
Chapter 1.1

Climate Change, Population Growth, and Crop Production: An Overview

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Introduction

The publication of the Stern Review on the Economics of Climate Change in 2006 and the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) in 2007 have pushed the scientific and public debate on climate change a decisive step forward. It is now beyond doubt that anthropogenic greenhouse gas (GHG) emissions are the main cause for recently observed climate change and that early and bold mitigation measures will eventually be much cheaper than later adaptation to potentially drastic climate impacts. The agricultural sector is directly affected by changes in temperature, precipitation, and CO₂ concentrations in the atmosphere, but it is also contributing about one-third to total GHG emissions, mainly through livestock and rice production, nitrogen fertilization, and tropical deforestation. Agriculture currently accounts for 5% of world economic output, employs 22% of the global workforce, and occupies 40% of the total land area. In the developing countries, about 70% of the population lives in rural areas, where agriculture is the largest supporter of livelihoods. In many developing countries, the economy is heavily depending on agriculture. The sector accounts for 40% of gross

domestic product (GDP) in Africa and 28% in South Asia. However, in the future, agriculture will have to compete for scarce land and water resources with growing urban areas and industrial production.

A large share of the world's poor population lives in arid or semiarid regions, which are already characterized by highly volatile climate conditions. Under conditions of future climate change, a worldwide increase in climate variability and extreme weather events is very likely. The connections between agricultural development and climate change reveal some fundamental issues of global justice. The industrialized countries, mostly located in medium to high latitudes, are responsible for the major share of accumulated GHG emissions. They are economically less dependent on agriculture, they will be less affected by climate impacts, and they have on average a higher adaptive capacity. Most developing countries are located in the lower latitudes, they are dependent on agriculture, they will be strongly affected by climate impacts, and they have lower (or nonexistent) adaptive capacity. Creating more options for climate change adaptation and improving the adaptive capacity in the agricultural sector will be crucial for improving food security and preventing an increase

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in global inequality in living standards in the future. However, in the developing world, this is often prevented by the lack of information, financial resources, and good governance.

Global scenarios on future greenhouse gas emissions and population growth

Future emissions of anthropogenic GHG mainly depend on population growth, socioeconomic development, and technological change. Future trends in these driving forces are highly uncertain, especially over the course of the next decades until the end of the century. For a systematic description of the range of possible futures, the IPCC has developed a set of long-term emission scenarios that were published in the Special Report on Emission Scenarios (SRES; Nakicenovic et al. 2000). Four different narrative storylines were developed to represent different demographic, social, economic, technological, and environmental conditions and trends, thus covering a wide range of possible GHG emission outcomes. For each storyline, several emission scenarios were developed using different integrated assessment modeling approaches.

Table 1.1.1 summarizes the main driving forces for the four emission scenarios by the end of the century.

The *A1 storyline* describes a future world of very rapid economic growth, global population that peaks at about 9 billion in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The underlying theme is that regions will converge and cultural and social interactions will increase with a substantial reduction in regional differences in per capita income. The scenario groups are determined by different directions of technological change in the energy system. A1FI is fossil intensive, A1T heavily uses nonfossil energy sources, and the A1B is a scenario with a balance across all energy sources.

The *A2 storyline* describes a very heterogeneous world. The underlying theme is self-

reliance and preservation of local identities. Population will continuously increase, up to 15 billion in 2100, and economic development is primarily regionally oriented. Per capita economic growth and technological change are more fragmented and slower than in other storylines. The *B1 storyline* describes a convergent world with the same global population as in A1 that peaks at mid-century and declines thereafter. However, major differences come from rapid changes in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The main feature is a global solution to economic, social, and environmental sustainability with improved equity but without additional climate initiatives. The *B2 storyline* describes a world of local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2 (about 10 billion in 2100), intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines.

