Global food security under climate change

Josef Schmidhuber*† and Francesco N. Tubiello‡§

*Global Perspective Studies Unit, Food and Agriculture Organization, 00100 Rome, Italy; ‡Center for Climate Systems Research, Columbia University, New York, NY 10025; and §Land Use Change Program, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

Edited by William Easterling, Pennsylvania State University, University Park, PA, and accepted by the Editorial Board August 16, 2007 (received for review March 3, 2007)

This article reviews the potential impacts of climate change on food security. It is found that of the four main elements of food security, i.e., availability, stability, utilization, and access, only the first is routinely addressed in simulation studies. To this end, published results indicate that the impacts of climate change are significant, however, with a wide projected range (between 5 million and 170 million additional people at risk of hunger by 2080) strongly depending on assumed socio-economic development. The likely impacts of climate change on the other important dimensions of food security are discussed qualitatively, indicating the potential for further negative impacts beyond those currently assessed with models. Finally, strengths and weaknesses of current assessment studies are discussed, suggesting improvements and proposing avenues for new analyses.

hunger | vulnerability | food supply | agriculture

The Food and Agriculture Organization (FAO) defines food security as a "situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (1). This definition comprises four key dimensions of food supplies: availability, stability, access, and utilization. The first dimension relates to the availability of sufficient food, i.e., to the overall ability of the agricultural system to meet food demand. Its subdimensions include the agro-climatic fundamentals of crop and pasture production (2) and the entire range of socio-economic and cultural factors that determine where and how farmers perform in response to markets. The second dimension, stability, relates to individuals who are at high risk of temporarily or permanently losing their access to the resources needed to consume adequate food, either because these individuals cannot ensure *ex ante* against income shocks or they lack enough "reserves" to smooth consumption *ex post* or both. An important cause of unstable access is climate variability, e.g., landless agricultural laborers, who almost wholly depend on agricultural wages in a region of erratic rainfall and have few savings, would be at high risk of losing their access to food. However, there can be individuals with unstable access to food even in agricultural communities where there is no climate variability, e.g., landless agricultural laborers who fall sick and cannot earn their daily wages would lack stable access to food if, for example, they cannot take out insurance against illness. The third dimension, access, covers access by individuals to adequate resources (entitlements) to acquire appropriate foods for a nutritious diet. Entitlements are defined as the set of all those commodity bundles over which a person can establish command given the legal, political, economic, and social arrangements of the community of which he or she is a member. Thus a key element is the purchasing power of consumers and the evolution of real incomes and food prices. However, these resources need not be exclusively monetary but may also include traditional rights, e.g., to a share of common resources. Finally, utilization encompasses all food safety and quality aspects of nutrition; its subdimensions are therefore related to health, including the sanitary conditions across the entire food chain. It is not enough that someone is getting what appears to be an adequate quantity of food if that person is unable to make use of the food because he or she is always falling sick.

Agriculture is not only a source of the commodity food but, equally importantly, also a source of income. In a world where trade is possible at reasonably low cost, the crucial issue for food security is not whether food is "available," but whether the monetary and nonmonetary resources at the disposal of the population are sufficient to allow everyone access to adequate quantities of food. An important corollary to this is that national self-sufficiency is neither necessary nor sufficient to guarantee food security at the individual level. Note that Hong Kong and Singapore are not self-sufficient (agriculture is nonexistent) but their populations are food-secure, whereas India is self-sufficient but a large part of its population is not food-secure.

Numerous measures are used to quantify the overall status and the regional distribution of global hunger. None of these measures covers all dimensions and facets of food insecurity described above. This also holds for the FAO indicator of undernourishment (1), the measure that was used in essentially all studies reviewed in this article. The FAO measure, however, has a number of advantages. First, it covers two dimensions of food security, availability and access; second, the underlying methodology is straightforward and transparent; and third, the parameters and data needed for the FAO indicator are readily available for past estimates and can be derived without major difficulties for the future.

This article reviews recent studies that have quantified the impacts of climate change on global food security. It starts with an overview of the principal aspects of climate change and their impacts on the four dimensions of food security. It then reviews model-based results and discusses the main findings that have arisen from these assessments. Finally, limitations of the current modeling systems are discussed; this final section includes a discussion of potential surprises and some suggestions to improve future assessments to enhance their overall robustness and their relevance for policy makers.

Climate Change and Food Security

Impacts on Food Production and Availability. Climate change affects agriculture and food production in complex ways. It affects food production directly through changes in agro-ecological conditions and indirectly by affecting growth and distribution of incomes, and thus demand for agricultural produce. Impacts have been quantified in numerous studies and under various sets of assumptions (3). A selection of these results is presented in *Quantifying the Impacts on Food Security*. Here it is useful to summarize the main alterations in the agro-ecological environment that are associated with climate change.

