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Effects of climate change on global food production under SRES emissions and socio-economic scenarios

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Abstract

This paper analyses the global consequences to crop yields, production, and risk of hunger of linked socio-economic and climate scenarios. Potential impacts of climate change are estimated for climate change scenarios developed from the HadCM3 global climate model under the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) A1FI, A2, B1, and B2. Projected changes in yield are calculated using transfer functions derived from crop model simulations with observed climate data and projected climate change scenarios. The basic linked system (BLS) is used to evaluate consequent changes in global cereal production, cereal prices and the number of people at risk from hunger.

The crop yield results elucidate the complex regional patterns of projected climate variables, CO_2 effects, and agricultural systems that contribute to aggregations of global crop production. 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. The contrast between the yield change in developed and developing countries is largest under the A2a–c 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.

When 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. However, this outcome is achieved through production in the developed countries (which mostly benefit from climate change) compensating for declines projected, for the most part, for developing nations. While global production appears stable, regional differences in crop production are likely to grow stronger through time, leading to a significant polarisation of effects, with substantial increases in prices and risk of hunger amongst the poorer nations, especially under scenarios of greater inequality (A1FI and A2).

The use of the SRES scenarios highlights several non-linearities in the world food supply system, both in the biophysical sense, where the levels of atmospheric CO_2 tested reach new levels, and the socio-economic sense, where changes in population dynamics and economic and political structures complicate the translation of biophysical climate change impacts into social indices, such as the number of people at risk of hunger.

Keywords: Climate change; SRES emissions scenarios; Global food security; Cereal yields; Risk of hunger

1. Introduction

In this study, we consider 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 characterised by the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC). 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

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interactions, and how they affect people at risk of hunger in the coming decades.

This work is an extension of previous studies that assumed a single best-estimate population and economic future (Rosenzweig and Parry, 1994; Parry et al., 1999). These and other previous studies have shown that climate change associated with increasing levels of carbon dioxide is likely to affect developed and developing countries differentially, with major vulnerabilities occurring in low-latitude regions (e.g., Reilly et al., 2001; Darwin and Kennedy, 2000).

The main drivers of agricultural responses to climate change are biophysical effects and socio-economic factors. Crop production is affected biophysically by meteorological variables, including rising temperatures, changing precipitation regimes, and increased atmospheric carbon dioxide levels. Biophysical effects of climate change on agricultural production will be positive in some agricultural systems and regions, and negative in others, and these effects will vary through time. Socio-economic factors influence responses to changes in crop productivity, with price changes and shifts in comparative advantage. The power of this work is in the coupling of biophysical (yield functions) and socio-economic methods, yielding answers that are otherwise impossible to elaborate when using the two approaches separately.

2. Methods

There are two main components of the research: first, we estimate the responses of crop yields to greenhouse gas-induced climate change, and second, we simulate the agro-economic consequences of these potential changes in crop yields—changes in regional productivity, fluctuations in global commodity prices and the resultant impact on the total number of people considered at risk of hunger worldwide.

The socio-economic development pathways assumed in this study are derived from the IPCC SRES report and are described elsewhere in this issue (Arnell et al., this issue). Consistent climate change scenarios have been taken from SRES-driven experiments conducted using the UK Hadley Centre's third generation coupled atmosphere–ocean global climate model (HadCM3) (Johns et al., 2003). The use of a transient 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 (Parry et al., 1999) where further detail regarding the crop modelling procedure can be, while full documentation on the world food trade model, the basic linked system (BLS) is given in Fischer et al. (1996, 2001).

2.1. *Impacts and adaptation at the crop level*

2.1.1. *Yield transfer functions*

Crop yield changes are estimated with yield transfer functions derived from dynamic crop simulation models as described in Parry et al. (1999) and Iglesias et al. (2000). The production functions incorporate: (a) crop responses to changes in temperature and precipitation with the current management; (b) crop responses to temperature and precipitation with farm-level and regional adjustments (see section on adaptation); and (c) crop responses to carbon dioxide.

The crops modelled are wheat, rice, maize, and soybean, which account for approximately 85% of the world cereal exports. Table 1 shows the current percentages of world production of wheat, rice and maize for the countries where detailed information was available to calibrate regional transfer functions.

Statistical analyses were used to derive agroclimatic regional yield transfer functions from previously simulated site-level results (e.g., Parry et al., 1999; Iglesias et al., 2000; Rosenzweig and Iglesias, 1998; Rosenzweig et al., 1999). Relationships between crop yield and temperature and precipitation anomalies over the entire crop growing period were analysed using correlation coefficients. This exploratory analysis served to identify those variables that explained a significant proportion of the observed yield variance.

Yield responses to combined changes in temperature and precipitation were then statistically analysed. The yield responses were taken from results from over 50 previously published and unpublished regional climate change impact studies (between 10 and 200 simulations per crop and agroclimatic region) summarised in Rosenzweig and Iglesias, 2003a, b, http://sedac.ciesin.columbia.edu/giss_crop_study/.

In the modelled regions, the correlations between simulated crop yields and yields derived from the transfer functions are over 70%. The highest correlations are in high and mid latitudes and the lowest are in tropical areas.

These transfer functions were then applied to the spatial climate change data (scenario changes in regional temperature and precipitation, and assigned CO_2 levels

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

	Globally averaged 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
Soybean	2.3	79,410	179,917	96

for three timeslices—2020s, 2050s, and 2080s; see below) to derive scenario estimates of potential yield changes for individual crops. Projected temperature and precipitation changes (and hence soil moisture availability for crop growth) were taken from the seven HadCM3 climate change scenarios. 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 (Rosenzweig and Parry, 1994; Rosenzweig and Iglesias, 1998, 2003a, b).

Most plants growing in atmospheric CO_2 higher than ambient exhibit increased rates of photosynthesis. High CO_2 also reduces the stomatal openings of some crop plants. By so doing, CO_2 reduces transpiration per unit leaf area while enhancing photosynthesis. Thus it may lead to improve water-use efficiency (the ratio of crop biomass to amount of water used in evapotranspiration). As a result of these interactions, elevated CO_2 alone tends to increase growth and yield of most agricultural plants. Most of the studies have been conducted either under controlled environmental conditions (chambers), or under optimal field conditions (i.e., FACE experiments, Kimball et al., 2002). Experimental effects of CO_2 on crops have been reviewed by Kimball et al. (2002). In all cases, potential CO_2 effects on plant biomass depend on the nutrient and water levels (Derner et al., 2003). Most agricultural models used in climate change impact studies have been modified to simulate the direct effects of CO_2 on crops (for a review, see Tubiello and Ewert, 2003).

In this study, the estimates of increased crop yield due to CO_2 incorporate a quantitative foundation for the estimation of physiological CO_2 effects on crop yields based on an extensive review of previous simulation studies (Fig. 1). The data in Fig. 1 was incorporated to the yield transfer functions used in this study.

2.2. Estimation of world food trade responses

The BLS of National Agricultural Policy Models (BLS) is a world-level general equilibrium model system developed by the Food and Agriculture Program of the International Institute for Applied Systems Analysis (Fischer et al., 2001). It consists of some 35 national and/or regional models: 18 national models, two models for regions with close economic co-operation (EC-9 and Eastern Europe and former Soviet Union), 14 aggregate models of country groupings, and a small component that accounts for statistical discrepancies and imbalances during the historical period. For a detailed breakdown of the models see Parry et al. (1999). The individual models are linked together by means of a world market module.

