medium–low income
Latin American high-income importers	Rest of the World

world totals of cereal production contained in this study are believed to be substantiated adequately. Another source of uncertainty lies in the simulation of grain crops only, leading to estimation of yield changes for other commodities, such as root crops and fruit, based primarily on previous estimates. The previous estimates tended to be less negative than the crop responses modelled in this study, and this introduced a bias in favour of these other crops in the world food trade model.

2.4.5. Estimation of world food trade responses

The national crop yield changes derived from the first component of the study were used as inputs into a world food trade model, the Basic Linked System (BLS), developed at the International Institute for Applied Systems Analysis (IIASA) (Fischer et al., 1988). The BLS was run first for a reference scenario projecting the agricultural system to the end of the 2080s assuming no change in climate, and then with four HadCM2 and one HadCM3 climate change scenarios. In this study socio-economic variables were kept constant between runs so as to isolate the effect of the slightly different GCM runs. Outputs from the BLS simulations, providing information on food production, food prices and on the number of people at risk of hunger (defined as the population with an income insufficient to either produce or procure their food requirements) for these scenarios, were projected up to the 2080s.

2.4.6. The world food trade model

The world food system is a complex dynamic interaction of producers and consumers, interacting through global markets. Related activities include input production and acquisition, transportation, storage and processing. While there is a trend towards internationalisation in the world food system, only about 15% of total world production currently crosses national borders (Fischer et al., 1990). National governments shape the system by imposing regulations and by investments in agricultural research, infrastructure improvements, and education. The system functions to meet the demand for food, to produce food in increasingly efficient ways, and to trade food within and across national borders. Although the system does not guarantee stability, it has generated long-term real declines in prices of major food staples (Fischer et al., 1990).

The basic linked system (BLS) consists of linked national agricultural sector models. The BLS was designed at IIASA for food policy studies but it also can be used to evaluate the effect of climate-induced changes in yield on world food supply and agricultural prices. It currently consists of 18 national models, 2 models for regions with close economic co-operation (the EU and former Soviet Union), 14 regional group models and a small component that accounts for statistical discrepancies and imbalances during the historical period (See Table 2). The 20 models in the first two groups cover about 80% of attributes of the world food system such as demand, land and agricultural production. The remaining 20% is covered by 14 regional models for countries which have broadly similar attributes (e.g., African oil-exporting countries, Latin American high income exporting countries, Asian low-income countries etc.). The grouping is based on country characteristics such as geographical location, income per capita and the country's position with regard to net food trade (Fischer et al., 1995).

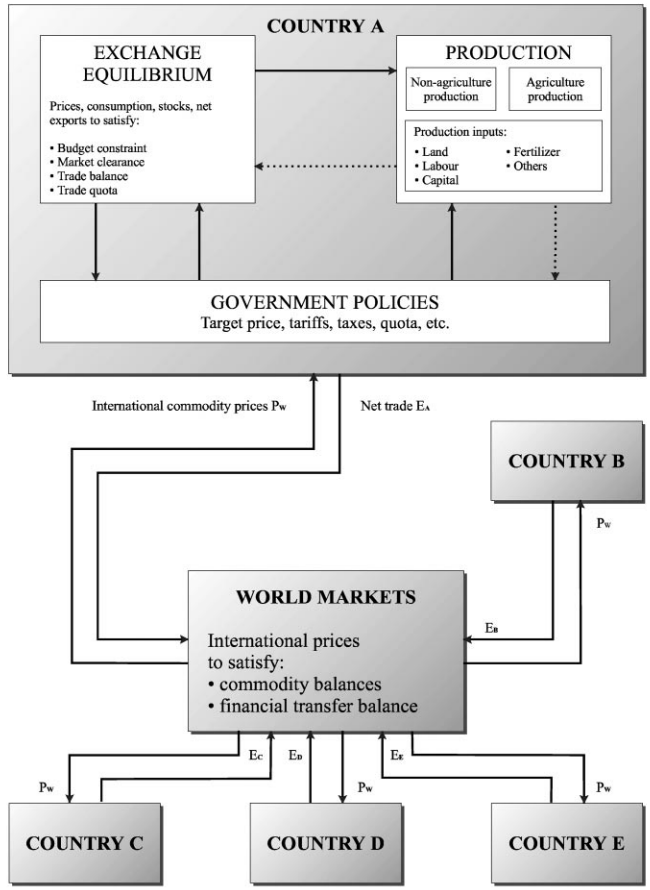


Fig. 4. The Basic Linked System — relationships between country components and world markets. Arrows to countries represent international commodity prices; arrows to world markets represent net trade (from Rosenzweig et al., 1993).

The BLS is a general equilibrium model system, that comprises a representation of all major economic sectors, empirically estimated parameters and no unaccounted supply sources or demand sinks (see Fischer et al. (1988) for a complete description of the model). In the BLS, countries are linked through trade, world market prices and financial flows (Fig. 4). It is a recursively dynamic system: a first round of exports from all countries is calculated for an assumed set of world prices and international market clearance is checked for each commodity. World prices are then revised, using an optimising algorithm, and again transmitted to the national model. Next, these generate new domestic equilibria and adjust net exports. This process is repeated until the world markets for all commodities are cleared. At each stage of the iteration, domestic markets are in equilibrium. This process yields international prices as influenced by governmental and inter-governmental agreements. The system is solved in annual increments, simultaneously for all countries. Summary indicators of the sensitivity of the world system include world cereal production, world cereal prices and prevalence of population in developing countries at risk of hunger.

The BLS does not incorporate any climate relationships per se. Effects of changes in climate were introduced to the model as changes in the average national or regional yield per commodity. Ten commodities are included in the model: wheat, rice, coarse grains, protein feed, bovine and ovine meat, dairy products, other animal products, other food, non-food agriculture and non-agriculture. Yield change estimates for coarse grains were based on the percentage of maize grown in the country or region; soybean crop model results were used to estimate the protein feed category; the estimates for the non-grain crops were based on the modelling grain crops and previous estimates of climate change impacts as described above. A positive bias toward non-grain crops was introduced by this procedure, since the previous estimates of yield changes of the non-grain crops were less negative than the modelled results from this study.

