Climate Change and Agriculture

Threats and Opportunities

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On behalf of
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for Economic Cooperation
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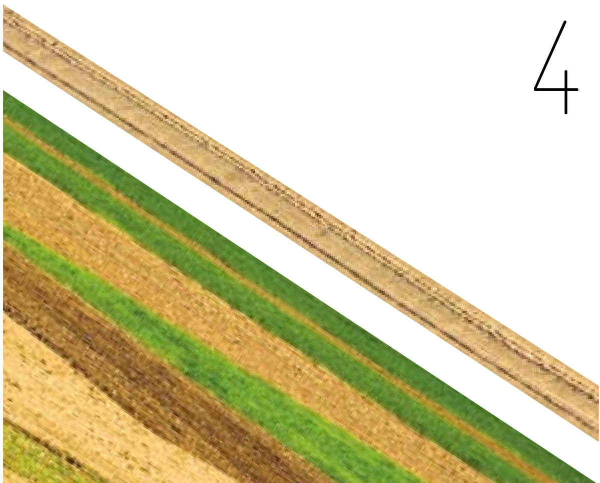

Preface

Climate change is real and already taking place, according to the IPCC's most recent Assessment Report (IPCC IV 2007). According to the report, the impacts of climate change and their associated costs will fall disproportionately on developing countries threatening to undermine achievement of the Millennium Development Goals, reduce poverty, and safeguard food security. A major component of development assistance is support for the agriculture sector since agricultural production worldwide is increasingly under pressure to meet the demands of rising populations. At the same time, there is concern also about the contributions that the agriculture sector makes to greenhouse gas emissions and climate change.

This paper provides an insight into the different climate-change-related challenges that the agricultural sector in developing countries will face and explores opportunities for emission reductions and adaptation. The study concludes that adaptation measures in the agriculture sector are highly significant for poverty reduction. It also highlights that agriculture in developing countries can play a significant role in mitigating greenhouse gases and that it is critical to work out incentives that are conducive to emission reductions in this sector. Specifically, it may be worthwhile to explore the potential contribution to mitigation and mobilize resources from the carbon market for investment in pro-poor and sustainable agricultural development. It also reconfirms that sustainable management of natural resources is key to both mitigation of emissions and adaptation in the agricultural sector.

Agriculture has not figured very prominently in the climate discussion so far. This study very clearly indicates that the sector deserves more attention when it comes to both climate change threats and opportunities. Understanding interrelations and interactions in the agricultural sector and considering its implications for development cooperation is crucial for adequate development responses. By presenting this study, we aim to advance this understanding and the promotion of practical approaches to the challenges posed by climate change to agriculture and development cooperation.

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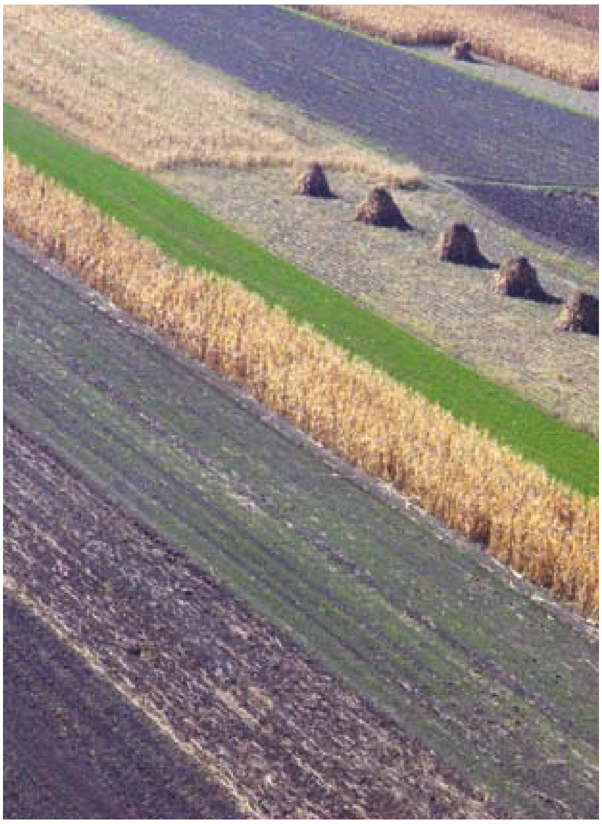


Introduction

> "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."
>
> Intergovernmental Panel on Climate Change,
> Fourth Assessment Report, 2007

Global agriculture will be under significant pressure to meet the demands of rising populations using finite, often degraded, soil and water resources that are predicted to be further stressed by the impact of climate change. The ongoing buildup of greenhouse gases in the atmosphere is prompting shifts in climate across the globe that will affect agro-ecological and growing conditions. In addition, agriculture and land use change are prominent sources of global greenhouse gas emissions. The application of fertilizers, rearing of livestock, and related land clearing influences both levels of greenhouse gases in the atmosphere and the potential for carbon storage and sequestration. Therefore, whilst ongoing climatic changes are affecting agricultural production, the sector itself also presents opportunities for emissions reductions.

Despite these opportunities, warming of the climate — as the IPCC warns above — is unequivocal. Even if emissions from all sectors were reduced to zero, climate warming would continue for decades to come. As a result, it is of interest to stakeholders in the agricultural sector to understand the kind of impact climate change will have on food and crop production. There will undoubtedly be shifts in agro-ecological conditions that will warrant changes in processes and practices — and adjustments in widely accepted truths — in order to meet daily food requirements. In addition, climate change could become a significant constraint on economic development in developing countries that rely on agriculture for a substantial share of gross domestic production and employment.

At the end of this assessment, two central ideas for dealing with climate change will become clear, namely, mitigation and adaptation. Mitigation — or a decline in the release of stored carbon and other greenhouse gases — must take place. There are opportunities for mitigation in the agricultural sector to help reduce the impact of climate change, and there is significant room for promoting pro-poor mitigation methods. In addition, as a change in climate has already begun, adaptation — or the modification of agricultural practices and production — will be imperative to continue meeting the growing food demands of modern society. Both mitigation and adaptation will require the attention of governments and policy makers in order to coordinate and lead initiatives. It is apparent that a system of regulation to ensure the economic value of carbon sequestration will be an important policy development in the agricultural sector.

In this paper, the impact of climate change on production and opportunities for emissions reductions is reviewed with a focus on developing countries, including the implications for food security and livelihoods for the poor. In order to highlight specific on-farm and soil management practices, this paper will focus on emissions and impacts related to food production (mainly crop and livestock production), plus corresponding mitigation and adaptation strategies. Following the introduction, the impact of agricultural production on global warming and climate change is considered, including possibilities for mitigation. The second part considers how the release of carbon and greenhouse gases will impact the agricultural sector, drawing heavily on future climate projections. Part three discusses adaptation strategies for individuals and governments and their capacity to respond to increasing climate variability. Part four offers a conclusion. The objective is to provide a synthesis of the evidence relating to the impact of agriculture on climate change, as well as the impact climate change is projected to have on this sector. The intention is to provide a clear message for development practitioners and policy makers in order to enable them to cope with the threats, as well as understand the opportunities, presented by ongoing climate change.