Changes in temperature and precipitation associated with

Author contributions: J.S. and F.N.T. designed research, contributed new reagents/analytic tools, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. W.E. is a guest editor invited by the Editorial Board.

Abbreviations: ha, hectares; AEZ, agro-ecological zone; BLS, Basic Linked System; GCM, general circulation model; GDP, gross domestic product; FAO, Food and Agriculture Organization; IIASA, International Institute for Applied Systems Analysis; IPCC, Intergovernmental Panel on Climate Change; SRES, Special Report on Emissions Scenarios.

†To whom correspondence should be addressed. E-mail: josef.schmidhuber@fao.org.

continued emissions of greenhouse gases will bring changes in land suitability and crop yields. In particular, the Intergovernmental Panel on Climate Change (IPCC) considers four families of socio-economic development and associated emission scenarios, known as Special Report on Emissions Scenarios (SRES) A2, B2, A1, and B1 (4). Of relevance to this review, of the SRES scenarios, A1, the "business-as-usual scenario," corresponds to the highest emissions, and B1 corresponds to the lowest. The other scenarios are intermediate between these two. Importantly for agriculture and world food supply, SRES A2 assumes the highest projected population growth of the four (United Nations high projection) and is thus associated to the highest food demand. Depending on the SRES emission scenario and climate models considered, global mean surface temperature is projected to rise in a range from 1.8°C (with a range from 1.1°C to 2.9°C for SRES B1) to 4.0°C (with a range from 2.4°C to 6.4°C for A1) by 2100 (5). In temperate latitudes, higher temperatures are expected to bring predominantly benefits to agriculture: the areas potentially suitable for cropping will expand, the length of the growing period will increase, and crop yields may rise. A moderate incremental warming in some humid and temperate grasslands may increase pasture productivity and reduce the need for housing and for compound feed. These gains have to be set against an increased frequency of extreme events, for instance, heat waves and droughts in the Mediterranean region or increased heavy precipitation events and flooding in temperate regions, including the possibility of increased coastal storms (6); they also have to be set against the fact that semiarid and arid pastures are likely to see reduced livestock productivity and increased livestock mortality (3). In drier areas, climate models predict increased evapotranspiration and lower soil moisture levels (5, 8). As a result, some cultivated areas may become unsuitable for cropping and some tropical grassland may become increasingly arid. Temperature rise will also expand the range of many agricultural pests and increase the ability of pest populations to survive the winter and attack spring crops.

Another important change for agriculture is the increase in atmospheric carbon dioxide (CO_2) concentrations. Depending on the SRES emission scenario, the atmospheric CO_2 concentration is projected to increase from ≈379 ppm today to >550 ppm by 2100 in SRES B1 to >800 ppm in SRES A1FI (4, 5). Higher CO_2 concentrations will have a positive effect on many crops, enhancing biomass accumulation and final yield. However, the magnitude of this effect is less clear, with important differences depending on management type (e.g., irrigation and fertilization regimes) and crop type (8). Experimental yield response to elevated CO_2 show that under optimal growth conditions, crop yields increase at 550 ppm CO_2 in the range of 10% to 20% for C_3 crops (such as wheat, rice, and soybean), and only 0–10% for C_4 crops such as maize and sorghum (3). Yet the nutritional quality of agricultural produce may not increase in line with higher yields. Some cereal and forage crops, for example, show lower protein concentrations under elevated CO_2 conditions (8).

Finally, a number of recent studies have estimated the likely changes in land suitability, potential yields, and agricultural production on the current suite of crops and cultivars available today. Therefore, these estimates implicitly include adaptation using available management techniques and crops, but excluding new cultivars from breeding or biotechnology. These studies are in essence based on the FAO/International Institute for Applied Systems Analysis (IIASA) agro-ecological zone (AEZ) methodology (9), such as refs. 10–12. For instance, pioneering work in ref. 9 suggested that total land and total prime land would remain virtually unchanged at the current levels of 2,600 million and 2,000 million hectares (ha), respectively.[¶] The same study also showed, however, more pronounced regional shifts, with a considerable increase in suitable cropland at higher latitudes (developed countries +160 million ha) and a corresponding decline of potential cropland at lower latitudes (developing countries −110 million ha). An even more pronounced shift within the quality of cropland is predicted in developing countries. The net decline of 110 million ha is the result of a massive decline in agricultural prime land of ≈135 million ha, which is offset by an increase in moderately suitable land of >20 million ha. This quality shift is also reflected in the shift in land suitable for multiple cropping. In sub-Saharan Africa alone, land for double cropping would decline by between 10 million and 20 million ha, and land suitable for triple copping would decline by 5 million to 10 million ha. At a regional level (9), similar approaches indicate that under climate change, the biggest losses in suitable cropland are likely to be in Africa, whereas the largest expansion of suitable cropland is in the Russian Federation and Central Asia.