2.4.7. Economic growth rates

Economic growth rates are a product of several BLS functions. Non-agricultural production utilises a Cobb–Douglas production function with labour and capital as production factors. Non-agricultural labour input depends primarily on population growth (predetermined in the form of the World Bank 1995 medium long-range scenario) and somewhat on relative prices between agriculture and non-agriculture by means of a sector migration function. Capital accumulation depends on investment and depreciation, which in turn depend on saving and depreciation rates. Depreciation rates and saving rates are estimated from historical data and are kept constant after 1990. There is an exogenous assumption based on historical data for technical progress in the production function. The primary economic growth rates used in this study are those produced by the Energy Modelling Forum (EMF14, 1995).

2.4.8. Yield trends

Representing improvement in agriculture productivity due to technological progress, the annual yield trends used in the BLS for the period 1980–2000 are 1.2, 1.0, and 1.7% for global, developed country, and developing countries, respectively. According to FAO data, yields have been growing at an average of around 2% annually during the period 1951–80, both for developed and developing (excluding China) countries (FAO, 1991), Recent increase (1965–85) in annual productivity for less-developed countries is about 1.5%/yr. In the 1980s, however, yields grew globally at an average yield increase of only 1.3%, implying a falling trend in yield growth rates.

The falling growth rates utilised in the reference case of the BLS may be justified for several reasons. Historical trends suggest decreasing rates of increase, and yield improvements from biotechnology have yet to be realised. Much of the large yield increases in developed countries in the 1950s and 1960s and in developing countries thereafter has been due to intensification of chemical inputs and mechanisation. Apart from economic reasons and environmental concerns which suggest that maximum input levels may have been reached in many developed countries, there are likely be diminishing rates of return for further input increases. In some developing countries, especially in Africa, increase in input levels and intensification of production are likely to continue for some time, but may also ultimately level off. Furthermore, since Africa has the lowest average cereal yields of all the regional groups combined with a high population growth rate, it will contribute an increasing share of cereal production, thereby reducing average global yield increases.

2.4.9. Arable land

Availability of arable land for expansion of crop production is based on FAO data. In the BLS standard national models, a piece-wise linear time-trend function is used to impose upper bounds (inequality constraints) on land use. In addition, this time trend function is modified with an elasticity term (usually 0.05 or less) that reacts to changes in shadow prices of land in comparison to 1990 levels. The upper limits imposed by the time trend function utilise the FAO data on potential arable land. The arable land limits are not adjusted due to climate change, even though they may be affected positively in some locations by extension of season length or drying of wet soils or negatively, by sea-level inundation or desertification.

2.4.10. Risk of hunger indicator

The indicator of number of people at risk from hunger used in the BLS is defined as the population with an income insufficient either to produce or procure their food requirements in developing countries (excluding China). The measure is derived from FAO estimates and methodology for developing market economies (FAO, 1987). The FAO estimates were obtained by stipulating that calorie consumption distribution in a country is skewed and can be represented by a beta distribution. The parameters of these distributions were estimated by FAO for each country based on country-specific data and cross-country comparisons. The estimate of the energy requirement of an individual is based on the basal metabolic rate (time in a fasting state and lying at complete rest in a warm environment). Body weight, age and sex have an impact on this requirement. FAO presents two estimates of undernourished people, based on minimum maintenance requirements of 1.2 and 1.4 (the latter judged as more appropriate) basal metabolic rate. The BLS estimate for 1990, based on the 1.4 basal metabolic rate requirements, is 521 million undernourished people in the developing world, excluding China.

2.4.11. Limitations of world food trade model

The economic adjustments simulated by the BLS are assumed not to alter the basic structure of the production functions. These relationships may be altered in a changing climatic regime and under conditions of elevated CO_2. For example, yield responses to nitrogen fertilisation may be altered due to changing nutrient solubilities in warmer soils. Furthermore, in the analysis of BLS results, consideration is limited to the major cereal food crops, even though shifts in the balance of arable and livestock agriculture are also likely under changed climatic regimes. Livestock production is a significant component of the global food system and is also potentially sensitive to climatic change. The non-agriculture sector is poorly modelled in the BLS, leading to simplifications in the simulation of responses to climatic change.

3. The set of model experiments

The estimates of climate-induced changes in food production potential were used as inputs to the BLS in order to assess possible impacts on future levels of food production, food prices and the number of people at risk from hunger (see Fig. 1). Impacts were assessed for three time steps, 2020s, 2050s and 2080s, with population growth, technology trends and economic growth projected through these periods to 2100. Assessments were first made for a reference scenario assuming no climate change and subsequently with the four HadCM2 and one HadCM3 climate change scenarios. In every case the difference between the reference and climate change assessments was taken as the estimated climate-induced effect.

Results are described for the following scenarios:

3.1. The reference scenario

The reference scenario projects the agricultural system to 2080 with no climate change. The scenario is based upon a series of assumptions not only concerning the world food trade system but other exogenous factors such as population growth and GNP. The assumptions used are as follows:

- No major changes in the political or economic context of world food trade.
- Population growth to occur as projected by the World Bank (1994) — 10.7 billion by the 2080s.
- GNP to accumulate as projected by the EMF 14 (1995) — see Table 3.
- A 50% trade liberalisation in agriculture is introduced gradually by 2020.