Figure 1.1.1 shows the projected temperature increases for the four SRES scenario groups, including the different energy technology options of A1. Each emission scenario was analyzed with several global climate models, to take uncertainties about the climate sensitivity of different models into account. Highest temperature increases are projected for A1FI due to very high emissions. The mean model results for global temperature increase across all climate models range between 2.4°C (B1) and 4.6°C (A1FI), compared to the preindustrial level. Several models show a wider range of outcomes, possibly as low as 1.6°C for the B1 scenario but also as high as 6.4°C for the fossil-fuel-intensive A1FI scenario.

Climate impacts on crop productivity

Plant growth and yield will be both positively and negatively affected by climate change. Diverging

Table 1.1.1. Overview of main driving forces for the four SRES storylines in 2100.

	People ^a billion (B)	Economic growth ^b % p.a.	Income ^c GDP/capita	Primary energy use	Hydrocarbon resource use ^d	Land use change ^b
A1	Low ~7 B. 1.4 IND 5.6 DEV	Very high 1990-20: 3.3 1990-50: 3.6 1990-100: 2.9	Very high IND 107,300 DEV 66,500	Very high 2,226 EJ Low intensity 4.2 MJ/US\$	Scenario: Oil low—VH 20.8 ZJ Gas high—VH 42.2 ZJ Coal med—VH 15.9 ZJ	Low 1990-100: cropland +3% grassland +6% forests +2%
A2	High 15 B. 2.2 IND 12.9 DEV	Medium 1990-20: 2.2 1990-50: 2.3 1990-100: 2.3	Low in DEV Medium in IND IND 46,200 DEV 11,000	High 1,717 EJ High intensity 7.1 MJ/US\$	Scenario: Oil VL—med 17.3 ZJ Gas low—high 24.6 ZJ Coal Med - VH 46.8 ZJ	Medium n.a.
B1	Low ~7 B. 1.4 IND 5.7 DEV	High 1990-20: 3.1 1990-50: 3.1 1990-100: 2.5	High IND 72,800 DEV 40,200	Low 514 EJ Very low intensity 1.6 EJ/US\$	Scenario: Oil VL—high 19.6 ZJ Gas med—high 14.7 ZJ Coal VL—high 13.2 ZJ	High 1990-100: cropland -28% grassland -45% forests +30%
B2	Median ~10 B. 1.3 IND 9.1 DEV	Medium 1990-20: 3.0 1990-2050: 2.8 1990-100: 2.2	Medium IND 54,400 DEV 18,000	Medium 1,357 EJ Medium intensity 5.8 MJ/US\$	Scenario: Oil low—med 19.5 ZJ Gas low—med 26.9 ZJ Coal low—VH 12.6 ZJ	Medium 1990-100: cropland +22% grassland +9% forests +5%

Source: Nakicenovic et al. (2000), Table 4.4a, <http://www.grida.no/climate/ipcc/emission/097.htm>.

^aIND, industrialized countries; DEV, developing countries.

^b1990 > 2000.

^cUS\$.

^dVL, very low; med, medium; VH, very high.

effects are caused by rising CO₂ concentrations, higher temperatures, changing precipitation patterns, changing water availability, increased frequency of weather extremes (i.e., floods, heavy storms and droughts), climate-induced soil erosion, and sea-level rise. While some of these impacts have been studied in isolation, complex interactions between different factors and especially extreme events are still not well understood.

CO₂ fertilization

Yields of most agricultural crops increase under elevated CO₂ concentration. Free air carbon enrichment (FACE) experiments indicate productivity increases in the range of 15–25% for C₃ crops (like wheat, rice, and soybeans) and 5–10% for C₄ crops (like maize, sorghum, and sugarcane). Higher levels of CO₂ also improve water-use efficiency of both C₃ and C₄ plants.