Impacts on the Stability of Food Supplies. Global and regional weather conditions are also expected to become more variable than at present, with increases in the frequency and severity of extreme events such as cyclones, floods, hailstorms, and droughts (3, 8). By bringing greater fluctuations in crop yields and local food supplies and higher risks of landslides and erosion damage, they can adversely affect the stability of food supplies and thus food security.

Neither climate change nor short-term climate variability and associated adaptation are new phenomena in agriculture, of course. As shown, for instance, in ref. 9, some important agricultural areas of the world like the Midwest of the United States, the northeast of Argentina, southern Africa, or southeast Australia have traditionally experienced higher climate variability than other regions such as central Africa or Europe. They also show that the extent of short-term fluctuations has changed over longer periods of time. In developed countries, for instance, short-term climate variability increased from 1931 to 1960 as compared with 1901 to 1930, but decreased strongly in the period from 1961 to 1990. What is new, however, is the fact that the areas subject to high climate variability are likely to expand, whereas the extent of short-term climate variability is likely to increase across all regions. Furthermore, the rates and levels of projected warming may exceed in some regions the historical experience (3, 8).

If climate fluctuations become more pronounced and more widespread, droughts and floods, the dominant causes of short-term fluctuations in food production in semiarid and subhumid areas, will become more severe and more frequent. In semiarid areas, droughts can dramatically reduce crop yields and livestock numbers and productivity (8). Again, most of this land is in sub-Saharan Africa and parts of South Asia, meaning that the poorest regions with the highest level of chronic undernourishment will also be exposed to the highest degree of instability in food production (13). How strongly these impacts will be felt will crucially depend on whether such fluctuations can be countered by investments in irrigation, better storage facilities, or higher food imports. In addition, a policy environment that fosters freer trade and promotes investments in transportation, communications, and irrigation infrastructure can help address these challenges early on.

Impacts of Climate Change on Food Utilization. Climate change will also affect the ability of individuals to use food effectively by altering the conditions for food safety and changing the disease pressure from vector, water, and food-borne diseases. The IPPC

[¶]These estimates refer to the difference between SRES A1FI and a no-climate-change scenario. Total land includes the classes very suitable, suitable, and moderately suitable, while agricultural prime land is limited to very suitable and suitable land. Crops are limited to major food and fiber crops.

Working Group II provides a detailed account of the health impacts of climate change in chapter 8 of its fourth assessment report (3). It examines how the various forms of diseases, including vector-borne diseases such as malaria, are likely to spread or recede with climate change. This article focuses on a narrow selection of diseases that affect food safety directly, i.e., food and water-borne diseases.

The main concern about climate change and food security is that changing climatic conditions can initiate a vicious circle where infectious disease causes or compounds hunger, which, in turn, makes the affected populations more susceptible to infectious disease. The result can be a substantial decline in labor productivity and an increase in poverty and even mortality. Essentially all manifestations of climate change, be they drought, higher temperatures, or heavy rainfalls have an impact on the disease pressure, and there is growing evidence that these changes affect food safety and food security (3).

The recent IPCC report also emphasizes that increases in daily temperatures will increase the frequency of food poisoning, particularly in temperate regions. Warmer seas may contribute to increased cases of human shellfish and reef-fish poisoning (ciguatera) in tropical regions and a poleward expansion of the disease (14–17). However, there is little new evidence that climate change significantly alters the prevalence of these diseases. Several studies have confirmed and quantified the effects of temperature on common forms of food poisoning, such as salmonellosis (18–20). These studies show an approximately linear increase in reported cases for each degree increase in weekly temperature. Moreover, there is evidence that temperature variability affects the incidence of diarrhoeal disease. A number of studies (21–24) found that rising temperatures were strongly associated with increased episodes of diarrhoeal disease in adults and children. These findings have been corroborated by analyses based on monthly temperature observations. Several studies report a strong correlation between monthly temperature and diarrhoeal episodes on the Pacific Islands, Australia, and Israel (25–27).

Extreme rainfall events can increase the risk of outbreaks of water-borne diseases particularly where traditional water management systems are insufficient to handle the new extremes (3). Likewise, the impacts of flooding will be felt most strongly in environmentally degraded areas, and where basic public infrastructure, including sanitation and hygiene, is lacking. This will raise the number of people exposed to water-borne diseases (e.g., cholera) and thus lower their capacity to effectively use food.

