Book Chapter in Manfred Schulz and Uwe Kracht (eds.): "Food and Nutrition Security in the Process of Globalization"

25. Global environmental change as projected by IPCC and its impact on food availability

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Keywords

Climate change, temperature rise, CO_2 concentration, precipitation, water, IPCC, food supply, adaptation, emission scenarios, integrated assessment

Summary

Human activities, above all burning of fossil fuels and changes in land cover, are modifying the concentration of atmospheric constituents and properties of the Earth's surface. This has led to a rise in global mean temperatures of about 0.6°C over the 20th century. Additional warming, changes in precipitation patterns, sea-level rise, and increase in extreme climate events should be expected in the future. Degradation of natural resources, such as water and soils, could negatively affect agricultural production capacity. Currently available studies of climate impacts on agriculture conclude that food prices are likely to continue to fall over the coming decades and that impacts on aggregate welfare will account for only a small percentage of GDP. However, these results remain very uncertain: many interactions between environmental and social impacts have not been explicitly taken into account, the distributional impacts of climate change may be severe, and large-scale discontinuities in the Earth system provide reasons for concern.

Careers

Hermann Lotze-Campen holds a Ph.D. in Agricultural Economics and has published several articles on modelling of agricultural policies and international agricultural trade. He has worked as an agricultural policy consultant and in a business development project on agricultural applications of satellite remote sensing data. Currently he coordinates the Sustainability Geoscope project at the Potsdam Institute for Climate Impact Research (PIK) and works on the interaction between global food demand, agricultural production and water use.

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1. Scenarios on global change – an overview of the IPCC results

Human activities have reached a level and intensity such that they are among the key factors influencing important sub-systems of the Earth. Human society is no longer just affected by natural environmental changes, it rather plays a key role in shaping not only social but also environmental conditions on a global scale. The era we have now entered, in which the human and the natural part of the Earth system have definitely become inseparable and in which it is no longer meaningful to analyse human action and environmental changes in isolation, has been called the "anthropocene" (Crutzen and Stoermer 2000).

Human activities – primarily burning of fossil fuels and changes in land cover – are modifying the concentration of atmospheric constituents or properties of the Earth's surface that absorb or scatter radiant energy. Over the 20th century globally averaged surface temperatures have increased by 0.6 ± 0.2°C. In the light of new evidence and taking into account the remaining uncertainties, it is likely that most of the observed warming has been due to the increase in greenhouse gas concentrations in the atmosphere. Future changes in climate are expected to include additional warming, changes in precipitation patterns and amounts, sea-level rise, and changes in frequency and intensity of some extreme events (White et al. 2001: 21).

Many parts of the Earth system will be affected by the projected climate change, including the water cycle, carbon and nutrient cycles, the productivity and structure of natural ecosystems as well as the productivity of agricultural, grazing, and timber land. Changes in these systems in response to climate change would affect human welfare, positively as well as negatively. Human welfare would be impacted through changes in supplies of and demand for water, food, energy, and other tangible goods that are derived from these systems. Climate change impacts will affect the prospects of sustainable development in different parts of the world and may further widen existing inequalities. Possible impacts range from substantial damage to and irreversible loss of some sub-systems of the Earth to modest impacts to which systems may readily adapt and impacts that would even be beneficial for some systems (White et al. 2001: 22).

The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization and the United Nations Environment Programme (UNEP) in 1988 to assess scientific, technical, and socio-economic information that is relevant in understanding human-induced climate change, its potential impacts, and options for mitigation and adaptation. In 2001 IPCC completed its Third Assessment Report (TAR) which provides a broad overview and a summary of recent scientific advances in understanding global change (White et al. 2001: 21).

The analytical framework for the study of climate impacts and global environmental changes is based on extensive scenario development by the IPCC. The backbone of these scenarios are projections and assumptions about key socio-economic developments such as growth of population and gross domestic product (GDP). These deliver important inputs for greenhouse gas emission scenarios which are developed with the use of global circulation models (GCMs). Since the spatial resolution of GCMs is rather low, the results have to be interpolated and downscaled for use in regional impact studies.

Land-use and land-cover scenarios together with scenarios on non-climate-related environmental trends and sea-level rise scenarios complete the picture of the most relevant global changes to be considered. For the special analysis of climate impacts on agricultural production the most important variables are CO_2 concentration in the atmosphere, temperature and regional water availability. These have a yield impact which can be assessed by the use of crop simulation models (CSMs). Yield changes can then be converted into socio-economic impacts using economic modelling tools (White et al. 2001: 26).

The Special Report on Emissions Scenarios (SRES) of the IPCC (Nakicenovic and Swart 2000) provides a basic reference for the scenario framework on global change analysis, covering the period from 1990 to 2100. Table 1 provides a summary description of these scenarios and their implications for major aspects of global change.

