# The Implications of Climate Change for Crop Yields, Global Food Supply and Risk of Hunger

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## Abstract

This paper reviews the series of studies, from 1994 to 2007, which have evaluated the potential effects of climate change on crop yield, food production and risk of hunger. There are two global studies of crop yield responses and several additional estimates of production that are based on the first of these. The studies cover three broad type of analysis: 1) effects under climate change but with underlying socio-economic characteristics largely unspecified, 2) effects under both changes in climate and with varying development pathways assumed to affect underlying socio-economics, and 3) effects under different policies of stablisation of greenhouse gases. There are some conclusions common to all studies: that climate change will generally reduce production potential and increase risk of hunger, and that Africa is the most adversely affected region. An additionally important initial conclusion is that pathways of sustainable economic development have a marked effect in reducing the adverse effects on climate change.

Key Words: climate change, agriculture, food supply, crop yields, food prices, risk of hunger

## 1. Introduction

The purpose of this paper is to review and summarise the conclusions of the series of studies since the early 1990s that have considered the effects of climate change on crop yield potential, cereal production, food prices and the implications for changes in the number of hungry people. The IPCC has recently concluded that, while there is extensive potential to adapt to small amounts of warming, and that the next few decades might even bring benefits to higher latitudes through longer growing seasons, at lower latitudes even small amounts of warming would tend to decrease yields and, beyond about two degrees of warming would decrease yields in almost all parts of the world [1]. This regional unevenness of effect climate change on agriculture around the world has very great implications for food security, especially when (even without the challenge of climate change) almost 800 million people in the developing world are estimated to be to experiencing some form of shortage in food supply [2]. Where crops are grown near their maximum temperature tolerance and where dryland, non-irrigated agriculture predominates, the challenge of climate change could be overwhelming, especially on the livelihoods of subsistence farmers and pastoral people, who are weakly coupled to markets.

The paper is divided into four parts, reflecting the four main sets of studies that have been published: 1) Studies in the early 1990s using point-based crop growth models with what are now termed 'low resolution' models of climate, 2) later studies which used higher resolution models, 3) Ricardian and other economic approaches that used the yield estimates from the foregoing to develop estimates of production, and 4) studies which have incorporated more spatially resolute analyses of altered yield potential based on GIS systems rather than point-based modelling.

## 2. Initial analyses using 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 marginalised economies [3]. In these studies there were two main tasks:

Firstly, the estimation of potential changes in crop yield 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) [4,5]. The crops modelled were wheat, rice, maize and soybean, accounting for more than 85% of the world's traded grains and legumes. Secondly, the estimation of food production, prices and the number of people at risk of hunger by using estimated yield changes in a world food trade model, The Basic Linked System (BLS) developed at the International Institute for Applied Systems Analysis (IIASA) [6].

The scenarios for these early studies were created by changing the observed data on current climate (1951-80) according to doubled $CO_2$ simulations of three general circulation models (GCMs). The

GCMs used were those from the Goddard Institute for Space Studies (GISS) [7,8], Geophysical Fluid Dynamics Laboratory (GFDL)[9] and the United Kingdom Meteorological Office (UKMO) [10].

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 [11]. 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 [12 ,13], maize [14,15], paddy and upland rice [16] and soybean [17]. The analyses included the effects of enhanced ambient C02 levels on crop growth both through altered water-use efficiency and rates of photosynthesis [19,20 21,22,23,24,25,] . but the crop models did not simulate effects of altered climate on weeds and insect pests.

Regional yield estimates were derived from the modelled site information, assuming the current mix of rainfed and irrigated production, the current crop varieties, nitrogen management and soils. Although the number of sites was limited (112 in all) it was argued that these related to regions that account for about 70% of the world’s grain production [26], and thus could enable credible conclusions concerning world production to be drawn.

The altered yield data was input to a dynamic model of the world food system (the Basic Linked System) 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[27]. 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 with regard to net food trade [3,27]. 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.

As in most studies of impacts of climate change, the modelled yields were first estimated for a baseline scenario (a trended future case assuming no climate change). This involved projection of the agricultural system to the year 2060 with projected yields and a projected political and economic context of the world food trade. These projections assumed: a world population of 10.2 billion by 2060 (the UN median estimate); 50% trade liberalisation in agriculture introduced gradually by 2020; moderate economic growth (ranging from 3.0% per year in 1980-2000 to 1.1% per year in 2040-2060); crop yield for world total, developing and developed countries increasing annually by 0.7%, 0.9% and 0.6%, respectively.

Three further scenarios were introduced: those which assumed differing levels of adaptation, which assumed varying amounts of future economic and population growth , and assumed full rather than partial trade liberalisation,

### *2.1 Effects on yields and production*

The results show that climate change scenarios which exclude the direct physiological effects of $CO_2$ predict decreases in simulated yields in many cases, while the direct effects of increasing atmospheric $CO_2$ 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.

Under the estimated effects of climate change and atmospheric $CO_2$ on crop yields, world cereal production is estimated to decrease between 1 and 7% depending on the GCM climate scenario (Figure 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. Decreases in production are estimated by the BLS to lead to increase in prices (by 25 to 150%) and increases in hunger (by 10 to 60 %) (Figure 1).

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

### *2.2 Effect under different levels of adaptation*

Level 1 adaptations largely offset the negative climate change induced effects in developed countries, improving their comparative advantage in world markets (Figure 2). In these regions cereal production increases by 4% to 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 c 5-50% (Figure 3). This indicates that Level 1 adaptations would have relatively little influence on reducing the global effects of climate change.

More extensive adaptation (Level 2) reduces impacts by a third and in some cases virtually eliminates them. 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 to 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 of net cereal imports into developing countries. Under the UKMO scenario large cereal price increases limit the increase of 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.

### *2.3 Effects assuming full trade liberalisation and lower economic and population growth rates.*

Assuming full trade (rather than 50 per cent) liberalisation 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.

Estimates were also made of impacts under a lower economic growth scenario (10% lower than reference), which leads to 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.

Assuming the UN Low rather than Mid Estimate gives a population in 2060 of 7.3 instead of 5.9 billion, and leads to a model estimate of higher GDP/capita (about 10%) and 40% fewer people at risk from hunger compared with the reference scenario.

## 3. Subsequent analyses using higher resolution climate models, and for different time periods

After 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 were now 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 [29,30]. All climate change scenarios were based on an IS92a-type forcing (one which assumes greenhouse gas emissions stem from a 'business-as-usual' future in economic and social terms).

### *3.1 The reference scenario (the future without climate change)*

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

Cereal prices are estimated at an index of 92.5 (1990 = 100) for the 2080s, thus continuing the trend of falling real cereal prices over the last 100 years. This occurs because the BLS standard reference scenario has two phases of price development. Between 1990 to 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% liberalisation of trade has been realised, prices begin to fall again. This has obvious ramifications for the number of hungry people which is now estimated at about 300 million or about 3% of total population in the 2080s (~ 521 million in 1990, about 10% of total current population).

### *3.2 Effects of climate change*

Changes in cereal production, cereal prices, and people at risk of hunger estimated for the HadCM2 climate change scenarios (with the direct $CO_2$ effects taken into account) show that world is generally able to feed itself in the next millennium. Only a small detrimental effect is observed on cereal production, manifested as a shortfall on the reference production level of around 100mmt (-2.1%) by the 2080s (+/-10mmt 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 160mmt (about -4%) by the 2080s (Figure 4)[31].

Reduced production leads to increases in prices. Under the HadCM2 scenarios cereal prices increase by as much as 17% (+/- 4.5%) by the 2080s (Figure 4). 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 ~250 million) by the 2080s (Figure 4). The HadCM3 results are again more extreme, falling outside the HadCM2 range with an estimated 125+ million additional people at risk of hunger by the 2080s. All BLS experiments allow the world food system to respond to climate-induced supply shortfalls of cereals and higher commodity prices through increases in production factors (cultivated land, labour, and capital) and inputs such as fertiliser.

## 4. Analyses for different socio-economic scenarios

More recently, the projected effects of climate change on global food supply have been considered 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 was to understand the nature of these complex interactions, and how they affect people at risk of hunger in the coming decades[33].

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)[32]. 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 [3,31,33]. Population levels for each SRES scenario for given timelines were taken from the CIESIN database[33]. 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.

### *4.1 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. 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 1)[33]. 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 percent. 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.

The contrast between the yield change in developed and developing countries is largest under the A2 scenarios. Under the A2 scenarios, crop yields in developed countries increase as a result of moderate temperature increases, and the direct effects of the high concentration of $CO_2$. In contrast, crop yields decrease in developing countries as a result of regional decreases in precipitation and temperature increases. The results highlight the complex regional patterns of projected climate variables, $CO_2$ effects, and agricultural systems that affect crop production under the different SRES futures.