Impacts of Climate Change on Access to Food. Access to food refers to the ability of individuals, communities, and countries to purchase sufficient quantities and qualities of food. Over the last 30 years, falling real prices for food and rising real incomes have led to substantial improvements in access to food in many developing countries. Increased purchasing power has allowed a growing number of people to purchase not only more food but also more nutritious food with more protein, micronutrients, and vitamins (28). East Asia and to a lesser extent the Near-East/North African region have particularly benefited from a combination of lower real food prices and robust income growth. From 1970 to 2001, the prevalence of hunger in these regions, as measured by FAO's indicator of undernourishment, has declined from 24% to 10.1% and 44% to 10.2% respectively (13, 29). In East Asia, it was endogenous income growth that provided the basis for the boost in demand for food, which was largely produced in the region; in the Near-East North African region demand was spurred by exogenous revenues from oil and gas exports, and additional food supply came largely from imports. But in both regions, improvements in access to food have been crucial in reducing hunger and malnutrition.

FAO's longer-term outlook to 2050 (30) suggests that the importance of improved demand side conditions will even become more important over the next 50 years. The regions that will see the strongest reductions in the prevalence of undernourishment are those that are expected to see the highest rates of income growth. South Asia stands to benefit the most. Spurred by high income growth the region is expected to reduce the prevalence of undernourishment from >22% currently to 12% by 2015 and just 4% by 2050 (30). Progress is also expected for sub-Saharan Africa, but improvements will be less pronounced and are expected to set in later. Over the next 15 years, for instance, the prevalence of undernourishment will decline less than in other regions, from ≈33% to a still worrisome 21%, as significant constraints (soil nutrients, water, infrastructure, etc.) will limit the ability to further increase food production locally, while continuing low levels of income rule out the option of importing food. In the long run, however, sub-Saharan Africa is expected to see a more substantial decline in hunger; by 2050, <6% of its total population are expected to suffer from chronic hunger (30). It is important to note that these FAO projections do not take into account the effects of climate change.

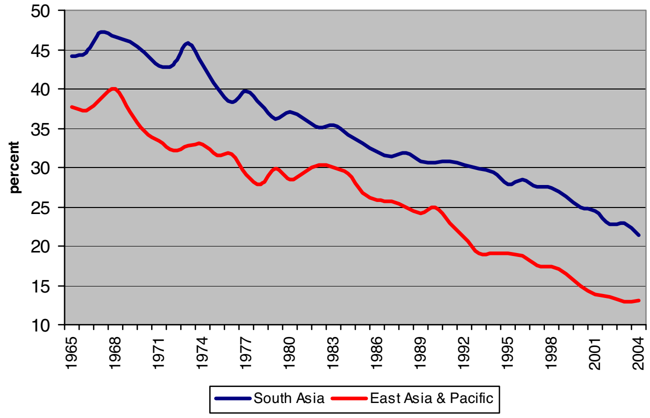

Fig. 1. The share of agriculture in total GDP in many developing countries has rapidly declined over the last decades; it is worth noting that in the high-income Organization for Economic Cooperation and Development countries today, the share of agriculture in GDP is <2%.

By coupling agro-ecologic and economic models, others (e.g., refs. 9 and 31) have gauged the impact of climate change on agricultural gross domestic product (GDP) and prices. At the global level, the impacts of climate change are likely to be very small; under a range of SRES and associated climate-change scenarios, the estimates range from a decline of −1.5% to an increase of +2.6% by 2080. At the regional level, the importance of agriculture as a source of income can be much more important. In these regions, the economic output from agriculture itself (over and above subsistence food production) will be an important contributor to food security. The strongest impact of climate change on the economic output of agriculture is expected for sub-Saharan Africa, which means that the poorest and already most food-insecure region is also expected to suffer the largest contraction of agricultural incomes. For the region, the losses in agricultural GDP, compared with no climate change, range from 2% to 8% for the Hadley Centre Coupled Model, version 3 and 7–9% for the Commonwealth Scientific and Industrial Research Organisation projections.[‖]

Impacts on Food Prices. Essentially all SRES development paths describe a world of robust economic growth and rapidly shrinking importance of agriculture in the long run and thus a continuation of a trend that has been underway for decades in many developing regions (Fig. 1). SRES scenarios describe a world where income

‖All projected changes in GDP and agricultural GDP are in constant 1990 prices. For further regional and climate-specific details see table 4.11 in ref. 9.