Table 1: Ranges of socio-economic developments according to the SRES scenarios and their implications for atmospheric composition, climate and sea level (White et al. 2001: 27)

Date	Global population (billions)	Global GDP (trillion 1990 US$ per year)	CO_2 concentration (ppm)	Global temperature change (°C)	Global sea-level rise (cm)
1990	5.3	21	354	0	0
2000	6.1-6.2	25-28	367	0.2	2
2050	8.4-11.3	59-187	463-623	0.8-2.6	5-32
2100	7.0-15.1	197-550	478-1099	1.4-5.8	9-88

Given the range of SRES emissions and uncertainties about the carbon cycle, atmospheric CO_2 concentration is estimated to rise to between 478 and 1099 parts per million (ppm) by the year 2100. This would cause a rise in global average temperatures of 1.4–5.8°C between the years 1990 and 2100, assuming a range of climate sensitivities. Over most land areas the rates of temperature increase are expected to be greater than the global average, and they will be most pronounced at high latitudes in winter. Northern hemisphere snow cover will be reduced. In southern and southeast Asia and southern South America warming will be below global averages between June and August.

There will be increases in average water vapour and precipitation on a global scale. Regionally, December-February precipitation is expected to increase in medium to high latitudes of the northern hemisphere and tropical Africa. Precipitation is expected to decrease over central America, with little change in southeast Asia. Precipitation between June and August is estimated to increase in high northern latitudes and south Asia; it is expected to change little in southeast Asia and to decrease in central America, Australia, southern Africa, and the Mediterranean region (White et al. 2001: 28).

Changes in the frequency and intensity of extreme climate events can also be expected. It is very likely that daytime maximum and minimum temperatures will increase, accompanied by an increased frequency of hot days. Heat waves will become more frequent, and the number of cold days and frost days will decline. Increases in high-intensity precipitation events are likely at many locations; Asian summer monsoon precipitation variability also is likely to increase. The frequency of summer drought will increase in many continental interior locations, and both droughts and floods associated with El Niño events are likely to intensify (White et al. 2001: 29).

2. Responses of agro-ecosystems to global environmental changes

Global climate change as described in the SRES scenarios may cause serious degradation of natural resources such as water, soils, forests, marine fisheries, and air, which in turn could affect agricultural production capacity. However, neither the extent nor the direction of the effects are clear in many cases, and especially the dynamic interactions between various environmental changes are not yet well understood. Moreover, global average effects may occur very differently under specific regional conditions. Frequently, simulation results are model dependent in their spatial extension, so that there are no clear conclusions to be drawn from a wide range of case studies.

Climate change will impact agriculture by causing damage as well as gain at scales ranging from individual plants or animals to global trade networks. At the plant or field scale, rising CO_2 concentrations are likely to interact with changes in temperature, water availability, soil conditions, climate variability, extreme events like floods and droughts, and other environmental changes to affect crop and animal physiology. Hence, crops and forage plants are likely to be affected by a combination of various pressures, which have to be taken into account in crop simulation studies (Gitay et al. 2001: 252).

Effects of enhanced CO_2 on crop growth

The photosynthetic activity of plants, i.e. conversion of water and CO_2 into carbohydrates, can be expected to increase with higher atmospheric CO_2 concentration. However, there is a difference between different physiological classes of plants, so-called C3 and C4 types. While C4 species like maize, sorghum, sugar cane, and millet tend to be less responsive to concentrations enriched beyond present levels, C3 plants like wheat, rice and soybeans respond readily to increased CO_2 (Rosenzweig and Hillel 1995).

Short-term responses to elevated CO_2 of plants grown in artificial conditions are notoriously difficult to extrapolate to crops in the field. Even the most realistic free-air CO_2 enrichment (FACE) experiments undertaken to date create a modified area, analogous to a single irrigated field in a dry environment, and impose an abrupt change in CO_2 concentration. At a CO_2 concentration of 550 ppm, in some experiments spring wheat increased grain yields by 8-10% under well-watered conditions. Other studies under optimal nitrogen and irrigation increased final grain yield by 15% and 16% for two growing seasons at 550 ppm CO_2, compared with control treatments. If these latter results are linearly extrapolated to the possible effect of a doubling of the current atmospheric CO_2 concentration, i.e. 700 ppm, yields under ideal conditions would be 28% higher (Gitay et al. 2001: 255).

Higher levels of atmospheric CO_2 also induce plants to close their stomates, i.e. small leaf openings, so that they may use less water while producing more carbohydrates. This dual effect will probably improve water-use efficiency. However, this effect will be moderated through the interaction with other climatic changes (Rosenzweig and Hillel 1995).

Effects of higher temperature

In middle and higher latitudes, global warming will extend the length of the potential growing season, allowing earlier planting of crops in the spring, earlier maturation and harvest, and the possibility of completing two or more cropping cycles during the same season. Crop-producing areas may expand to the north in Canada and Russia, but yields may be lower due to poorer soil quality and limited crop adaptation to longer daylight in summer. In warmer, lower latitude regions, increased temperatures may accelerate release of CO_2 by plant respiration, leading to less optimal growth conditions. Another important effect of high temperature is accelerated physiological development, resulting in hastened maturation and reduced yield (Rosenzweig and Hillel 1995, Lucht et al. 2002).