Table 3
GDP growth rates (Baseline is 1990 GDP/cap). Source: EMF14 (1995)

Region	Trillions (p/c)	Per capita growth rates						
		1990–2000	2000–2025	2025–2050	2050–2075	2075–2100	2100–2150	2150–2200
USA	5.52 (22,080)	2.50% (2.18)	2.30% (1.97)	1.50% (1.62)	1.10% (1.14)	1.10% (1.12)	0.80% (0.80)	0.60% (0.60)
EEC	5.71 (16,599)	2.50% (2.15)	2.30% (2.09)	1.50% (1.60)	1.10% (1.14)	1.10% (1.11)	0.80% (0.80)	0.60% (0.60)
Other OECD	4.97 (19,189)	2.70% (2.24)	2.30% (2.11)	1.50% (1.59)	1.10% (1.13)	1.10% (1.13)	0.80% (0.80)	0.60% (0.60)
FSU	1.31 (4533)	− 1.50% (− 2.0)	4.30% (3.90)	3.50% (3.33)	2.00% (1.89)	2.00% (1.93)	1.00% (1.00)	0.80% (0.80)
China	1.33 (1173)	4.00% (2.71)	3.50% (2.66)	3.25% (2.93)	3.00% (2.89)	3.00% (2.85)	2.00% (2.00)	1.00% (1.00)
Other non-OECD	3.11 (1045)	3.75% (1.44)	4.20% (2.55)	3.40% (2.42)	2.80% (2.38)	2.80% (2.60)	2.00% (2.00)	1.00% (1.00)
World Total	21.95 (4179)	2.63% (0.93)	2.84% (1.59)	2.27% (1.55)	1.94% (1.62)	2.11% (1.94)	1.60% (1.60)	0.90% (0.90)

- Technology is projected to increase yields over time but at a slightly slower rate than recently experienced (i.e. about one per cent per year).

This scenario is used as a reference. The differences between it and the scenarios of climate change are taken as the impacts of climate change.

3.2. Climate change scenarios

The crop models were run for current climate conditions and for climate conditions predicted by the Hadley Centre's GCMs known as HadCM2 (Mitchell et al., 1995) and HadCM3 (see Hulme et al., 1999). For the first time the four ensemble members of HadCM2 (see Hulme et al., 1999) are used (HadCM2GGa1-4). Until now only HadCM2GGa1 has been widely used (DETR, 1995, 1997). All climate change scenarios are based on an IS92a-type forcing (one which assumes greenhouse gas emissions stem from a 'business-as-usual' future in economic and social terms).

4. Estimated effects on yields

4.1. Effects on Crop yields

Fig. 5a–c show the estimated potential changes in average national grain crop yields for the four HadCM2 and one HadCM3 climate change scenarios, allowing for the direct effects of CO_2 on plant growth. The maps are created from the nationally averaged yield changes for wheat, rice and maize. Regional variations within countries are not shown.

The latitudinal variations in crop yields illustrated in Fig. 5a–c are mainly due to differences in current growing conditions. Higher temperatures tend to shorten the growing period. This is especially true at low latitudes where crops are currently grown at higher temperatures and are nearer the limits of temperature tolerances for heat and water stress. Warming at low latitudes leads to more severe heat and water stress and greater yield decreases than at higher latitudes. Under the HadCM2 scenario, in many mid- and high-latitude areas, where current temperature regimes are low, the increase in surface temperatures tends to lengthen the growing season thus increasing yields. However, IPCC Working Group II in its second assessment report (IPCC, 1996) acknowledged that a latitudinal shift in temperature patterns would not strictly correspond to a simple shift in latitude of suitable areas for usual crops. This is because many plants are sensitive to photoperiod and have adapted to a specific combination of temperature and photoperiod ranges. Therefore, new genotypes will be required to take advantage of any potential climate change benefits. In this study the potential for expansion of cultivated land is embedded in the BLS world food trade model and is reflected in shifts in production calculated by that model.

This potentially beneficial effect is not evident under the HadCM3 scenario. The intensified polar warming experienced under HadCM3 is so great that the threshold concerning positive effects of warmer temperatures at higher latitudes is exceeded and a decrease in yields occurs in some of these regions.

Another difference evident from Fig. 5a–c is that, while the area most adversely affected under HadCM2 is the Indian subcontinent, under HadCM3 it is western Africa and the USA. In summary the negative effects of climate change are far more evident under the HadCM3 climate change scenario than under the HadCM2 scenarios. The primary causes of decreases in simulated yields are:

- *Shortening of the growing period.* Higher temperatures during the growing season speed annual crops through their development (especially grain-filling stage), allowing less grain to be produced. This occurs at all sites except those with the coolest growing-season temperatures in Canada and Russia.
- *Decrease in water availability.* This is due to a combination of increases in evapotranspiration rates in the warmer climate, enhanced losses of soil moisture and, in some cases, a projected decrease in precipitation in the climate change scenarios.
- *Poor vernalization.* Vernalization is the requirement of some temperate cereal crops, e.g. winter wheat, for a period of low winter temperatures to initiate or accelerate the flowering process. Low vernalization results in low flower bud initiation and ultimately reduced yields. Decreases in winter wheat yields at some sites in Canada and the former USSR are due to lack of vernalization.

5. Estimated effects on food production, food prices and risk of hunger

5.1. The reference scenario (*the future without climate change*)

Assuming no effects of climate change on crop yields and current trends in economic and population growth rates, world cereal production is estimated at 4012 million metric tons (mmt) in the 2080s ($\sim$ 1800 mmt in 1990).

Cereal prices are estimated at an index of 92.5 (1990 = 100) for the 2080s, thus continuing the trend of falling real cereal prices over the last 100 years. This occurs because the BLS standard reference scenario has two phases of price development. Between 1990 and 2020, while trade barriers and protection are still in place but are being reduced, there are increases in relative