The general equilibrium approach upon which the BLS is constructed necessitates that all relevant economic activities are broadly represented in the model. Financial flows as well as commodity flows within a country and at the international level are consistent in the sense that they balance. Whatever is produced will be demanded, either for human consumption, feed or intermediate input; it might be traded or put into storage. Consistency of financial flows is imposed at the level of the economic agents in the model (individual income groups, governments, etc.), at the national as well as the international level. This implies that total expenditures cannot exceed total income from economic activities and from abroad, in the form of financial transfers, minus savings. On a global scale, no more can be spent than what is earned.

The country models are linked through trade, world market prices and financial flows. The system is solved in annual increments, simultaneously for all countries. It is assumed that supply does not adjust instantaneously to new economic conditions. Only supply that will be marketed in the following year is affected by possible

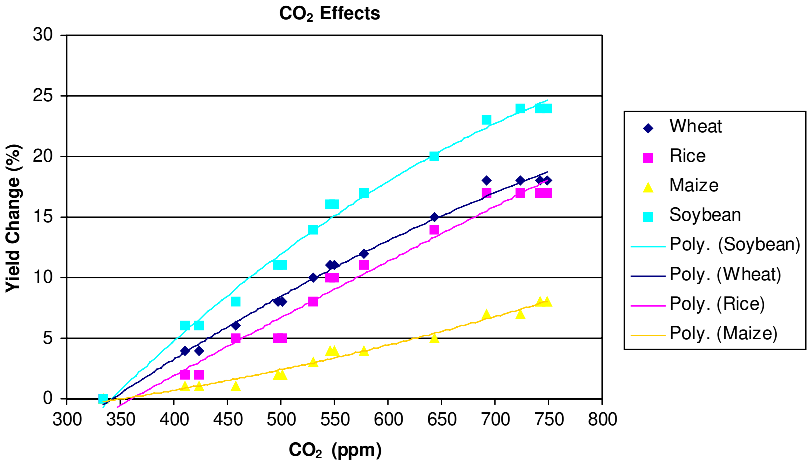

Fig. 1. The potential increases in yield exhibited by wheat, rice, maize and soybean under elevated levels of CO_2 (source: GISS analysis, multiple citations).

changes in the economic environment. A first round of exports from all the countries is calculated for an initial 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 models. Next, these generate new domestic equilibria and adjust net exports. This process is repeated until the world markets are cleared in all commodities. Since these steps are taken on a year-by-year basis, a recursive dynamic simulation results.

Although the BLS contains different types of models, all adhere to some common specifications. The models contain two main sectors: agriculture and non-agriculture. Agriculture produces nine aggregated commodities. All non-agricultural activities are combined into one single aggregate sector. Production is critically dependent on the availability of the modelled primary production factors, i.e., of land, labour and capital. The former is used only in the agricultural sector, while the latter two are determinants of output in both the agricultural and the non-agricultural sectors.

For agricultural commodities, acreage or animal numbers and yield are determined separately. Yield is represented as a function of fertiliser application (crops) or feeding intensity (livestock). To keep these interdependencies intact, the approach chosen was to harmonise rates of economic growth generated in the BLS with those projected in the SRES scenarios through adjustment of production factors and of assumed technical progress. Growth rates in the national models of the BLS are endogenously determined based on three elements: (a) capital accumulation through investment and depreciation, related to a savings function that depends on lagged GDP levels as well as balance of trade and financial aid flows; (b) dynamics of the labour force as a result of demographic changes; and (c) (exogenous) technical progress. The national-level estimates were aggregated into 11 broad regions (Table 2). The harmonisation of production factors and GDP for the period 1990–2080 was then carried out on a region-by-region basis.

Population levels for each SRES scenario for given timelines were taken from the CIESIN database (Arnell et al., this issue). 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

Table 2
Aggregation of national economic units into the 11 SRES/IIASA regions

Region	Countries
North America (NAM)	Puerto Rico, United States of America, Canada, Virgin Islands
Latin America and the Caribbean (LAM)	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts, and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Sub-Saharan Africa (AFR)	Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe
Middle East and North Africa (MEA)	Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen
Western Europe (WEU)	Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom
Central and Eastern Europe (EEU)	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia
Newly independent states of the former Soviet Union (FSU)	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
Centrally planned Asia and China (CPA)	Cambodia, China, Hong Kong, Korea (DPR), Lao (PDR),Mongolia, Viet Nam
South Asia (SAS)	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
Other Pacific Asia (PAS)	American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan, China, Thailand, Tonga, Vanuatu, Western Samoa
Pacific OECD (PAO)	Australia, Japan, New Zealand

(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.

2.3. Adaptation

The data used to derive the production functions incorporated *farm-level adaptation* strategies, such as changes in planting date, and application of additional fertilization and irrigation in the current irrigated areas. In addition, *regional-scale adaptation* is considered by modifying the yield changes derived from the production functions in developed countries to represent potential changes that require investments such as development of new cultivars and irrigation infrastructure. Adaptation that implies *economic adjustments* to the yield changes is tested by the BLS world food trade model which result in national and regional production changes and price responses. Economic adjustments represented by the BLS include: increased agricultural investment, re-allocation of agricultural resources according to economic returns (including crop switching), and reclamation of additional arable land as a response to higher cereal prices.

2.4. Limitations

2.4.1. Crop yield change estimates

The yield change estimates include different sources of uncertainty. At the site level, the main source of uncertainty relates to the use of crop models used to derive the yield functions. The crop models embody a number of simplifications. For example, weeds, diseases, and insect pests are assumed to be controlled; and there are no problem soil conditions (e.g., salinity or acidity). No estimate is made as to the negative effects of acid deposition and how this may affect yield levels. The complex and uncertain assessment of the contribution of the direct effects of CO_2 to agricultural crop remains a crucial research question.

The crop models simulate the effect of drought conditions, but they do not respond to flooding (Rosenzweig et al., 1999). At the regional level, the functions may not represent the variability of agricultural systems within similar agro-ecological zones, or dissimilar agricultural regions.

The farm-level adaptation included in the functions was derived from the crop models that simulate the current range of agricultural technologies available around the world, but by the 2080s agricultural technology is likely to be very different and the models may underestimate the farm production achievable. (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, such as the development of bioengineered varieties.)

2.4.2. World food trade estimates

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.

2.4.3. Global climate models

The HadCM3 climate scenarios employ grids of 2° latitude by 2° longitude. At this resolution, many smaller-scale elements of climate are not properly represented, such as warm and cold fronts and hurricanes, as well as the diversities of ecosystems and land-use. Accurate modelling of hydrological processes is particularly crucial for determining climate change impacts on agriculture, but simulation of infiltration, runoff, and evaporation, and other hydrological processes is highly simplified. Precipitation, in particular, is poorly represented both spatially and temporally in GCMs results. This lack of realism, in particular, limits accurate simulation of crop responses. In addition, global climate models often fail to simulate current climate in other respects, such as high- or low-pressure systems, monsoonal circulations, ocean heat transport, etc.