Emissions mitigation in agriculture

1.

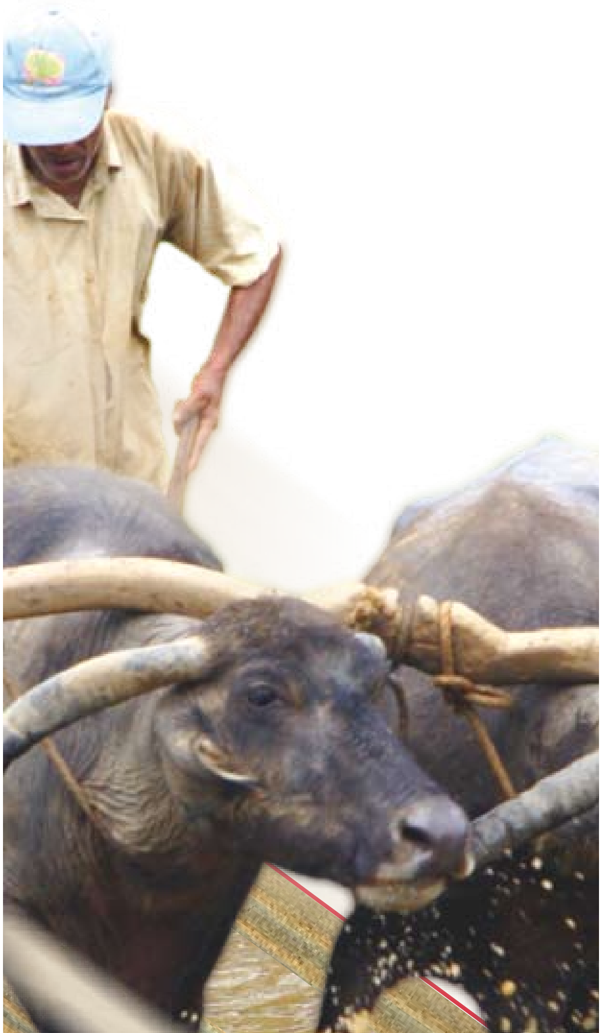
Mitigation is a response strategy to global climate change, and can be defined as measures that reduce the amount of emissions (abatement) or enhance the absorption capacity of greenhouse gases (sequestration). The total global potential for mitigation depends on many factors, including emissions levels, availability of technology, enforcement, and incentives. In many situations, the efficiency of agriculture can be improved at a low cost. However, when low cost incentives are unavailable, policy development is important. The following is a short summary of key points from this section.

Greenhouse gas emissions (GHG) from agriculture:

- The share of agricultural emissions in total GHG emissions in 2000 was 13 percent. In developing countries, such emissions are expected to rise in the coming decades due to population and income growth, amongst other factors.
- Within the agricultural sector, fertilizer application, livestock and manure management, rice cultivation, and savanna burning are the major sources of emissions.

Mitigation potential and options in agriculture:

- The technical potential for GHG mitigation in developing country agriculture by 2030 indicates significant opportunities for emissions reductions, together with an enhanced income earning potential for farmers, and associated benefits from lower natural resource degradation.
- Developing countries are estimated to account for three-fourths of global technical potential, with Asia accounting for 40 percent, Africa 18 percent, and Latin America and the Caribbean 15 percent (Smith *et al.*, 2007a, b).
- The economic potential for mitigation in agriculture depends on the price of carbon and on policy, institutional, and transaction cost constraints. It is estimated that the



economic potential is about 36 percent of technical potential at carbon prices of up to $25 per t CO_2-eq, 44 percent at prices of up to $50/t CO_2-eq, and 58 percent at prices of up to $100/t CO_2-eq (Smith *et al.*, 2007a, b).

- Based on USEPA (2006) results, rice cultivation mitigation strategies have the highest economic potential for emissions reductions in developing countries. However, Smith *et al.* (2007a, b) have found that soil carbon sequestration offers the highest economic potential, and with best prospects in developing countries.

Conditions for realizing the mitigation potential:

- Agriculture in developing countries can play a role in the mitigation of greenhouse gases, but the economic potential for mitigation is constrained by poor incentives to investing in this area. At the same time, a major challenge lies in aligning growing demand for agricultural products with sustainable, emissions-saving development paths.

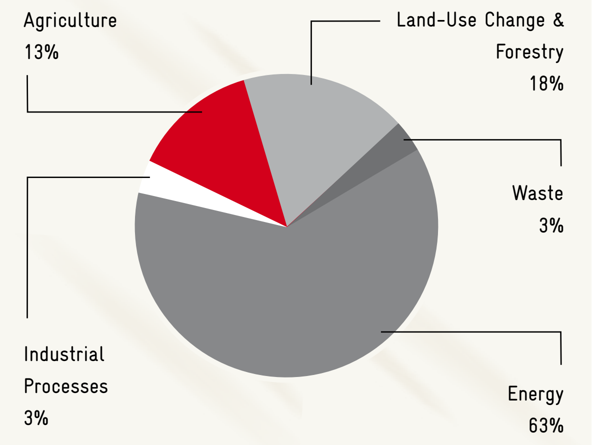
The carbon market for the agricultural sector is underdeveloped because of limited access under the Clean Development Mechanism, plus the high cost of verification, monitoring and transactions, especially with respect to small farmers. However, mitigation potential can be enhanced by improving the sector's access to carbon markets under the post-Kyoto international agreement currently being negotiated. Costs for agricultural carbon trades can also be reduced by simplifying and improving the measurement, monitoring and verification methods required for such trading, as well as through capacity building.

- With these reforms, policies focused on mitigating GHG emissions, if carefully designed, can help create a new development strategy; one which encourages the creation of new value in pro-poor investments by increasing the profitability of environmentally sustainable practices.

1.1 Emissions trends

Climate change is the result of an increase in the concentration of greenhouse gases (GHG) like carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Rising GHG emissions are associated with economic activity, particularly as related to energy, industry, transport, and patterns of land use (the latter covers agricultural production and deforestation). As shown in Figure 1, agriculture, including land use change and forestry or LUCF, accounts for nearly one-third of global GHG emissions (WRI, 2008).