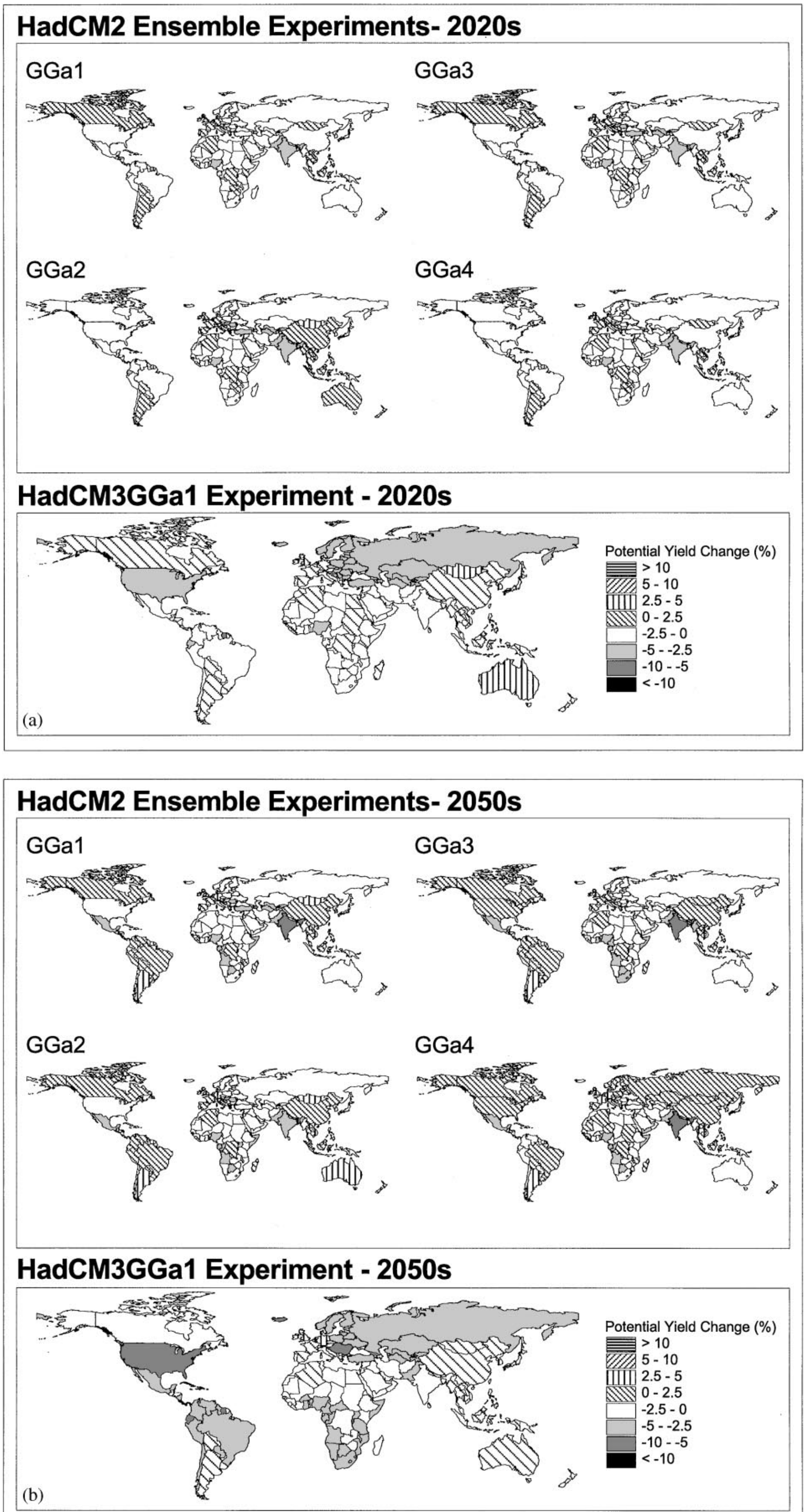


Fig. 5 (*continued*).

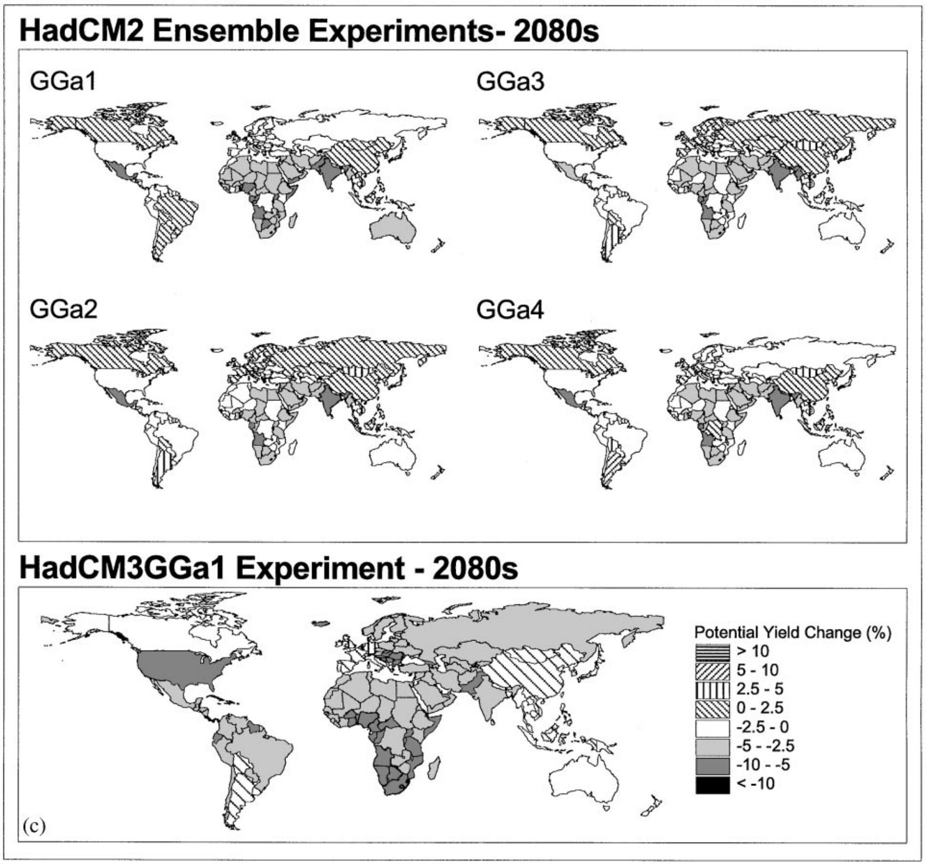


Fig. 5. (a) Potential changes (%) in national cereal yields for the 2020s (compared with 1990) under the four HadCM2 ensemble members (GGa1-4) and the single HadCM3 climate change scenarios. (b) Potential changes (%) in national cereal yields for the 2050s (compared to 1990) under the four HadCM2 ensemble members (GGa1-4) and the single HadCM3 climate change scenarios. (c) Potential changes (%) in national cereal yields for the 2080s (compared to 1990) under the four HadCM2 ensemble members (GGa1-4) and the single HadCM3 climate change scenarios.