### *4.2 Effects on cereal production, cereal prices, and risk of hunger*

*The reference case - the future without climate change.* The BLS projects year-on-year increases in production, assuming no change in climate, as indicated in Table 1 and Figure 5. The differences between the SRES scenarios reflects different assumptions about population (and resulting demand) and income levels (and resulting consumption).

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, in the A1 and B1 worlds, after a moderate increase of between 30 and 70% by the 2050s, a decline in cereal prices towards the end of this century is projected in accordance with the expected decline in global populations (Figure 6). 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 (Figure 7).

*The future with climate change.* Figure 8 shows the impact of climate change on global cereal production under the seven SRES scenarios. The changes are shown as reductions in millions 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 per cent reductions for B1 and B2 by the 2080s, and 10 per cent 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 CO2 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 Figure 8.

As would be expected, an inverse pattern in the estimated change in global cereal prices tends to occur (Figure 9); with large price increases (under no $CO_2$) for 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 c. 2020.

The measure risk of hunger is based on the number of people whose incomes allow them to purchase sufficient quantities of cereals[31], 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 (that is, compared with the reference case) is shown in Figure 10. Assuming no $CO_2$ 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 (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.

## 5. Analyses of production potential using Ricardian methods

Based on broadly the same set of the crop yield estimates [34] a recent study has used a series of Ricardian country and regional models to estimate altered food production due to climate change [35]. The assumed climate scenarios are the same as previously discussed, but the economic models allow for land-use changes that would accompany shifts in land values due to alterations in comparative advantage between crops, giving a more realistic indication of the potential response.

The results differ only in degree from those of the previous studies. Global agricultural output is estimated to decrease by 16 per cent assuming no carbon fertilisation, and by 3 per cent with full carbon fertilisation (Table 2). The regional pattern shows quite strong adverse effects on yield in tropical areas, especially Africa, the Middle East and the south Asia (Figures 11 and 12).

## 6. Analyses based on changes in agro-ecological zones.

A very different approach from point-based crop-growth modelling is the study of how zones of crop suitability may shift location in response to changes of climate. When combined with modelling of the length of crop growing season, either due to changes in moisture or heat availability, this method enables evaluation of both changes in yield at any given place in combination with changes in extent of suitability [36].

Table 3 shows estimated changes in production for two SRES futures (A2 and B2) for four GCMs. These broadly mirror the estimates on the point-based modelling of a decade earlier, showing decreases in cereal output in developing countries and increases in developed countries. Increases in potential occur in northern parts of North America and Europe, in contrast to decreases in Africa and South America (Figure 13). These geographical differences are reflected in the additional numbers estimated to be at risk of undernourishment due to climate, which for 2080 range from 40 (for the smallest amount of warming, B2) to 170 million (for the highest, A1FI) (Figure 14).

The two different analyses ( crop model and crop zone suitability) give broadly similar estimates of global numbers additional at risk from hunger or under-nourishment. While both use the BLS the two approaches adopt quite different methods in modelling altered crop yields; and this gives greater confidence to estimates of ultimate effects on hunger (Table 4).

## 7. Comparing the range of analyses

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

One [37] uses six broad land classes around the world and analyses the change in extent of these due to altered moisture and temperature, the yield results from which are very similar to the analyses from crop models. But the economic assumptions in the approach, especially the land-use changes, eliminate three-quarters of the climate-induced reductions in production, at least until high levels of warming (above 3 deg C) start to reduce land suitability markedly.

A summary of the different approaches by the IPCC [38] indicates that all conclude a decrease in output and consequent increase in prices, but vary in their conclusion regarding when (along a pathway of increasing global temperature) this decrease will occur. The crop modelling and agro-ecological analyses conclude that prices will rise with even small amounts of warming ( 1 to 2 deg C), while the other analyses suggest that they will first decrease (due to increased potential with extended growing seasons at higher latitudes) before decreasing when temperature increases exceed 2 or 3 deg C (Figure 15). This point of inflection from a positive to a negative effect on global food output, and whether it occurs at 1 or 2 or 3 degrees C increase in global temperature, is central to the current debate as to whether global warming may, for the first few decades, have a beneficial effect. However, as we have seen, such a point of inflection is dependent on the very uncertain mix of the positive effects from higher CO2 and the negative effective from higher temperature.

## 8. Reducing impacts by stabilising $CO_2$ concentrations at lower levels

The final section of this paper explores the implications of the stabilisation of $CO_2$ concentrations at defined levels[39]. These stabilisation scenarios are among the set defined by the Intergovernmental Panel on Climate Change [40].

### *8.1 Scenarios*

Two stabilisation scenarios (stabilising at $CO_2$ concentrations of 550 ppmv and 750 ppmv) are considered, and compared with the IS92a unmitigated emissions scenario[41]. There is little difference in concentrations between the two scenariosup to the 2020s, but thereafter they begin to diverge. The S750 scenario stabilises $CO_2$ concentrations by 2250, whilst the S550 scenario assumes stabilisation occurs by 2150. Achieving stabilisation at 750 ppmv and 550 ppmv, under the pathways assumed here, requires cuts in annual $CO_2$ emissions of around 13% and 30% respectively by 2025, relative to the 2025 emissions assumed under IS92a. We interpret these stabilisation scenarios as representing actual $CO_2$ concentrations for the purposes of crop and vegetation modelling (e.g. actual $CO_2$ concentration reaches 750 ppmv by 2250), because there are no accepted stabilisation scenarios for the other radiatively-significant trace gases. We therefore assume that all other greenhouse gas concentrations remain constant at 1990 values.

### *8.2. Effects on yield potential*

Figure 16 shows the estimated changes in national potential grain yield by the 2080s, assuming no changes in crop cultivars, under the three emissions scenarios[39]. 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.

Stabilisation 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. Stabilisation 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 $CO_2$ concentrations, altered rainfall and optimal growing conditions. The intermediate combination of increases in temperatures, available moisture and ambient $CO_2$ 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 $CO_2$ 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 $CO_2$).

### *8.3. Implications for food security and hunger*

Table 1 summarises global cereal production (under realistic assumptions about trade liberalisation) in the absence of climate change and under the three emissions scenarios (unmitigated, S70 and S550). Table 7 shows the number of people at risk from hunger. Stabilisation at 750 ppmv reduces the unmitigated impacts by around 75%, while stabilisation at 550 ppmv achieves are more modest reduction of around 50%. The assumption of full CO2 effects appears to explain this, the beneficial effects of higher levels of CO2 under 750 compensating for the adverse effects of higher temperatures. Under less optimal conditions of CO2 effect, the reverse would be likely.

Global figures, however, hide considerable regional variations. The vast majority (~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**.** It appears that the beneficial effects of stabilisation are also less in this region. Under an S750 world the additional number of people at risk of hunger is reduced by ~30% while under an S550 future the reduction in the climate induced impact is only 20%. Since this conclusion assumes full CO2 effects, more analysis is needed of the consequences of mitigation assuming partial effects of CO2 fertilisation.

## 9. Conclusions

From the range of studies currently available the indication is that 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 geographic 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 $CO_2$ on crop growth. Current estimates are based upon field experiments that have assumed near-optimal applications of fertiliser, pesticide and water, and it is possible that the actual ‘fertilising’ effect of higher levels of $CO_2$ 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.