Table 1. The impacts of climate change and socio-economic development paths on the number of people at risk of hunger in developing countries

	No. of people at risk of hunger in developing countries, in millions					
	Year 2020		Year 2050		Year 2080	
Scenario	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS	AEZ-BLS	DSSAT-BLS
Reference						
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						
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						
A1	NA	726	NA	308	NA	370
A2	794	845	788	933	950	1,320
B1	NA	792	NA	275	NA	125
B2	652	685	356	415	257	384

Data are taken from refs.10 and 34. Reference depicts reference projections, under the SRES scenario and no climate change. CC includes climate change impacts, based on Hadley Centre Coupled Model, version 3 output, including the positive effect of elevated CO_2 on crops. CC, no CO_2 includes climate change, but assumes no effects of elevated CO_2. Projections from 2020 to 2080 are given for two crop modeling systems: AEZ and DSSAT (Decision Support System for Agrotechnology Transfer), each coupled to the same economic and food trade model, BLS (3). The models are calibrated to give 824 million undernourished people in 2000, according to FAO data. NA, not available.

growth will allow the largest part of the world's population to address possible local production shortfalls through imports and, at the same time, find ways to cope with safety and stability issues of food supplies (4, 9). It is also a world where real incomes rise more rapidly than real food prices, which suggests that the share of income spent on food should decline and that even high food prices are unlikely to create a major dent in the food expenditures of the poor. However, not all parts of the world perform equally well in the various development paths and not all development paths are equally benign for growth. Where income levels are low and shares of food expenditures are high, higher prices for food may still create or exacerbate a possible food security problem.

There are a number of studies that have ventured to measure the likely impacts of climate change on food prices (e.g., refs. 9, 32, and 33). The basic messages that emerge from these studies are: first, on average, prices for food are expected to rise moderately in line with moderate increases of temperature (until 2050); some studies even foresee a mild decline in real prices until 2050. Second, after 2050 and with further increases in temperatures, prices are expected to increase more substantially. In some studies (32) and for some commodities (rice and sugar) prices are forecast to increase by as much as 80% above their reference levels without climate change. Third, price changes expected from the effects of global warming are, on average, much smaller than price changes from socio-economic development paths. For instance, the SRES A2 scenario would imply a price increase in real cereal prices by $\approx$170%. The (additional) price increase caused by climate change (in the Hadley Centre Coupled Model, version 3, climate change case) would only be 14.4%. Overall, this appears to be the sharpest price increase reported and it is not surprising that this scenario would imply a stubbornly high number of undernourished people until 2080. However, it is also needless to say that a constant absolute number of undernourished people would still imply a sharp decline in the prevalence of hunger, and, given the high population assumptions in the SRES A2 world (>13.6 billion people globally and >11.6 billion in the developing world) this would imply a particularly sharp drop in the prevalence from currently 17% to $\approx$7% by 2080.

Quantifying the Impacts on Food Security

A number of studies have recently quantified the impacts of climate change on food security (e.g., refs. 9–12 and 31). In terms of quantifying agronomic yield change projections, these studies are either based on the AEZ tools developed by the IIASA analysis or the Decision Support System for Agrotechnology Transfer suite of crop models; all use the IIASA-Basic Linked System (BLS) economic model for assessing economic impacts (see, e.g., ref. 34). These tools, with some modifications relating to how crop yield changes are simulated, have also been used by others to undertake similar assessments and provide sensitivity analyses across a range of SRES and general circulation model (GCM) projections. Many other simulations have also examined the effects of climate change with and without adaptation (induced technological progress, domestic policy change, international trade liberalization, etc.), with and without mitigation (e.g., CO_2 stabilization, variants for temperature, rainfall change and distribution) or provide impact assessments for different speeds of climate change (33). This section focuses on the quantitative results for food security, trying to illuminate some of the differences and extract the main messages that emerge from the various studies. Unless indicated, all simulation results discussed below include the combined effects of climate change and elevated CO_2 on crops. The key messages can be summarized as follows:

First, it is very likely that climate change is likely to increase the number of people at risk of hunger compared with reference scenarios with no climate change; the exact impacts will, however, strongly depend on the projected socio-economic developments (Table 1). For instance, it is estimated (9, 31) that climate change would increase the number of undernourished in 2080 by 5–26%, compared with no climate change or by between 5 million and 10 million (B1 SRES) and 120 million to 170 million people (A2 SRES), with within-SRES ranges depending on GCM climate projections. Using only one GCM scenario, others (10, 11) projected small reductions by 2080, i.e., − 5%, or −10 million (B1) to −30 million (A2) people, and slight increases of +13%–26%, or $\approx$10 million (B2) to 30 million (A1) people.