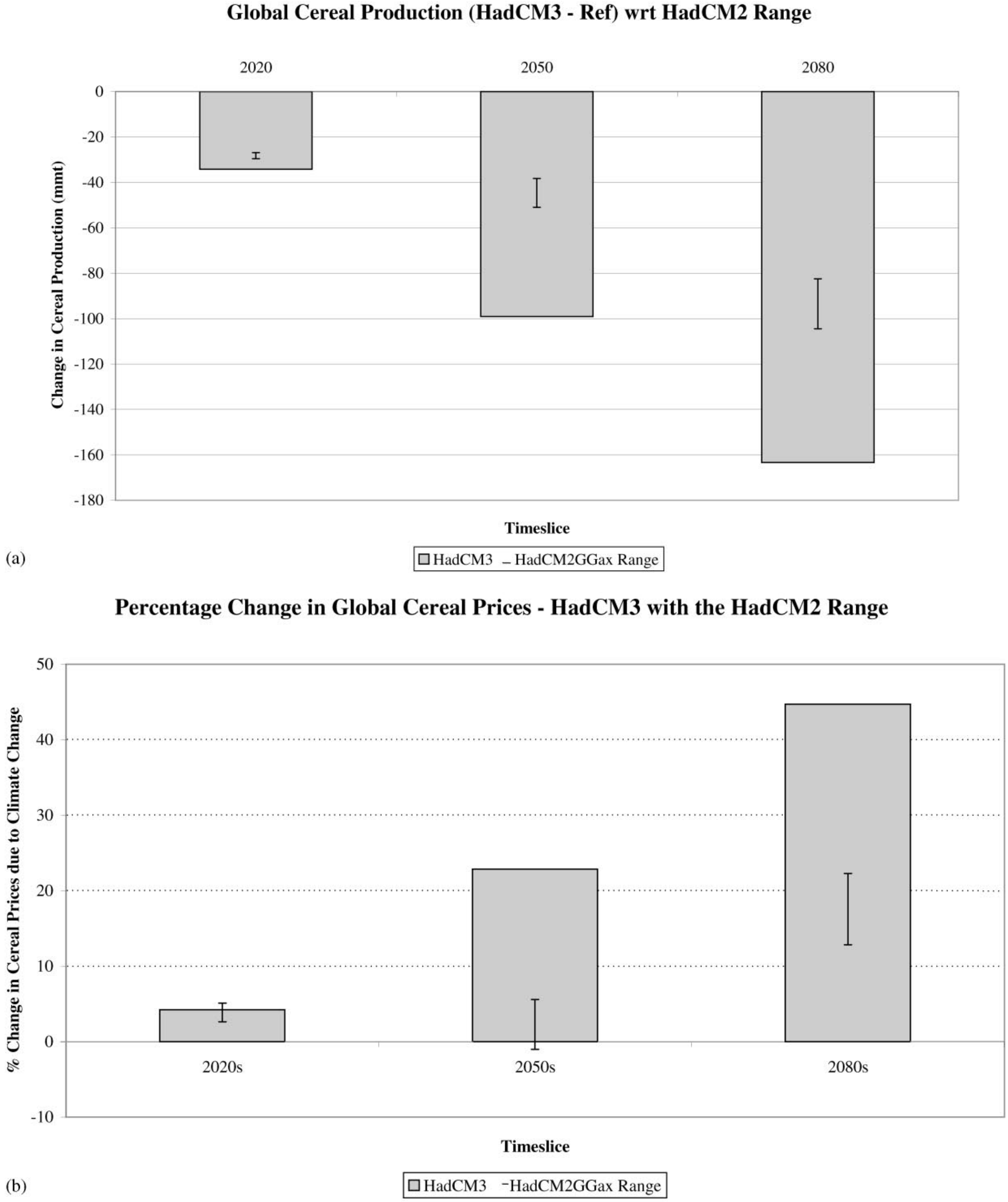
prices due to the increase in demand brought about by the growing world population. However, after 2020, by which time a 50% liberalisation of trade has been realised, prices begin to fall again. This has obvious ramifications for the number of hungry people which is now estimated at about 300 million or about 3% of total population in the 2080s ($\sim$ 521 million in 1990, about 10% of total current population).

5.2. *Effects of climate change*

5.2.1. *Global effects*

Changes in cereal production, cereal prices, and people at risk of hunger estimated for the HadCM2 climate change scenarios (with the direct CO_2 effects taken into account) show that world is generally able to feed itself in the next millennium. Only a small detrimental effect is observed on cereal production, manifested as a shortfall on the reference production level of around 100 mmt (-2.1%) by the 2080s ($\pm$ 10 mmt depending on which HadCM2 climate simulation is selected). In comparison, HadCM3 produces a greater disparity between the reference and climate change scenario – a reduction of more than 160 mmt ($- \sim 4\%$) by the 2080s (Fig. 6a).

Reduced production leads to increases in prices. Under the HadCM2 scenarios cereal prices increase by as much as 17% ($\pm$ 4.5%) by the 2080s (Fig. 6b). The greater negative impacts on yields projected under HadCM3 are carried through the economic system with prices estimated to increase by about 45% by the 2080s. In turn these production and price changes are likely to affect the number of people with insufficient resources to purchase adequate amounts of food. Estimations based upon dynamic simulations by the BLS show that the number of people at risk of hunger increases, resulting in an estimated additional 90 million people in this condition due to climate change (above the reference case of $\sim$ 250 million) by the 2080s (Fig. 6c). The HadCM3 results are again more extreme, falling outside the HadCM2 range with an estimated 125 + million additional people at risk of hunger by the 2080s. All BLS experiments allow the world food system to respond to climate-induced supply shortfalls of cereals and higher commodity prices through increases in production factors (cultivated land, labour, and capital) and inputs such as fertiliser.



