

Climate change, global food supply and risk of hunger

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This paper reports the results of a series of research projects which have aimed to evaluate the implications of climate change for food production and risk of hunger. There are three sets of results: (a) for IS92a (previously described as a ‘business-as-usual’ climate scenario); (b) for stabilization scenarios at 550 and 750 ppm and (c) for Special Report on Emissions Scenarios (SRES). The main conclusions are: (i) the region of greatest risk is Africa; (ii) stabilization at 750 ppm avoids some but not most of the risk, while stabilization at 550 ppm avoids most of the risk and (iii) the impact of climate change on risk of hunger is influenced greatly by pathways of development. For example, a SRES B2 development pathway is characterized by much lower levels of risk than A2; and this is largely explained by differing levels of income and technology not by differing amounts of climate forcing.

Keywords: climate change; agriculture; food supply; crop yields; food prices; risk of hunger

1. INTRODUCTION

This paper is a review of a number of previous studies, carried out by the authors, of the possible effects of climate change on global agricultural yield potential, on cereal production, food prices and the implications for changes in the number of hungry people. At present, almost 800 million people in the developing world are estimated to be experiencing some form of shortage in food supply (FAO 1999). In general, the conclusion from recent research has been that, while one may be reasonably optimistic about the prospects of adapting the agricultural production system to the early stages of global warming, the distribution of the vulnerability among the regions and people are likely to be uneven. Where crops are near their maximum temperature tolerance and where dryland, non-irrigated agriculture predominates, yields are likely to decrease with even small amounts of climate change. The livelihoods of subsistence farmers and pastoral people, who are already weakly coupled to markets, could also be negatively affected. In regions where there is a likelihood of decreased rainfall, agriculture could be substantially affected regardless of latitude (IPCC 2001).

The story of how we have arrived at this conclusion is traced below. We outline the research method, its testing and the first evaluation of effects on food supply with those climate change scenarios available in the early 1990s (Rosenzweig & Parry 1994). This is followed by an assessment of effects under some of the most recent scenarios developed for the Intergovernmental Panel on Climate Change (IPCC; Parry *et al.* 1999a). Finally, we consider the effects of various mitigation strategies and different development pathways.

2. INITIAL ESTIMATIONS FOR CLIMATE SCENARIOS FROM LOW RESOLUTION CLIMATE MODELS

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

- (i) *The estimation of potential changes in crop yield.* Potential changes in national grain crop yields were estimated using crop models and a decision support system developed by the US Agency for International Development’s International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT 1989). The crops modelled were wheat, rice, maize and soybean. These crops account for more than 85% of the world’s traded grains and legumes. The estimated yield changes for 18 countries were interpolated to provide estimates of yield changes for all regions of the world and for all major crops, by reference to all available published and unpublished information.
- (ii) *Estimation of world food trade responses.* The yield changes 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). Outputs from simulations by the BLS provided information on food production, food prices and the number of people at risk of hunger.

(a) *Climate change scenarios*

Scenarios of climate change were developed to estimate the effect on yields and food supply. The range of

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scenarios used aimed to capture the range of possible effects and set limits on the associated uncertainty. The scenarios for this study were created by changing the observed data on current climate (1951–80) according to doubled carbon dioxide (CO₂) simulations of three general circulation models (GCMs). The GCMs used were those from the Goddard Institute for Space Studies (GISS; Hansen *et al.* 1983, 1988), Geophysical Fluid Dynamics Laboratory (GFDL; Manabe & Wetherald 1987) and the United Kingdom Meteorological Office (UKMO; Wilson & Mitchell 1987).

(b) Crop models and yield simulations

(i) Crop models

The IBSNAT crop models were used to estimate how climate change and increasing levels of carbon dioxide may alter yields of work crops at 112 sites in 18 countries representing both major production areas and vulnerable regions at low, mid and high latitudes (Rosenzweig & Iglesias 1994). The IBSNAT models employ simplified functions to predict the growth of crops as influenced by the major factors that affect yields, e.g. genetics, climate (daily solar radiation, maximum and minimum temperatures and precipitation), soils and management practices. Models used were for wheat (Ritchie & Otter 1985; Godwin *et al.* 1989), maize (Jones & Kiniry 1986; Ritchie *et al.* 1989), paddy and upland rice (Godwin *et al.* 1993) and soybean (Jones *et al.* 1989).

The IBSNAT models were selected for this study because they have been validated over a wide range of environments (Otter-Nacke *et al.* 1986) and are not specific to any particular location or soil type. They are thus suitable for use in large-area studies in which crop growing conditions differ greatly. The validation of the crops models over different environments also improves the ability to estimate effects of changes in climate. Furthermore, because management practices, such as the choice of varieties, planting date, fertilizer application and irrigation may be varied in the models, they permit experiments that simulate adjustments by farmers and agricultural systems to climate change.

(ii) Physiological effects of CO₂

Most plants growing in experimental environments with increased levels of atmospheric CO₂ exhibit increased rates of net photosynthesis (i.e. total photosynthesis minus respiration) and reduced stomatal opening (Acock & Allen 1985; Cure 1985). By so doing, CO₂ reduces transpiration per unit leaf area while enhancing photosynthesis. Thus, it often improves water-use efficiency (the ratio of crop biomass accumulation or yield to the amount of water used in evapotranspiration). The crop models used in this study account for the beneficial physiological effects of increased atmospheric CO₂ concentrations on crop growth and water use (Kimball 1983; Rogers *et al.* 1983; Cure & Acock 1986; Allen *et al.* 1987; Peart *et al.* 1989).

(iii) Limitations of crop growth models

The crop growth 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. high salinity or acidity) and there are no extreme weather events such as heavy storms. The crop models simulate the current range of agricultural technologies available around the world. They do not include induced improvements in such technology, but may be used to test the effects of some potential improvements, such as varieties with higher thermal requirements and the installation of irrigation systems.

(iv) Yield simulations

Crop modelling simulation experiments were performed at 112 sites in 18 countries for the baseline climate (1951–80) and the GCM-doubled CO₂ climate change scenarios, with and without the physiological effects of CO₂. This involved the following tasks.

(c) Deriving estimates of potential yield changes

(i) Aggregation of site results

Crop model results for wheat, rice, maize and soybean from all sites and 18 countries were aggregated by weighting regional yield ranges (based on current production) to estimate change in national yields. The regional yield estimates represent the current mix of rainfed and irrigated production, the current crop varieties, nitrogen management and soils. Since the site results relate to regions that account for about 70% of the world's grain production (FAO 1996), the conclusions concerning world production total contained in this report are believed to be adequately substantiated.

(d) The world food trade model

The estimates of climate-induced changes in yields were used as inputs to a dynamic model of the world food system (the BLS) in order to assess the possible impacts on the future levels of food production, food prices and the number of people at risk from hunger (Rosenzweig *et al.* 1993). Impacts were assessed for the year 2060, with population growth, technology trends and economic growth projected to that year. Assessments were first made assuming no climate change and subsequently with the climate change scenarios described above. The difference between the two assessments is the climate-induced effect. A further set of assessments examined the efficacy of a number of adaptations at the farm level in mitigating the impact and the effect on future production of liberalizing the world food trade system, and of different rates of growth of economy and population.