Because temperature increase enhances photorespiration in C3 species, the positive effects of CO_2 enrichment on photosynthetic productivity are usually greater when temperature rises. With moderate temperatures, long-term doubling of current ambient CO_2 under field-like conditions leads to a 30% enhancement in the seed yield of rice, despite a 5-10% decline in the number of days to heading. However, at higher temperatures, yields are likely to decline under CO_2-enriched conditions for rice, soybeans and wheat (Gitay et al. 2001: 255).

Water availability and quality

Agriculture of any kind is strongly influenced by the availability of water. Climate change will modify precipitation, evaporation, groundwater recharge, surface runoff, and soil moisture storage. The effect of climate change on stream flow and groundwater recharge varies regionally and among scenarios, largely following projected changes in precipitation.

Changes in total seasonal precipitation or in its pattern of variability are both important. The occurrence of moisture stress during flowering, pollination, and grain-filling is especially harmful to maize, soybeans, and wheat. Increased evaporation from the soil and accelerated transpiration in the plants themselves will cause moisture stress (Rosenzweig and Hillel 1995). Some studies conclude that higher temperatures and reduced snow cover may cause reduced soil moisture in Northern Hemisphere mid-latitude summers. However, the local effects of climate change on soil moisture will vary not only with the degree of climate change but also with soil characteristics like water-holding capacity (Arnell and Liu 2001: 199).

The demand for water for irrigation is projected to rise in a warmer climate, causing increased competition between agriculture on the one hand and urban and industrial users, whose demands are also expected to increase due to population growth. Agriculture accounts for about three quarters of water withdrawals on a global scale, and while irrigated land accounts for only 16% of total arable land, it produces 40% of the world's crops. However, there are signs of a slowing rate of expansion of irrigation, as 10-15% of irrigated land is degraded to some extent by waterlogging and salinisation caused by intensified evaporation. Peak irrigation demands are also predicted to rise due to more severe heat waves (Gitay et al. 2001: 253).

In the absence of water deficit, C4 photosynthesis is believed to be CO_2 saturated at present atmospheric CO_2 concentration, but it could become CO_2-limited under drought. Although increased productivity from increased water-use efficiency is the major response to elevated CO_2 in a C3 or C4 crop that is exposed frequently to water stress, changes in climatic factors (temperature, rainfall) may interact with elevated CO_2 to alter soil water status, which in turn will influence hydrology and nutrient relations. Therefore, to realistically project impacts on crop yields and regional evaporation, more research is needed on the interactions of elevated CO_2, high temperature and precipitation (Gitay et al. 2001: 255).

Soil fertility and erosion

Soil degradation emerges as one of the major challenges for global agriculture. It is induced via erosion, chemical depletion, water saturation, and solute accumulation. Various estimates put the total loss of land at 5-10 million hectare per year. The severity, frequency, and extent of soil erosion are likely to be altered by changes in rainfall amount and intensity and by changes in wind. By reducing the water-holding capacity and organic matter contents of soils, erosion tends to increase the magnitude of nutrient and water stress. Hence, in drought-prone and low-nutrient environments soil erosion is likely to aggravate the detrimental effects of a rise in air temperature on crop yields (Gitay et al. 2001: 257).

There is not yet any clear consensus regarding the magnitude and sign of interactions between elevated CO_2 and nutrient availability for crop growth. On average, plants grown at high nutrient supply respond more strongly to elevated CO_2 than nutrient-stressed plants. Nevertheless, a rise in atmospheric CO_2 concentration may help plants to cope especially with low nitrogen availability. Plants grown under elevated CO_2 generally increase the allocation of carbohydrates to roots which increases the capacity and/or activity of below-ground carbon sinks in some systems. The relationship between C and N turnover in soils after exposure to elevated CO_2 is not fully understood and it is still a matter of debate whether the availability of soil nitrogen for crop plants is reduced after an increase in atmospheric CO_2 concentration (Gitay et al. 2001: 256).

Soil organic carbon stocks result from the balance between inputs and decomposition of soil organic matter (SOM). Increased air and soil temperatures can be expected to increase the mineralisation rate of SOM fractions that are not physically or chemically protected. This may lead in the long term to negative effects on structural stability, water-holding capacity, and nutrient availability. However, experiments that impose sudden changes in temperature and CO_2 and last only a few years are unlikely to predict the magnitude of long-term responses in crop productivity, soil nutrients and carbon sequestration (Gitay et al. 2001: 256).

Climate variability, extreme events and sea-level rise

In all agricultural regions, the effects of natural climate variability are likely to interact with human-induced climate change to determine the magnitude of impacts on agricultural production. If weather variability increases, as indicated by some authors, average grain yield for wheat may be reduced. However, the distinction between natural variability and human-induced climate remains difficult for some regions (Gitay et al. 2001: 258).

The importance of diurnal climate variability should also be noted. Differential warming, with daily minima more affected than daily maxima, may lead to less water loss through evapo-transpiration and better water use efficiency. This is likely to lead to enhanced photosynthesis, crop growth, and yield – although at a possible loss of nutritional quality (Gitay et al. 2001: 258).

Extreme meteorological events, such as heat waves, heavy storms, floods or droughts, may disrupt crop production. A large part of fertile agricultural land is located either along rivers or in coastal zones, which may be affected by more frequent floods and sea-level rise. On the other hand, agricultural production in continental areas could be subject to more serious droughts.