Second, it is likely that the magnitude of these climate impacts will be small compared with the impact of socio-economic development (e.g., ref. 12). As evident from Table 1, and within the limitations of socio-economic forecasts, these studies suggest that robust economic growth and a decline in population growth projected for the 21st century will, in all but one scenario (SRES A2), significantly reduce the number of people at risk of hunger in 2080. At any rate, the prevalence of undernourishment will decline as all scenarios assume that world population will continue to grow to 2080, albeit at lower rates. Compared with FAO estimates of 820 million undernourished in developing countries today, several studies (9–12, 31) estimate reductions of >75% by 2080, or ≈560 million to 700 million people, projecting 100 million to 240 million undernourished by 2080 (A1, B1, and B2). As mentioned, the only exception is scenario A2, where the number of the hungry is forecast to decrease only slightly by 2080; but the higher population growth rates in A2 compared with other scenarios mean that the prevalence of undernourishment will decline drastically (9–12, 31). However, these analyses also confirm that the progress will be unevenly distributed over the developing world, and more importantly progress will be slow during the first decades of the outlook. With or without climate change, the millennium development goal of halving the prevalence of hunger by 2015 is unlikely to be realized before 2020–2030 (31, 35).

In addition to socio-economic pressures considered within the IPCC SRES scenarios, food production may increasingly compete with bio-energy in coming decades; studies addressing possible consequences for world food supply have only started to surface, providing both positive (36, 37) and negative views (38). Importantly, none of the major world food models discussed herein have yet considered such competition.

Third, sub-Saharan Africa is likely to surpass Asia as the most food-insecure region. However, this is largely independent of climate change and is mostly the result of the socio-economic development paths assumed for the different developing regions in the SRES scenarios. Throughout most SRES and climate-change scenarios sub-Saharan Africa accounts for 40–50% of global hunger by 2080, compared with ≈24% today (9–11, 31); in some simulations sub-Saharan Africa even accounts for 70–75% of global undernourishment by 2080. These high estimates have emerged from slower growth variants of the A2 and B2 scenarios (9, 10); also an A2 variant with slower population growth yields a sharper concentration of hunger in sub-Saharan Africa (12). For regions other than sub-Saharan Africa, results largely depend on GCM scenarios and therefore are highly uncertain.

Fourth, although there is significant uncertainty on the effects of elevated CO_2 on crop yields, this uncertainty is carried to a much lesser extent on food security. This result emerges from a comparison of climate change simulations with and without CO_2 fertilization effects on crop yields. As can be seen from Table 1, higher CO_2 fertilization would not greatly affect global projections of hunger. In view of the fact that essentially all SRES worlds are characterized by much higher real incomes, much improved transportation and communication options, and still sufficient global food production, the somewhat smaller supplies will not be able to make a dent in global food security outcomes (34). Many studies (9–11, 31) find that climate change without CO_2 fertilization would reduce the number of undernourished people by 2080 only by some 20 million to 140 million (120 million to 380 million for SRES A1, B1, and B2 without, compared with 100 million to 240 million with CO_2 fertilization effect). The exception again in these studies is SRES A2, under which the assumption of no CO_2 fertilization results in a projected range of 950 million to 1,300 million people undernourished in 2080, compared with 740 million to 850 million projected under climate change, but with CO_2 effects on crops.

Finally, recent research suggests large positive effects of climate stabilization for the agricultural sector. However, as the stabilizing effects of mitigation measures can take several decades to be realized from the moment of implementation, the benefits for crop production may be realized only in the second half of this century (12, 39). Importantly, even in the presence of robust global long-term benefits, regional and temporal patterns of winners and losers that can be projected with current tools are highly uncertain and depend critically on the underlying GCM projections (12).

Uncertainties and Limitations

The finding that socio-economic development paths have an important bearing on future food security and that they are likely to top the effects of climate change should not, or at least not only, be interpreted as a probability-based forecast. This is because SRES scenarios offer a range of possible outcomes "without any sense of likelihood" (40). Yet SRES scenarios, like all scenarios, do not overcome the inability to accurately project future changes in economic activity, emissions, and climate.

Second, the existing global assessments of climate change and food security have only been able to focus on the impacts on food availability and access to food, without quantification of the likely important climate change effects on food safety and vulnerability (stability). This means that these assessments neither include potential problems arising from additional impacts due to extreme events such as drought and floods (for a similar critique, also see e.g., ref. 41) nor do they quantify the potential impacts of changes in the prevalence of food-borne diseases (positive as well as negative) or the interaction of nutrition and health effects through changes in the proliferation of vector-borne diseases such as malaria. On the food availability side, they also exclude the impacts of a possible sea-level rise for agricultural production or those that are associated with possible reductions of marine or freshwater fish production.

Third, it is important to note that even in terms of food availability, all current assessments of world food supply have focused only on the impacts of mean climate change, i.e., they have not considered the possibility of significant shifts in the frequency of extreme events on regional production potential, nor have they considered scenarios of abrupt climate or socio-economic change; any of these scenario variants is likely to increase the already negative projected impacts of climate change on world food supply. Models that take into account the specific biophysical, technological, and market responses necessary to simulate realistic adaptation to such events are not yet available.