3. Results

3.1. Crop yield responses

Changes in regional crop yields under each SRES scenario are the result of the interactions among temperature and precipitation effects, direct physiological effects of increased CO_2, and effectiveness and availability of adaptations. Figs. 2–11 show the potential changes in world and regional wheat, rice, maize, and soybean production for the 2020s, 2050s and 2080s

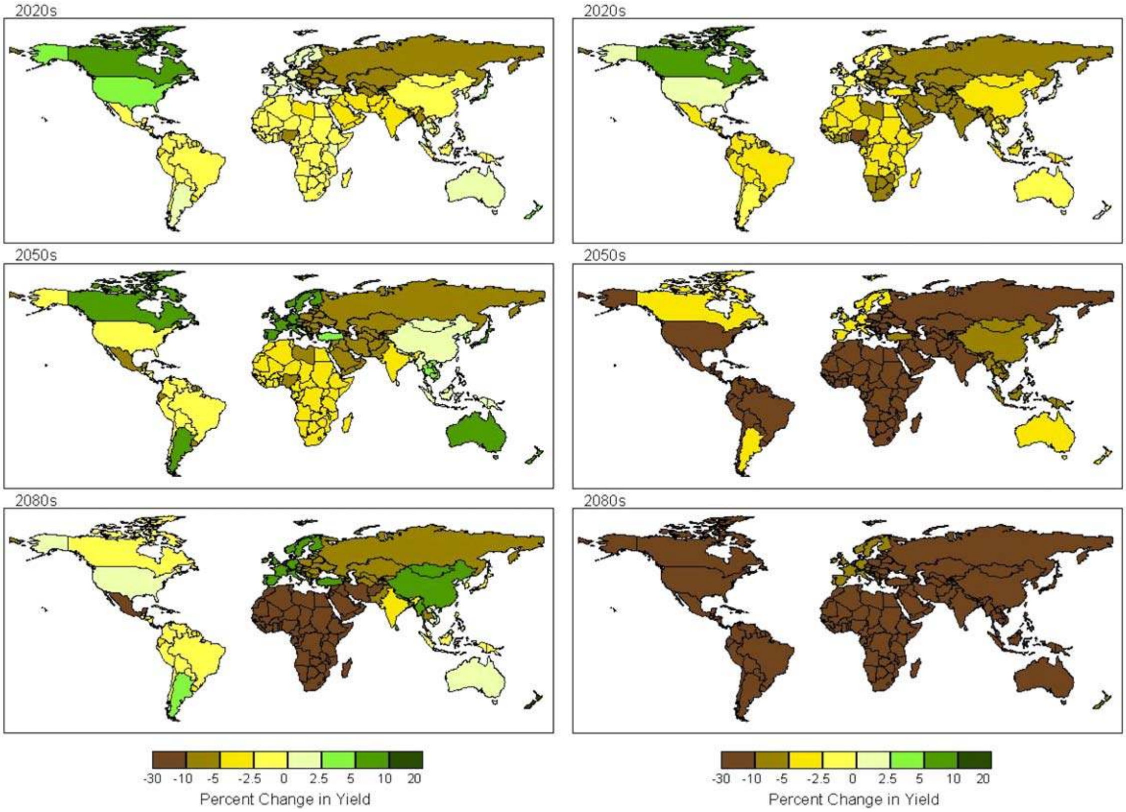

Fig. 2. Potential changes (%) in national cereal yields for the 2020s, 2050s and 2080s (compared with 1990) under the HadCM3 SRES A1FI with and without CO_2 effects.

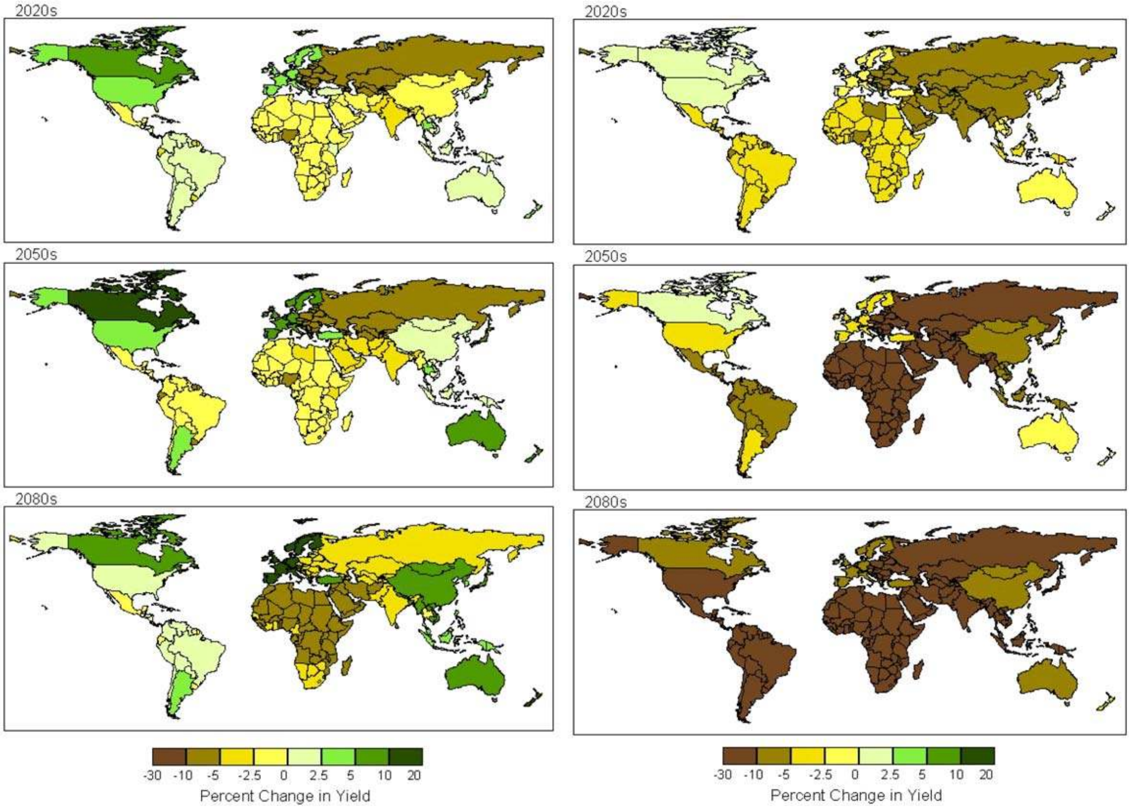

Fig. 3. Potential changes (%) in national cereal yields for the 2020s, 2050s and 2080s (compared with 1990) under the HadCM3 SRES A2a scenario with and without CO_2 effects.