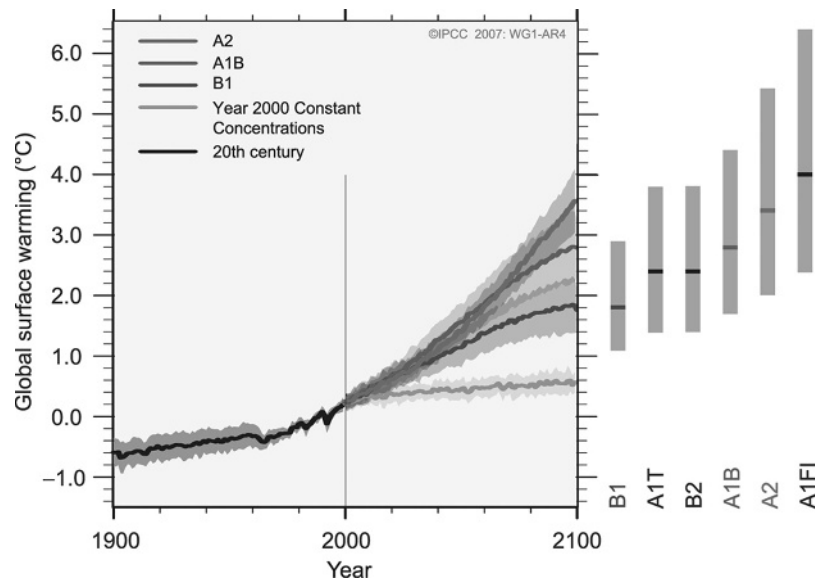


Fig. 1.1.1. Projected temperature increases for the four SRES emission scenario groups. (Source: IPCC 2007, p. 14.)

However, the experiments do not address important colimitations because of water and nutrient availability. Some studies expect much less favorable crop response to elevated CO₂ in practice than that asserted on experimental sites (e.g., Long et al. 2006), while others agree with findings from FACE experiments (Tubiello et al. 2007). Thus, the magnitude of the positive yield effect due to enhanced CO₂ concentration is still uncertain (Parry et al. 2004; Easterling et al. 2007).

Higher temperatures

Warming is observed over the entire globe, but with significant regional and seasonal variations. Highest rates can be found at Northern latitudes and during winter and spring (Solomon et al. 2007). In the Northern Hemisphere, in higher latitudes, rising temperatures imply lengthening of the growing season by 1.2–3.6 days per decade (Gitay et al. 2001). This allows earlier planting of crops in spring, earlier maturing and harvest, and the possibility for two or more cropping cycles. An expansion of suitable crop area may become possible in the Russian Federation, North

America, Northern Europe, and Northeast Asia. In contrast, significant losses are predicted for Africa due to heat and water stress and an expansion of arid and semiarid regions (Fischer et al. 2005). Temperature increases are likely to support positive effects of enhanced CO₂ until temperature thresholds are reached. Beyond these thresholds, crop yields will be negatively affected. Increased water supply can help to balance high temperatures. In the tropics, additional warming of less than 2°C will lead to crop yield losses, while crops in temperate regions will broadly benefit from temperature increases of up to 2°C. Further warming will negatively affect plant health in temperate regions (Easterling et al. 2007).

Water availability

Agriculture highly depends on water availability. More than 80% of global cropland is rainfed, but irrigated cropland with an area share of 16% produces about 40% of the world's food. Agricultural irrigation accounts for around 70% of global freshwater withdrawals (Gitay et al. 2001). Because of growing global food demand

and rising temperatures, even more water will be required in the future. Climate impacts on crop productivity will fundamentally depend on precipitation changes. Precipitation projections show large variability of quantity and distribution. This is also due to the fact that historical climate records as an input for modeling are scarce in many poor countries. Annual mean runoff largely follows projected changes in precipitation with an increase in high latitudes and the wet tropics, and with a decrease in mid-latitudes and some parts of the dry tropics (Solomon et al. 2007). The decline in water availability will affect areas currently suitable for rainfed crops, like the Mediterranean basin, Central America, and subtropical regions of Africa and Australia (Easterling et al. 2007). Moreover, in warmer and dryer regions, agricultural water demand will increase. Global irrigation requirements are estimated to increase by 5–8% by 2070 with regional differences of up to +15% in South Asia (Döll 2002). While irrigated agriculture is expected to become more important, water supply may be insufficient. In regions that are depending on steady water supplies from glaciers (e.g., Andes and Himalaya), water availability may increase in the near to medium term due to accelerating glacier retreat, whereas it may break down later, once glaciers are completely melted. In some regions (e.g., northern India and Midwest United States) groundwater is depleted at fast rates, which could clearly lead to water shortages in the future. In addition to decreasing water supply, agriculture in many fast-growing regions will also face increasing competition for water due to rising demand from households and industry.