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**Figure 1. Change in cereal production, cereal prices and people at risk of hunger in 2060. The reference case for 2060 assumes no climate change: Cereal production = global 3286 mmt, developed 1449 mmt, developing 1836 mmt; cereal prices 1970 = 100; and 641 million people at risk of hunger [3,27]**

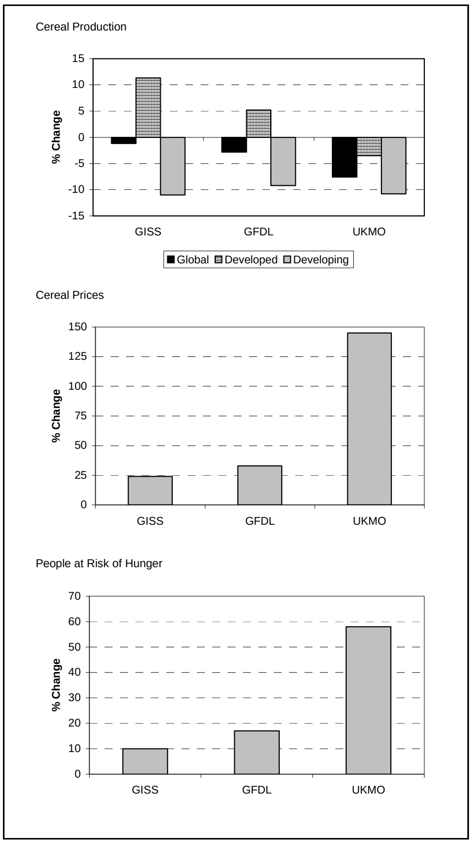

**Figure 2a. Change in cereal production under three equilibrium climate change scenarios in 2060 assuming implementation of Adaptation Level 1 (AD1)** [3,27]**.**

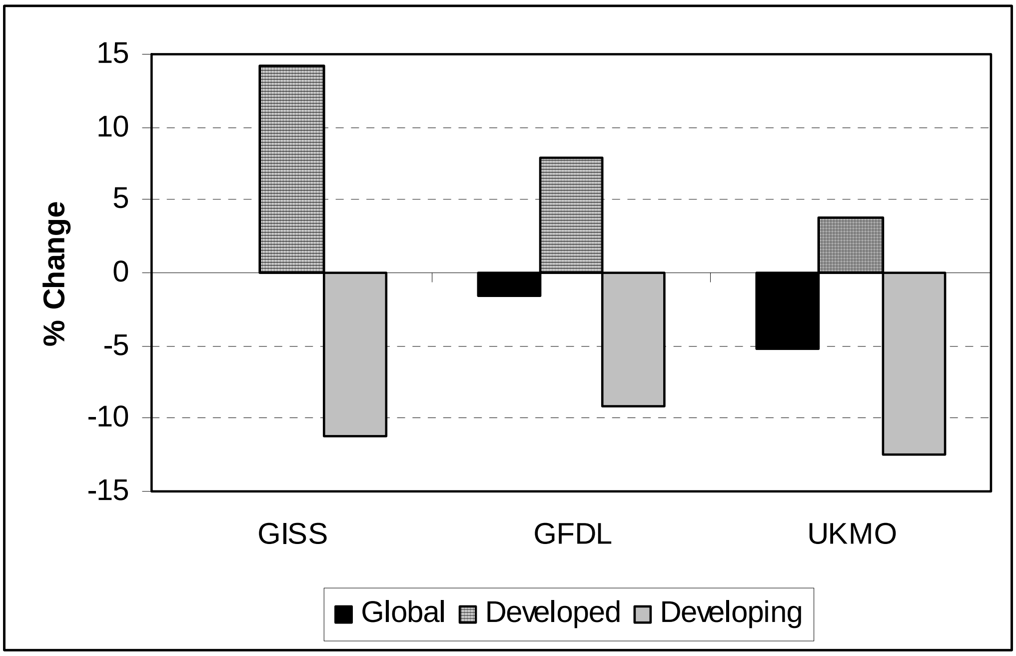

**Figure 2b. Change in cereal production under three equilibrium climate change scenarios in 2060 and assuming the implementation of Adaptation Level 2 (AD2)** [3,27]

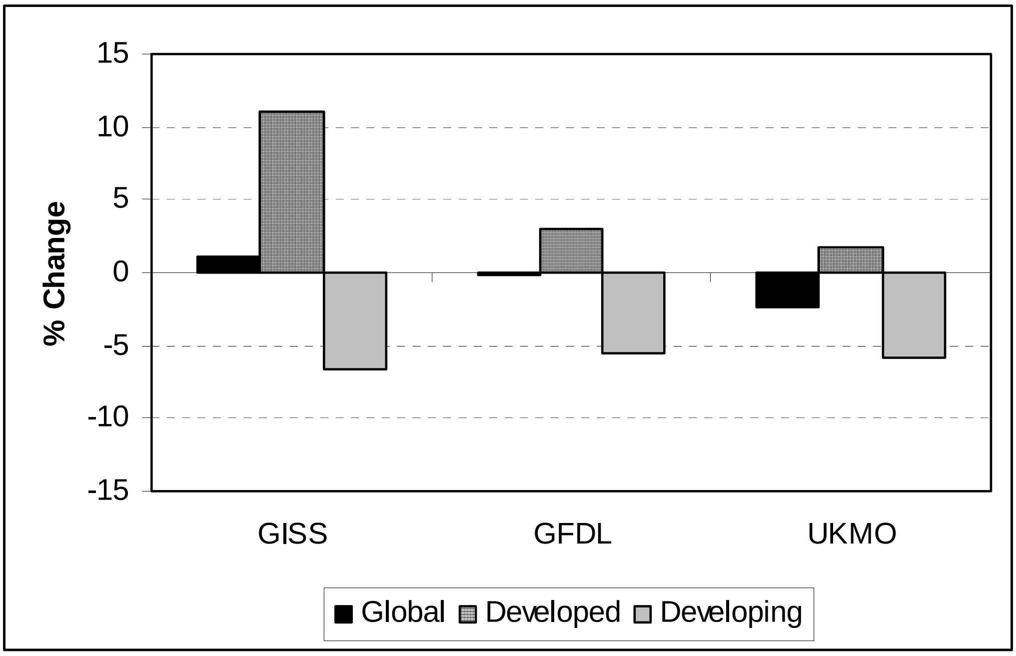

**Figure 3. Change in cereal prices and people at risk of hunger for climate change scenarios (CC) and with Adaptation Levels 1 and 2 (AD1 and AD2)**[3,27]

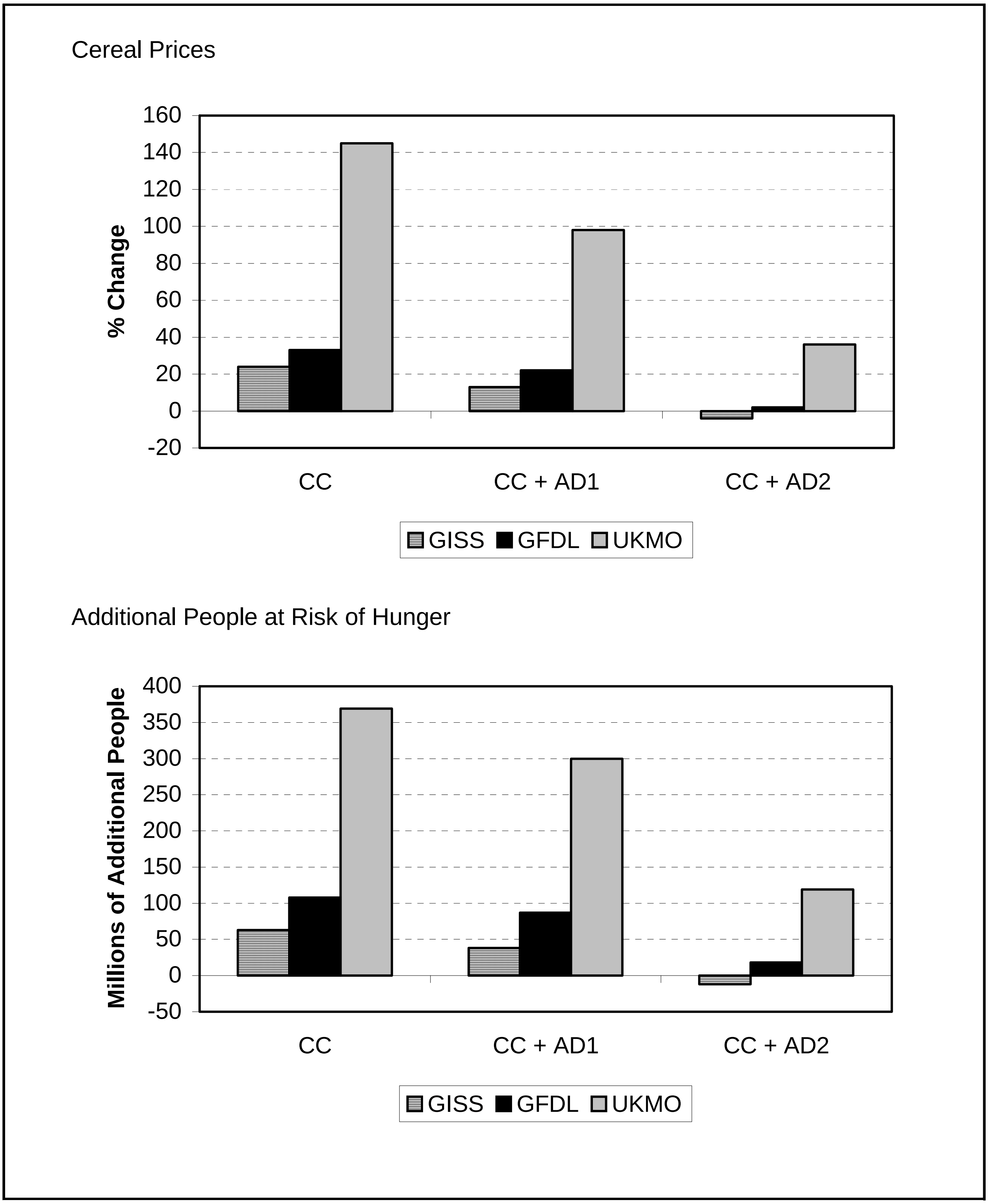

**Figure 4a. Changes in global cereal production (mmt). Grey blocks are the production change projected under the HadCM3 climate change scenario (compared with the reference case). Bars depict the range of change under the four HadCM2 ensemble simulations** [31]

