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Climate impacts and adaptation options in agriculture: what we know and what we don't know

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1 Introduction

Since publication of the Stern Review on the Economics of Climate Change in 2006 and the IPCC Fourth Assessment Report in 2007 it is clear 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 CO_2 concentrations in the atmosphere, but it is also contributing about one third to total greenhouse gas emissions, mainly through nitrogen fertilization, livestock and rice production, land use change and deforestation. Agriculture currently accounts for 5% of world economic output, employs 22% of the global population, and occupies 40% of the land area. In the developing countries, 70% of people live in rural areas, where agriculture is the largest supporter of livelihood and the economy is dominated by the agricultural sector. Agriculture accounts for 40% of GDP in Africa and 28% in South Asia. A large share of the world's poor population lives in arid or semi-arid regions, which are already characterized by highly volatile climate conditions. Under conditions of climate change, a world-wide 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 industrialised 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 non-existent) 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 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.

2 Climate impacts on crop productivity

Plant growth and yield will be both positively and negatively affected by climate change. Diverging effects are caused by rising CO_2 concentrations, higher temperature and changing precipitation patterns, changes in water availability, increased frequency of weather extremes such as floods, heavy storms and droughts, soil erosion, and other environmental changes. While some of these impacts have been studied in isolation, complex interactions between different factors and especially extreme events are still not well understood.

2.1 CO_2 fertilization

Yields of most agricultural crops increase under elevated CO_2 concentration. Free Air Carbon Enrichment (FACE) experiments indicate productivity increases in the range of 15-25% for C_3 crops (like wheat, rice and soybeans) and 5-10% for C_4 crops (like maize, sorghum and sugar cane). Higher levels of CO_2 also improve water-use efficiency of both C_3 and C_4 plants. However, the experiments do not address important co-limitations due to water and nutrient availability. Some studies expect much less favorable crop response to elevated CO_2 in practice than asserted on experimental sites (e.g. Long et al. 2006), while others agree with previous findings (Tubiello et al. 2007). Thus, the magnitude of the positive effect due to enhanced CO_2 concentration is still uncertain (Parry et al. 2004, p.55; Easterling et al. 2007, p.282).

2.2 Higher temperature

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, p.37). 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, p.247). 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 East Asia. In contrast, significant losses are predicted for Africa due to heat and water stress and an increase of arid and semi-arid regions (Fischer et al. 2005, p.2073f). Temperature increases are likely to support positive effects of enhanced CO_2 until limit temperatures are reached. Beyond there thresholds, crop yields will be negatively affected. Increased water supply can help to balance high temperatures. In the tropics, additional warming of less than two 2°C will already 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 also in temperate regions (Easterling et al. 2007, p.276).

2.3 Water availability

Agriculture highly depends on water availability. More than 80% of global cropland is rain-fed, 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, p.253). Due to growing global food demand and rising temperature, 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. 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, p.40f). The decline in water availability will affect areas currently suitable for rain-fed crops like the Mediterranean basin, Central America and sub-tropical regions of Africa and Australia (Easterling et al. 2007, p.280). Moreover, in warmer and dryer regions water demand will increase. While irrigated agriculture is expected to become more important, water supply may be insufficient. Global irrigation requirements are estimated to increase by 5% to 8% by 2070 with regional differences of up to +15% in South Asia (Döll 2002, p.291).

2.4 Climate variability

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, p.40ff). 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 sub-tropics, droughts have been longer and more intensive since the 1970’s because of higher temperatures and less precipitation (Solomon et al. 2007, p.40ff). Climate change will deepen these trends. In arid and semi-arid 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, p. 283f). The European heat wave in the summer of 2003 with temperatures of 6°C above long-term averages and a precipitation shortfall of up to 300 mm 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% compared to 2002 (Easterling et al. 2007, p.277).

2.5 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 due to a stimulation of microbial activity. If mineralization exceeds plant uptake, nutrient leaching will be the consequence. It primarily occurs during winter time when plant demand is low or plants are absent 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, p.36). Soil erosion is induced by intensive rainfall which is likely to increase under climate change. 1% 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, p.36).

2.6 Weeds, pests and pathogens

In current agriculture, pre-harvest losses to pests in major food and cash crops are estimated to be 42% of global potential production (Gitay et al. 2001, p.257). Temperature rise and elevated CO_2 concentration could increase plant damage from pests in future decades, although only a few quantitative analyses exist to date (Easterling et al. 2007, p.283, Ziska and Runion 2007, p.269). Weeds, like crops, show positive response to elevated CO_2. Moreover, weeds show a larger range of responses, including larger growth, to elevated CO_2 due to their greater genetic diversity (Ziska and Runion 2007, p.268). Several important crop weeds in the USA have expanded since the 1970’s which is consistent with climate trends (Gitay et al. 2001, p.257). 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, p.271). Pathogens are recognized as a significant limitation on agronomic productivity. Similar to the insects case, elevated CO_2 will not directly affect the pathogens but 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, p.275).