Climate variability, extreme events, and sea-level rise

Extreme climate events such as heat waves, heavy storms, floods, or droughts may damage crops in specific development stages. A substantial and widespread increase in the number of heavy rainfall events is expected, even in regions

where total precipitation amount decreases (Solomon et al. 2007). Heavy rainfalls are very likely in Southern and Eastern Asia and in Northern Europe, which are major agricultural production areas. On the other hand, observations show an increase in frequency and duration of warm weather extremes. In many regions, especially in the tropics and subtropics, droughts have been longer and more intensive since the 1970s because of higher temperatures and reduced precipitation (Solomon et al. 2007). Climate change will deepen these trends. In arid and semiarid regions, higher rainfall intensity will increase risks of soil erosion and salinization. Rice yield is already close to the limit of maximum temperature tolerance in South Asia. Thus, even higher temperatures will negatively affect yields. Additionally, increasing flood frequency will damage crop production in countries like Bangladesh. In the United States, heavy precipitation events are expected to cause severe production losses already by 2030 (Rosenzweig and Hillel 1995; Easterling et al. 2007). The European heat wave in the summer of 2003 with temperatures of 6°C above long-term averages and severe precipitation shortfalls caused severe economic losses for the agricultural sector across Europe. In Northern Italy, a record yield drop of 36% was observed, while in France maize yield was reduced by 30% when compared to 2002 (Easterling et al. 2007).

In low-lying countries with long coastlines, sea-level rise will threaten large areas of fertile land. This is a special problem, e.g., in Bangladesh and many Pacific Islands. Another problem related to rising sea levels is saltwater intrusion, which may negatively affect soil fertility and quality of irrigation water in coastal areas.

Soil degradation

Climate change affects soils by increasing the rate of nutrient leaching and soil erosion. Nutrient conservation is affected by warmer temperatures because higher temperatures are likely

to increase the natural decomposition of organic matter because of a stimulation of microbial activity. If mineralization exceeds plant uptake, nutrient leaching will be the consequence. It primarily occurs when plant demand is low and rising soil temperature increases nitrogen mineralization rates. This process is enforced by increased precipitation and loss of snow cover as predicted for many temperate regions (Niklaus 2007). Soil erosion is increased by intensive rainfall, which is likely to increase under climate change. One percent increase in precipitation is expected to lead to 1.5–2% increase in erosion rates (Nearing et al. 2004). Extreme rainfall and shifting from snow to rain will also increase the rate of erosion. Changes of plant biomass can further increase these effects: plant canopies reduce soil erosion by weakening the power of rain, roots stabilize soils, and crop residues reduce sediment transportation. In arid and semi-arid regions, dry soils are sensitive to soil erosion through wind and rain. Increased frequency of droughts further intensifies erosive losses as plant biomass and its positive effects on soils are reduced (Nearing et al. 2004; Niklaus 2007).

Weeds, pests, and pathogens

In current agriculture, preharvest losses to pests in major food and cash crops are estimated to be 42% of global potential production (Gitay et al. 2001). Temperature rise and elevated CO₂ concentration could increase plant damage from pests in future decades, although only a few quantitative analyses exist to date (Easterling et al. 2007; Ziska and Runion 2007). Weeds, like crops, show positive response to elevated CO₂. Moreover, weeds show a larger range of responses, including larger growth, to elevated CO₂ because of their greater genetic diversity (Ziska and Runion 2007). Several important crop weeds in the United States have expanded since the 1970s, which is consistent with climate trends (Gitay et al. 2001). However, future weed distribution and the accompanied changes in weed–crop competition remain

highly uncertain. Temperature rise will boost insect growth and development by increasing geographical distribution and increasing overwintering (Ziska and Runion 2007). Pathogens are recognized as a significant limitation on agronomic productivity. While elevated CO₂ will not directly affect the pathogens, it will alter plant defense mechanisms. Especially, higher winter temperatures will lead to an increasing occurrence of plant diseases in cooler regions (Ziska and Runion 2007).