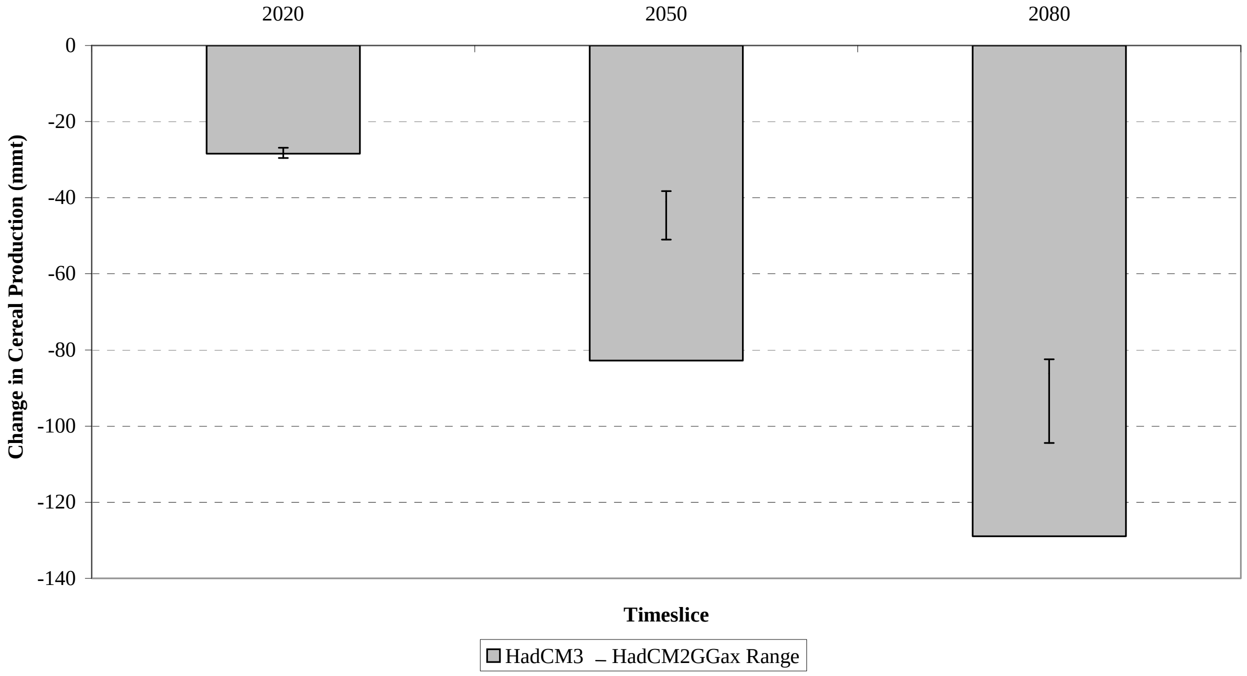

**Figure 4b. Percentage change in cereal prices. Grey blocks are the price changes projected under the HadCM3 climate change scenario (relative to the reference case). Bars depict the range of price change under the HadCM2 ensemble experiments**[31]

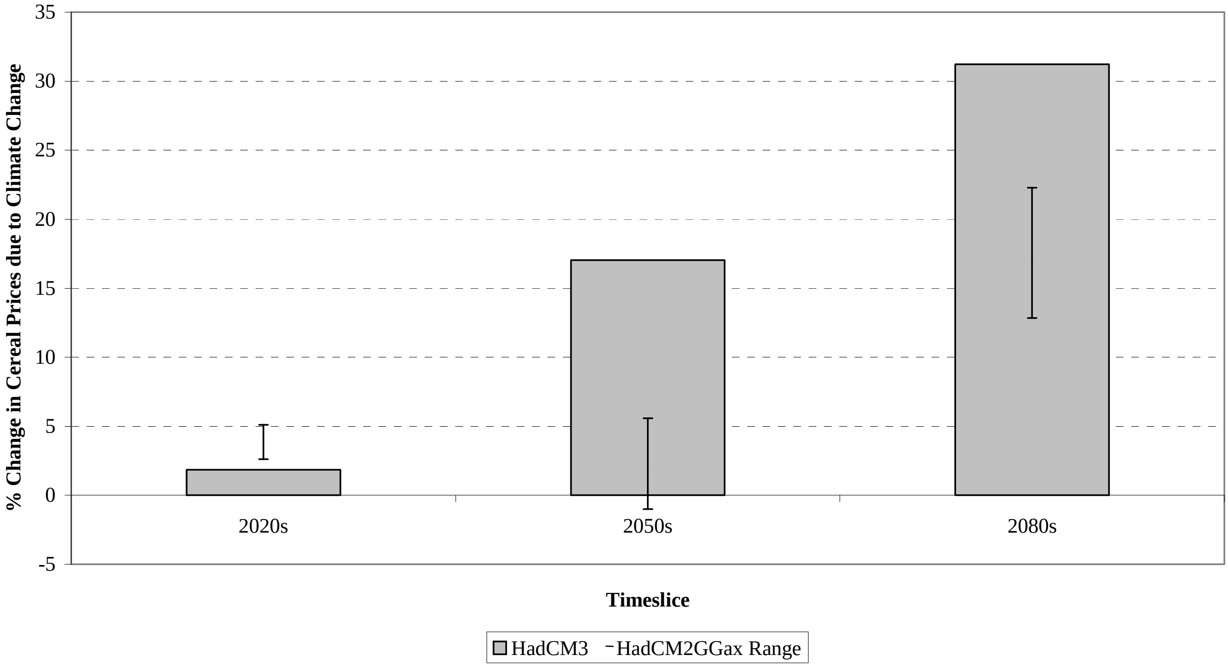

**Figure 4c. Global estimates of the additional number of people at risk of hunger due to climate change compared with the reference case. HadCM3 estimates are represented by the grey blocks. Bars represent the range of results under the four HadCM2 ensemble simulations** [31]

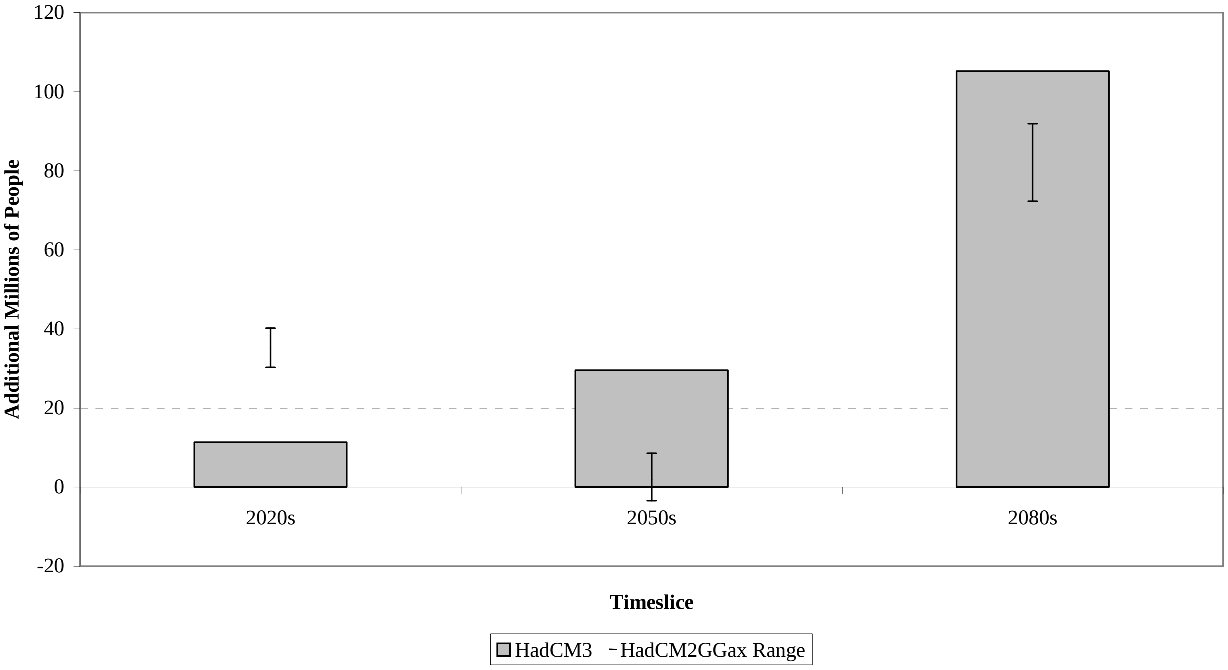

**Figure 5. Future reference case estimates of cereal production under the four SRES marker scenarios (no climate change)[33]**