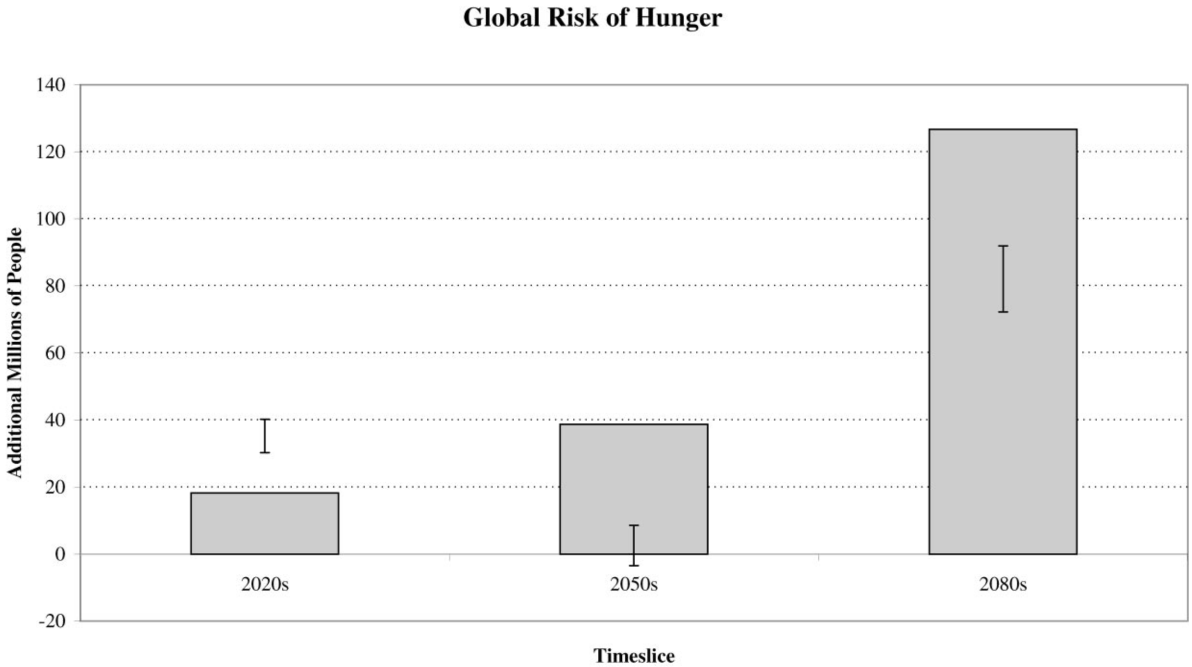
(a)

(b)

Fig. 6. (a). Changes in global cereal production (mmt). Blocks are the production change projected under the HadCM3 climate change scenario (compared with the reference case). Bars depict the range of change under the four HadCM2 ensemble simulations. (b) Percentage change in cereal prices. Blocks are the price changes projected under the HadCM3 climate change scenario (relative to the reference case). Bars depict the range of price change under the HadCM2 ensemble experiments. (c) Global estimates of the additional number of people at risk of hunger due to climate change compared with the reference case. HadCM3 estimates are represented by the Blocks. Bars represent the range of results under the fourHadCM2 ensemble simulations.

5.2.2. Regional effects

The global estimates presented above mask important regional differences in impacts. For example, under the HadCM2 scenarios yield increases at high and high mid-latitudes lead to production increases in these regions, a trend that may be enhanced due to the greater adaptive capacity of countries here. Both Canada and Europe are good examples of this. In contrast, yield



(c)

Fig. 6 (*continued*).

decreases at lower latitudes, and in particular in the arid and sub-humid tropics, lead to production decreases and increases in the risk of hunger, effects that may be exacerbated where adaptive capacity is lower than the global average.

Under the HadCM2 scenarios the largest negative changes occur in developing regions, which on average varies between -3.5 and -16.5%, though the extent of decreased production varies greatly by country depending on the projected climate. Disparities in crop production between developed and developing countries are estimated to increase. However, our results based on the HadCM3 experiment show that the relationship between global warming and increased yields in the higher latitudes is finely balanced. Under HadCM3 the higher latitudes get warmer and drier than under the HadCM2 scenarios. The result is that for the first time negative impacts on cereal yields and production figures are evident in North America, Eastern Europe and the Russian Federation as early as the 2020s (Fig. 7).

The additional range values provided by the HadCM2 ensemble simulations suggests that developing regions may not only have to meet the challenge of a warmer world but also a more variable one. Developing regions appear less able to deal with the range of multi-decadal climate variability that is presented under the four HadCM2 scenarios. In Africa cereal productivity under the HadCM2 scenarios is estimated to be reduced by about 12% or 30 mmt ($\pm 2\%$ depending on which HadCM2 ensemble member is chosen) from the reference case by 2080 (Fig. 7). The figure for South East Asia is ca. 23% ($\pm 1\%$). As a consequence the number of people at risk of hunger in developing regions is estimated to increase: in Africa by more than one-third, while in Latin America we might expect to see a doubling over reference case levels (Fig. 8).

6. Conclusions

Climate change due to increasing greenhouse gases is likely to affect crop yields differently from region to region across the globe. Under the HadCM2 climate change scenarios used in this study, the effects on crop yields in mid- and high-latitude regions appear to be beneficial while those in low-latitude regions are expected to be detrimental. The HadCM3 scenario suggests that the beneficial effects at higher latitudes will occur within a specific climate range. If this is exceeded then even high mid-latitudes will witness adverse effects of climate change on agriculture.