The BLS consists of linked national models. The BLS was designed at the 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 consists of 20 national and/or regional models that cover around 80% of the world food trade system. The remaining 20% is covered by 14 regional models for the countries that have broadly similar attributes (e.g. African oil exporting countries, Latin American high income exporting countries, Asian low income countries). The grouping is based on country characteristics such as geographical location, income per capita and the country's position

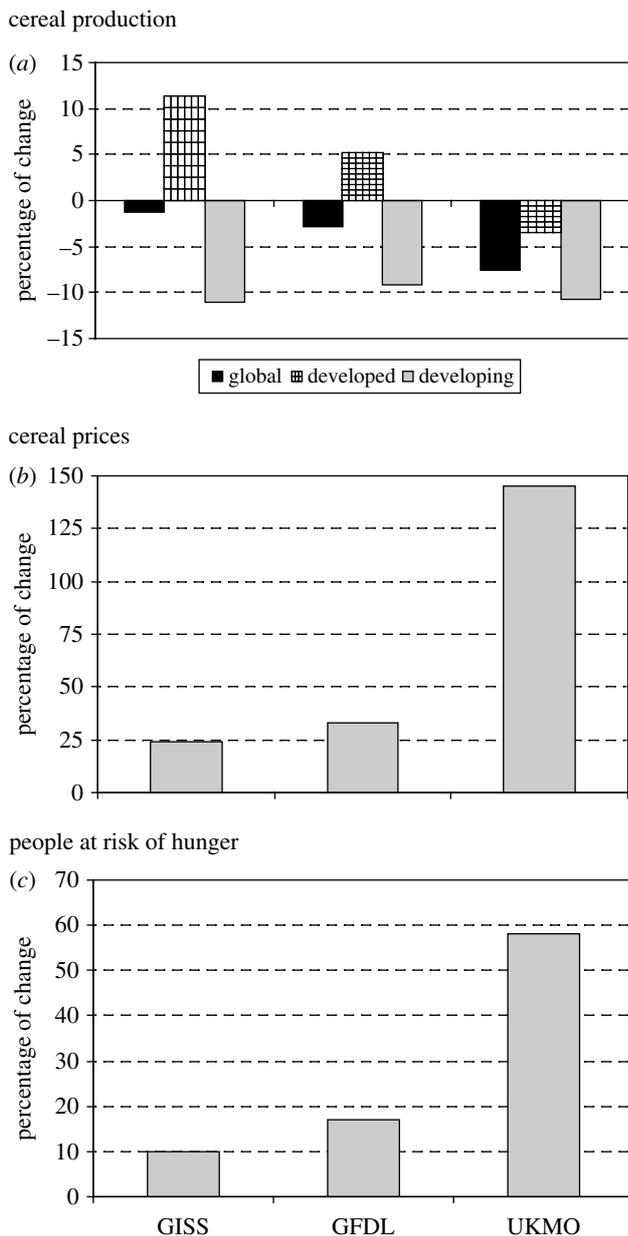


Figure 1. (a) Change in cereal production, (b) cereal prices and (c) people at risk of hunger in 2060. The reference case for 2060 assumes no climate change: cereal production = global 3286 mt, developed 1449 mt, developing 1836 mt; cereal prices 1970 = 100 and 641 million people at risk of hunger (Rosenzweig *et al.* 1993; Rosenzweig & Parry 1994).

with regard to net food trade (figure 1; Rosenzweig *et al.* 1993; Rosenzweig & Parry 1994).

The BLS is a general equilibrium model system, with representation of all economic sectors, empirically estimated parameters and no unaccounted supply sources or demand sinks (Rosenzweig *et al.* 1993). In the BLS, countries are linked through trade, world market prices and financial flows. 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 optimizing 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 are cleared of all

commodities. At each stage of the reiteration domestic markets are in equilibrium. This process yields international prices as influenced by governmental and intergovernmental agreements.

The system is solved in annual increments, simultaneously for all countries. Summary indicators of the sensitivity of the world system used in this report include world cereal production, world cereal prices and prevalence of world population at risk from hunger (defined as the population with an income insufficient to produce or procure their food requirements).

The BLS does not incorporate any climate relationships *per se*. Effects of changes in climate were introduced to the model as changes in average national or regional yield per commodity as estimated above. Ten commodities are included in the model: wheat, rice, coarse grains (e.g. maize, millet, sorghum and barley), bovine and ovine meat, dairy products, other animal products, protein feeds, other food, non-food agriculture and non-agriculture. In this context, however, consideration is limited to the major grain food crops.

(e) *The set of model experiments*

The results described in this paper consider the following scenario (United Nations 1989).

(i) *The reference scenario*

This involved projection of the agricultural system to the year 2060 with no effects of climate change on yields and with no major changes in political or economic context of the world food trade. It assumed:

- (i) UN medium population estimates (10.2 billion by 2060);
- (ii) 50% trade liberalization in agriculture introduced gradually by 2020;
- (iii) moderate economic growth (ranging for 3.0% per year in 1980–2000 to 1.1% per year in 2040–2060);
- (iv) technology is projected to increase yields over time (cereal yields for world total, developing countries and developed countries are assumed to increase annually by 0.7, 0.9 and 0.6%, respectively);
- (v) no changes in agricultural productivity due to climate change.

(ii) *Three climate change scenarios*

These are projections of the world food trade system including the effects on agricultural yields under different climate scenarios (the '2×CO₂ scenarios' for the GISS, GFDL and UKMO GCMs). The food trade simulations for these three scenarios were started in 1990 and assumed a linear change in yields until the double CO₂ concentration was reached in 2060. Simulations were made both with and without the physiological effects of 555 ppmv CO₂ on crop growth and yield for the equilibrium yield estimates. In these scenarios, internal adjustments in the model occur, such as increased agricultural investment, reallocation of agricultural resources according to economic returns and reclamation of additional arable land as an

adjustment to higher cereal prices, based on shifts in comparative advantage among countries and regions.

(iii) *Scenarios including the effect of farm-level adaptations*

The food trade model was first run with yield changes assuming no external adaptation to climate change and was then re-run with different climate-induced changes in yield assuming a range of farm-level adaptations. These included such measures as altering planting dates and crop varieties and the use of different amounts of irrigation and fertilizer. Two adaptation levels to cope with potential effects on yield and agriculture were considered. Adaptation level 1 included those adaptations at the farm level that would not involve any major changes in agricultural practices. It thus took account of changes in planting date, amounts of irrigation and the choice of crop varieties that are currently available. Adaptation level 2 encompassed, in addition to the former, major changes in agricultural practices, such as large shifts of planting date, the availability of new cultivars, extensive expansion of irrigation and increased fertilizer application. This level of adaptation would be likely to involve policy changes both at the national and international level and significant costs. However, policy, cost and water were not studied explicitly.

(iv) *Scenarios of different future trade, economic and population growth*

A final set of scenarios assumed changes to the world tariff structure and different rates of growth of economy and population. As with previous experiments, these were conducted both with and without climate change impacts. These scenarios included:

- (i) *full trade liberalization*. Full trade liberalization in agriculture introduced gradually by 2020;
- (ii) *lower economic growth* (ranging from 2.7% per year in 1980–2000 to 1.0% in 2040–2060). Global GDP in 2060 is 10.3% lower than the reference scenario, 11.2% lower in developing countries and 9.8% lower in developed countries;
- (iii) *low population growth*. UN low population estimates (ca 8.6 billion by 2060).

(f) Effects on yields

The results show that climate change scenarios excluding the direct physiological effects of CO₂ predict decreases in simulated yields in many cases, while the direct effects of increasing atmospheric CO₂ mitigate the negative effects primarily in mid and high latitudes. The differences between countries in yield responses to climate change are related to differences in current growing conditions. At low latitudes crops are grown nearer the limits of temperature tolerance and global warming may subject them to higher stress. In many mid and high latitude areas, increasing temperatures may benefit crops, otherwise limited by cold temperatures and short growing seasons in the present climate.