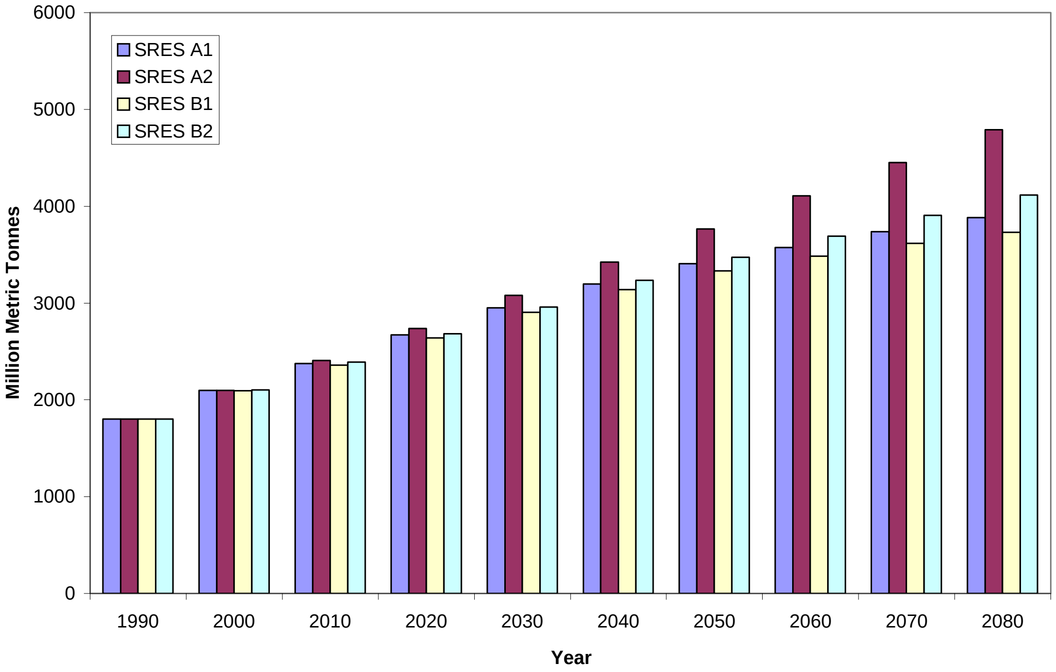

**Figure 6. Future reference case global cereal prices, relative to 1990 prices, for the four SRES marker scenarios (no climate change)** [33]

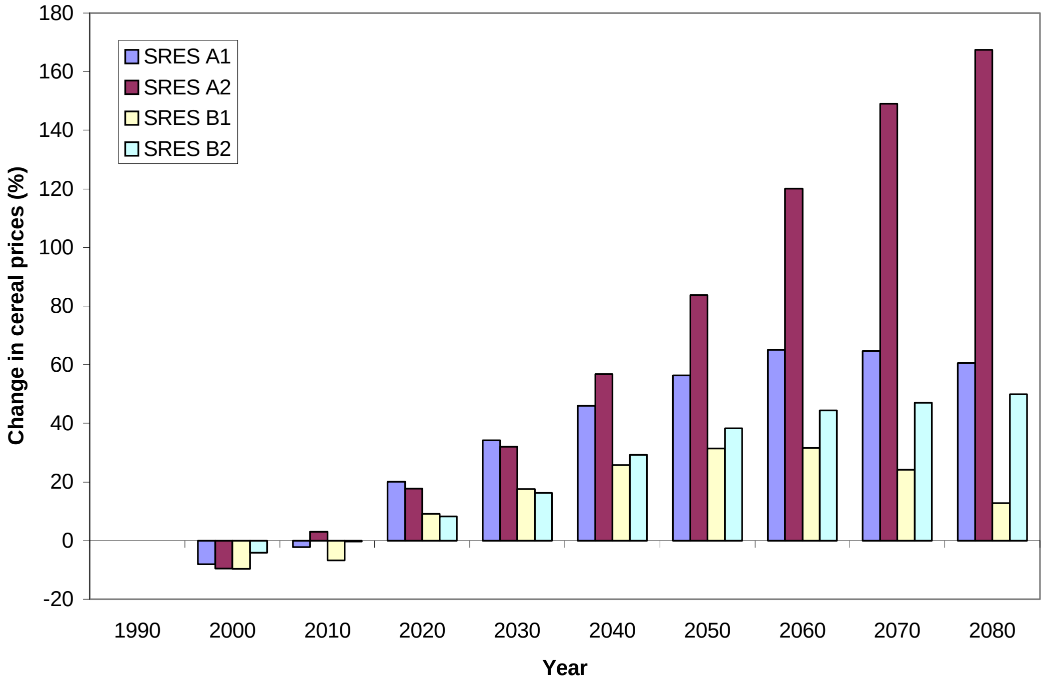

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Figure 7. Future reference case estimates of the numbers of people at risk of hunger, for the four SRES marker scenarios (no climate change)[33]

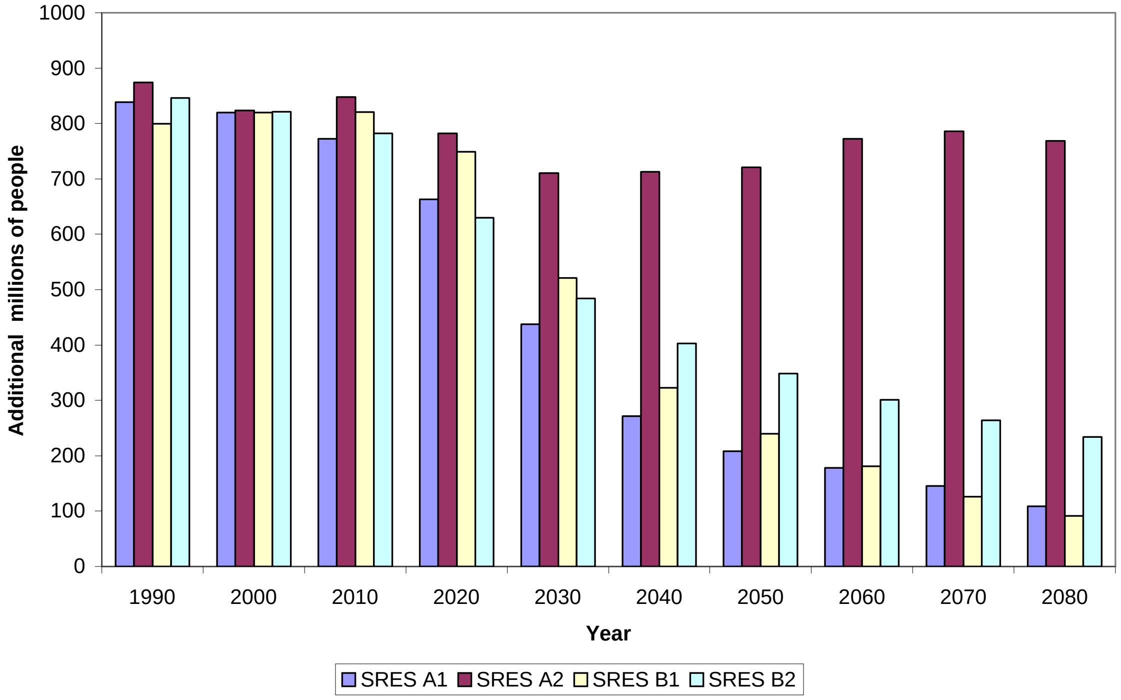


**Figure 8. Changes in global cereal production due to anthropogenic climate change under seven SRES scenarios with and without $CO_2$ effects, relative to the reference scenario (no climate change)** [33]