Fig. 1



Share of global GHG emissions by sector, year 2000

Source: Drawn from data from WRI (2008)

Further analysis of Figure 1 indicates that agriculture alone contributed 13 percent of total global GHG emissions in 2000, or 5,729 Mt CO_2-equivalents[1]. Emissions from this sector are primarily CH_4 and N_2O, making the agricultural sector the largest producer of non-CO_2 emissions. Indeed, 60 per cent of total global non-CO_2 emissions came from this source in 2000 (WRI, 2008). Whilst agriculture also generates very large CO_2 fluxes (both to and from the atmosphere via photosynthesis and respiration),

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[1] One million metric tons (MMt) of methane (CH_4) emissions equals 21 million metric tons of carbon dioxide (CO_2) emissions. 1 MMt CH_4 = 21 MMt CO_2. Similarly, 1 MMt N_2O = 320 MMt CO_2. This indicates that the global warming potential of methane and nitrous oxide is higher than that for carbon dioxide, because these exist longer in the atmosphere. Yet, due to their significantly smaller concentrations, the actual radioactive forcing of CH_4 and N_20 is one-third and one-tenth of CO_2, respectively.

these are nearly balanced on existing agricultural lands. Significant carbon release, however, results from the conversion of forested land, which is accounted for under the LUCF category.[2] Finally, certain GHG emissions arising from agricultural activity are accounted for in other sectors, such as those relating to (upstream) manufacture of equipment, fertilizers, and pesticides, plus on-farm use of fuels and the transportation of agricultural products.

Records of regional variations in emissions (non-CO_2) from agricultural sources indicate that non-OECD countries emit nearly 75 percent of global emissions (WRI, 2008). As a result, the theoretical potential for agricultural sector mitigation is greater for developing countries than for industrialized nations. Asian countries account for 37 percent of total world emissions from agricultural production, with Latin America and Europe a distant second and third place, with 16 and 12 percent, respectively (WRI, 2008). In Asia, China accounts for over 18 percent of the total, while Brazil alone is responsible for nearly 10 percent of agricultural emissions in Latin America (WRI, 2008).

Tab. 1

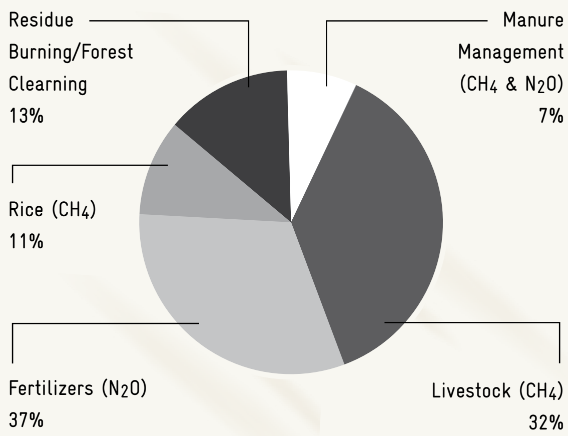
Country	1990	2000	2010	2020
Africa	664	934	1098	1294
China/CPA	1006	1159	1330	1511
Latin America	890	1097	1284	1505
Middle East	62	74	99	125
Non-EU Eastern Europe	21	19	21	24
Non-EU FSU	410	217	246	279
OECD90 & EU	1346	1283	1306	1358
SE Asia	823	946	1084	1214
World Total	5223	5729	6468	7311

Agricultural Emissions by Region, 1990 to 2020 (Mt CO_2-eq)

Source: Drawn from data used in USEPA (2006)

Emissions from agriculture come from four principal sub-sectors: agricultural soils, livestock and manure management, rice cultivation, and the burning of agricultural residues and savanna for land clearing. Figure 2 presents the share of pollutants derived from each of these sectors. Agricultural soils (N_2O) and the enteric fermentation and manure management (CH_4) associated with livestock production account for the largest of these shares. Emissions from agriculture are expected to rise due to increased demand for agricultural production, improved nutrition, and the changing dietary preferences of growing populations that favor larger shares of meat and dairy products (e.g. Delgado *et al.*, 1999). This will also lead to increased pressure on forest resources due to agricultural expansion. Figure 3 presents the projected growth in emissions from each source for the years 1990 to 2020. Global agricultural emissions were found to increase by 14 percent from 1990 to 2005, and a 38 percent rise is expected for the entire period 1990 to 2020. Figure 4 illustrates the share of expected emissions growth likely to come from developing countries for each sector. Agricultural emissions in developing countries are expected to increase by 58 percent in 2020. Meanwhile, emissions from the burning of agricultural residues and savanna and N_2O from soils are projected to grow by over 40 percent from 1990 levels. From a mitigation perspective, one of the largest challenges lies in aligning increasing demands for food, shifts in dietary tastes, and demand for agricultural commodities for non-food uses with sustainable, low-emitting development paths.

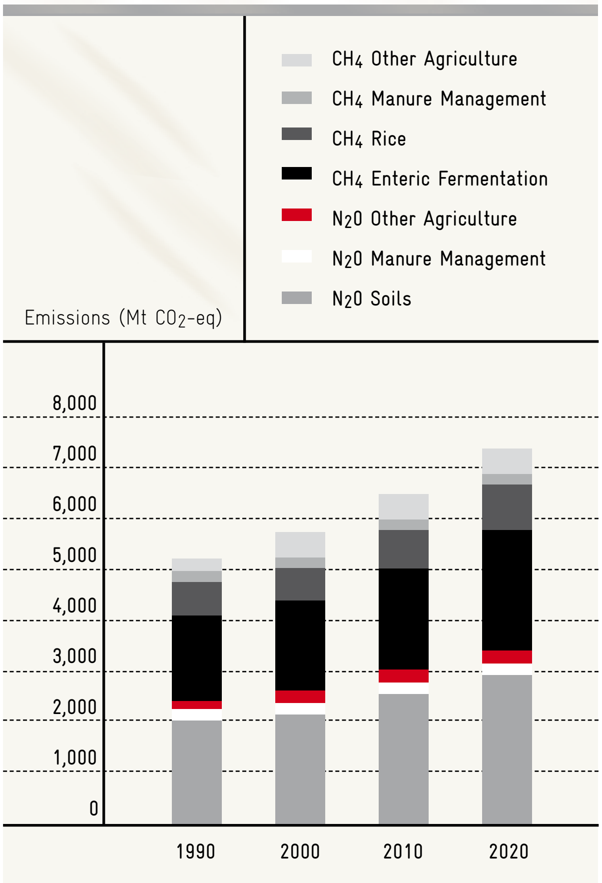
Fig. 2



Sources of emissions from the agricultural sector (2000)

Source: Drawn from data presented in USEPA (2006)