The primary causes of decreases in yield are:

- (i) *shortening of the growing period (especially the grain filling stage) of the crop*. This occurs at some sites in all countries;
- (ii) *decreases in water availability*. Depletion of soil water is increased by greater evapotranspiration and, in some cases, a decrease in precipitation in the climate change scenarios. This occurred in Argentina, Brazil, Canada, France, Japan, Mexico and USA;
- (iii) *poor vernalization*. Some temperate cereal crops require a period of low temperature in winter to initiate the flowering process. Inadequate vernalization results in low flower bud initiation and ultimately in reduced yields. This caused decreases in winter wheat yields in some sites in Canada and the former USSR.

(g) Effects on world food trade

(i) *Effects on food production*

The future without climate change. Assuming no effects of climate change on crop yields but that population growth and economic growth are as stated above, world cereal production is estimated at 3286 million tonnes (mt) in 2060 compared with 1795 mt in 1990. Cereal prices are estimated at an index of 121 (1970=100). The number of people at risk of hunger is estimated at about 640 million (cf. 530 million estimated in 1990).

Effects of climate change with internal adjustment in the model but without adaptation. Under the estimated effects of climate change and atmospheric CO₂ on crop yields, world cereal production is estimated to decrease between 1 and 7% depending on the GCM climate scenario (figure 3). Under the UKMO scenario, global production is estimated to decrease by more than 7%, while under the GISS scenario (which assumes lower temperature increases), cereal production is estimated to decrease by just over 1%. The largest negative changes occur in developing countries, averaging –9 to –11%. By contrast, in developed countries production is estimated to increase under all but the UKMO scenario (+11 to –3%). Thus, existing disparities in crop production between the developed and developing countries are estimated to grow.

(ii) *Effects of climate change on production under different levels of adaptation*

The study tested the efficacy of two levels of adaptation: level 1 implies little change to existing agricultural systems reflecting farmer response to a changing climate, whereas level 2 implies a more substantial change to agricultural systems possibly requiring resources beyond the farmer's means. Level 2 adaptation represents an optimistic assessment of world food agriculture's response to climate change conditions as predicted by the GCMs tested in this study. In each case, the adaptations were tested as possible responses to the worst climate change scenario (usually, but not always, the UKMO scenario). Changes in economics or domestic

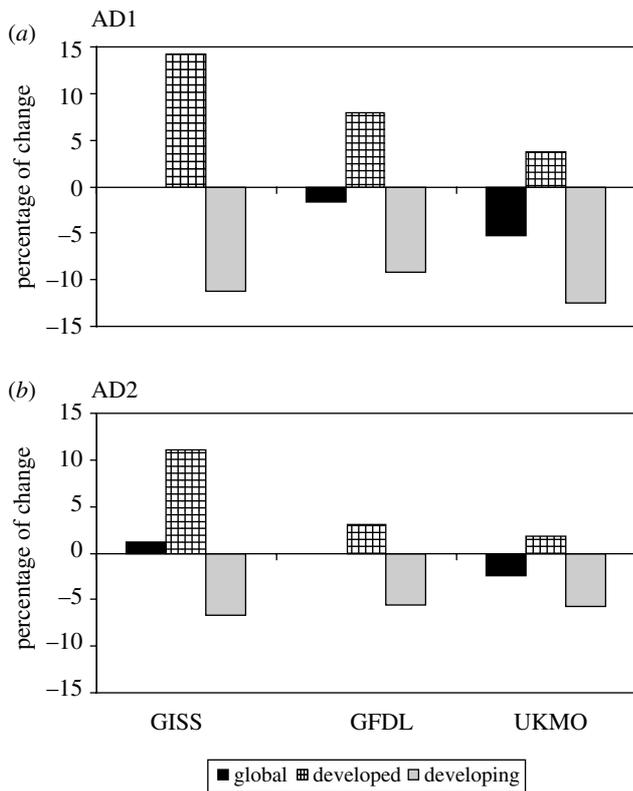


Figure 2. (a) Change in cereal production under three equilibrium climate change scenarios in 2060 assuming implementation of adaptation level 1 (AD1; Rosenzweig *et al.* 1993; Rosenzweig & Parry 1994). (b) Change in cereal production under three equilibrium climate change scenarios in 2060 and assuming the implementation of adaptation level 2 (AD2; Rosenzweig *et al.* 1993; Rosenzweig & Parry 1994).

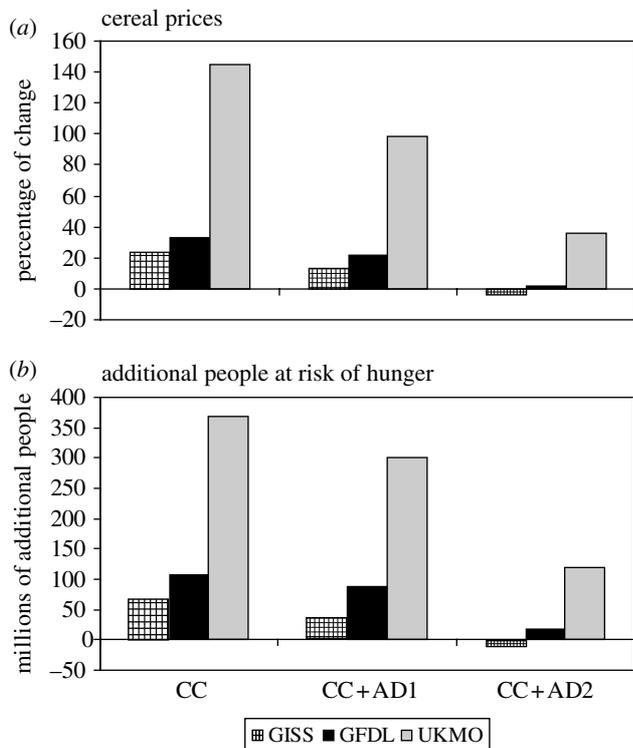


Figure 3. (a) Change in cereal prices and (b) people at risk of hunger for climate change scenarios (CC) and with adaptation levels 1 and 2 (AD1 and AD2; Rosenzweig *et al.* 1993; Rosenzweig & Parry 1994).

agricultural policies were beyond the scope of this study; the costs of adaptation and future water availability under the climate change scenarios were also not considered.

Level 1 adaptation included:

- (i) shifts in planting date that do not imply major changes in the crop calendar;
- (ii) additional application of irrigation water to crops already under irrigation; and
- (iii) changes in crop variety to currently available varieties better adapted to the projected climate.

Level 2 adaptation included:

- (i) large shifts in planting date;
- (ii) increased fertilizer application;
- (iii) development of new varieties; and
- (iv) installation of irrigation systems.

Yield changes for both adaptation levels were based on crop model simulations where available, and were extended to other crops and regions using the estimation methods described above. The adaptation estimates were developed only for the scenarios including the direct effects of CO₂ as these were judged to be the most realistic. The two levels of adaptation estimates for the UKMO scenario were also examined. With the high level of global warming projected by the UKMO climate change scenario, neither level 1 nor level 2 adaptation mitigated climate change effects on crop yields in most countries.

Adaptation level 1. Figure 2a shows the effects of level 1 adaptation on estimated changes in cereal production. These largely offset the negative climate change induced effects in developed countries, improving their comparative advantage in world markets. In these regions cereal production increases by 4–14% over the reference case. However, developing countries are estimated to benefit little from adaptation (–9 to –12%). Averaged global production is altered by between 0 and –5% from the reference case. As a consequence, world cereal prices are estimated to increase by 10–100% and the number of people at risk from hunger by ca 5–50% (figure 3). This indicates that level 1 adaptations would have relatively little influence on reducing the global effects of climate change.