Climate impacts on agricultural markets

According to currently available studies, aggregated global impacts of climate change on world food production are likely to be small. Parry et al. (2004) predict negative impacts on world crop production by –5% by the end of the century. According to Fischer et al. (2005), production losses in developing countries in the range of 5–15% will be compensated by similar increases of production in the developed countries, in particular North America and Russia. Thus, climate change will result in larger trade flows from mid- and high-latitudes to the low latitudes (Easterling et al. 2007). However, most of the studies available to date only cover gradual scenarios of climate change and related impacts. If tipping points in the climate system are transgressed, the picture is likely to become much bleaker (Battisti and Naylor 2009). Even without climate change, there will be a growing dependency of developing countries on net cereal imports. Climate change will further increase this dependency by 10–40% (Fischer et al. 2005). In the past, the average rate of productivity growth in agriculture and food production exceeded population growth. Supply exceeded demand, which resulted in a long-term decline of real food prices until the turn of the millennium. Even if the strong food price increases in 2007/2008 may have been an exception, it can be expected that world food prices will gradually increase in the future. Besides climate change, the dynamics of population, income, and

technology will continue to play an important role. Furthermore, depending on technological and policy changes in the energy sector, an increasing demand for bioenergy will have an impact on agricultural markets. In poor, net food importing countries, food security could deteriorate as a result. For countries with a strong production potential, bioenergy demand could also become an engine for agricultural and economic growth.

Climate impacts on food security

Food security has four major components: Food availability through production and trade; stability of food supplies; access to food; and actual food utilization. They all can be affected by climate change (Gregory et al. 2005; Easterling et al. 2007). Assessments of crop production can therefore only provide a partial assessment of climate change impacts on food security. In addition, climate change is not the only factor that may cause food security problems. Regional conflicts, changes in international trade agreements and policies, infectious diseases, and other societal factors may exacerbate the impacts (Easterling et al. 2007). The capacity to cope with environmental stress is as important as the degree of exposure to climate-related stresses. Thus, projections of undernourishment depend on climate impacts and also on economic development, technical conditions, and population growth (Gregory et al. 2005). At the beginning of the millennium, between 800 and 900 million people were at risk of hunger. Most of them lived in Asia and sub-Saharan Africa (FAO 2006, p. 8). In the future, many factors including climate change and socioeconomic development will influence the number of people at risk, and there are still a lot of uncertainties about regional climate impacts on food supply and demand. However, it is very likely that sub-Saharan Africa will surpass South Asia as the most food-insecure world region (Tubiello and Fischer 2007). Few studies have tried to quantify the impacts of climate change and socioeconomic

factors on food security (Fischer et al. 2002, 2005; Parry et al. 2004; Tubiello and Fischer 2007). They indicate that the number of people at risk of hunger will mostly depend on socioeconomic development. Economic growth and slowing population growth can significantly reduce the number of people at risk of hunger. In a pessimistic scenario with strong global warming, high population growth, and no CO₂-fertilization effects, the number of additional people at risk of hunger may be as high as 500–600 million by 2080 (Parry et al. 2004). Again, the situation may become even worse, if tipping points in the climate system are transgressed (Battisti and Naylor 2009).

Adaptation options in agriculture

Agricultural vulnerability

In the past, adaptation in agriculture was the norm rather than the exception. Farmers have demonstrated sufficient adaptive capacity to cope with weather variations on weekly, seasonal, annual and even longer timescales (Burton and Lim 2005; Rosenzweig and Tubiello 2007). Modern agricultural technologies have minimized climate impacts through irrigation, the use of pesticides and fertilizers, and the manipulation of genetic resources (Kandlikar and Risbey 2000). In the future, however, climate will change at a rate that has not been previously experienced in human history. Adaptive capacity of farmers is determined by their wealth, human capital, information and technology, material resources and infrastructure, and institutions and entitlements of the society (Kandlikar and Risbey 2000; Belliveau et al. 2006; Easterling et al. 2007). It is obvious that rich countries are better equipped to cope with climate variations than developing countries, where decisions are made in the context of the local agricultural cycle, poverty, and often limited access to markets. Many possible adjustments are prevented by the lack of information, financial resources, and institutional support. New technologies are often not

implemented due to lack of education (Kandlikar and Risbey 2000; Smithers and Blay-Palmer 2001).