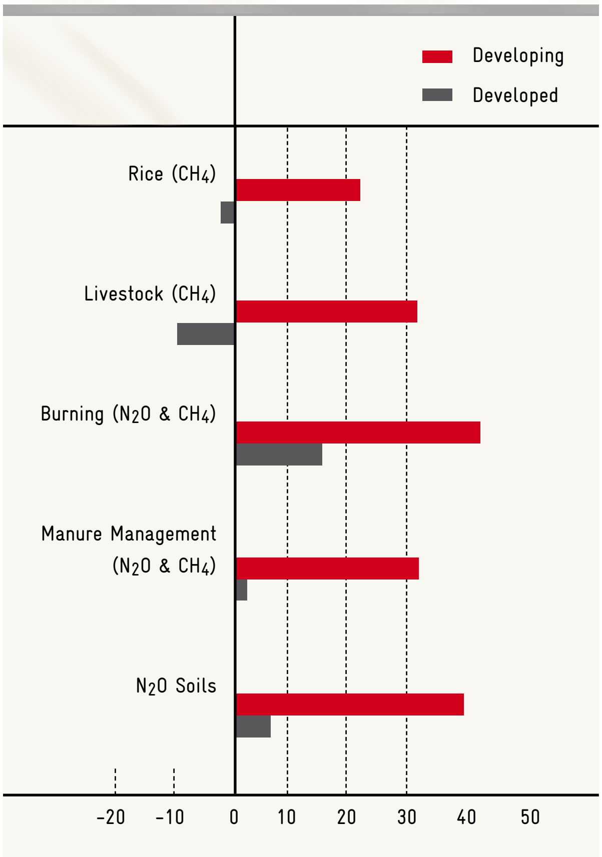
Fig. 3



Projected agricultural emissions by subsector, 1990-2020

Source: Drawn from data used in USEPA (2006)

Fig. 4



Percentage change in sector emissions in developed and developing country groups, 1990 to 2020

Source: Drawn from data presented in USEPA (2006)

1.1.1 Agricultural soils

Nitrous oxide (N_2O) is the largest source of GHG emissions from agriculture, accounting for 38 percent of the global total. N_2O is produced naturally in soils through the processes of nitrification and denitrification. Agricultural activity may add nitrogen to soils either directly or indirectly. Direct additions occur through nitrogen fertilizer usage, application of managed livestock manure and sewage sludge, production of nitrogen-fixing crops and forages, retention of crop residues, and cultivation of soils with high organic matter content. Indirect additions occur through volatilization and subsequent atmospheric deposition of applied nitrogen, as well as through surface runoff and leaching of applied nitrogen into groundwater and surface water (USEPA, 2006).

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[2] Total LUCF emissions, inclusive of biomass clearing and burning for agricultural and urban expansion, as well as timber and fuel wood harvesting, were nearly 18 percent of total GHG emissions in the year 2000, or 7,618 Mt CO_2-equivalents. Concerning food production specifically, it is difficult to estimate the total amount of emissions in this sector that result from land conversion for agricultural extensification purposes. However, according to one estimate, 9 percent of total global emissions — one half of LUCF emissions — are due to expansion into forests for feed crop and livestock production (Steinfeld *et al.*, 2006).

Direct application of nitrogen-containing fertilizers, both synthetic and organic, will likely be a major source of growth in N_2O emissions. Under a “business as usual” scenario, these emissions are expected to increase by 47 percent from 1990 to 2020. In 1990, the OECD and China accounted for approximately 50 percent of all N_2O emissions from agricultural soils. However, projections for the period to 2020 indicate that emissions are likely to remain relatively static for the OECD, but increase significantly from China (50 percent increase), Africa, Latin America, and the Middle East (100 percent increases). The sharpest increase in fertilizer application is forecast for developing countries, which are seen using 36 million tons more than developed countries by 2020 (Bumb and Baanante, 1996).

1.1.2 Livestock and manure management

Enteric fermentation or the natural digestive processes in ruminants, such as cattle and sheep, accounts for the majority of methane production in this category. It is the second largest source of total emissions from agriculture, with a 34 percent global share. Other domesticated animals, such as swine, poultry and horses, also emit methane as a by-product of enteric fermentation. Manure management includes the handling, storage and treatment of manure, and accounts for 7 percent of agricultural emissions. Methane is produced by the anaerobic breakdown of manure, while nitrous oxide results from handling manure aerobically (nitrification) and then anaerobically (denitrification), and is often enhanced when available nitrogen exceeds plant requirements.

Demand for beef and dairy products is expected to rise globally, with sharp increases in consumption and production forecast for the developing world. By 2020, over 60 percent of meat and milk consumption is expected to take place in the developing world, and the production of beef, meat, poultry, pork, and milk is likely to at least double from 1993 levels (Delgado *et al.*, 1999). As a result, methane emissions from enteric fermentation are projected to increase by 32 percent by 2020, with China, Brazil, India, the U.S. and Pakistan being the likely top sources (USEPA, 2006). In addition, methane and nitrous oxide emissions from manure management are expected to increase an estimated 21 and 30 percent, respectively, again largely due to China and Brazil (USEPA, 2006).

1.1.3 Rice cultivation

Flooded rice fields are the third largest source of agricultural emissions, contributing to 11 percent in the form of methane arising from anaerobic decomposition of organic matter. China and South-East Asian countries produce the lion’s share of methane emissions from rice, accounting for over 90 percent in 1990. Due to population increases in these countries, emissions are expected to increase by 36 percent in South-East Asia and by 10 percent in China by 2020 (USEPA, 2006).

1.2 Options for mitigation in agriculture

The biological processes associated with agriculture are natural sources of greenhouse gases. Anthropogenic activities have the potential to impact the quantity of emissions through management of carbon and nitrogen flows and, thus, can be directed towards reducing — or mitigating — emissions of greenhouse gases. Mitigation is defined as any anthropogenic intervention that can either reduce sources of GHG emissions (abatement) or enhance their carbon sinks (sequestration). Following this, there are two categories of mitigation methods in agriculture: carbon sequestration in soils and on-farm emissions reductions. Another mitigation strategy is considered to be the displacement of fossil fuels through the production of cleaner-burning bioenergy, such as ethanol, biogas, and methane, which can all be derived from agricultural production. These three options for mitigation in agriculture will be further discussed below.