A sea-level rise of up to 50 cm by the mid of the 21st century could pose a threat to agriculture in low-lying coastal areas, where impeded drainage of surface water and of groundwater might take place. In parts of Egypt, Bangladesh, Indonesia, China, the Netherlands, and Florida agriculture is likely to become increasingly difficult to sustain (Rosenzweig and Hillel 1995).

Weeds, pests and diseases

Pre-harvest losses to pests in major food and cash crops are estimated to be 42% of global potential production. Warmer climates provide more favourable conditions for the proliferation of insect pests. Altered wind patterns may change the spread of both wind-borne pests and of bacteria and fungi that are the agents of crop disease. Ranges of several important crop pests in the US have expanded since the 1970s, which may be partly explained by consistent climate trends. Any direct yield gain caused by increased CO_2 could be partly offset by losses caused by insects, pests and weeds. These biotic constraints have been neglected in many studies on climate change impacts on crop yields (Gitay et al. 2001: 257).

Impact on food and forage quality

For rice, the amylose content of the grain – a major determinant of cooking quality – is increased under elevated CO_2, implying firmer grains after cooking. The protein content of the grain decreases under combined increases of temperature and CO_2. With wheat, elevated CO_2 reduces the protein content of grain and flour by 9-13%, while increased temperature tends to decrease dough strength. Hence, the quality of flour for bread-making is degraded under conditions of increased CO_2 levels and high temperatures.

The quality of forage is likely to be affected only in tropical climates, where the protein-to-energy ratio is critical. Basically, lowering of the protein-to-energy ratio in forage could reduce the availability of microbial protein to ruminants for growth and production, leading to more inefficient utilisation of the feed base and more waste, including emissions of methane which is also an important greenhouse gas (Gitay et al. 2001: 254).

Impacts on livestock

Direct effects on farm animals involve heat exchanges between the animal and its environment, which affect well-being, health and performance. For example, milk production in some regions of the US might decline by an additional 5-14% beyond normal summer reductions. Conception rates of dairy cows were reduced by as much as 36% during the summer season in the southeastern US. Indirect effects may occur with regard to quality and quantity of feedstuffs and the severity and distribution of livestock diseases and parasites (Gitay et al. 2001: 257).

3. Adaptation of agricultural production systems

Agricultural production systems have a wide variety of adaptive actions at their disposal to lessen or overcome adverse effects of changes in climate and other environmental conditions. Farm-level adjustments include the introduction of more suitable crop varieties or species, switching cropping sequences, adjusting sowing dates and other field operations, increasing fertiliser applications, adopting soil-moisture-conserving tillage, and improving irrigation efficiency. A major adaptive response will be the breeding of heat- and drought-resistant crop varieties by utilising genetic resources that may be better adapted to new climatic and atmospheric conditions. Genetic engineering may also help to exploit the beneficial effects of CO_2 enhancement on growth and water use, but these prospects remain very uncertain.

Livestock production is likely to adjust successfully to climate change, as livestock producers have historically shown their ability to cope with climate variability. However, this conclusion remains rather vague, since there is a serious lack of systematic simulation studies comparable to the available modelling work on crops (Gitay et al. 2001: 266).

Economic adjustments include shifts in regional production centres, changes in production input shares, and shifts in commodity trade flows according to changing comparative advantages. Overall market adjustments have the potential to moderate regional impacts of reduced yields (Rosenzweig and Hillel 1995).

Adaptive capacity and costs of adaptation

The actual impact of climate change on agricultural production heavily depends on the specific regional capacity of the agricultural sector to adapt to these changes. The ability to adapt plays a critical role not only in mean impacts but also in spatial variability of impacts. Climate change is likely to have its greatest adverse impacts on areas where resource endowments are poorest and the ability of farmers to respond and adapt is most limited (Gitay et al. 2001: 268).

Historically the agricultural sector has shown enormous capacity to adjust to social and environmental changes, including experience with historical climate fluctuations, translocation of crops across agro-climatic zones, substitution of new crops for old ones, and resource substitution induced by scarcity. Examples are the Argentine Pampas, the US Great Plains, and Northern China. However, adaptation processes are hardly considered in most case studies on climate change impacts. Only a small number of studies compare yield changes with and without agronomic adaptation. Usually, the adaptation strategies being modelled are limited to a small subset of a much larger universe of possibilities, which may underestimate adaptive capacity (Gitay et al. 2001: 265). As one study on dry-land grain production in Montana shows: with climate change, CO_2 fertilisation, and including adaptation, mean farm returns change by –11 to +6% relative to the base climate, and variability in returns increases by +7 to +25%. On the other hand, without adaptation mean returns change by –8 to –31% and variability increases by +25 to +83% (Gitay et al. 2001: 268).