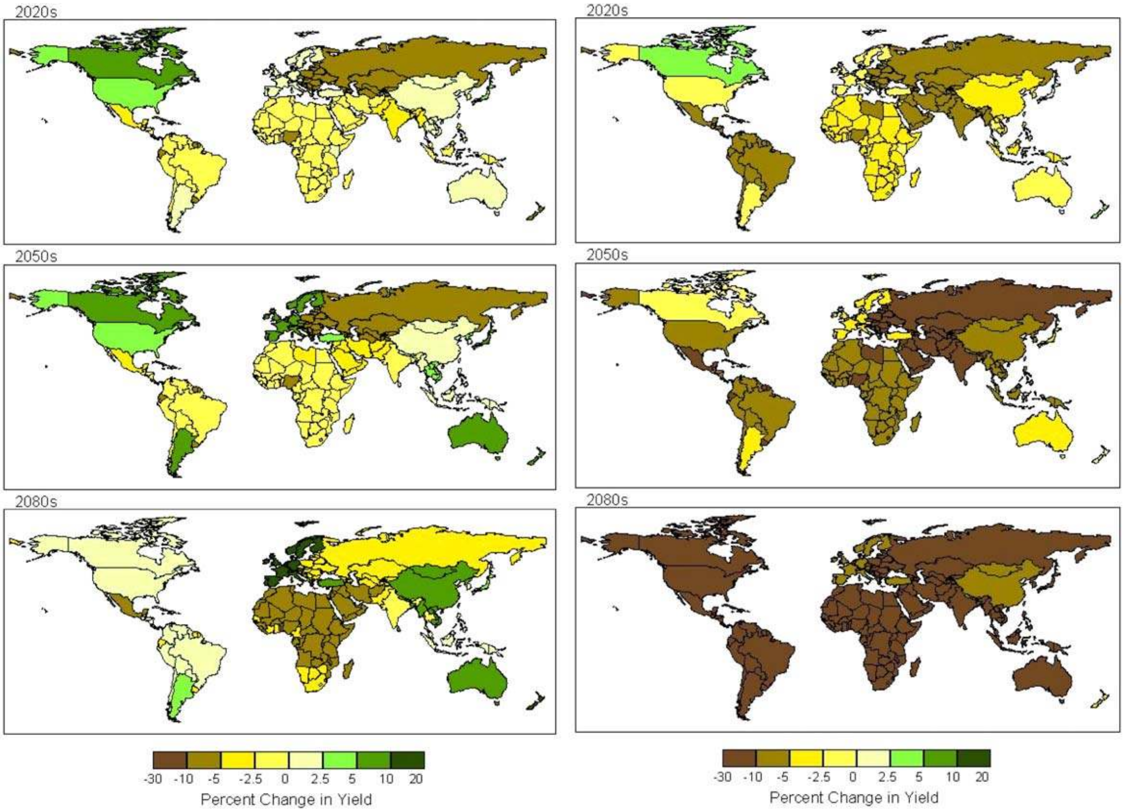

Fig. 4. Potential changes (%) in national cereal yields for the 2020s, 2050s and 2080s (compared with 1990) under the HadCM3 SRES A2b scenario with and without CO_2 effects.

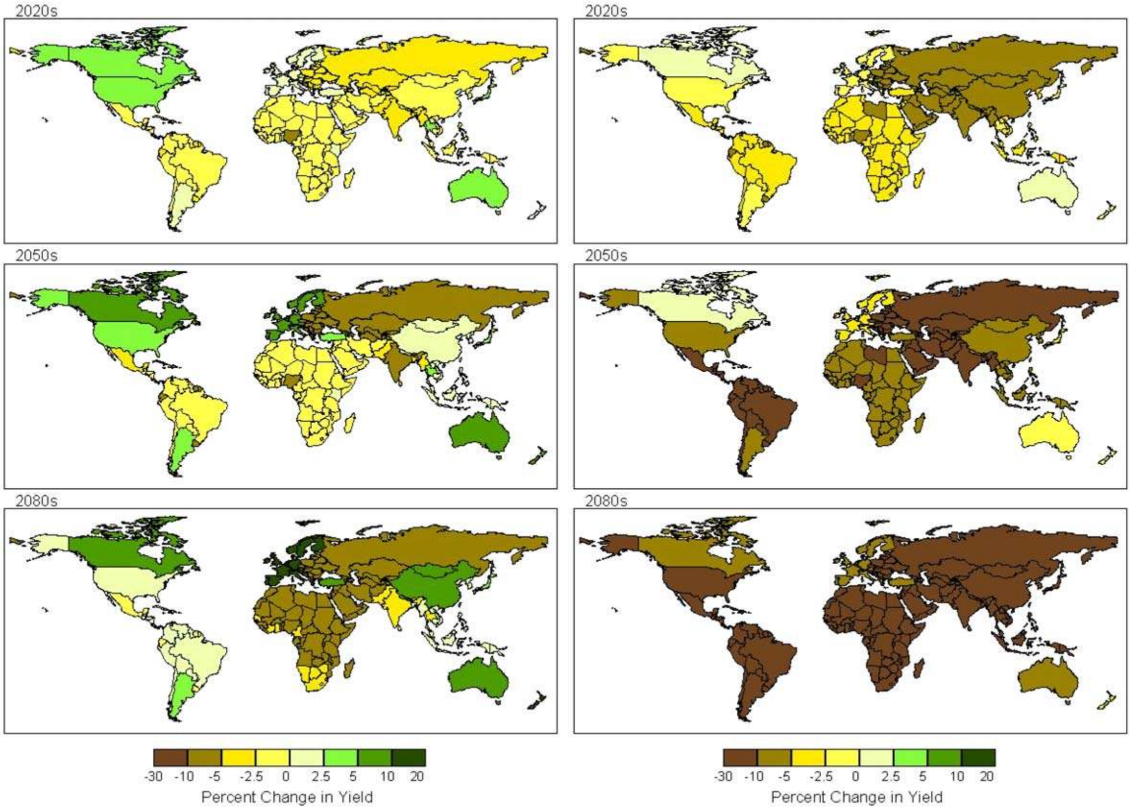

Fig. 5. Potential changes (%) in national cereal yields for the 2020s, 2050s and 2080s (compared with 1990) under the HadCM3 SRES A2c scenario with and without CO_2 effects.

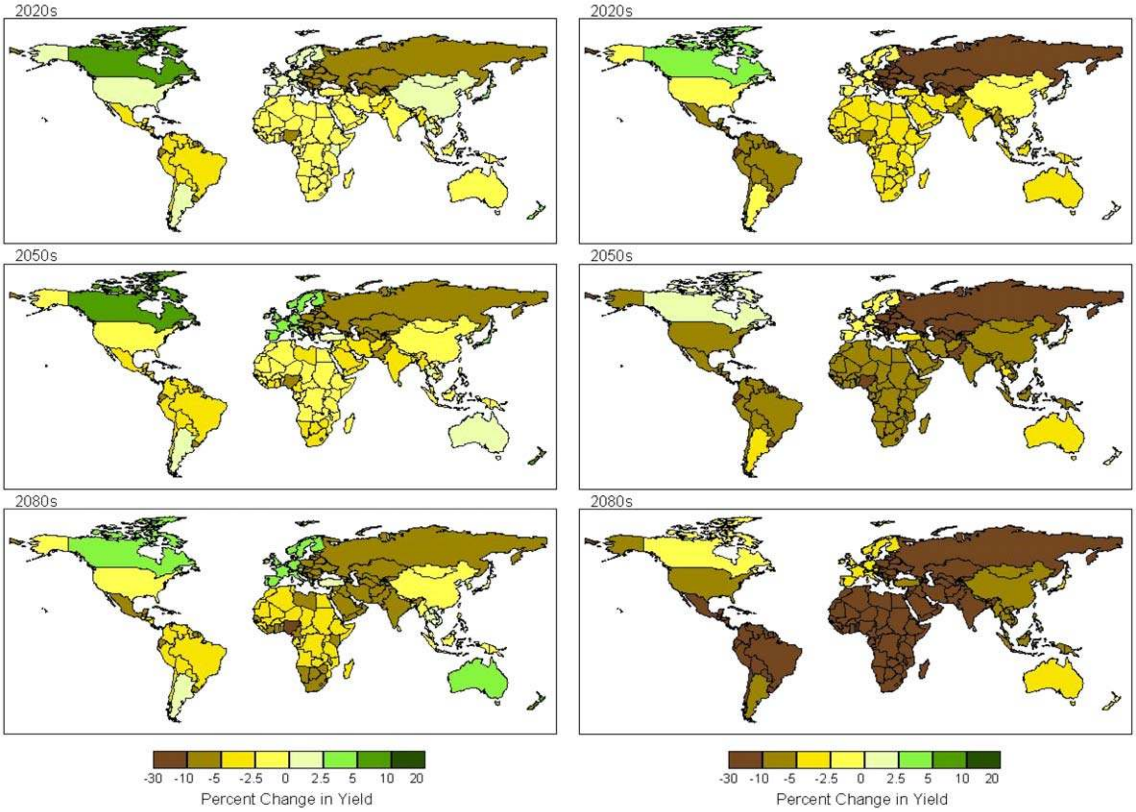

Fig. 6. Potential changes (%) in national cereal yields for the 2020s, 2050s and 2080s (compared with 1990) under the HadCM3 SRES B1a scenario with and without CO_2 effects.