Adjustments in production technology

Technical improvements and management adjustments at the farm level include the following:

- Shifted dates of planting allow farmers to take advantage of the longer growing season that is permitted by higher winter temperatures in higher latitudes. Earlier planting can lead to an increase in the yield potential by using cultivars that need longer time to mature. The potential for earlier harvesting can avoid heat and drought stress in late summer (Easterling 1996; Olesen and Bindi 2002; Rosenzweig and Tubiello 2007).
- New crop varieties can provide more appropriate thermal requirements and increased resistance to heat shock and drought. Breeding of new varieties is certainly a major option for improved adaptation, but development of new varieties, which are well adapted to specific regional conditions, is expensive and typically needs a decade or longer until they can be distributed to farmers. Hence, breeding programs need to be planned at a longer timescale (Olesen and Bindi 2002; Smit and Skinner 2002; Rosenzweig and Tubiello 2007).
- Altering and widening existing crop rotations can help to adapt to changing climate conditions by introducing new, better adapted crop types. A broader crop mix will decrease the dependency on weather conditions in a certain growing season and hence stabilize production and farm income under higher climate variability. However, it will also require technical and management adjustments and may reduce some gains from specialization in the production of certain crops (Olesen and Bindi 2002; Easterling et al. 2007; Rosenzweig and Tubiello 2007).
- Rising water demand caused by higher temperatures can be balanced by improved water management and irrigation. A shift from

rainfed to irrigated agriculture may be an option, although water availability, costs, and competition with other economic sectors need to be considered. Adjustments like timing of irrigation and improvement of water-use efficiency can ensure water supply for crops even under warmer and dryer climate. Moreover, crop residue retention and altered tillage practices can reduce water demand. Various types of low-cost “rainwater harvesting” practices have been developed in poor countries (Easterling 1996; Smithers and Blay-Palmer 2001; Smit and Skinner 2002).

These adjustments, alone or in combination, can minimize climate impacts on agriculture. On average, adaptation can provide around 10–15% yield benefit compared to a situation without adaptation measures. Thus, adaptation may shift negative yield changes caused by rising temperatures from 1.5°C to 3°C warming in low latitude regions and from 4.5°C to 5°C in mid- to high-latitude regions. If temperatures rise above these thresholds, the adaptive capacity is likely to be exhausted and severe losses are to be expected (Easterling et al. 2007). However, interactions between different adaptation options and economic, institutional, and cultural barriers to adaptation are not considered in most available studies (Easterling et al. 2007).

Insurance schemes

In addition to changes in production technology, insurance schemes (e.g., crop insurance or income stabilization programs) can provide compensation for crop and property damages caused by climate-related hazards, like droughts or floods. However, these options are not available for farmers everywhere, not even in all developed countries (Bielza et al. 2007). There are specific challenges for insurance schemes in the agricultural sector. Extreme weather events can affect a large group of people at the same time, and the insurance pool may not be able to cover all the claims. If reinsurance mechanisms

or government support schemes are not available, insurance companies would have to charge high premiums, which may be unaffordable for most farmers. Thus, agricultural insurance schemes are usually supported by the public sector to provide broad coverage at affordable premiums (European Commission 2001; Bielza et al. 2007). In some developed countries, financial support for crop insurance and disaster payments are a major part of their agricultural sector policies. The United States, Canada, and Spain have the most developed agricultural insurance policies. Up to 60% of farmers in these countries purchase at least one insurance policy (Garrido and Zilberman 2007). Insurance in developing countries is only available to a limited extent. In India, the National Agriculture Insurance Scheme was implemented to protect farmers against losses due to crop failure caused by drought, flood, hailstorm, cyclone, fire, pests, and diseases. All food crops, oilseeds, and annual commercial and horticultural crops are covered. However, only 4% of farmers are currently protected by the crop insurance scheme. Almost half of the farmers in India still do not even know about the insurance option (Bhise et al. 2007).