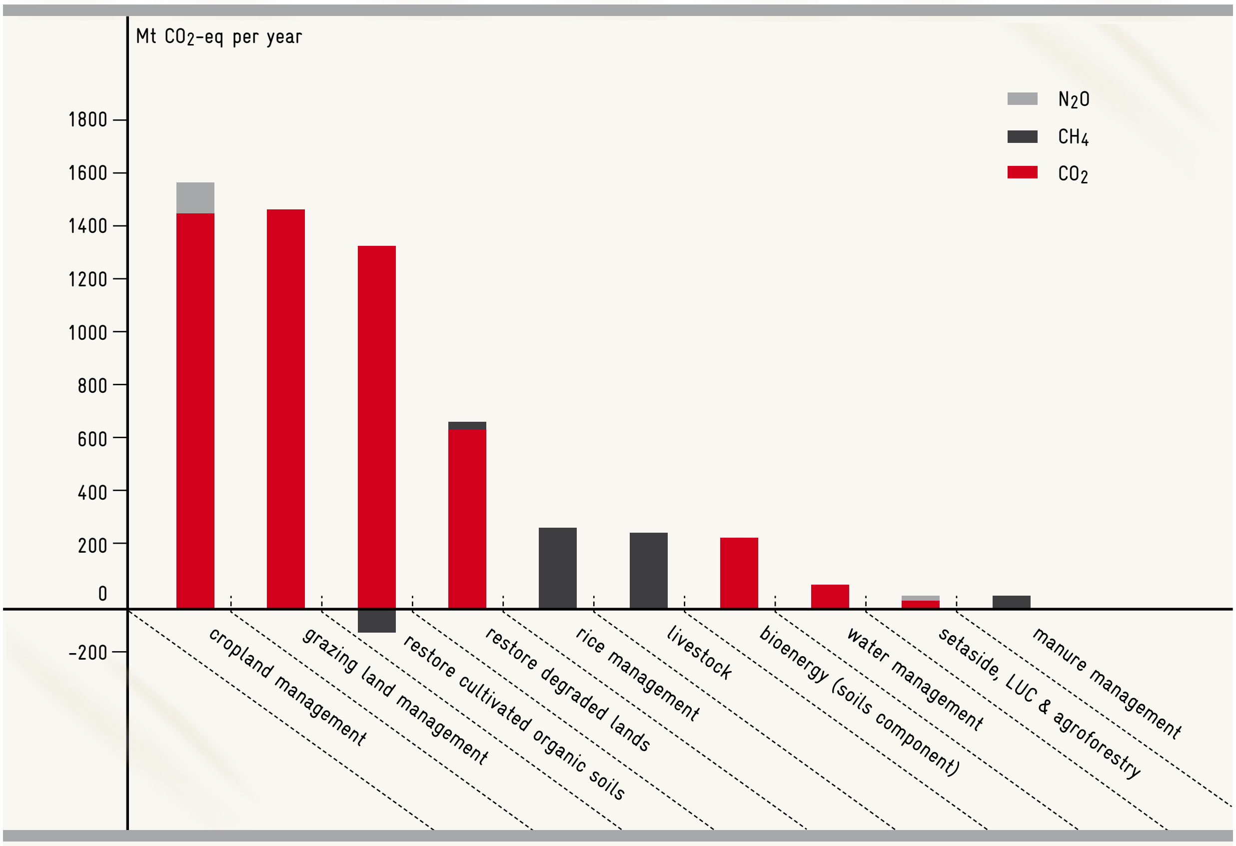
1.2.1 Technical potential for mitigation

The technical potential is the theoretical amount of emissions that can be reduced and the amount of carbon that can be sequestered given the full application of current technologies, discounting implementation costs. The technical potential describes the magnitude of mitigation allowed by current methods, and does not provide realistic estimates of the amount of carbon that will be reduced under current policy and economic conditions. In general, it neither considers trade-offs with other goals, such as income generation or food security, nor the heterogeneity in management capacity or cultural appropriateness.

Carbon sequestration

Sequestration activities enhance and preserve carbon sinks and include any practices that store carbon through cropland management "best practices", such as no-till agriculture, or slow the amount of stored carbon released into the atmosphere through burning, tillage, and soil erosion. Sequestered carbon is stored in soils, resulting in increases in soil organic carbon (SOC). However, SOC is seen approaching a new equilibrium over a 30 to 50 year period and will therefore ultimately be limited by saturation. In addition, there is potential for the re-release of SOC into the atmosphere through fire or tillage, which raises concerns as to the "permanence" of SOC storage. On the other hand, emissions abatement through improved farm management practices could be sustained indefinitely. Despite its limitations, soil carbon sequestration is estimated to account for 89 percent of the technical mitigation potential in agriculture, compared to 11 percent for emissions abatement (Smith *et al.*, 2007a). Figure 5 shows the dominance of soil carbon sequestration (CO_2) compared to other management practices in terms of technical mitigation potential.

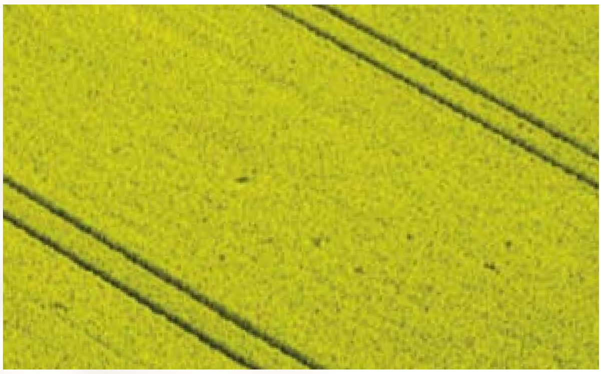
Fig. 5



Global technical mitigation potential by 2030 for each agricultural management practice showing corresponding GHG impacts

Source: Smith et al. (2007a)

There are numerous "best" management practices in agriculture that raise SOC, including reducing the amount of bare fallow, restoring degraded soils, improving pastures and grazing land, irrigation, crop and forage rotation, and no-tillage practices (Smith *et al.*, 2007a). The technical potential of global cropland soils to sequester carbon through a combination of these techniques has been estimated at 0.75 to 1 Gt/year total (Lal and Bruce, 1999). One technique emphasized in the literature as having a high mitigation potential is no-till agriculture. Estimates indicate that tillage reductions on global cropland could provide a full "wedge" of emissions reductions — up to 25 Gt over the next 50 years (Pacala and Socolow, 2004). Others, however, have noted that tillage reductions may not be feasible in all soil types (Chan *et al.*, 2003). Baker *et al.* (2007) argue that improper sampling techniques, together with modern, gas-based measurements, cast doubt on previous findings of positive carbon offsets through tillage reductions.



Other ways to increase SOC include grazing land management to increase the cover of high productivity grasses and overall grazing intensity. It is estimated that 18 to 90 Mt CO_2-eq/ year could be sequestered by improving US grazing lands (Follett *et al.*, 2001). In addition, a large potential for this exists in developing countries such as India and Brazil, which have the world's largest grazing land area.