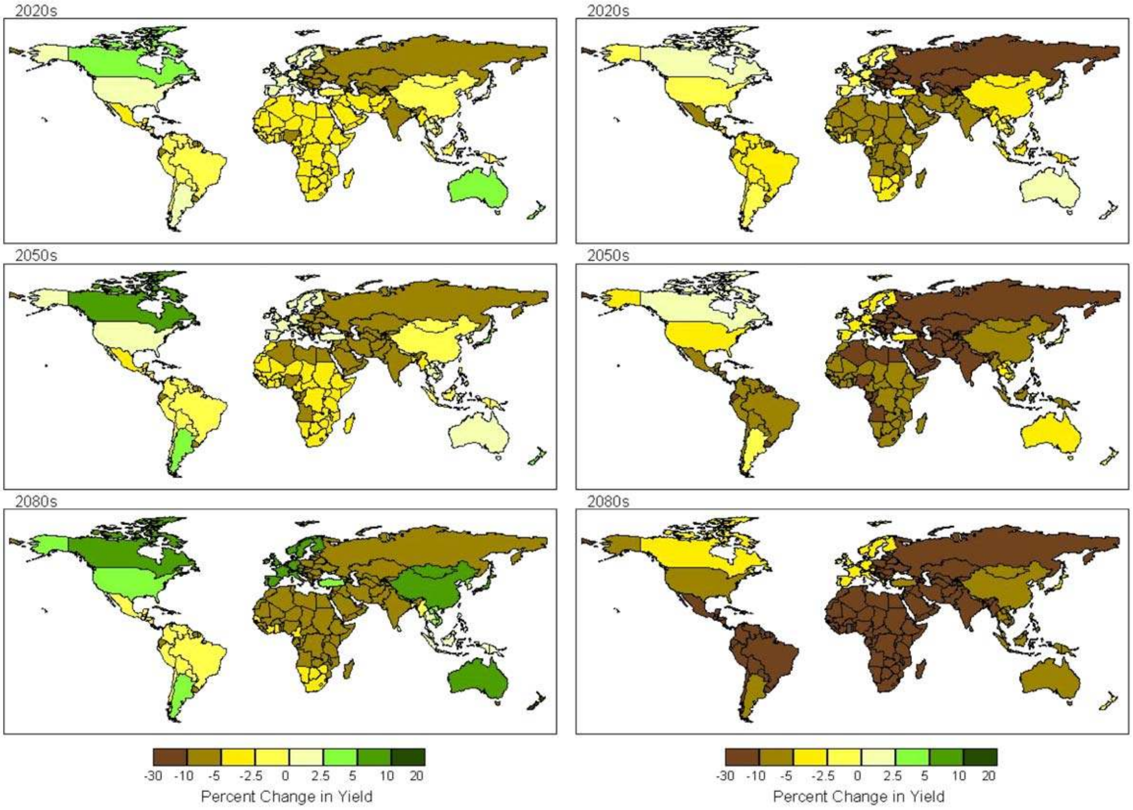

Fig. 7. Potential changes (%) in national cereal yields for the 2020s, 2050s and 2080s (compared with 1990) under the HadCM3 SRES B2a scenario with and without CO_2 effects.

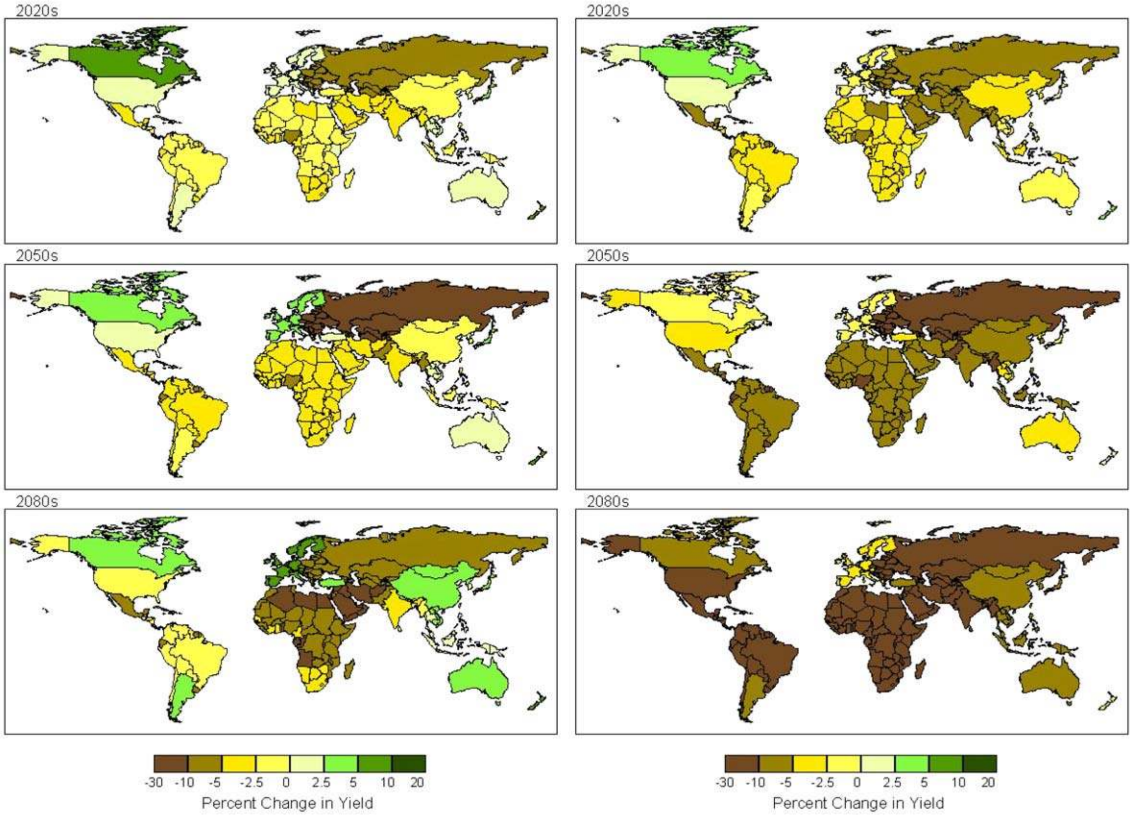

Fig. 8. Potential changes (%) in national cereal yields for the 2020s, 2050s and 2080s (compared with 1990) under the HadCM3 SRES B2a scenario with and without CO_2 effects.