Adaptation level 2. More extensive adaptation virtually eliminates negative cereal yield impacts at the global level under the GISS and GFDL scenarios and reduces impacts under the UKMO scenario by one-third (figure 2b). However, the decrease in the comparative advantage of developing countries under these scenarios leads to decreased areas planted to cereals in these areas. Cereal production in developing countries still decreases by around 5%. Globally, however, cereal prices increase by only 5–35%, and the number of people at risk from hunger is altered by between –2 and +20% from the reference case (figure 3). This suggests that level 2 adaptations are required to mitigate the negative effects of climate change but that these still do not eliminate them in developing countries.

Net imports of cereals into developing countries will increase under all scenarios. The change in cereal imports is largely determined by the size of the assumed yield changes, the change in relative productivity in developed and developing regions, the change in world market prices and changes in incomes of developing countries. Under the GISS climate scenario, productivity is depressed largely in favour of developed countries, resulting in pronounced increases in net cereal imports into developing countries. Under the UKMO scenario, large cereal price increases limit the increase in exports to developing countries. Consequently, despite its beneficial impact for developed countries, the adaptation level 1 scenarios show only small improvements for developing countries as compared to the corresponding impacts without such adaptation.

(iii) *Effects of climate change assuming full trade liberalization and lower economic and population growth rates.*

Full trade liberalization. Assuming full trade liberalization in agriculture by 2020 provides for more efficient resource use and leads to 3.2% higher value added in agriculture globally and a 5.2% higher agriculture GDP in developing countries (excluding China) by 2060 compared with the reference case. This policy change results in almost 20% fewer people at risk from hunger. Global cereal production is increased by 70 mt, with most of the production increases occurring in developing countries. Global impacts due to climate change are slightly reduced under most climatic scenarios, with enhanced gains in production occurring to developed countries but losses in production in being greater in developing countries. Price increases are reduced slightly from what would occur without full trade liberalization and the number of people at risk from hunger is reduced by about 100 million.

Reduced rate of economic growth. Estimates were also made of impacts under a lower economic growth scenario (10% lower than reference). Lower economic growth results in a tighter supply situation, higher prices and more people below the hunger threshold. Prices are 10% higher and the number of people at risk from hunger is 20% greater. The effect of climate change on these trends is generally to reduce production, increase prices and increase the number of people at risk from hunger by the same ratio as is the case with a higher economic growth rate, but the absolute amounts of change are greater.

Altered rates of population growth. The largest impact of any of the policies considered would result from an accelerated reduction in population growth in developing countries. Simulations based on rates of population growth according to UN Low Estimates result in a world population about 17% lower in year 2060 as compared with the UN Mid Estimates used in the reference run. The corresponding reduction in the developing countries (excluding China) would be about 19.5% from 7.3 to 5.9 billion. The combination of higher GDP per capita (about 10%) and lower world population produces an estimated 40% fewer people at risk from hunger in the year 2060 compared with the reference scenario.

Even under the most adverse of the three climate scenarios (UKMO), the estimated number of people at risk from hunger is some 10% lower than that estimated for the reference case without any climate change. Increases in world prices of agricultural products, in particular cereals, under the climate change scenarios employing the low population growth projection are around 75% of those using the UN medium estimate.

3. ESTIMATED EFFECTS FROM HIGHER RESOLUTION GCMs AND FOR DIFFERENT TIME PERIODS

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

In the next suite of experiments, the crop models were run for current climate conditions and for three future climate conditions (2020s, 2050s and 2080s) predicted by the Hadley Centre's GCMs known as HadCM2 and HadCM3 (Mitchell *et al.* 1995; Hulme *et al.* 1999). 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).

(a) *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 mt in the 2080s (*ca* 1800 mt 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 prices due to the increases in demand brought about by the growing world population. However, after 2020, by which time a 50% liberalization of trade has been realized, 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 (*ca* 521 million in 1990, about 10% of total current population).

(b) *Effects of climate change*

(i) *Global effects*

Changes in cereal production, cereal prices and people at risk of hunger estimated for the HadCM2 climate change scenarios (with the direct CO₂ effects taken into account) show that world is generally able to feed itself in the next millennium. Only a small detrimental effect

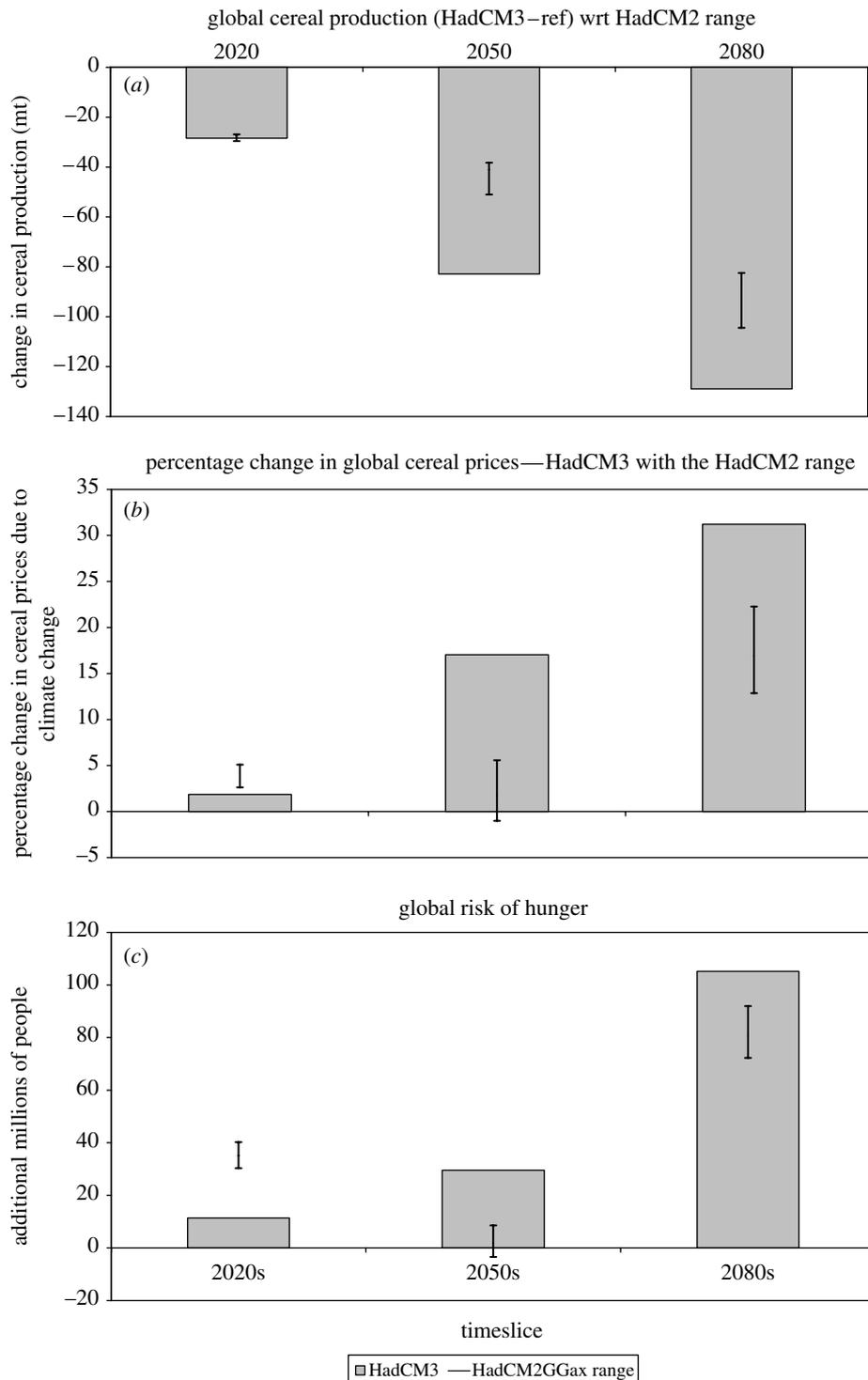


Figure 4. (a) Changes in global cereal production (mt). Grey blocks are the production change projected under the HadCM3 climate change scenario (compared with the reference case). Bars depict the range of change under the four HadCM2 ensemble simulations (Parry *et al.* 1999b). (b) Percentage change in cereal prices. Grey 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 (Parry *et al.* 1999b). (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 grey blocks. Bars represent the range of results under the four HadCM2 ensemble simulations (Parry *et al.* 1999b).

is observed on cereal production, manifested as a shortfall on the reference production level of around 100 mt (-2.1%) by the 2080s (± 10 mt 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 mt (about -4%) by the 2080s (figure 4a; Parry *et al.* 1999b).