While adaptation cannot be taken for granted, the actual costs of adaptation are neglected in most studies. Improvements in agricultural production depend upon investments in research and infrastructure. Some options for agricultural adaptation may be inexpensive, while others, especially high-efficiency, water-conserving technologies, involve major investments. Increased demand for water by competing sectors may limit the viability of irrigation as an adaptation to climate change. To give some examples, costs to retrain farmers in new practices, to develop additional irrigation, or to apply more fertiliser may be considerable. Most studies also fail to account for the process of long-term, endogenous adaptation of technology, which may have important cost-benefit implications. Changes in fixed capital for on-farm and off-farm infrastructure may be the most significant cost associated with adaptation to climate change. The ability of any country to take advantage of the opportunities and to avoid the drawbacks related to climate change will depend on the availability of adequate resources as well as on the quality of the research base (Gitay et al. 2001: 269; Rosenzweig and Hillel 1995).

Environmental and natural resource consequences

Climate change may cause substantial shifts in the mix of crops grown and the related changes in land cover. Only very few studies analyse the environmental consequences of increased demands on land and water resources. For example, competition from crop production could aggravate direct climate-induced losses of forests in moist tropical regions. Expanded irrigation may lead to groundwater depletion, soil salinisation, and waterlogging. If extra water needs for agricultural irrigation are drawn from rivers or aquifers, the direct effect of climate change on hydrological regimes and ecosystems may be enhanced. Changes in agricultural land use may affect water balance and water quality in river catchments (Arnell and Liu 2001: 224).

Increased demand for irrigation is likely to increase the opportunity cost of water and reduce water availability for wildlife and natural ecosystems. One important adaptation strategy is to increase irrigation efficiency, as the current difference in irrigation efficiency between the developed-country average and some important agricultural areas in developing countries are huge and provide high potential for improvement. Climate-induced adaptive changes in agricultural land use and management are likely to have greater impacts on soil carbon stocks than the direct effects of climate alone (Gitay et al. 2001: 269).

4. Global and regional impacts on food supply

In order to model the net effects of global environmental changes on agricultural production and to assess the effectiveness of possible adaptation measures, a well-founded reference scenario has to be defined. However, this already reveals considerable uncertainties, especially about long-term socio-economic developments, which contribute to an overall uncertain outcome of climate impact studies on agriculture.

Current status of the global food system

Climate change aside, several recent studies anticipate that aggregate food production is likely to keep pace with demand, so that real food prices will be stable or will slowly decline during the first two decades of the 21^{st} century (Gitay et al. 2001: 253).

Relatively few studies have attempted to predict likely paths for food demand and supply beyond 2020. There are reasons for optimism that growth in food supply is likely to continue apace with demand beyond 2020. For example, population growth rates are projected to decline during the 21^{st} century, and multiple lines of evidence suggest that agricultural productivity potential is likely to continue to increase. Rosegrant and Ringler (1997) project that current and future expected yields will remain below theoretical maximums for the foreseeable future, implying opportunities for further productivity growth (Gitay et al. 2001: 253).

Other analysts are less optimistic about long-term world food prospects. The supply of the best arable land is being exhausted and rates of productivity growth are declining. Some studies indicate concerns about declining rates of investment in agricultural productivity. Despite the advances in biotechnology, most yield improvements during the first decades of the 21^{st} century are likely to continue to come from conventional plant and animal breeding techniques. Hence, simple extrapolation of yield for impact assessment may be too optimistic. The implication is that confidence in predictions of the world food demand and supply balance and price trends beyond the early part of the 21^{st} century is low (Gitay et al. 2001: 253).

Global socio-economic impacts of climate change

The results of a range of global modelling efforts as well as regional case studies on the effects of climate change on the global agro-food system have been summarised by the IPCC as follows: On a global scale, with the average warming expected by SRES scenarios over the next century, agricultural production and prices are likely to continue to follow the downward path observed in the 20^{th} century. As a result, impacts on aggregate welfare are a small percentage of GDP and tend to be positive, especially when the effects of CO_2 fertilisation are incorporated. However, these conclusions remain very uncertain, as a lot of the above-mentioned interactions between various environmental and social impacts have not been explicitly taken into account to the present date. Moreover, impacts of climate change may be larger and more adverse in poorer parts of the world, where farmers and consumers are less able to adapt. By the 2080s, the additional number of people at risk of hunger as a result of climate change is estimated to be about 80 million, of whom about two thirds will live in Africa. (Gitay et al. 2001: 269-270). Table 2 provides a selective overview of model results surveyed by the IPCC, with a focus on results with global coverage.

Table 2: Climate change impacts on global agricultural production. Summary results of selected recent studies; percentage changes relative to a situation without climate change (Gitay et al. 2001: 259-261).