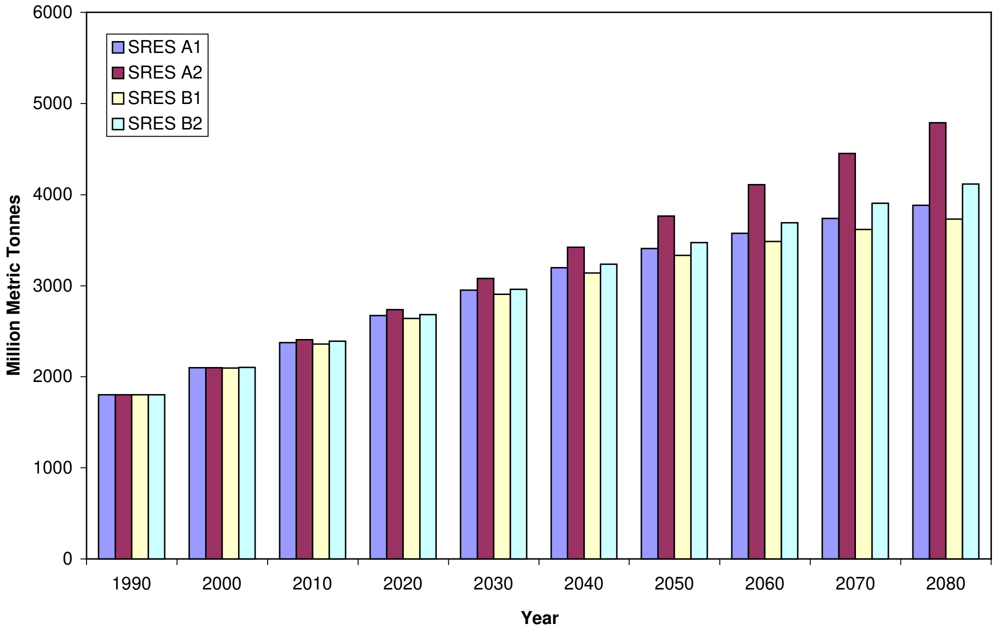

Fig. 9. Future reference case estimates of cereal production under the four SRES marker scenarios (no climate change).

(compared with 1990) under the HadCM3 SRES scenarios with and without CO_2 effects. The yield changes include result from both rainfed and irrigated estimates, based on the current mix of these practices, and farm-level adaptations. For each scenario, there are two estimates: one with and one without the physiological

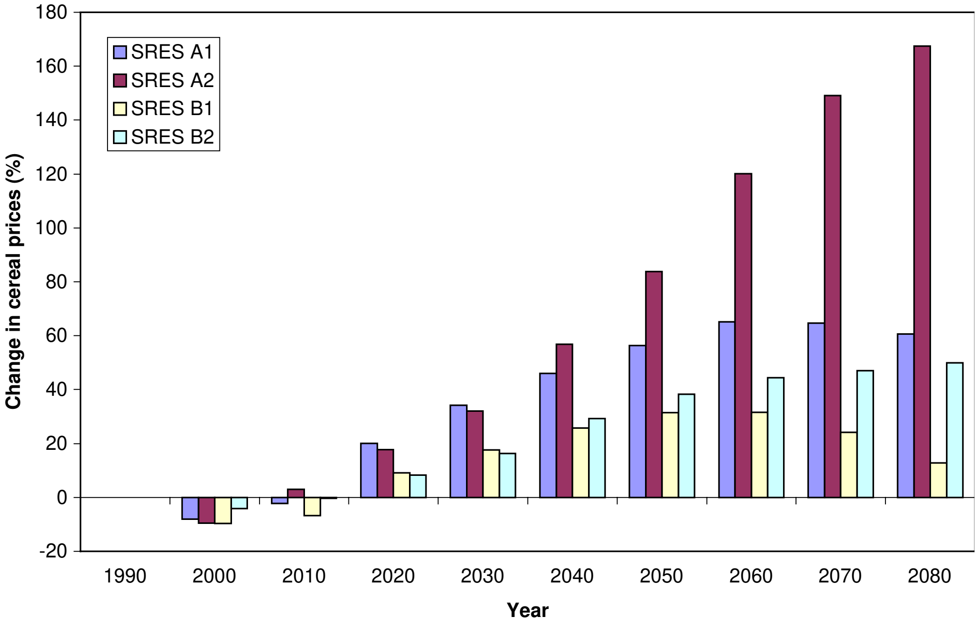

Fig. 10. Future reference case global cereal prices, relative to 1990 prices, for the four SRES marker scenarios (no climate change).

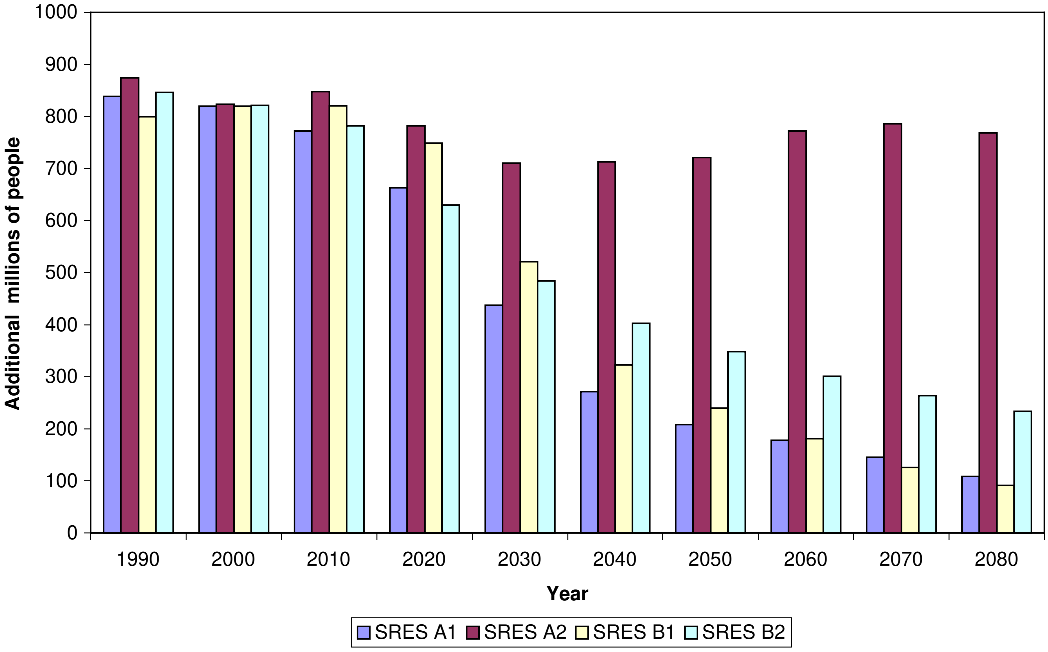

Fig. 11. Future reference case estimates of the numbers of people at risk of hunger, for the four SRES marker scenarios (no climate change).

effects of elevated atmospheric CO_2 concentrations. These effects help to mitigate the negative impact of climate change on crop yields. The maps are created from the nationally averaged yield changes for wheat, rice, maize, and soybean estimates; these are the basic agricultural inputs to the BLS simulations. Regional variations within countries are not reflected.

Each HadCM3 climate change scenario produced by the four different SRES emissions scenarios instigates a different development path for global crop yields. 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 (FAO, 2002). 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. 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 CO_2. In North America, South East South America, and Australia, the effects of CO_2 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 CO_2. 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, CO_2 effects, and agricultural systems that contribute to aggregations of global crop production for the different SRES futures.

A1FI: Analysis of the global impact on cereal yields suggests that an A1FL world will be far more challenging for arable-land farmers, beginning in the middle of the century. In the A1FI world—the warmest of the SRES scenarios considered—the impacts of climate change become evident with the arrival of the 2050s. Assuming no CO_2 effects, cereal yields fall by as much as 10% throughout Eastern Europe, FSU and parts of Africa, primarily as a result of the impact of increasing temperatures. Major areas of maize production are reduced by up to 18%, and rice production is reduced by ~10%. This picture of stressed cultivars throughout the world worsens towards the 2080s with regional temperatures, in some cases, exceeding 8°C and precipitation totals down by as much as 90% compared to the 1961–90 reference period. In such conditions, even wheat and barley yields are impacted by as much as ~20% throughout Africa and Latin America. The result is that aggregated cereal yield worldwide are depressed by, on average, 10%.