However, the more favourable effects on yield in temperate regions depend to a large extent on full realisation of the potentially beneficial direct effects of CO_2 on crop growth. These regional differences are likely to grow stronger through time, leading to a significant polarisation of effects, with beneficial effects on yields and production occurring in the developed world and negative

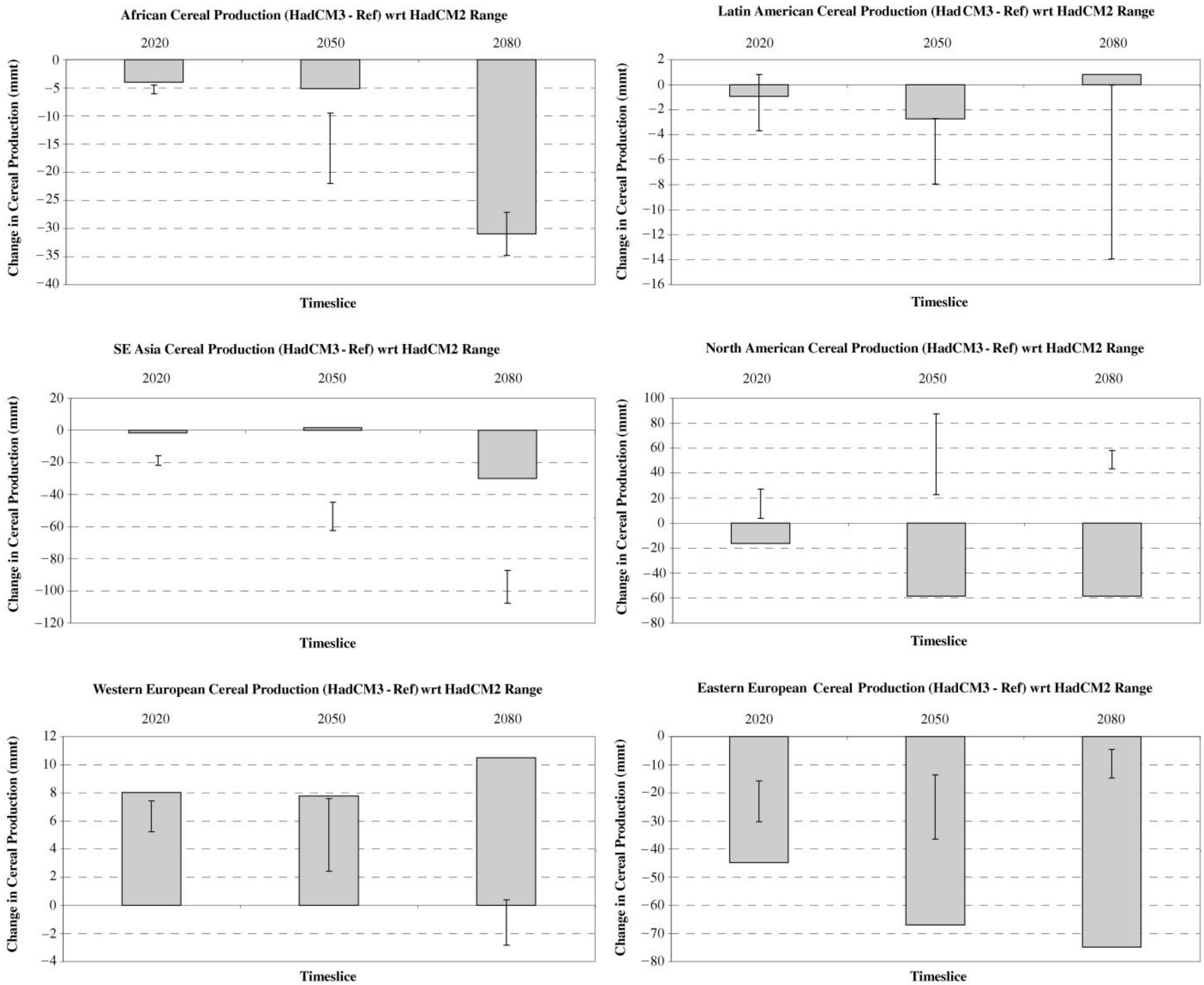


Fig. 7. Regional climate change impacts on cereal production. Blocks show HadCM3 driven impacts while HadCM2 range is depicted by the bars.

effects in the developing world (excluding China). Decreases in potential crop yields are likely to be caused by a shortening of the crop growing period, decreases in water availability due to higher rates of evapotranspiration, and poor vernalization of temperate cereal crops.

It should be emphasised that the results reported here are not a forecast of the future. There are very large uncertainties that preclude this, due to:

- The uncertainties about climate change at the regional level.
- The effects of future technological change on agricultural productivity.
- The potential realisation of any benefits from the CO_2 "fertilisation effect"
- Uncertainties about water availability for irrigation in the future
- Trends in demand (including population growth), and the wide array of possible adaptations.

The adoption of efficient adaptation techniques is far from certain. In developing countries there may be social or technical constraints, and adaptive measures may not necessarily result in sustainable production over long time frames. The availability of water supplies for irrigation and the costs of adaptation are important aspects of further research. This study should therefore be considered more an exploratory assessment of the sensitivity of the world food system, rather than a prediction of its future.