International trade

On average, global food production is likely to be sufficient to meet global consumption over the coming decades. However, climate change will reduce crop yield in some regions, while it will have beneficial effects in others. A well-functioning system of international trade flows, which is responsive to price signals, will be needed to balance production and consumption between and within nations. Increased agricultural output in a region where agricultural production improves can then be used to compensate potential losses in other regions (Juliá and Duchin 2007). It has been shown in the past that open markets are promoting economic development. In the agricultural sector, protectionist policies in the industrialized countries are still preventing the developing countries from participating to a larger share in international markets.

In the future, international trade between rich and poor countries, but also among poor countries, can to a certain degree serve as an insurance mechanism against severe production shortfalls due to extreme weather events. Even in a changing climate, it is unlikely that extremely bad harvests will occur at the same time in several major supply regions.

Government policies to support adaptation in agriculture

The adaptive capacity at the farm level is unlikely to be sufficient in many poor regions. Nonclimatic forces such as economic conditions and policies have significant influences on agricultural decision-making. Therefore, changes in national and international policies for the agricultural sector are needed to support adaptation at the local level (Smit and Skinner 2002; Rosenzweig and Tubiello 2007). The weight given to climate change in the policy process will depend on national and local circumstances, including local risks, needs, and capacities. Further reform of agricultural policies in developed countries should not only make agricultural production more climate-friendly, but also provide better options for poor countries to improve their adaptive capacity. More financial resources have to be shifted away from direct farm income support toward better agricultural education, research, and technological development to assure yield improvement and yield stabilization under changing climate and market conditions. Improved infrastructure is needed for the extension of irrigation or for appropriate storage, transportation facilities, and better weather forecasting and climate impact research. Low density of weather stations and limited historical weather data, especially in Africa and other developing regions, is one reason for high uncertainties in current climate model scenario outputs. This in turn makes it more difficult for these countries to develop appropriate adaptation strategies (Belliveau et al. 2006; Easterling et al. 2007).

Improved policies can also guide transitions where major land use changes, changes of

industry locations, or migration occur. Financial and material support can create alternative livelihood options. Planning and management of such transitions may also result in less habitat loss and lower environmental damage. The establishment of functioning and accessible markets for inputs such as seeds, fertilizers, and labor, as well as financial services can improve income security for farmers (Easterling et al. 2007).

Conclusions

Climate impacts on agriculture strongly depend on regional and local circumstances. Adaptive capacity and adaptation options are largely determined by the level of economic development and institutional setting, which also differ widely across the globe. While positive and negative effects of climate change on global agriculture may on average almost compensate each other, the uneven spatial distribution is likely to affect food security in a harmful way in many regions. Food security could be severely threatened, if tipping points in the climate system are transgressed. One prominent example of a climate tipping point is the dynamics of the Indian monsoon, which could be disrupted under certain conditions (Zickfeld et al. 2005). This would negatively affect agricultural production conditions in large parts of South Asia. Generally speaking, developing countries in the tropics will face the strongest direct climate impacts, while having the lowest level of adaptive capacity. The most affected regions are expected to be sub-Saharan Africa and the Indian subcontinent. If global mean temperature will rise by more than 2–3°C compared to preindustrial levels, countries in mid and high latitudes will also be strongly affected. Uncertainties still prevail with regard to future precipitation patterns and water availability at the regional level, the impacts of extreme events on agriculture, and changes in soil fertility and agricultural pests and pathogens. Further research is also required on the interactions between various climate-related stress factors. The role of CO₂ fertilization in

connection with nutrient and water limitations needs further clarification. Negative climate impacts on agriculture may be reduced through a range of adaptation measures. Adjustments in production technology and soil management, crop insurance schemes, diversified international trade flows, and better designed agricultural policies can improve regional food availability and security of farm income. However, limited resources such as fertile soils, freshwater, financial means, and institutional support may often prevent the required adjustments.

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