3 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, p.297). It must be mentioned, though, that 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 et al. 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, p.2079). In the past, the average rate of productivity growth 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. For poor, net food importing countries this could negatively affect food security. For countries with a strong production potential, bioenergy demand could also become an engine for growth.

4 Climate impacts on food security

Food availability through production and trade, stability of food supplies, access to food and food utilization are the four components of food security and they can all be affected by climate change (Gregory et al. 2005, p.2140; Easterling et al. 2007, p.297). Assessments of crop production can therefore provide only a partial assessment of climate change impacts on food security. In addition, climate change is not the only factor which 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, p.297). 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, p.2143). Today, between 800 and 900 million people are at risk of hunger. Most of them live in Asia and Sub-Saharan Africa (FAO 2006, p.8). Many factors including climate change and socio-economic 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, p.1041). Few studies have tried to quantify the impacts of climate change and socio-economic 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 socio-economic 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 CO_2-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, p.66). Again, the situation may become even worse, if tipping points in the climate system are transgressed (Battisti et al. 2009).

5 Adaptation options in agriculture

5.1 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, p.193; Rosenzweig and Tubiello 2007, p.860). 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, p.529). 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, p.531; Belliveau et al. 2006, p.8; Easterling et al. 2007, p.278). 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, p.534; Smithers and Blay-Palmer 2001, p.179).

5.2 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 which is permitted by higher winter temperatures. Earlier planting can lead to an increase in the yield potential by using cultivars which need longer time to mature. The potential for earlier harvesting can avoid heat and drought stress in late summer (Easterling 1996, p.10ff; Olesen and Bindi 2002, p.252; Rosenzweig and Tubiello 2007, p.860f).
- 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 time scale (Olesen and Bindi 2002, p.252; Smit and Skinner 2002, p.96ff; Rosenzweig and Tubiello 2007, p.860f).
- 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 whether 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 (Olesen and Bindi 2002, p.252; Easterling et al. 2007, p.294; Rosenzweig and Tubiello 2007, p.860f).

- Rising water demand caused by higher temperatures can be balanced by improved water management. A shift from rain-fed to irrigated agriculture may be an option, although water availability, costs and competition with other 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, p.11f; Smithers and Blay-Palmer 2001, p.178; Smit and Skinner 2002, p.97ff).

These adjustments, alone or in combination, can minimize climate impacts on agriculture. On average, adaptation can provide around 10-15% yield benefit compared to no adaptation practice. 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 exceeded and severe losses become probable (Easterling et al. 2007, p.295). 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, p.295).

5.3 Government policies

The adaptive capacity at the farm level is unlikely to be sufficient in many poor regions. Non-climatic forces such as economic conditions and policies have significant influences on agricultural decision-making. Therefore changes of national and international policies for the agricultural sector are needed to support adaptation at the local level (Smit and Skinner 2002, p.88; Rosenzweig and Tubiello 2007, p.855). 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 towards more 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 (Belliveau et al. 2006, p.8; Easterling et al. 2007, p.296). 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 provide income security for farmers (Easterling et al. 2007, p.296).

5.4 Insurance schemes

Insurance schemes like 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 in every country, not even in all developed countries (Bielza 2007, p.5f). 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, such that the insurance pool may not be able to cover all the claims. To express the effectiveness of an insurance pool, the ratio of paid premiums and asserted claims is used. A claim-to-premium ratio of greater than one indicates higher payouts than incoming payments from the insured farmers. Crop insurance policies often have a claim-to-premium ratio greater than one, even if aggregated over a country. If re-insurance or state guarantee are not available, insurance companies would have to charge high premiums which may be unaffordable for farmers. Thus, agricultural insurance schemes are usually supported by the public sector to provide broad coverage at affordable premiums (European Commission 2001, p.24; Bielza 2007, p.5f). In some developed countries financial support for crop insurance and disaster payments are a fundamental part of their agricultural stabilization strategies. 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, p.3). 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, p.11).

5.5 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, p.394). 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 climate events. Even under a changing climate, it is unlikely that extremely bad harvests will occur at the same time in several major supply regions.

6 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. Developing countries in the tropics will face the strongest direct climate impacts, while having the lowest level of adaptive capacity. The most affected region is expected to be Sub-Saharan Africa. If global mean temperature will rise by more than 2-3°C compared to pre-industrial 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 CO_2 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, modified agricultural policies, and diversified international trade flows 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.

7 Literature

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