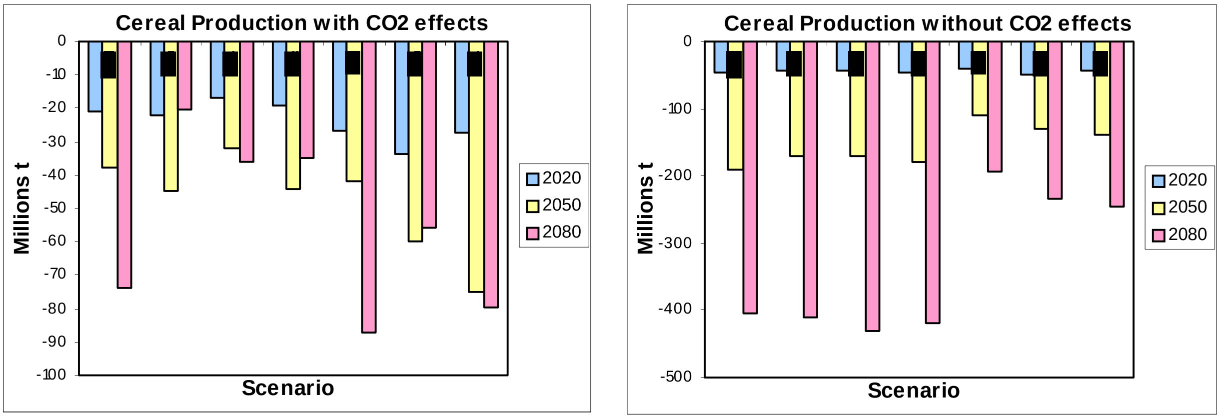


**Figure 9. Changes in global cereal prices under seven SRES scenarios with and without $CO_2$ effects, relative to the reference scenario (no climate change)** [33]

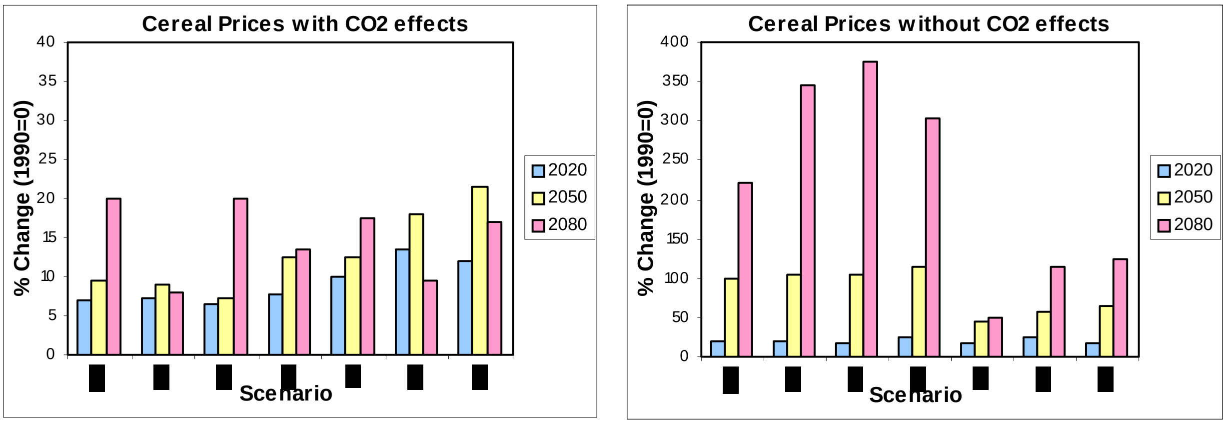


Figure 10. **Additional millions of people at risk under seven SRES scenarios with and without $CO_2$ effects, relative to the reference scenario (no climate change)** [33]

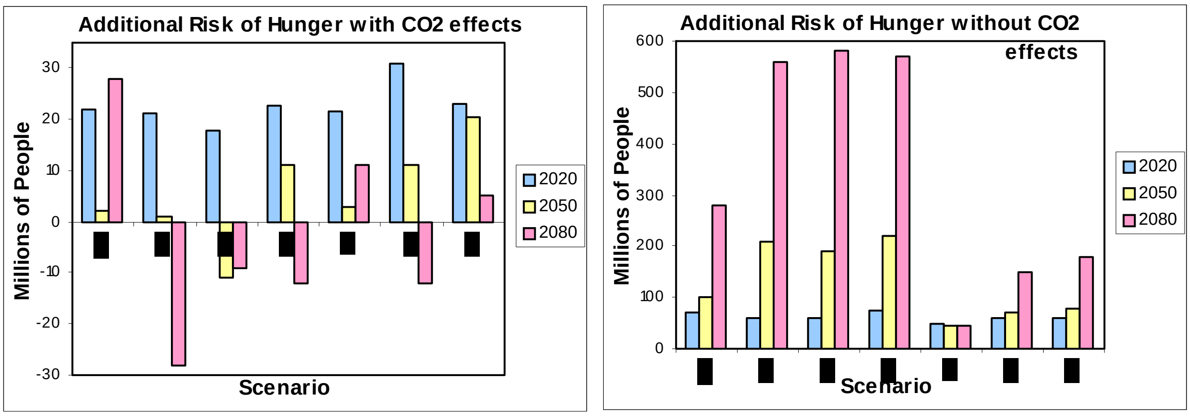


**Figure 11. Changes in yields, 2080s, without CO2 effects. Ricardian economic analysis.** [35]

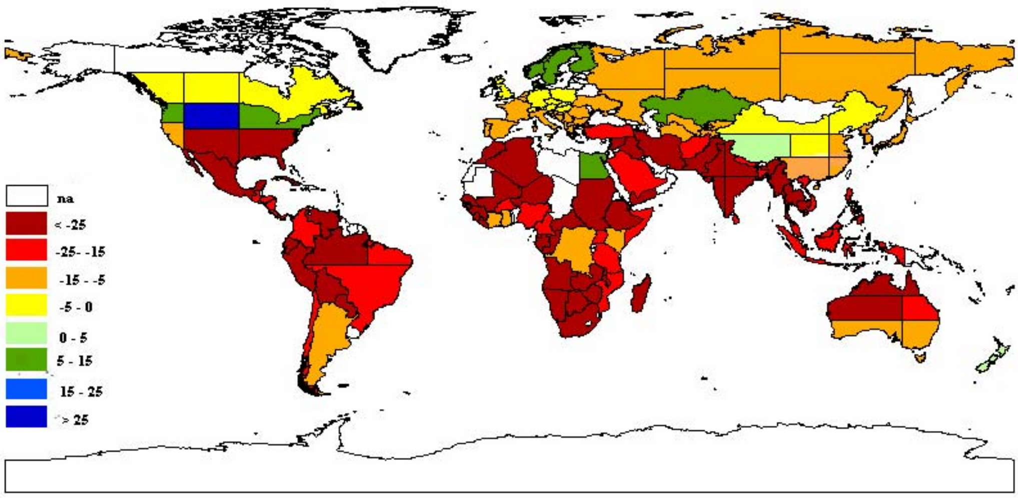


**Figure 12. Changes in yields, 2080s, with CO2 effects. Ricardian economic analysis** [35]

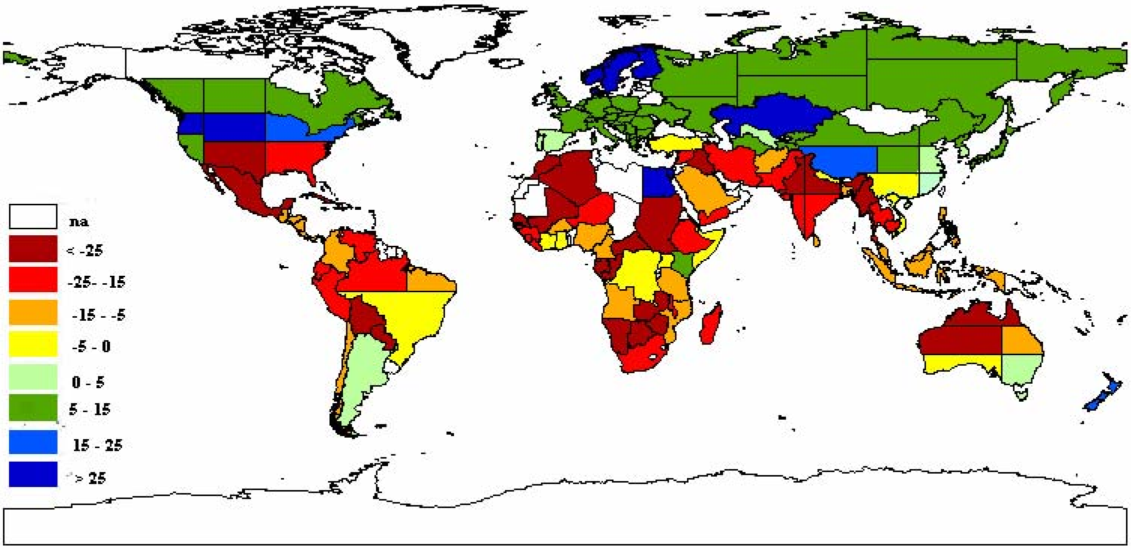


**Figure 13. Comparison of land with rain-fed cop production potential for current climate, for future climate projected by HadCM3-A1FI scenario in 2080s, and land in use for cultivation in 1994-1996 (million ha).** [36]