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 (figure 4b). 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 *ca* 250 million) by the 2080s (figure 4c). 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 fertilizer.

4. REDUCING IMPACTS BY STABILIZING CO₂ CONCENTRATIONS AT LOWER LEVELS

In this section, we explore the implications for a range of global-scale impacts of climate change of the stabilization of CO₂ concentrations at defined level (Parry *et al.* 1999b). These stabilization scenarios (at 550 ppmv by 2150 and 750 ppmv by 2250) are among the set defined by the IPCC (1997).

(a) Scenarios

Two stabilization scenarios (stabilizing at CO₂ concentrations of 550 and 750 ppmv) are considered, and compared with the IS92a unmitigated emissions scenario (Mitchell *et al.* 2000). There is little difference in concentrations between the two scenarios to the 2020s, but thereafter they begin to diverge. The S750 scenario stabilizes CO₂ concentrations by 2250, whilst the S550 scenario assumes stabilization occurs by 2150. Achieving stabilization at 750 and 550 ppmv, under the pathways assumed here, requires cuts in annual CO₂ emissions of around 13 and 30%, respectively, by 2025, relative to the 2025 emissions assumed under IS92a. We interpret these stabilization scenarios as representing actual CO₂ concentrations for the purposes of crop and vegetation modelling (e.g. actual CO₂ concentration reaches 750 ppmv by 2250), because there are no accepted stabilization scenarios for the other radiatively significant trace gases. We therefore assume that all other greenhouse gas concentrations remain constant at 1990 values.

(b) Effects on yield potential

Figure 5 shows the estimated changes in national potential grain yield by the 2080s, assuming no changes in crop cultivars, under the three emissions scenarios (Arnell *et al.* 2001). Under unmitigated emissions, positive changes in mid and high latitudes are overshadowed by reductions in yield in the lower latitudes. These reductions are particularly substantial in Africa and the Indian subcontinent. However, many of the mapped changes in yield are small and indistinguishable from the effects of natural climate variability.

Stabilization at 550 ppmv produces far fewer reductions in yield, although there would still be reductions in the Indian subcontinent, most of the Pacific Islands, Central America and the majority of

African nations. Stabilization at 750 ppmv to a large extent produces intermediate changes. However, there are some interesting anomalies. Significant increases in yields are seen in the mid-latitudes of both hemispheres under S750 which are not replicated under S550. To a certain extent, this reflects differences in simulated regional climate—particularly precipitation—between scenarios due to natural climatic variability, but there is also a complex balance between the effects of higher temperatures, higher atmospheric CO₂ concentrations, altered rainfall and optimal growing conditions. The intermediate combination of increases in temperatures, available moisture and ambient CO₂ concentrations experienced under S750 lead in some regions to an enhancement of crop productivity that is not witnessed in the unmitigated world (which has higher CO₂ concentrations, but is warmer and with more extreme changes in moisture) or the S550 world (which does not see as large changes in temperature, moisture availability or the beneficial effects of atmospheric CO₂).

It should also be noted that the larger regional increases and decreases in crop yields witnessed under S550 and S750 by the 2080s fall outside the range of previously reported results from the ensemble of unmitigated HadCM2-driven experiments. Table 1 summarizes global cereal production (under realistic assumptions about trade liberalization) in the absence of climate change and under the three emissions scenarios.

(c) Implications for food security and hunger

The changes in total global cereal production shown in table 1 appear small, but can have significant effects on global food prices and the consequent risk of hunger. Food prices are simulated in the BLS, and are projected to rise relative to the baseline case with no climate change because of the lower production. This increase in prices exacerbates the stress of regional shortfalls in production leading to an increase in the risk of hunger. More cases emerge where populations are not only unable to grow enough food due to a sustained deterioration in their resource base, but are also unable to reduce the food deficit by purchasing additional foodstuffs on the world markets because of regional inequalities in economic growth.

Table 2 shows the number of people at risk from hunger in the absence of climate change and under the three emissions scenarios. With no climate change, the number of people at risk from hunger, following historical trends, decreases from more than 500 million in 1990 to about 270 million in the 2080s. This is the result of increased agricultural production due to technological advances combined with the assumption that living standards will rise while the incidence of poverty in developing countries will continue to fall. Under the unmitigated emissions scenario, it is estimated that the additional number of people at risk from hunger due to climate change would be around 20 million by the 2050s, increasing to around 80 million by the 2080s. The numbers of people affected are smaller by the 2050s, largely because the effects of climate change on prices are lower at this time, which is itself because at this time horizon—unlike the others—grain production increases in the United States under two of the four