Considering the positive effects of elevated atmospheric CO_2 concentrations under the A1FI scenario climates, many areas witness yield increases with the obvious exception of Africa. Here the CO_2 "fertilisation" effect is unable to counter the ~20% reduction in cereal yields. For example, maize production is unable to fully realise the beneficial effects of elevated CO_2 levels and falls by as much as 30%. By the 2080s, few differences exist and those that do are relatively small.

A2: Results from the three members of the A2 ensemble are generally consistent. Differences are most pronounced during the 2020s where multidecadal variability predominates over the climate change signal. As a result, all A2 ensemble members are discussed collectively hereafter. The responses of the major crops and cultivars to climate change in an A2 future world follow that of the A1FI world up until the 2080s. The 2020s are dominated by multidecadal variability and 2050s are comparable to those of A1FI—both experience similar absolute changes in temperature and precipitation. The 2080s under the A2 world, however, are significantly different, at least in the northern hemisphere where temperatures are on average 2°C cooler in an A2 world than an A1FI world. The result is that aggregated cereal yields are, assuming no CO_2 effects, depressed by no more than 10% anywhere in the world.

Re-running the models to include the positive effect of elevated CO_2 levels again reduces the negative impacts across all regions. However, beneficial effects are particularly evident in the mid- and high-latitude areas where temperate cereals tend to be grown. Southern Asia also sees a significant benefit due to the deeper penetration of the monsoon during the summer months, lengthened growing season and elevated CO_2 levels.

B1: In the coolest of the future SRES worlds, the overall impacts on cereal yields as a result of anthropogenic climate change are not significantly smaller than in the other scenarios. In this scenario, the difference between countries in the Northern and Southern Hemispheres is less pronounced than in the other scenarios. Scandinavia and the Baltic States, in particular, are affected as rising temperatures are not accompanied by the large increases in precipitation witnessed in other scenarios such as B2. Incorporating the effect of an increase in ambient CO_2 levels has less effect in the B1 world as concentrations are only half that experienced under A1FI.

B2: In the B2 world, as with the A2 ensemble of experiments, only small differences exist between the two members. Results for the 2020s are, again, dominated by the influence of natural variability. Without the masking effect of the CO_2 "fertilisation" effect, the negative effects witnessed in a mid-to-high latitude B2 world fall between those experienced in the A2 and B1 worlds. The exception is South America and Africa where even the modest increases in regional temperatures and decreases in precipitation result in the widespread collapse of crop productivity. The result of incorporating the potential benefits of CO_2 into the estimates of potential yield changes reduces, as expected, many of the potential negative impacts, especially in South America and Africa. As in the A2 world, the lengthened growing season associated with moderate increases in near-surface temperatures and precipitation and combined with an almost doubling of CO_2 by the 2020s associated with the B2 world, lead to a potential increase in the yield in North America, Western Europe and South and Southeast Asia.

At the greater amounts of climate change tested in the A1 and A2 SRES scenarios, the disparities in cereal yields between developed and developing countries are likely to increase and to do so in a more significant way than has been found in previous studies (Table 3).

3.2. Cereal production, cereal prices, and risk of hunger responses

3.2.1. 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 (~1800) to ~3900, ~4800, ~3700 and ~4100 million metric tons (mmt) per year by the 2080s under the A1, A2, B1 and B2 SRES scenarios, respectively (Fig. 9). 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 (Fig. 10). The difference between the A1 and B1 worlds which share identical population growth projections is primarily due to the higher level of 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 (Fig. 11).

3.2.2. The future with climate change

Fig. 12 shows the impact of climate change on global cereal production under the seven SRES scenarios. The changes are shown as reduction in million of metric tonnes from the reference case (the future without climate change). Substantial reductions in production are estimated assuming no beneficial effects of CO_2, 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 CO_2 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 fertilisation effects under B1 and B2 lead to greater reductions than A1 and A2. Much thus depends on how these CO_2 effects play out in reality. At present we do not know, suffice to say that the effects will fall somewhere between the "with CO_2" levels and the "without CO_2" levels shown in Fig. 12.

As would be expected, an inverse pattern in the estimated change in global cereal prices tends to occur (Fig. 13); with large price increases (under no CO_2) for

Table 3
Aggregated developing–developed country differences (per cent) in average crop yield changes from baseline for the HadCM2 and HadCM3 scenarios

	HadCM3—2080s							HadCM2—2080s	
Scenario	A1FI	A2a	A2b	A2c	B1a	B2a	B2b	S550	S750
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

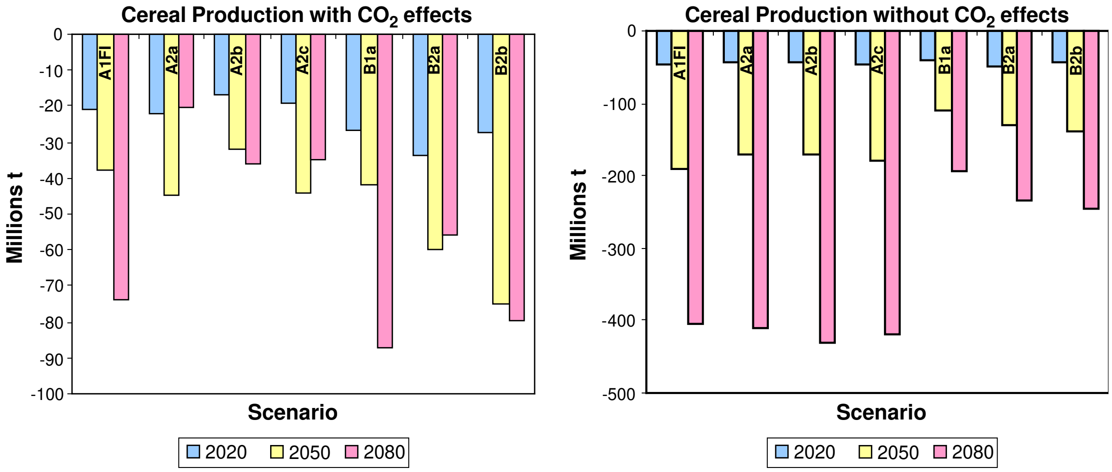

Fig. 12. Changes in global cereal production due to anthropogenic climate change under seven SRES scenarios with and without CO_2 effects, relative to the reference scenario (no climate change).

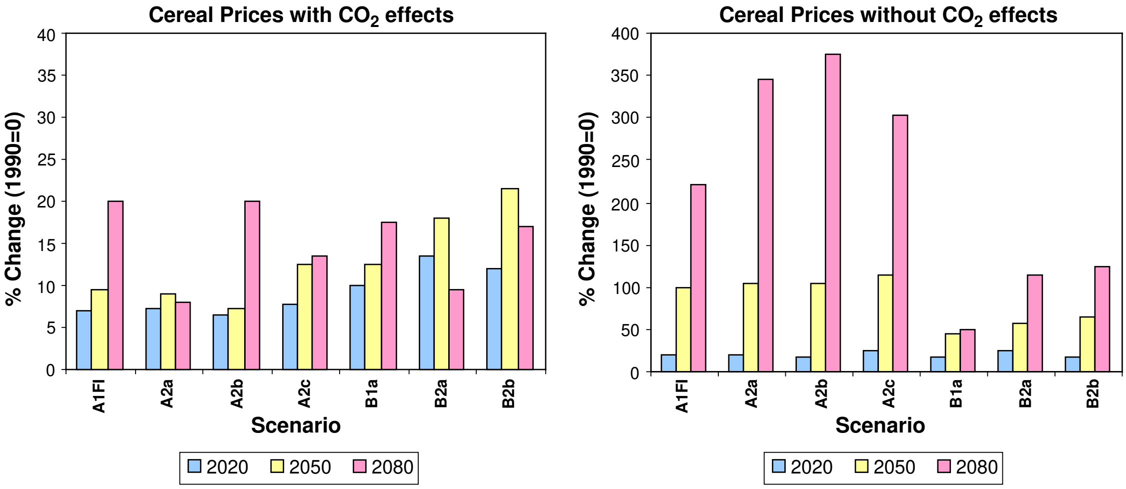

Fig. 13. Changes in global cereal prices under seven SRES scenarios with and without CO_2 effects, relative to the reference scenario (no climate change).

the A1 and A2 scenarios, more than a three-fold increase over the reference case by the 2080s, and less than half this increase under B1 and B2. Under both scenarios there is little sign of any effect until after 2020. And the picture is much more mixed when CO_2 fertilisation is fully assumed.