Fourth, this review finds that recent global assessments of climate change and food security rest essentially on a single modeling framework, the IIASA system, which combines the FAO/IIASA AEZ model with various GCM models and the IIASA BLS system, or on close variants of the IIASA system (e.g., refs. 11 and 42). This has important implications for uncertainty, given that the robustness of all these assessments strongly depends on the performance of the underlying models. There is, therefore, a clear need for continued and enhanced validation efforts of both the agro-climatological and food trade tools developed at IIASA and widely used in the literature.

Finally, we note that assessments that do not only provide scenarios, but also attach probabilities for particular outcomes to come true could provide an important element for improved or at least better-informed policy decisions. A number of possibilities are offered (41) to address the related modeling challenges. One option would be to produce such estimates with probability-based estimates of the (key) model parameters. Alternatively, the various scenarios could be constructed so that they reflect expert judgements on a particular issue. It would be desirable to attach probabilities to existing scenarios. Information on how likely the suggested outcomes are would contribute greatly to their usefulness for policy makers and help justify (or otherwise) policy measures to adapt to or mitigate the impacts of climate change on food security.

Conclusions

Climate change will affect all four dimensions of food security, namely food availability (i.e., production and trade), access to food, stability of food supplies, and food utilization (1, 43). The importance of the various dimensions and the overall impact of climate change on food security will differ across regions and over time and, most importantly, will depend on the overall socio-economic status that a country has accomplished as the effects of climate change set in.

Essentially all quantitative assessments show that climate change will adversely affect food security. Climate change will increase the dependency of developing countries on imports and accentuate existing focus of food insecurity on sub-Saharan Africa and to a lesser extent on South Asia. Within the developing world, the adverse impacts of climate change will fall disproportionately on the poor. Many quantitative assessments also show that the socio-economic environment in which climate change is likely to evolve is more important than the impacts that can be expected from the biophysical changes of climate change.

Less is known about the role of climate change for food stability and utilization, at least in quantitative terms. However, it is likely that differences in socio-economic development paths will also be the crucial determinant for food utilization in the long run and that they will be decisive for the ability to cope with problems of food instability, be they climate-related or caused by other factors.

Finally, all quantitative assessments we reviewed show that the first decades of the 21st century are expected to see low impacts of climate change, but also lower overall incomes and still a higher dependence on agriculture. During these first decades, the biophysical changes as such will be less pronounced but climate change will affect those particularly adversely that are still more dependent on agriculture and have lower overall incomes to cope with the impacts of climate change. By contrast, the second half of the century is expected to bring more severe biophysical impacts but also a greater ability to cope with them. The underlying assumption is that the general transition in the income formation away from agriculture toward nonagriculture will be successful.

How strong the impacts of climate change will be felt over all decades will crucially depend on the future policy environment for the poor. Freer trade can help to improve access to international supplies; investments in transportation and communication infrastructure will help provide secure and timely local deliveries; irrigation, a promotion of sustainable agricultural practices, and continued technological progress can play a crucial role in providing steady local and international supplies under climate change.

We thank Sumiter Broca and Jelle Bruinsma of the FAO for comments and two anonymous reviewers who helped improve the clarity of this manuscript.