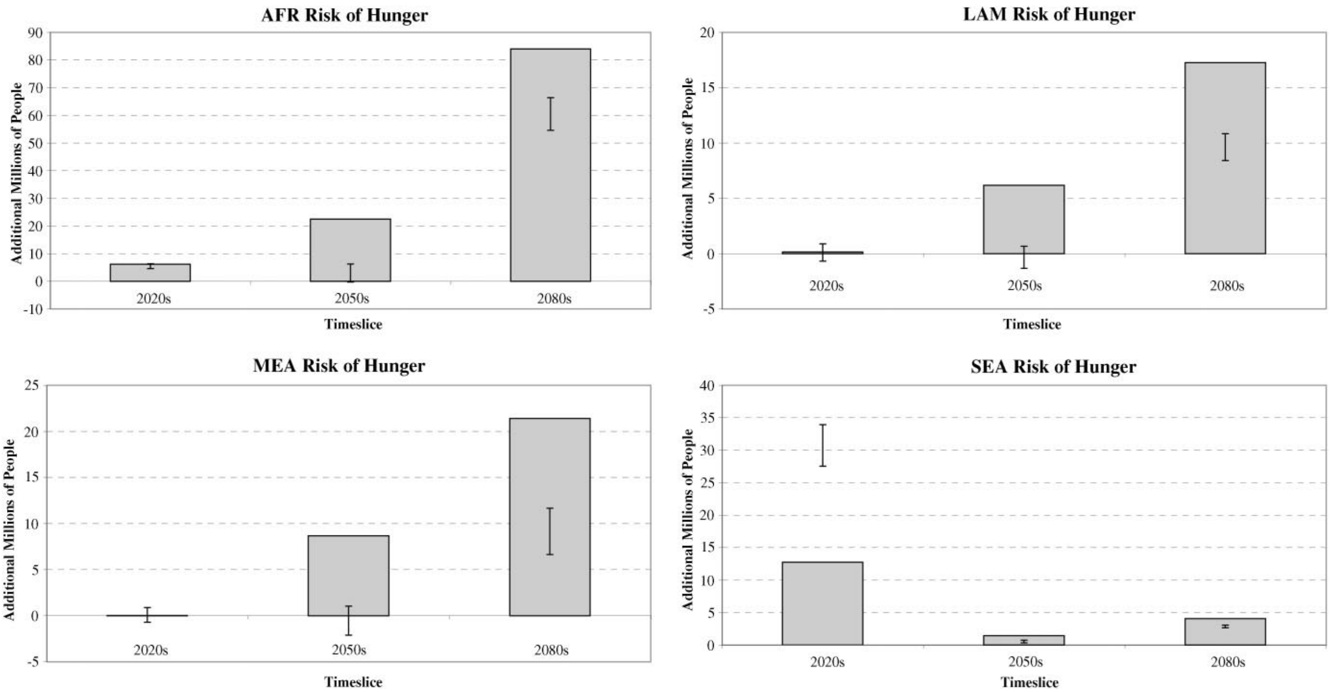


Fig. 8. Regional climate change impacts on the number of people at risk of hunger. Grey blocks show HadCM3 while the HadCM2 range is depicted by the bars.

Acknowledgements

The authors would like to thank the Department of Transport, Regions and the Environment (DETR) for its support in the production of this study under contract EPG 1/1/72. The HadCM2 and HadCM3 experiments were supported by the Department of Transport, Regions and the Environment under contract PECD/7/12/37. The authors would also like to express their gratitude to the Climate Impacts LINK Project (UK DETR Contract EPG 1/1/68) for it part in processing and distributing of the GCM results.

References

Cure, J.D., Acock, B., 1986. Crop responses to carbon dioxide doubling: a literature survey. Agricultural and Forest Meteorology 38, 127–145.

DETR, 1997. Climate change and its impacts: a global perspective. Department of the Environment, Transport and the Regions/UK Meteorological Office, 16p.

EMF14, 1995. Second round study design for EMF14. Energy Modelling Forum.

FAO, 1987. Fifth World Food Survey. United Nations Food and Agriculture Organization, Rome.

FAO, 1991. AGROSTAT/PC. United Nations Food and Agriculture Organization, Rome.

FAO, 1995. Production Yearbook. United Nations Food and Agriculture Organization, Rome.

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

Fischer, G., Frohberg, K., Keyzer, M.A., Parikh, K.S., Tims, W., 1990. Hunger – Beyond the Reach of the Invisible Hand. International Institute for Applied Systems Analysis. Food and Agriculture Project Laxenburg.

Fischer, G., Frohberg, K., Parry, M.L., Rosenzweig, C., 1995. Climate change and world food supply, demand and trade. In: Climate Change and Agriculture: Analysis of Potential International Impacts. ASA Special Publication No. 59, American Society of Agronomy, Madison, USA.

Fischer, G., Frohberg, K., Parry, M.L., Rosenzweig, C., 1996. Impacts of potential climate change on global and regional food production and vulnerability. In: Downing, T.E. (Ed.), NATO ASI Series, Vol. 137, Climate Change and World Food Security. Springer, Berlin.

Godwin, D., Singh, U., Ritchie, J.T., Alocilja, E.C., 1993. A User's Guide to CERES-Rice. Muscle Shoals: International Fertilizer Development Center.

Hendry, G.R., 1993. FACE: Free-Air C02 Enrichment for Plant Research in the Field. CRC Press, Boca Raton.

Hulme, M., Mitchell, J., Ingram, W., Johns, T., New, M., Viner, D., 1999. Climate change scenarios for global impacts studies. Global Environmental Change 9, S3–S19.

International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). 1989. Decision Support System for Agrotechnology Transfer Version 2.1 (DSSAT V2.1). Dept. Agron. and Soil Sci. College Trop. Agric. And Hum. Resources. Univ. Hawaii, Honolulu.

IPCC, 1996. Watson, R.T., Zinyowera, M.C., Moss, R.H. (Eds.) Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

IPCC, 1998. Watson, R.T., Zinyowera, M.C., Moss, R.H. (Eds.) The regional impacts of climate change: an assessment of vulnerability. A Special Report of IPCC Working Group II, Cambridge University Press, Cambridge.

Jones, C.A., Kiniry, J.R., 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. Texas A&M Press, College Station.

Jones, J.W., Boote, K.J., Hoogenboom, G., Jagtap, S.S., Wilkerson, G.G., 1989. SOYGRO V5.42: Soybean Crop Growth Simulation Model Users' Guide. Gainesville: Department of Agricultural Engineering and Department of Agronomy, University of Florida.

Mitchell, J.F.B., Johns, T.C., Gregory, J.M., Tett, S., 1995. Climate response to increasing levels of greenhouse gases and sulphate aerosols. Nature 376, 501–504.

Otter-Nacke, S., Godwin, D.C., Ritchie, J.T., 1986. Testing and validating the CERES-Wheat model in diverse environments. AGGRISTARS YM-15-00407. Johnson Space Center, Houston, No. 20244.

Peart, R.M., Jones, J.W., Curry, R.B., Boote, K., Allen Jr., L.H., 1989. Impact of climate change on crop yield in the South-eastern USA. In: Smith, J.B., Tirpak, D.A. (Eds.), The Potential Effects of Global Climate Change on the United States. US Environmental Protection Agency, Washington, DC.

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

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

Rosenzweig, C., Parry, M.L., 1994. Potential impacts of climate change on world food supply. Nature 367, 133–138.

Rosenzweig, C., Parry, M.L, Fischer, G., Frohberg, K., 1993. Climate Change and World Food Supply, Research report No. 3, Environmental Change Unit, Univ. of Oxford, Oxford.

World Food Institute. 1988. World Food Trade and US. Agriculture, 1960–1987. Iowa State University, Ames.

World Bank, 1994. World Population Projections 1994–95. John Hopkins University Press.