Bioenergy

The production of liquid fuels from dedicated energy crops, such as grains and oilseeds, is being re-examined in response to concerns over the environmental sustainability of continued fossil fuel dependence. The potential of biofuels to reduce carbon emissions, however, is highly dependent upon the nature of the production process through which they are manufactured and cultivated. There tends to be a high degree of variance in the literature over the net carbon balance of various biofuels, due to differences in the technological assumptions used when evaluating the processes embedded in any life cycle assessment. Early life cycle assessments of biofuels found a net carbon benefit, which has contributed to consumer acceptance (e.g. Wang *et al.*, 1999). Yet, the net carbon benefit in comparison to traditional fossil fuels is being challenged through a number of studies (Pimentel and Patzek, 2005), especially when biofuel production requires land conversion from cover with a high carbon sequestration value, such as forests (Searchinger *et al.*, 2008). Considering the impact that continued crop cover would have on agricultural soil emissions, it is estimated that bioenergy production will have a technical potential of approximately 200 Mt CO_2-eq/ year in 2030 (Smith *et al.*, 2007a). But the potential for GHG savings is much higher when the offsetting potential from displacement of fossil fuels is considered. It is estimated that 5 to 30 percent of cumulative carbon emissions would be abated if bioenergy supplied between 10 to 25 percent of world global energy in 2030 (Ferrentino, 2007). However, a rapid expansion in bioenergy of this magnitude would have significant trade-offs with food security (e.g. Rosegrant *et al.*, forthcoming) and biodiversity (e.g. Eickhout *et al.*, 2008), as has already been seen in the past few years. Careful assessment of trade-offs as well as of net GHG gains, including land use change effects, needs to be undertaken for alternative bioenergy technologies as these develop.

On-farm mitigation

Improved management practices that reduce on-farm emissions include livestock and manure management, fertilizer management, and improved rice cultivation.

Methods to reduce methane emissions from enteric fermentation include enhancing the efficiency of digestion with improved feeding practices and dietary additives. The efficacy of these methods depends on the quality of feed, livestock breed and age, and also whether the livestock is grazing or stall-fed. Developing countries are assumed to provide lower quality feed to livestock, which raises the emissions rate per animal to over that for developed country herds. The technical potential to mitigate livestock emissions in 2030 is forecast at 300 Mt CO_2-eq/ year (Smith *et al.*, 2007a).

In manure management, cooling and using solid covers for storage tanks and lagoons, separating solids from slurry, and capturing the methane emitted are relevant techniques. Concerning developing countries, applying this sort of manure management may be difficult as animal excretion happens in the field. Composting manure and altering feeding practices may help reduce emissions to a certain extent. The technical potential of improved manure management in 2030 is an estimated 75 Mt CO_2-eq/ year (Smith *et al.*, 2007a).

Improving the efficiency of fertilizer application or switching to organic production can decrease the amount of nutrient load and N_2O emissions. However, overall benefits would need to be weighed against the potential impact on yield. Fertilizer reductions of 90 percent in rain-fed maize fields have been shown to reduce yields by 8.4 and 10.5 percent over the baseline in Brazil and China, respectively (USEPA, 2006). In addition, lack of access to soil nutrients needed for improving the quality of degraded soils is a hindrance to achieving food security in many parts of the developing world (Gruhn *et al.*, 2000). Overall, cropland management could reduce emissions in 2030 by up to 150 Mt CO_2-eq/ year (Smith *et al.*, 2007a).

Improved water management in high-emitting, irrigated rice systems through mid-season drainage or alternate wetting and drying has been shown to substantially reduce CH_4 emissions in Asia. However, these effects may be partially offset by an increased amount of N_2O emissions (Wassman *et al.*, 2006). The technical potential of improved rice management is estimated at 300 Mt CO_2-eq/ year (Smith *et al.*, 2007a).

Aggregated estimates for the global technical potential of both on-farm and sequestration techniques have been presented by the IPCC, and reveal a maximum global mitigation potential of 4.5 to 6 Pg (4500-6000 Mt) CO_2 equivalent per year by 2030 (Smith *et al.*, 2007a). Of this estimate, nearly 90 percent of the potential is from carbon sequestration, while 9 and 2 percent are from methane mitigation and soil N_2O emission reductions, respectively. Emissions estimates presented in earlier sections do not consider the sequestration potential in calculating net emissions; therefore, given that the sequestration potential is close to current emissions from agriculture, agriculture could be emissions neutral. While these figures give an order of magnitude, any global estimates should be interpreted with caution. Due to the high level of heterogeneity in agro-ecological conditions, the biophysical capability to sequester carbon should vary accordingly. In addition, technical potentials in general are not realistic, since they do not consider the impact of food security, heterogeneity in management capacity, or the costs of mitigation. As a result, the economic potential is often preferred, and this is discussed below.

1.2.2 Economic potential

Calculations of economic potential come from two main sources: Smith *et al.* (2007b) and USEPA (2006). In this paper, we utilize both sources. The results from USEPA (2006) are preferred for non-CO_2 emissions abatement due to a finer level of regional disaggregation, which enables the economic potential of lower income regions to be examined precisely. Smith *et al.* (2007a) conducted a comparison of Smith *et al.* (2007b) and USEPA (2006), finding consistent results across emissions sources. Smith *et al.* (2007a, 2007b), however, provide a more comprehensive assessment of the potential for soil carbon sequestration.

The USEPA (2006) estimates three categories of emissions mitigation: (i) cropland management (including N_2O from fertilizer reductions, soil carbon sequestration through no-tillage only, and split fertilization, in each case under both rainfed and irrigated conditions for rice, soybeans, and wheat); (ii) rice cultivation; and (iii) livestock and manure management.

Cropland management (N_2O and CO_2)

Compared to the baseline, approximately 15 percent of global cropland emissions can be abated at no cost, while approximately 22 percent of emissions can be mitigated for less than \$30/t CO_2-eq. Compared to actual projected emissions for the year 2020, a 15 percent reduction in emissions is approximately 134 Mt CO_2-eq. Beyond \$30/t CO_2-eq, abatement costs rise exponentially. These results are similar for all years considered.

Regional results indicate that the U.S. and the Russian Federation could each reduce emissions by 40.6 and 34.7 Mt CO_2-eq at a zero cost over baseline emissions in 2020, respectively. These would be the largest no-cost reductions for autonomous regions. For aggregated regions, in the same year, Annex 1 countries could reduce up to 102 Mt CO_2-eq at no cost.