1. Food and Agriculture Organization (2002) *The State of Food Insecurity in the World 2001* (Food and Agriculture Organization, Rome).
2. Tubiello FN, Soussana J-F, Howden SM (2007) *Proc Natl Acad Sci USA* 104:19686–19690.
3. Intergovernmental Panel on Climate Change (2007) *Climate Change: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK), in press.
4. Intergovernmental Panel on Climate Change (2000) *Special Report on Emissions Scenarios, Summary for Policy Makers, Working Group III, International Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
5. Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK), in press.
6. Rosenzweig C, Tubiello FN, Goldberg RA, Mills E, Bloomfield J (2002) *Global Environ Change* 12: 197–202.
7. Food and Agriculture Organization (2002) *World Agriculture: Toward 2015/2030, Summary Report* (Food and Agriculture Organization, Rome).
8. Intergovernmental Panel on Climate Change (2001) *Climate Change: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
9. Fischer G, Shah M, van Velthuizen H (2002) *Climate Change and Agricultural Vulnerability, A Special Report Prepared as a Contribution to the World Summit on Sustainable Development* (International Institute for Applied Systems Analysis, Laxenburg, Austria).
10. Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) *Global Environ Change* 14:53–67.
11. Parry ML, Rosenzweig C, Livermore M (2005) *Philos Trans R Soc* 360:2125–2138.
12. Tubiello FN, Fischer G (2007) *Tech Forecasting Social Change* 74:1030–1056.
13. Bruinsma J, ed (2003) *World Agriculture: Toward 2015/2030, A Food and Agriculture Organization Perspective* (Earthscan, London).
14. Lehane L, Lewis RJ (2000) *Int J Food Microbiol* 61:1–125.
15. Hall GV, D'Souza RM, Kirk MD (2002) *Med J Austral* 177:614–618.
16. Hunter PR (2003) *J Appl Microbiol* 94:37–46.
17. Korenberg E (2004) in *Climate Change and Public Health in Russia in the XXI Century, Proceedings of a Workshop*, eds Izmerov NF, Revich BA, Korenberg EI (Adamant, Moscow), pp 54–67.
18. D'Souza R, Becker N, Hall G, Moodie K (2004) *Epidemiology* 15:86–92.
19. Kovats RS, Edwards S, Hajat S, Armstrong B, Ebi KL, Menne B (2004) *Epidemiol Infect* 132:443–453.
20. Fleury M, Charron D, Holt J, Allen O, Maarouf A (2006) *Int J Biometeorol* 50:385–391.
21. Checkley W, Epstein LD, Gilman RH, Figueroa D, Cama RI, Patz JA, Black RE (2000) *Lancet* 355:442–450.
22. Speelmon EC, Checkley W, Gilman RH, Patz J, Calderon M, Manga S (2000) *J Am Med Assoc* 283:3072–3074.
23. Checkley W, Gilman RH, Black RE, Epstein LD, Cabrera L, Sterling CR, Moulton LH (2004) *Lancet* 363:112–118.
24. Lama JR, Seas CR, León-Barúa R, Gotuzzo E, Sack RB (2004) *J Health Population Nutr* 22:399–403.
25. Singh R, Hales S, deWet N, Raj R, Hearnden M, Weinstein P (2001) *Environ Health Perspect* 109:55–59.
26. McMichael A, Woodruff R, Whetton P, Hennessy K, Nicholls N, Hales S, Woodward A, Kjellstrom T (2003) *Human Health and Climate Change in Oceania: Risk Assessment, 2002* (Department of Health and Aging, Canberra, Australia).
27. Vasilev V (2003) *Epidemiol Infect* 132:51–56.
28. Schmidhuber J, Shetty P (2005) *Acta Agri Scand* 2/3–4: 150–166.
29. Alexandratos N, ed (1995) *World Agriculture: Toward 2010, A Food and Agriculture Organization Study* (Wiley, Chichester, UK).
30. Food and Agriculture Organization (2006) *World Agriculture: Toward 2030/2050, Interim Report* (Food and Agriculture Organization, Rome).
31. Fischer G, Shah M, Tubiello FN, van Velthuizen H (2005) *Philos Trans R Soc Ser B* 360:2067–2083.
32. Reilly J, Baethgen W, Chege FE, van de Geikn SC, Erda L, Iglesias A, Kenny G, Petterson D, Rogasik J, Rötter R, *et al*. (1996) in *Intergovernmental Panel on Climate Change, Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*, eds Watson RT, Zinyowera MC, Moss RH (Cambridge Univ Press, Cambridge, UK), pp 427–467.
33. Darwin R, Tsigas M, Lewandrowski J, Raneses A (1995) *World Agriculture and Climate Change, Economic Adaptations* (Department of Agriculture, Washington, DC), Agricultural Economic Report 703.
34. Tubiello FN, Amthor JA, Boote K, Donatelli M, Easterling WE, Fisher G, Gifford R, Howden M, Reilly J, Rosenzweig C (2006) *Eur J Agron* 26:215–223.
35. Tubiello FN (2005) in *Impact of Climate Change, Variability and Weather Fluctuations on Crops and Their Produce Markets*, ed Knight B (Impact Reports, Cambridge, UK), pp 70–73.
36. Alcamo J, van Vuuren D, Ringler C, Cramer W, Masui T, Alder J, Schulze K (2005) *Ecol Society* 10:19–48.
37. Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) *Proc Natl Acad Sci USA* 103:11206–11210.
38. Monbiot G (2005) *Renewable Energy Dev* 18:2–3.
39. Arnell NW, Cannell MGR, Hulme M, Kovats RS, Mitchell JFB, Nicholls RJ, Parry ML, Livermore MTJ, White A (2002) *Climatic Change* 53:413–446.
40. McKibbin W, Pearce D, Stegman A (2004) *Can the IPCC SRES Be Improved?* (Research School of Pacific and Asian Studies, Australian National University, Canberra, Australia).
41. Darwin R (2004) *Climatic Change* 66:191–238.
42. Rosenzweig C, Parry ML (1994) *Nature* 367:133–138.
43. Food and Agriculture Organization (2006) *The State of Food Insecurity in the World 2006* (Food and Agriculture Organization, Rome).