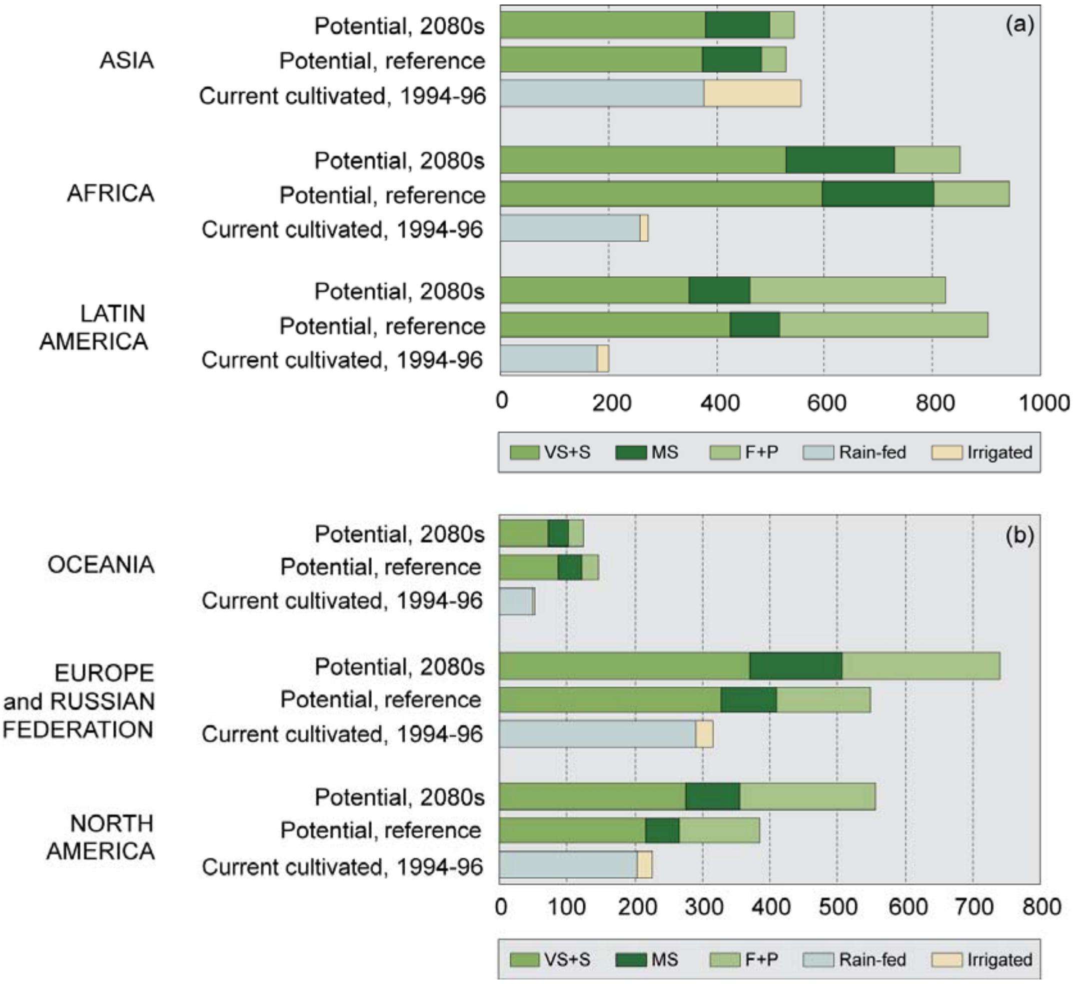


**Figure 14. Additional number of people at risk from under-nourishment due to climate change, by region, for socio-economic conditions of the SRES A2 scenario in the 2080s.** [36]

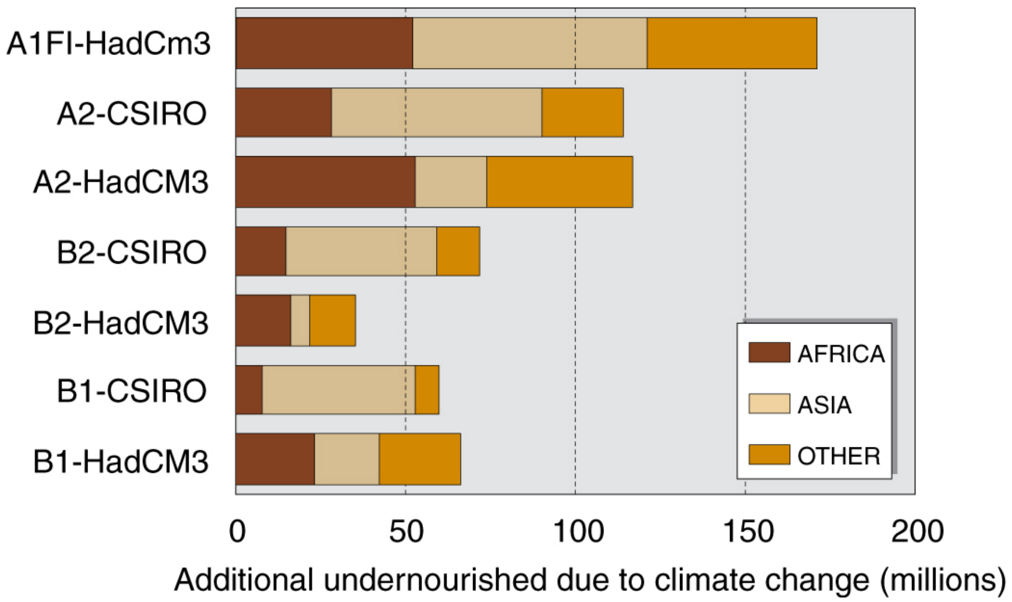


**Figure 15. Cereal prices (per cent of baseline) versus global mean temperature change for major modelling studies. Prices interpolated from point estimates of temperature effects.** [38]

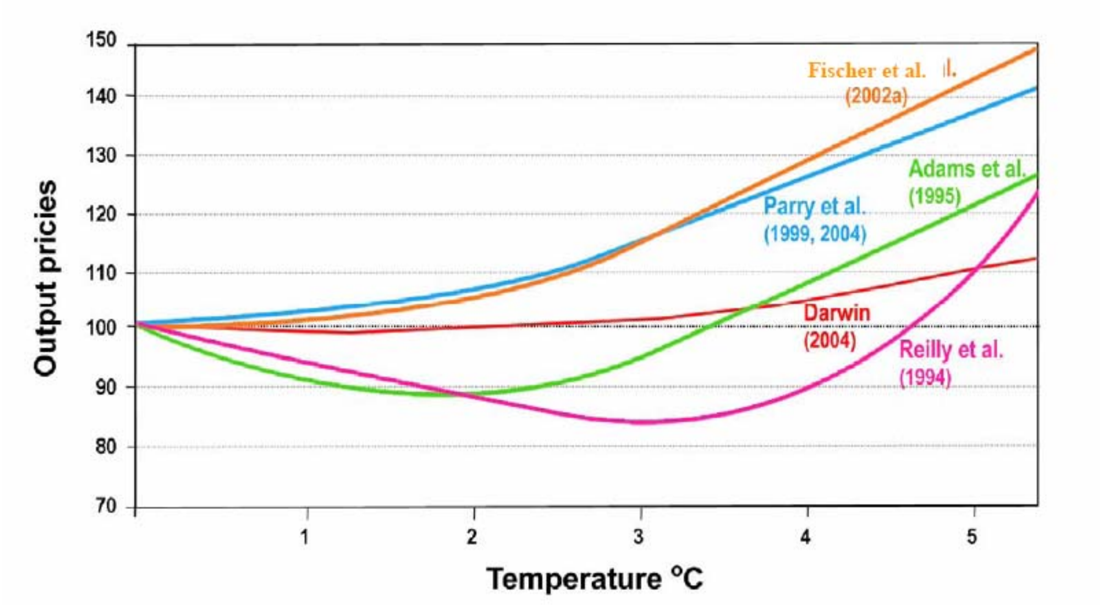


**Figure 16. Changes in national cereal crop yields by the 2080s under three different emissions scenarios - unmitigated (IS92a: top map), S750 (middle map) and S550 (bottom map)** [39]