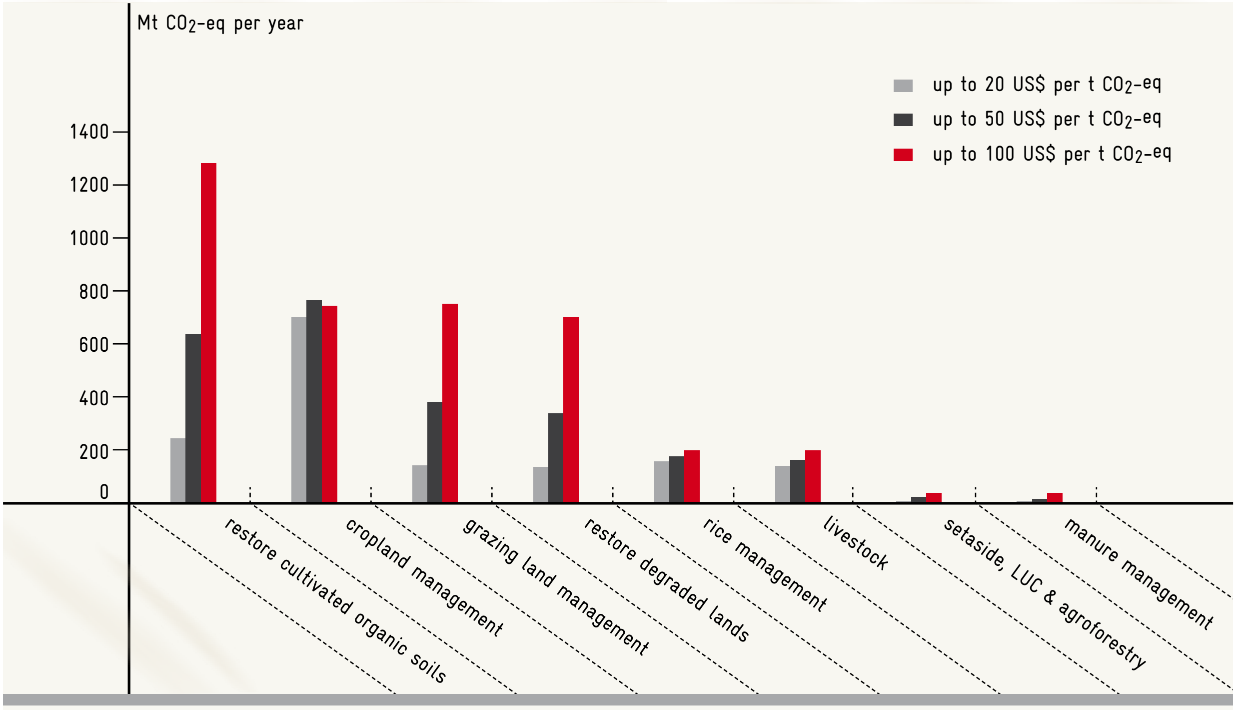
The reason why fertilizer reductions do not appear to have a strong mitigation potential for many developing regions may be current low levels of fertilizer usage, or the fact that yields are negatively affected by sub-optimal nutrient application. On the other hand, across the U.S., EU, Brazil, China, and India, converting from conventional tillage to no-till agriculture has resulted in yield increases for each crop involved. This indicates a large potential for this practice as a negative cost option or "no regret" scenario. According to global estimates, no-till agriculture is only practiced on 5 percent of the world's cultivated land, with the lowest rates of adoption in Africa and Asia (Lal *et al.*, 2004). As a result, the observation that farmers in these regions are not adopting no-tillage practices may be indicative of hidden cost barriers, for example variability in profits or complexities in management requirements (USEPA, 2006).

Smith *et al.* (2007a) expand the subject of cropland management for soil carbon sequestration to include a broader range of practices, such as reducing bare fallow and residue management. Considering a broader spectrum, the economic potential for soil carbon sequestration is seen increasing up to 800 Mt CO_2-eq in 2030 at carbon prices of up to \$20/t CO_2-eq (Figure 6). This compares to the USEPA (2006) estimate of approximately 145 Mt CO_2-eq (at \$15/t CO_2-eq) for the year 2020. Given that 70 percent of total emissions abatement could come from developing countries, soil carbon sequestration will likely be an important management practice.

Bioenergy

Neither USEPA (2006) nor Smith *et al.* (2007a) calculate the marginal abatement costs related to agricultural soils

Fig. 6



Economic potential for GHG agricultural mitigation by 2030 at a range of prices of CO_2-eq.

Source: Smith et al. (2007b)

used for bioenergy purposes. However, there are estimates for corresponding potential displacement of fossil fuels. Specifically for the transportation sector, where liquid biofuels are predicted to reach 3 percent of demand under the baseline scenario, and increase by up to 13 to 25 percent of demand under alternative scenarios in 2030 (IEA, 2006). This could reduce emissions by 1.8 to 2.3 Gt CO_2, which corresponds to between 5.6 and 6.4 percent of total emissions reductions across all sectors at carbon prices greater than US$25/t CO_2 (Ferrentino, 2007).

Rice cultivation

According to model results, only 3 percent of emissions from rice cultivation could have been abated at zero cost in the year 2000, and this figure could rise to 11 percent in 2010. Also in 2010, 22 percent of global emissions may be abated at a cost of $30/t CO_2-eq. South and South-East Asia and China could contribute the most reductions in 2010: 55 percent or 5560.6 Mt CO_2-eq at no cost and 43 percent or 97.9 Mt CO_2-eq at a cost of $30/t CO_2-eq, respectively. This is not surprising, given that China and South and South-East Asian countries produced over 90 percent of methane emissions from rice in 1990.

Enteric fermentation and manure management

Improved livestock and manure management together could reduce emissions by 3 percent at no cost, and between 6 and 9 percent at carbon prices of $30/t CO_2-eq. Annex 1 and OECD countries have the highest least-cost economic potential, while Africa and Mexico have the lowest. Moreover, those countries with the highest herd numbers, such as India and Brazil, also have a low to moderate economic potential. For example, Brazil is only expected to reduce 9 percent of total global livestock emissions in 2020 at carbon prices of $30 t CO_2-eq. In comparison, Annex 1 countries could contribute to reductions of approximately 50 percent. This is due to the centralized nature of livestock rearing in many Annex 1 countries, where the administration of anti-methanogens and collection of manure for controlled digestion is more cost-effective.

Based on USEPA (2006) results for NH_4, CH_4 and soil carbon, rice cultivation mitigation strategies have the highest economic potential in developing countries. Meanwhile, there is a moderate mitigation potential for no-till agriculture in Africa and improved livestock management in India and Brazil (Table 2). On considering a wider range of cropland management and soil carbon sequestration strategies, Smith *et al.* (2007a,b) found that 70 percent of global agricultural economic mitigation potential could come from non-OECD and non-Economies in Transition (EIT), which at carbon prices of $50/t CO_2 is equivalent to 1,780 Mt CO_2-eq (Smith *et al.*, 2007a).

1.3 Expanding the potential for mitigation

The economic potential for mitigation in agriculture depends on the price of carbon and on policy, institutional, and transaction cost constraints. To date little progress has been made in the implementation of mitigation measures at the global level. The potential for GHG mitigation would be enhanced by an appropriate international climate policy framework providing policy and economic incentives.