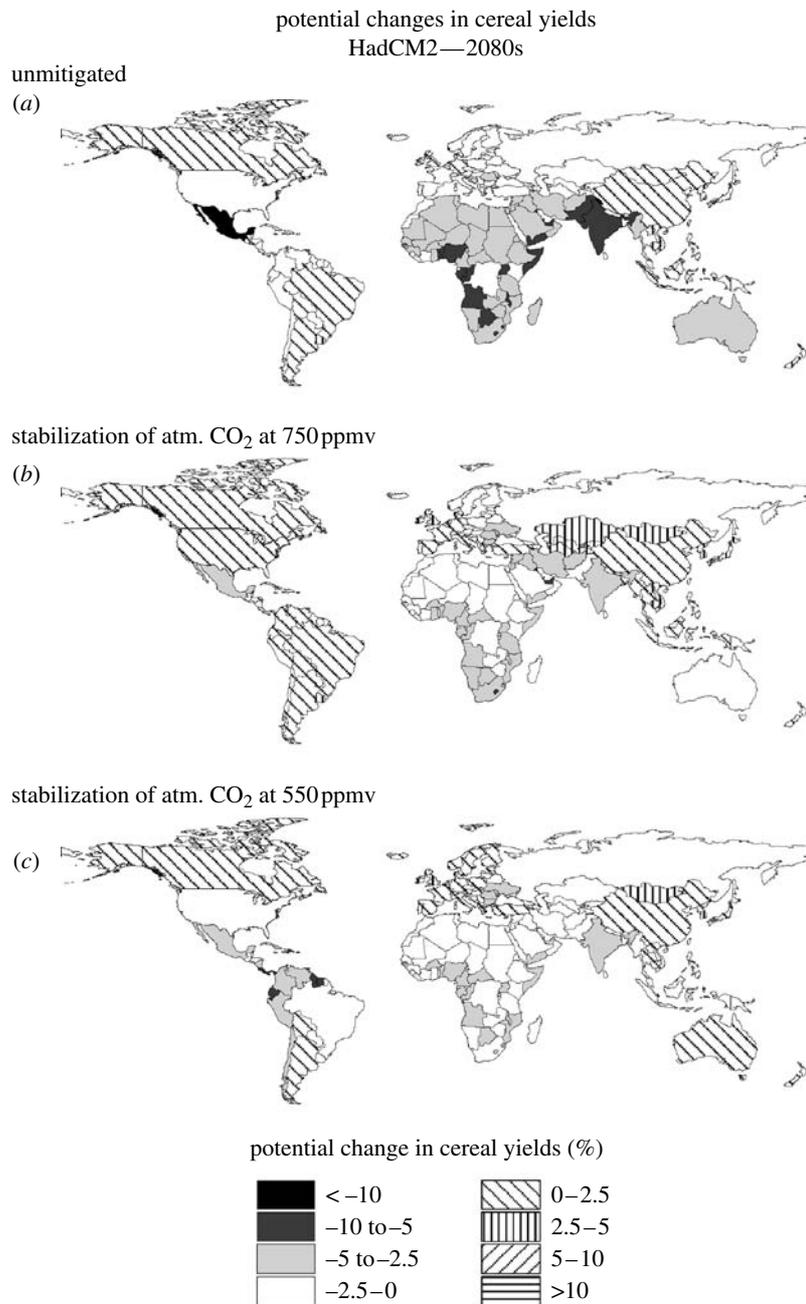


Figure 5. Changes in national cereal crop yields by the 2080s under three different emissions scenarios—(a) unmitigated (IS92a), (b) S750 and (c) S550 (Arnell *et al.* 2001).

ensemble members. Stabilization at 750 ppmv reduces the unmitigated impacts by around 75%, while stabilization at 550 ppmv achieves a more modest mitigating reduction of around 50% in the number of additional people at risk of hunger due to climate change.

Global figures, however, hide considerable regional variations. The vast majority (*ca* 65%) of the people at additional risk of hunger in the future are in Africa. This partly reflects the greater-than-average reduction in yields, but is also due to higher levels of vulnerability caused to some extent by the lower incomes in Africa. Increasing this regional disparity, it appears that the beneficial effects of stabilization are also less in this region. Under an S750 world, the additional number of people at risk of hunger is only reduced by *ca* 30%, while under an S550 future the reduction in the climate-induced impact is only 20%.

5. EFFECTS UNDER SRES EMISSIONS AND SOCIO-ECONOMIC SCENARIOS

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

Consistent climate change scenarios have been taken from SRES-driven experiments conducted using the UK Hadley Centre's third generation coupled

Table 1. Average annual cereal production (million tonnes; Arnell *et al.* 2001).

(The estimates assume no change in crop cultivar, and come from the Basic Linked System. The range in estimates for the unmitigated scenario represents the range between the four ensemble partners.)

	no climate change	unmitigated	S750	S550
1990	1800			
2020s	2700	2670–2674	2672	2676
2050s	3500	3475	3973	3477
2080s	4000	3927	3987	3949

Table 2. Number of people at risk of hunger (millions; Arnell *et al.* 2001).

(The range in estimates for the unmitigated scenario represents the range between the four ensemble partners.)

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

atmosphere–ocean global climate model (HadCM3; Johns *et al.* 2003). The use of a transient air–ocean general circulation model (AOGCM) (HadCM3) 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. The structure and research methods remain the same as in previous work (Rosenzweig & Parry 1994; Parry *et al.* 1999b).

Population levels for each SRES scenario for given timelines were taken from the CIESIN database (Parry *et al.* 2004). These levels, together with income level, drive estimated future demand for cereals in the BLS.

The BLS was first run for a reference case (i.e. assuming no climate change) for each SRES pathway (A1, A2, B1 and B2) where fluctuations in productivity and prices are solely the outcome of the socio-economic development pathway. The model was then re-run with estimated changes in regional cereal yields due to climate change entered into the model altering regional agricultural productivity, global food prices and the level of exposure of the global population to the risk of hunger.

(a) Effects on yields

Each HadCM3 climate change scenario produced by the four different SRES emissions scenarios instigates a different development path for global crop yields (table 3). These paths do not diverge, however, until mid-century. By the 2020s, small changes in cereal yield are evident in all scenarios, but these fluctuations are within historical variations. Although, there are differences in the mean impacts of the SRES scenarios, the range of the spatial variability projected is similar.

Generally, the SRES scenarios result in crop yield decreases in developing countries and yield increases in developed countries (table 3; Parry *et al.* 2004). The A1FI scenario, as expected with its large increase in

global temperatures, exhibits the greatest decreases both regionally and globally in yields, especially by the 2080s. Decreases are especially significant in Africa and parts of Asia with expected losses up to 30%. In these locations, effects of temperature and precipitation changes on crop yields are beyond the inflection point of the beneficial direct effects of CO₂. In North America, southeast South America and Australia, the effects of CO₂ on the crops partially compensate for the stress that the A1FI climate conditions impose on the crops and result in small yield increases. In contrast to the A1FI scenario, the coolest climate change scenario (B1) results in smaller cereal yield decreases that never exceed 10%.

The contrast between the yield change in developed and developing countries is largest under the A2a–c scenarios. Under the A2a–c scenarios, crop yields in developed countries increase as a result of regional increases in precipitation that compensate for the moderate temperature increases, and as a result of the direct effects of the high concentration of CO₂. In contrast, crop yields dramatically decrease in developing countries as a result of regional decreases in precipitation and large temperature increases in the A2a–c climate scenarios. Under the B1 and B2 scenarios, developed and developing countries exhibit less contrast in crop yield changes, with the B2 future crop yield changes being slightly more favourable than those of the B1 scenario. The results highlight the complex regional patterns of projected climate variables, CO₂ effects and agricultural systems that contribute to aggregations of global crop production for the different SRES futures.

(b) Cereal production, cereal prices and risk of hunger responses

(i) The reference case: the future without climate change

Assuming a future with no climate change and continued advances in agricultural technology, worldwide cereal yields are set to increase. The BLS therefore estimates that production will continue to grow year-on-year from current levels (*ca* 1800) to *ca* 3900, 4800, 3700 and 4100 mt per year by the 2080s under the A1, A2, B1 and B2 SRES scenarios, respectively (figure 6). The range in absolute amounts and the rates of growth between scenarios reflects (a) the variation in population growth and resulting demand for cereals in each world and (b) the balance of popular preference to cereals over meat products which is linked to increases in per capita gross domestic product.

While more cereals are being produced, the increase in demand ensures that global cereal prices also rise, most notably under the A2 world where increases of more than 160% (compared to current day market prices) are to be expected by the 2080s. In contrast, the A1 and B1 worlds, after a moderate increase of between 30 and 70% by the 2050s, will witness a decline in cereal prices towards the end of this century in accordance with the expected decline in global populations (figure 7). The difference between the A1 and B1 worlds which share identical population growth projections is primarily due to the higher level of

Table 3. Aggregated developing–developed country differences (%) in average crop yield changes from baseline for the HadCM2 and HadCM3 scenarios (Parry *et al.* 2004).

	HadCM3—2080s							HadCM2—2080s	
	A1FI	A2a	A2b	A2c	B1a	B2a	B2b	S550	S750
CO ₂ (ppm)	810	709	709	709	527	561	561	498	577
world	−5	0	0	−1	−3	−1	−2	−1	1
developed	3	8	6	7	3	6	5	5	7
developing	−7	−2	−2	−3	−4	−3	−5	−2	−1
difference (%)									
developed–developing	10.4	9.8	8.4	10.2	7.0	8.7	9.3	6.6	7.7

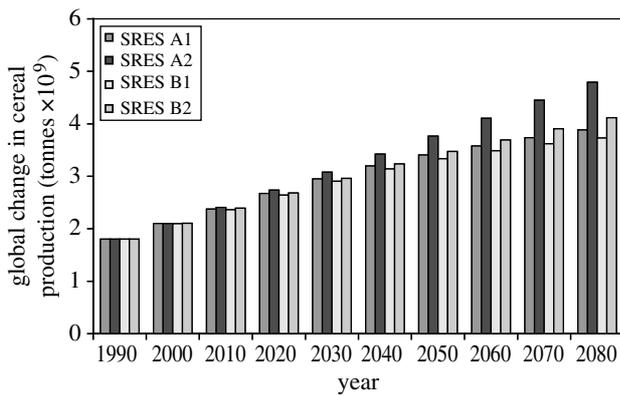


Figure 6. Future reference case estimates of cereal production under the four SRES marker scenarios (no climate change; Parry *et al.* 2004).