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., 1999), and 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 Fig. 14. Assuming no CO_2 effects, the number at risk are 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 (c.f. 7 billion in A1FI). And the number of people at risk is much lower in the B1 and B2 worlds which are characterised generally by fewer poor people.

Without the counteracting direct CO_2 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 ~3900, ~4800, ~3700 and ~4100 mmt in the 2080s under the A1, A2, B1 and B2 SRES scenarios, respectively. By comparison, 1990s estimates put global cereal production at ~1800 mmt.

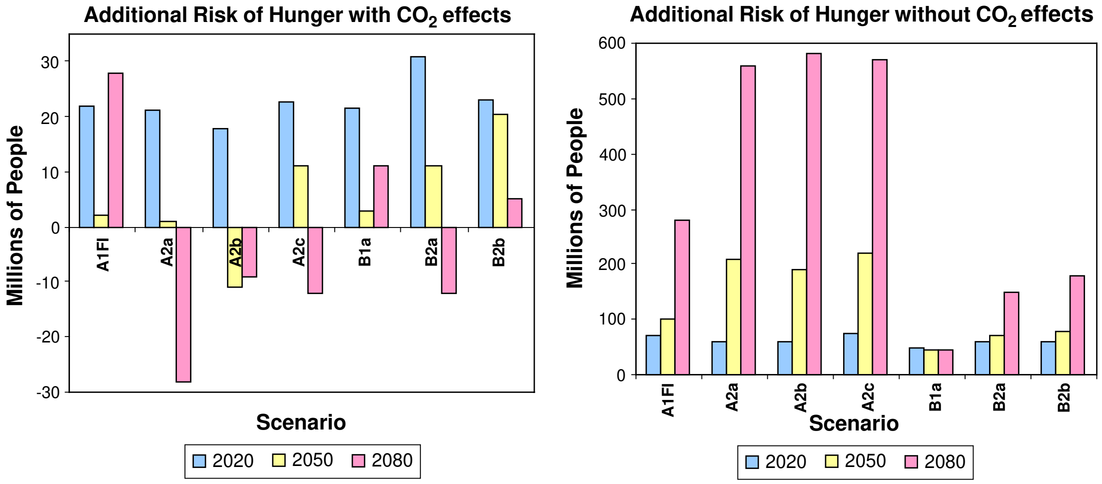

Fig. 14. Additional millions of people at risk under seven SRES scenarios with and without CO_2 effects, relative to the reference scenario (no climate change).

4. Conclusions

Four major points emerge from the changes in crop yield study. First, in most cases the SRES scenarios exerted a slight to moderate (0 to −5%) negative impact on simulated world crop yields, even with beneficial direct effects of CO_2 and farm-level adaptations taken into account. The only scenarios that increase global crop yields are derived from the SRES A2 ensemble assuming full realization of the CO_2 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 CO_2 effects on crop growth and water use as currently measured in experimental settings. The realization of these potential beneficial effects of CO_2 in the field remain 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%).

Second, 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 globalised world (A1FI and B1) experience greater reduction in yield than the scenarios of a more regionalised 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 polarisation 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 non-linearities in the food supply system. It has also highlighted the sensitivity of the results to the balance between CO_2 fertilisation and changes in climate, hence the presentation in this paper of yield change potentials with and without CO_2 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 policy-makers. 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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References

Darwin, R., Kennedy, D., 2000. Economic effects of CO_2 fertilization of crops: transforming changes in yield into changes in supply. Environmental Modeling and Assessment 5 (3), 157–168.

Derner, J.D., Johnson, H.B., Kimball, B.A., Pinter Jr, P.J., Polley, H.W., Tischler, C.R., Bouttons, T.W., LaMorte, R.L., Wall, G.W., Adam, N.R., Leavitt, S.W., Ottman, M.J., Matthias, A.D., Brooks, T.J., 2003. Above-and below-ground responses of C3-C4 species mixtures to elevated CO_2 and soil water availability. Global Change Biology 9, 452–460.

FAO, 2002. Food and Agriculture Organization of the United Nations. Agricultural databases, http://apps.fao.org/.

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, Climate Change and World Food Security, Vol. 137. Springer, Berlin.

Fischer, G., Shah, M., van Velthuizen, H., Nachtergaele, F.O., 2001. Global agro-ecological assessment for agriculture in the 21st Century. IIASA Research Report 02-02, International Institute for Applied Systems Analysis, Laxenburg, Austria, p. 119.

Iglesias, A., Rosenzweig, C., Pereira, D., 2000. Prediction spatial impacts of climate in agriculture in Spain. Global Environmental Change 10, 69–80.

Johns, T.C., Gregory, J.M., Ingram, W.J., Johnson, C.E., Jones, A., Lowe, J.A., Mitchell, J.F.B., Roberts, D.L., Sexton, D.M.H., Stevenson, D.S., Tett, S.F.B., Woodage, M.J., 2003. Anthropogenic climate change for 1860–2100 simulated with the HadCM3 model under up-dated emissions scenarios. Climate Dynamics 20, 583–612.

Kimball, B.A., Kobayashi, K., Bindi, M., 2002. Responses of agricultural crops to free-air CO_2 enrichment. Advances in Agronomy 77, 293–368.

Parry, M.L., Fischer, C., Livermore, M., Rosenzweig, C., Iglesias, A., 1999. Climate change and world food security: a new assessment. Global Environmental Change 9, S51–S67.

Reilly, J., Tubiello, F.N., McCarl, B., Melillo, J., 2001. Impacts of climate change and variability on agriculture. In: US National Assessment Foundation Document. National Assessment Synthesis Team, US Global Change Research Program, Washington, DC.

Rosenzweig, C., Iglesias, A., 1998. The use of crop models for international climate change impact assessment. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, pp. 267–292.

Rosenzweig, C., Iglesias, A., 2003a. Potential impacts of climate change on world food supply: data sets from a major crop modeling study, http://sedac.ciesin.columbia.edu/giss_crop_study/.

Rosenzweig, C., Iglesias, A., 2003b. Climate change and world food production: 1. Developing functions for impact assessment. 2. World food supply under several IPCC SRES scenarios. Goddard Institute for Space Studies, Special Report, New York, USA.

Rosenzweig, C., Iglesias, A., Fischer, G., Liu, Y., Baethgen, W., Jones, J.W., 1999. Wheat yield functions for analysis of land-use change in China. Environmental Modeling and Assessment 4, 128–132.

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

Tubiello, F.N., Ewert, F., 2003. Simulating the effects of elevated CO_2 on crops: approaches and applications for climate change. European Journal of Agronomy, in press.