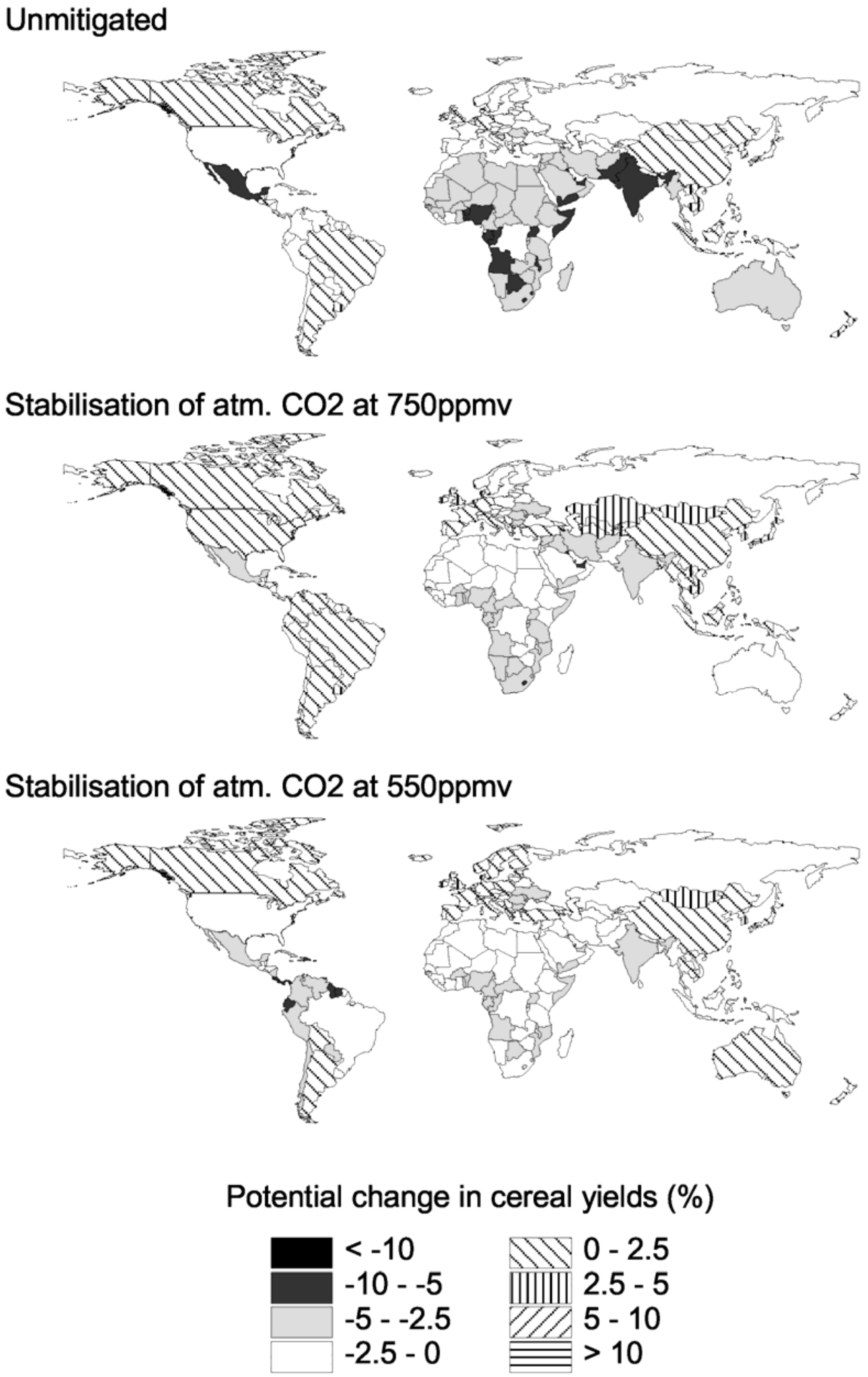


**Table 1. Aggregated developing-developed country differences (per cent) in average crop yield changes from baseline for the HadCM2 and HadCM3 scenarios[33, 39]**

| | 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 (%)<br>Developed-Developing | 10.4 | 9.8 | 8.4 | 10.2 | 7.0 | 8.7 | 9.3 | | 6.6 | 7.7 |

**Table 2. Estimated change in agricultural production, 2080s, with and without CO2 effects [35]**

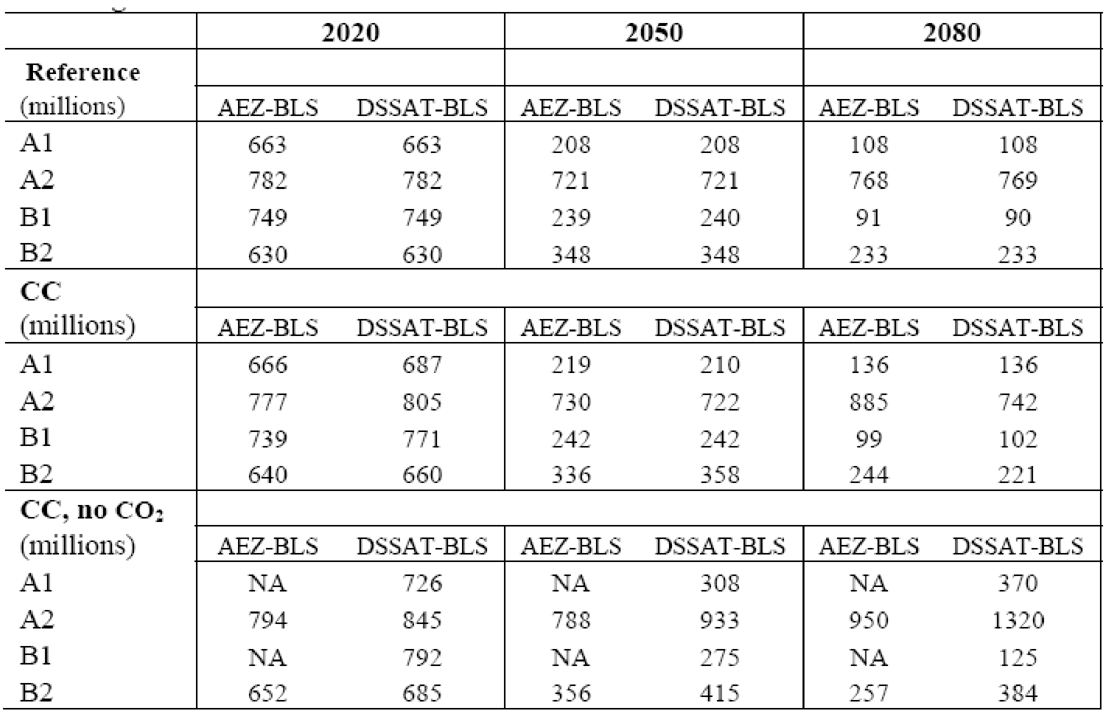
| | Without CO2 effects | With CO2 effects |
|---|---|---|
| Global | | |
| Output-weighted | -15.9 | -3.2 |
| Population-weighted | -18.2 | -6.0 |
| Median by country | -23.6 | -12.1 |
| | | |
| Industrial countries | -6.3 | 7.7 |
| Developing countries | -21.0 | -9.1 |
| Median | -25.8 | -14.7 |
| Africa | -27.5 | -16.6 |
| Asia | -19.3 | -7.2 |
| Middle East North Africa | -21.2 | -9.4 |
| Latin America | -24.3 | -12.9 |

**Table 3. Climate-change impacts on crop production, without economic adjustment, year 2080 (% change)** [36]

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

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

**Table 4. Additional number at risk of hunger. DSSAT= crop modelled yield analysis. AEZ= Agro-ecological zone analysis** [38]



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

**Table 5. Average annual cereal production (million metric tonnes)** [39]

| | No climate change | Unmitigated | S750 | S550 |
|---|---|---|---|---|
| 1990 | 1800 | | | |
| 2020s | 2700 | 2670-2674 | 2672 | 2676 |
| 2050s | 3500 | 3475 | 3973 | 3477 |
| 2080s | 4000 | 3927 | 3987 | 3949 |

Note: 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

**Table 6. Number of people at risk of hunger (millions)** [39]

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

Note: The range in estimates for the unmitigated scenario represents the range between the four ensemble partners