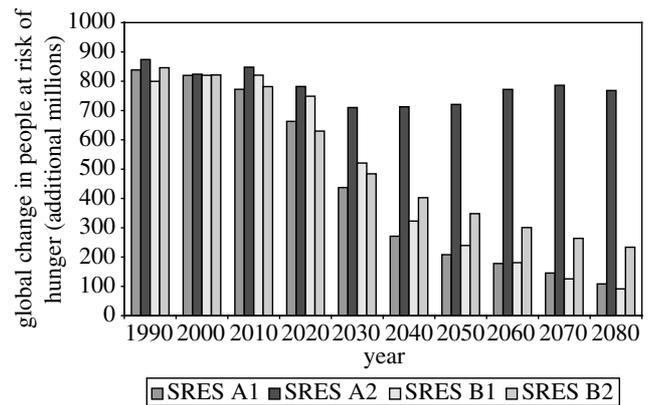


Figure 8. Future reference case estimates of the numbers of people at risk of hunger, for the four SRES marker scenarios (no climate change; Parry *et al.* 2004).

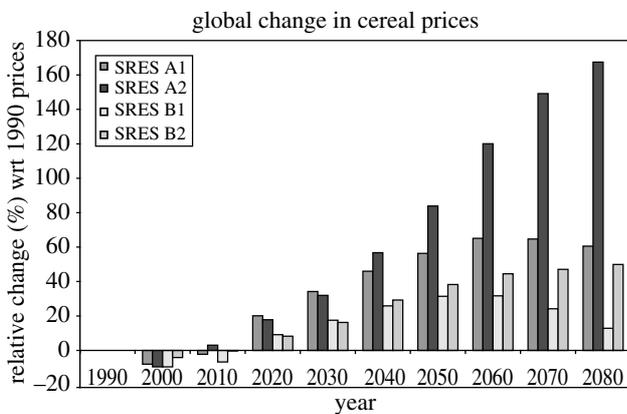


Figure 7. Future reference case global cereal prices, relative to 1990 prices, for the four SRES marker scenarios (no climate change; Parry *et al.* 2004).

economic development in the A1 world which allows higher market prices.

The result is that A1, B1 and B2 see a decline in the global number of people at risk of hunger throughout this century as the pressure caused by increases in cereal prices is offset by an increase in global purchasing power. In contrast, in the A2 world where inequality of income remains great, the number is largely unaltered, at around 800 million people (figure 8).

(ii) *The future with climate change*

Figure 9 shows the impact of climate change on global cereal production under the seven SRES scenarios.

The changes are shown as reduction in millions of tonnes from the reference case (the future without climate change). Substantial reductions in production are estimated assuming no beneficial effects of CO₂, about 5% reductions for B1 and B2 by the 2080s and 10% for A1 and A2. The difference can be explained by greater temperature increases in the latter.

However, when CO₂ effects are assumed to be fully operative, the levels of reduction diminish by about two-thirds, and the differences between the scenarios are much less clear. It appears that smaller fertilization effects under B1 and B2 lead to greater reductions than A1 and A2. Much thus depends on how these CO₂ effects play out in reality. At present we do not know, suffice to say that the effects will fall somewhere between the ‘with CO₂’ levels and the ‘without CO₂’ levels shown in figure 9.

As would be expected, an inverse pattern in the estimated change in global cereal prices tends to occur (figure 10); with large price increases (under no CO₂) for the A1 and A2 scenarios, more than double that of the reference case by the 2080s, and about half this increase under B1 and B2. Under both scenarios, there is little sign of any effect until after *ca* 2020. If CO₂ fertilization is fully assumed, the increases in cereal prices are greatly reduced and the picture as a whole is much more mixed.

The measure risk of hunger is based on the number of people whose incomes allow them to purchase sufficient quantities of cereals (Parry *et al.* 1999b), and

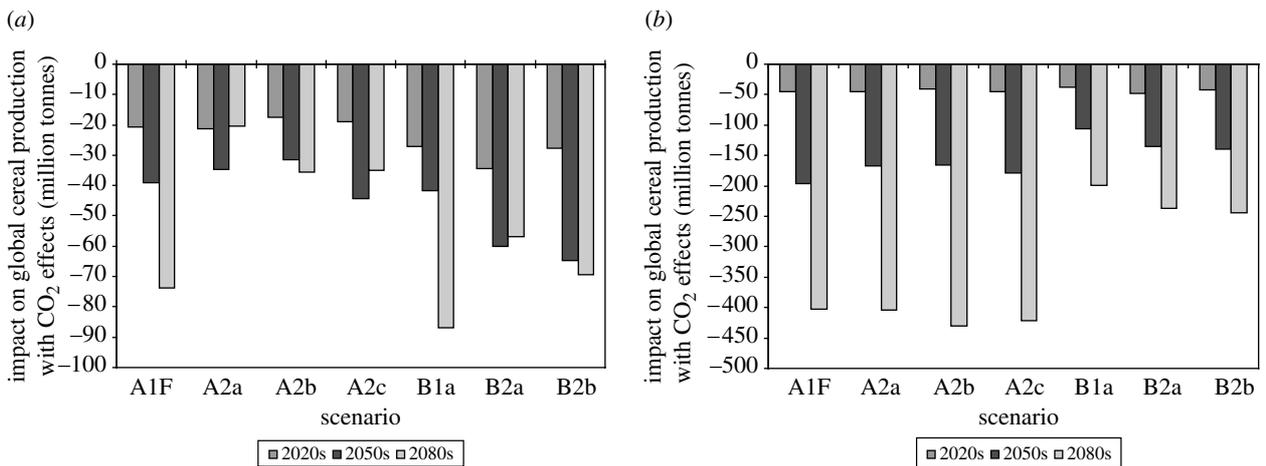


Figure 9. Changes in global cereal production due to anthropogenic climate change under seven SRES scenarios (a) with and (b) without CO₂ effects, relative to the reference scenario (no climate change; Parry *et al.* 2004).

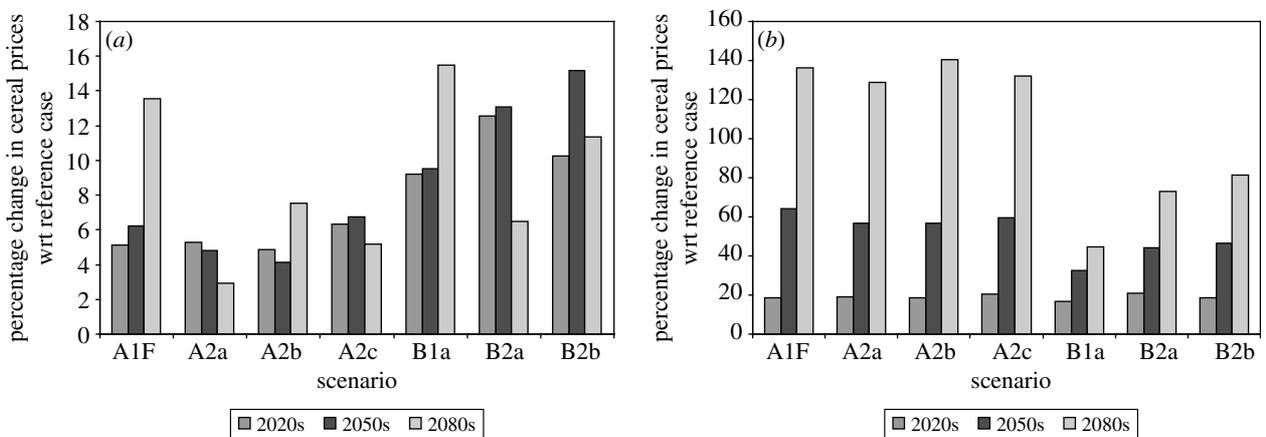


Figure 10. Changes in global cereal prices under seven SRES scenarios (a) with and (b) without CO₂ effects, relative to the reference scenario (no climate change; Parry *et al.* 2004).