Study	Crops	Yield impact	Socio-economic impact	Comments
Parry et al. 1999	Wheat, rice, maize, soybeans	All cereals by 2080: *Africa* (-10 to +3%) *Asia* (-10 to +5%) *Europe* (-10 to +3%) *Latin America* (-10 to +10%) *North America* (-10 to +3%)	By 2080: global cereal production (-4 to -2%), cereal prices (+13 to +45%), number of people at risk of hunger (+36 to +50%)	With farm-level adaptations and economic adjustments; no feedback between economic adjustments and yields; CO_2 direct effects included
Darwin et al. 1995	13 commodity groups: wheat, other grains, non-grains, livestock, fish/ meat/milk, other processed foods, plus 7 non-agric. groups		Agricultural prices: wheat (-10 to +3%) other grains (-6 to -4%) global GDP (+0.3 to +0.4%)	With adaptation through market-induced land-use change; CO_2 effect not included
Rosenzweig and Iglesias 1998	Wheat, rice, maize, soybeans (same sites as Parry et al. 1999)	Temperature +2°C: +8% (maize) to +16% (soybeans) Temperature +4°C: -8% (rice) to -2% (wheat) By 2050: Wheat (-18 to +25%) Maize (-26 to +13%) Soybeans (+23 to +24%)		Includes direct effects of CO_2; adaptation more successful at high and mid-latitudes than at low latitudes
Winters et al. 1999	Maize, rice, wheat, coarse grains, soybeans	*Africa*: Maize (-29 to -23%) Rice (0%) Wheat (-20 to -15%) Coarse grains (-30 to -25%) Soybeans (-2 to +10%) *Asia*: Maize (-34 to -20%) Rice (-12 to -3%) Wheat (-54 to -8%) Coarse grains (-34 to -22%) Soybeans (-9 to +10%) *Latin America*: Maize (-26 to -18%) Rice (-26 to -9%) Wheat (-34 to -24%) Coarse grains (-27 to -19%) Soybeans (-8 to +12%)	*Africa*: Total agricultural production (-13 to -9%) GDP per capita (-10 to -7%) Agricultural prices (-9 to +56%) *Asia*: Total agricultural production (-6 to 0%) GDP per capita (-3 to 0%) Agricultural prices (-17 to +48%) *Latin America*: Total agricultural production (-15 to -6%) GDP per capita (-6 to -2%) Agricultural prices (-8 to +46%)	With farm-level adaptations and CO_2 direct effects; yield impacts are weighted average of country-level yield changes; values for total agricultural production and GDP include both yield and price impacts

Regional impacts

The distribution of climate effects among regions and people will be uneven. The IPCC report provides a broad overview of regional case studies that model the yield impacts of climate change, with and without direct CO_2 effects, and with and without adaptation. In the tropics, most crops are near theoretical temperature optimums, and any additional warming is deleterious to yields. Subsistence farmers and pastoral people could also be negatively affected. By contrast, temperate crop yields benefited at least some of the time from climate change in two-thirds of the case studies surveyed. Generally positive changes at mid- and high latitudes (such as the US, Canada, and Australia) are likely to be offset by reductions in yields at low latitudes, mostly in developing countries. Countries with the lowest incomes and least adaptive capacity may be the hardest hit (Gitay et al. 2001: 258).

Africa

Africa is probably the continent most vulnerable to climate change. Diminishing water resources, desertification and agricultural production are issues of crucial concern. Climate change will worsen food security, adding to a situation which is already characterised by a major deficit in food production in many areas. Potential declines in soil moisture will be an additional burden. Food-insecure countries are at greater risk of adverse impacts of climate change. Inland and marine fisheries provide a significant contribution to protein intake in many African countries. As a result of water stress and land degradation, inland fisheries will be rendered more vulnerable to episodic drought and habitat destruction. Ocean warming is likely to impact coastal marine fisheries (White et al. 2001: 46).

Asia

Natural resources are already under stress in Asia, which accounts for more than 60% of the world's population. Climate change is likely to increase this pressure, although the magnitude would differ significantly across Asian sub-regions and countries. Food security appears to be the primary concern in Asia. Crop production and aquaculture would be threatened by thermal and water stress, sea-level rise, increased flooding, and strong winds associated with intensive tropical cyclones. This could negatively affect yields of major crops in China and India. Pests and diseases may spread more widely if Asia became warmer and wetter in temperate and tropical regions. On the other hand, areas in mid- and high latitudes will experience increases in crop yield, due to a northward shift of the agro-ecosystem boundary and a longer duration of the growing season (White et al. 2001: 47).

Australia and New Zealand

Water resources are already stressed in some areas; this stress brings problems especially related to salinisation and the competition between agriculture, power generation, urban areas, and environmental flows. Increased evaporation and possible decreases in rainfall in many areas would adversely affect water supply and agriculture. Drought frequency is likely to increase in parts of Australia and New Zealand. Enhanced plant growth and water-use efficiency resulting from CO_2 increases may provide initial benefits that offset any negative impacts from climate change. However, the balance is expected to become negative with warming in excess of 2-4°C and associated rainfall changes (White et al. 2001: 50-52).

Europe

Agricultural yields will increase for most crops as a result of increasing atmospheric CO_2 concentration. This increase in yields would be counteracted by the risk of water shortage in southern and eastern Europe and by shortening of the duration of growth in many grain crops due to increasing temperature. Northern Europe is likely to experience overall positive effects. Flood hazard is likely to increase across much of Europe (White et al. 2001: 53).

Latin America

Studies in Argentina, Brazil, Chile, Mexico, and Uruguay project decreased yields for numerous crops (e.g. maize, wheat, barley, and grapes) even when the direct effects of CO_2 fertilisation and implementation of moderate adaptation measures at the farm level are considered. Predicted increases in temperature will reduce crop yields in the region by shortening the crop cycle. Subsistence farming could be severely threatened in some parts of Latin America, especially north-eastern Brazil (White et al. 2001: 55-56).