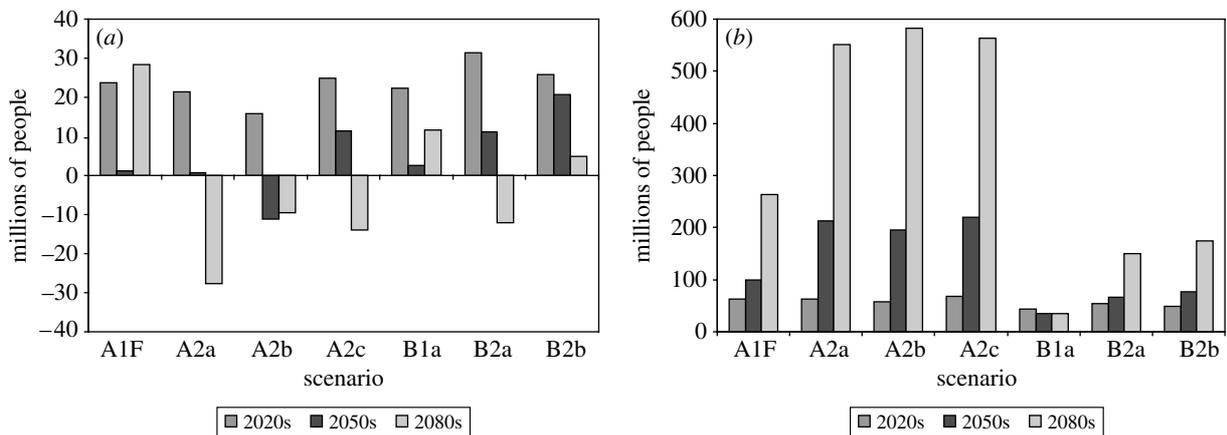


Figure 11. Additional millions of people at risk under seven SRES scenarios (a) with and (b) without CO₂ effects, relative to the reference scenario (no climate change; Parry *et al.* 2004).

therefore depends on the price of cereals and the number of people at given levels of income. The number of additional millions at risk of hunger due to climate change (i.e. compared with the reference case) is shown in figure 11. Assuming no CO₂ effects, the number at risk is very high under A2 (approaching double the reference case), partly because of higher temperatures and reduced yields, but primarily because there are many more poor people in the A2 world which has a global population of 15 billion (cf. 7 billion in

A1FI). And the number of people at risk is much lower in the B1 and B2 worlds which are characterized generally by fewer poor people.

Without the counteracting direct CO₂ effects, crop production responds approximately linearly to temperature increases across the suite of scenarios. Assuming no effects of climate change on crop yields and current trends in economic and population growth rates, world cereal production is estimated at *ca* 3900, 4800, 3700 and 4100 mt in the 2080s under the A1,

A2, B1 and B2 SRES scenarios, respectively. By comparison, the 1990s estimates put global cereal production at *ca* 1800 mt.

6. CONCLUSIONS

Broadly, climate change may lead to increases in yield potential at mid and high-mid-latitudes, and to decreases in the tropics and subtropics. But there are many exceptions, particularly where increases in monsoon intensity or where more northward penetration of monsoons leads to increases in available moisture.

Risk of hunger appears to increase generally as a result of climate change, particularly in southern Asia and Africa. However, this geographical distribution in some areas is more the result of projected increase in number of poor people in these regions (i.e. the exposed population) than of the regional pattern of climate change.

Much, of course, is uncertain. In particular, we are unclear about the potentially beneficial effects of elevated CO₂ on crop growth. Current estimates are based upon field experiments that have assumed near-optimal applications of fertilizer, pesticide and water, and it is possible that the actual 'fertilizing' effect of higher levels of CO₂ are less than we expect. Moreover, we have not taken into account effects of altered climate on pests and weeds, which are likely to vary greatly from one environment to another.

Although, we have considered two levels of adaptation, these barely begin to capture the range of options that is open to farmers. What is, however, initially evident (and intuitively makes sense) is that the potential for adaptation is greater in more developed economies and that this, together, with the generally more favourable effects of climate change on yield potential in higher rather than lower latitude regions, is likely on balance to bring more positive effects to the North and more negative effects to the South; in other words, to aggravate inequalities in development potential.

The only scenarios that increase global crop yields are derived from the SRES A2 ensemble assuming full realization of the CO₂ effects. The yield projections under the SRES A1FI scenario are the most negative. The results depend strongly on the full realization in the field of beneficial direct physiological CO₂ effects on crop growth and water use as currently measured in experimental settings. The realization of these potential beneficial effects of CO₂ in the field remains uncertain due primarily to potential, yet still undocumented, interactions with nutrients, water, weeds, pests and other stresses. If the climate change effects dominate, world crop yields are likely to be more negatively affected, as all scenarios project negative results (−9 to −22%), especially the A1 and A2 scenarios (−16 to −22%).

At the greater amounts of climate change tested in the A1 and A2 SRES scenarios, climate change is likely to increase the disparities in cereal yields between developed and developing countries in a more significant way than has been found in previous studies.

Third, the SRES scenarios of a more globalized world (A1FI and B1) experience greater reduction in yield than the scenarios of a more regionalized world (A2 and B2).

Fourth and finally, the use of ensemble realizations of the SRES scenarios highlights the regional uncertainties inherent even under similar greenhouse gas emissions pathways. Members of the A2 and B2 ensemble climate scenarios produce moderate differences in the crop yield results in some regions and timeslices. These results point to the need for agricultural managers to prepare for a range of agricultural futures at the regional level.

When the crop yield results are introduced to the BLS world food trade system model, the combined model and scenario experiments demonstrate that the world, for the most part, appears to be able to continue to feed itself under the SRES scenarios during the rest of this century. The explanation for this is that production in the developed countries generally benefits from climate change, compensating for declines projected for developing nations. While global production appears stable, regional differences in crop production are likely to grow stronger through time, leading to a significant polarization of effects, with substantial increases in risk of hunger amongst the poorer nations, especially under scenarios of greater inequality (A1FI and A2).

The results illustrate the complex nature of the food supply system where moderate increases in air temperatures do not necessarily mean shortfalls in cereals. More so than ever before, the use of the new SRES emissions and climate scenarios has highlighted the nonlinearities in the food supply system. It has also highlighted the sensitivity of the results to the balance between CO₂ fertilization and changes in climate, hence the presentation in this paper of yield change potentials with and without CO₂ enhancement.

It should also be noted that the impact range produced by the spatial and temporal variations evident between individual HadCM3 ensemble members is also significant. By the 2080s, the variation around the global average directly attributable to natural variability is more than 50% of the mean climate change signal. This uncertainty will need to be borne in mind by policymakers. These results suggest we should be looking not just to avoid a warmer world, but also looking for ways to adapt to a more uncertain world where in certain regions the risk of crop failure on a year-to-year basis is likely to increase.

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