North America

Small to moderate climate change will not imperil food and fibre production, although there will be strong regional production effects. There is a potential for increased drought in the US Great Plains and Canadian Prairies, and opportunities for a limited northward shift in production areas in Canada. Increased production from direct physiological effects of CO_2 and market level adjustments are likely to offset potential losses. Economic studies that include various adaptation mechanisms indicate that the negative effects of climate change on agriculture have probably been overstated by earlier studies that do not account for these adjustments (White et al. 2001: 59).

5. Reasons for concern and scope for further research

While the studies surveyed in the IPCC report on average show a rather modest impact of climate change on global agricultural systems and economic welfare, these results have been assigned a low degree of confidence. As it has not been quantified how uncertain these results are, there is a clear demand for further sensitivity analysis to determine key assumptions and parameters. Yield estimates for some crops vary from one impact model to another, indicating the outputs may in fact be model-dependent. The interaction between climate and soil factors and the potential impact of CO_2 on crop yields have only been considered in a limited number of studies. Moreover, the vast complexity of the Earth system and the wide range of interactions between agriculture, the general economy, and the environment suggest that some of the available projections may have to be modified, once these interactions are explicitly taken into account in the models.

The spatial resolution of crop models is another important source of uncertainty. Crop simulation models usually simulate processes at a scale of a few kilometres, whereas climate models operate at coarse scales of 1,000 km or more. Studies using down-scaling techniques have shown large simulated yield discrepancies between coarse-resolution and fine-resolution climate change scenarios. Yield impacts may even change signs, i.e. positive impacts could turn negative. Integrated assessments of agricultural impacts of climate change often link outputs from climate models with crop process models and economic models that together predict changes in land use, crop choice, production, prices, and impacts on economic welfare. These results are highly sensitive to alternative climate model inputs. For example, net US welfare changes, resulting from climate change, are estimated to be somewhere between –$16 billion and +$117 billion, depending on the climate scenario used. The limited number of sensitivity analyses that have been performed suggest that uncertainties in economic models alone are large, which considerably decreases the confidence in the resulting economic impacts of climate change on agriculture (Gitay et al. 2001: 268).

As another serious caveat, recent advances in climate impact research suggest that there may be thresholds and critical limits related to important sub-systems of the Earth which should not be surpassed if major disruptions are to be avoided. A mean global temperature rise of more than 2.5°C could lead to large-scale discontinuities in the climate system, increase the frequency of extreme weather events, lead to unfavourable conditions for plant growth, and consequently cause an increase in food prices (Gitay et al. 2001: 270). The IPCC has synthesised the current knowledge about climate change impacts, vulnerability, and adaptation and has framed five reasons for concern. Although these concerns have been formulated in general terms, they do also apply to agricultural and food systems in particular (Smith et al. 2001):

Unique and threatened systems: Small increases in global average temperature may cause significant and irreversible damage or loss to some ecosystems and species. These adverse impacts are likely to become more numerous and more serious at higher temperatures. Although it is very difficult to assign economic values to the ongoing loss of biodiversity, human societies and their economic activities, above all agricultural production, vitally depend on all kinds of ecosystem services.

Extreme climate events: The frequency and magnitude of extreme climate events will increase with a small temperature rise and will become greater at higher temperatures. Extreme events include floods, soil moisture deficits, tropical and other storms, anomalous temperatures, and fires. The impacts of extreme events are often large at a local scale and could strongly affect specific sectors and regions. Agriculture and water resources may be particularly vulnerable to changes in hydrological and temperature extremes. However, modelling of these events with the available data and research tools remains unsatisfactory.

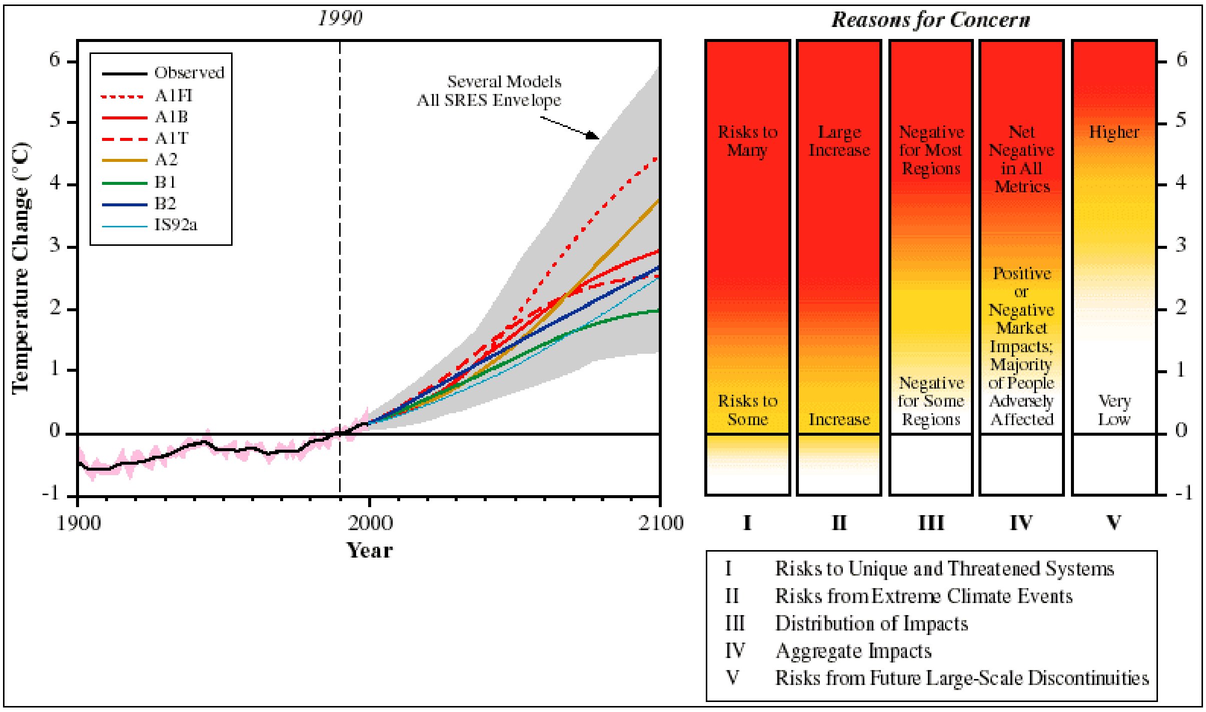
Distribution of impacts: A small temperature increase would have net negative economic impacts in many developing countries and net positive economic impacts in developed countries. At a medium temperature increase, net positive impacts would start to turn negative and negative impacts would be exacerbated. The currently unequal distribution of economic wealth within and between countries and regions is likely to be aggravated under climate change conditions. However, available estimates of these distributional effects are still very uncertain.

Aggregate impacts: With a small temperature increase, aggregate market impacts could amount to plus or minus a few percent of world GDP. With medium to higher temperature increases, benefits tend to decrease and damages increase, so the net change in global economic welfare becomes increasingly negative with greater warming. The overall results depend on potentially important factors like changes in extreme events, rapid change in regional climate and compounding effects of multiple stresses, including population growth and increased resource demand. Current estimates do not include all possible categories of impacts and are considered to be incomplete. The possibility of negative aggregate effects even at small temperature increases cannot be excluded.

Large-scale discontinuities: Human-induced climate change has the potential to trigger large-scale changes in sub-systems of the Earth that could have severe consequences at regional or global scales. One example of such a discontinuity would be a significant slowdown or even shutdown of the ocean circulation that transports warm water to the North Atlantic, with the effect of abrupt regional temperature changes by several degrees. The probabilities of triggering such events are poorly understood but should not be ignored, given the severity of their consequences.

Figure 1 illustrates these reasons for concern regarding climate change risks in connection with global mean temperature rise as projected in the SRES scenarios.

Figure 1: Reasons for concern about projected climate change impacts – a synthesis by IPCC (Ahmad et al. 2001: 5).



The left-hand panel displays the observed temperature increase relative to 1990 as estimated by Working Group I of the IPCC for the SRES scenarios. In the right-hand panel, white means no or virtually neutral impact or risk, yellow means somewhat negative impacts or low risks, and red means more negative impacts or higher risks. The assessment of impacts or risks takes into account only the magnitude of change and not the rate of change. For simplicity, global mean temperature change is used as a proxy for the magnitude of climate change.

The complexity of interactions and the uncertainties related to global environmental change and agricultural systems opens a wide scope for further research. The information base for integrated modelling and assessment of human and natural systems has to be improved, as currently available data in the social and natural sciences are often incompatible due to different temporal and spatial scales. Advanced monitoring and observation systems have to be established, in order to generate continuous data streams not only for research purposes, but also to raise public awareness of the global challenges ahead. Modern technologies, like satellite remote sensing, offer new opportunities e.g. for regular and more precise mapping of irrigated agricultural areas on a global scale (Droogers 2002). Specific local and regional impact studies may be linked to global assessments through systematic comparative case studies, i.e. a number of case studies on the same issue at various regional sites according to a common research protocol. Recently, a "Sustainability Geoscope" has been proposed as a monitoring system which collects systematic and compatible information on natural as well as social systems, in order to provide an empirical basis for improved integrated assessments. Comparative regional case studies would provide a good starting point for the establishment of such a comprehensive observation system. Data sources should be a combination of remote sensing and continuous ground-based observations, such as surveys, panels, etc. (Lotze-Campen et al. 2002). Operational examples of this concept with relevance to agriculture are the Human-Environment Regional Observatory (HERO) on land use changes and the International Farm Comparison Network (IFCN) on agricultural profitability. Recent advances in the modelling of nature-society interactions provide the appropriate tools for a better understanding of global change processes. "Syndromes of global change" have been identified by evaluating a large number of local and regional case studies with methods of qualitative modelling (Petschel-Held and Lüdeke 2001). The emerging regional patterns may be integrated into a global framework for modelling the dynamics of the Earth system, as it is developed and refined, e.g., by the task force on Global Analysis, Integration and Modelling (GAIM) (Sahagian and Schellnhuber 2001).

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