The emerging market for carbon emissions trading offers new possibilities for agriculture to benefit from land use that sequesters carbon or saves non CO_2 emissions. The Clean Development Mechanism (CDM) under the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) is the most important mechanism for payments to developing countries. Currently, the CDM limits eligible activities in agriculture to afforestation and reforestation, and reduction of non-CO_2 gases. Hence carbon sequestration activities, such as conservation tillage and restoration of degraded soils, are presently considered ineligible.

In mid-2008, there were 87 registered projects for the agriculture sector, representing 6 percent of the CDM portfolio (CDM, 2008). In addition, there was one afforestation/reforestation project, representing a corresponding 0.07 percent. The majority of registered agricultural projects are in Latin America, while only one project is located in

Tab. 2

	2010			2020		
Country/region	$0	$30	$60	$0	$30	$60
Africa	1.6%	3.6%	4.5%	1.4%	3.5%	4.4%
Annex I	11.1%	18.1%	20.0%	10.8%	16.2%	19.6%
Brazil	3.2%	5.8%	7.2%	3.1%	5.6%	7.0%
China	7.8%	14.1%	15.0%	6.3%	12.1%	12.9%
India	1.6%	9.5%	9.7%	1.5%	9.3%	9.3%
United States	14.2%	22.9%	25.0%	13.8%	23.4%	24.9%
World Total	7.1%	12.5%	14.3%	6.7%	11.6%	13.4%

Percentage of emissions reductions over the baseline at different carbon prices ($ per t CO_2-eq) by region

Source: USEPA (2006)

Africa. Total estimated emissions reductions from these 87 projects is 7.6 Mt CO_2-eq per year (CDM, 2008). This is approximately 0.1 percent lower than total agricultural sector emissions reported for the year 2000.

Soil carbon sequestration has the highest technical potential for mitigation in the agricultural sector, so there is room to expand mitigation by including carbon sequestration projects under the CDM. However, there are feasibility issues as regards selling agricultural soil carbon within a market-based credit trading program. Transaction costs involved would include obtaining the site-specific information required to assess the baseline stock of carbon and the potential to sequester carbon. The transaction costs per carbon ton associated with negotiating contracts are likely to decline as the size of contract increases, and a market for carbon credits is considered more viable for large, standardized contracts (e.g. 100,000 tons). For a typical individual farmer who can sequester 0.5 tons per hectare per year, related transaction costs would be too prohibitive.

The Chicago Climate Exchange (CCX) allows emissions trading of carbon offsets through no-till agriculture, demonstrating that technical barriers can be overcome by simplifying rules and using modern monitoring techniques that also allow for reduced transaction costs. Currently, eligible agricultural soil carbon sequestration projects include grass planting and continuous conservation tillage. The basic CCX specifications for soil carbon management offset projects include: a minimum five-year contract; a tillage practice that leaves two-thirds of the soil surface undisturbed and two-thirds of crop residue on the surface; conservation of between 0.2 to 0.6 metric tons of CO_2 per acre per year; enrollment through a registered offset aggregator; and independent verification. Effective use of offset aggregators as brokers for small projects is a crucial step towards achieving economies of scale.

In addition to including soil carbon offsets in the CDM, a number of other advancements are needed. To ensure that emerging carbon markets benefit developing countries, CDM rules should encourage the participation of small farmers and protect them against major risks to their livelihoods, whilst still meeting investor needs and rigorously protecting carbon goals. This can be supported by:

- *Promoting measures to reduce transaction costs:* Rigorous, but simplified procedures should be adopted for developing country carbon offset projects. Small-scale soil carbon sequestration projects should be eligible for simplified modalities to help reduce project costs. The permanence requirement for carbon sequestration should be revised to allow shorter-term contracts, or contracts that pay based on the amount of carbon saved per year.

- *Establishing international capacity building and advisory services:* Successful promotion of soil sequestration for carbon mitigation will require investment in capacity building and advisory services for potential investors, project designers and managers, national policymakers, and leaders of local organizations and federations (CIFOR, 2002).

- *Investing further in advanced measurement and monitoring:* This can dramatically reduce transaction costs. Measurement and monitoring techniques have been improving rapidly thanks to a growing base of field measurements and the use of statistics and computer modeling, remote sensing, global positioning systems, and geographic information systems. As a result, changes in carbon stocks can now be estimated more accurately and at a lower cost.

2.

Impacts of climate change on food production systems

Even with sufficient mitigation measures the current scientific consensus holds that greenhouse gas emissions and atmospheric concentrations are set to increase for some decades. Consequently, global mean surface temperature will continue to rise long after an emissions peak has passed. There is room for debate and uncertainty as to exactly how much warming there will be and at what rate it will unfold, but the general trend of the curve is clear. Predicted changes in temperature and other climate functions will impact agro-ecological conditions and food production. As a result, farmers will need to adjust technologies and practices in order to continue meeting food requirements. However, adapting to new climate scenarios may not be feasible in all situations. A lack of adaptive capacity due to constraints on resources, like access to weather forecasts or better seed varieties, may result in further food insecurity. In order to better prepare vulnerable regions, climate scientists and economists are using integrated assessment models to help identify those regions and crops that may be at high risk due to climate change and its resulting socio-economic impact. In this section, the results of these models are presented, along with key uncertainties. The following is a short summary of the major points arising from this section.

Potential direct effects on agricultural systems:

- Seasonal changes in rainfall and temperature could impact agro-climatic conditions, altering growing seasons, planting and harvesting calendars, water availability, pest, weed and disease populations, etc.
- Evapotranspiration, photosynthesis and biomass production is altered.
- Land suitability is altered.
- Increased CO_2 levels lead to a positive growth response

for a number of staples under controlled conditions, also known as the "carbon fertilization effect".

Model based predictions:

- Global models consistently highlight risk disparities between developed and developing countries.
- For temperature increases of only 1-2 °C, developing countries without adaptation will likely face a depression in major crop yields.
- In mid- to high latitudes, increases in temperature of 1-3 °C can improve yields slightly, with negative yield effects if temperatures increase beyond this range.
- Stronger yield-depressing effects will occur in tropical and sub-tropical regions for all crops, which reflect a lower growing temperature threshold capacity in these areas.
- Estimations predict that cereal imports will increase in developing countries by 10 to 40 percent by 2080.
- Africa will become the region with the highest population of food insecure, accounting for up to 75 percent of the world total by 2080.

Unknowns and uncertainties in model-based predictions:

- A positive effect from carbon fertilization on cereal yields is predicted to greatly impact results for world food production. However, global research on the possible consequences of this effect for a wide variety of crops is limited.
- Basic socio-economic scenario assumptions impact food security outcomes more than those for climate change, per se (e.g. Fischer *et al.*, 2005).

The range of potential negative predictions may be buffered by adaptation measures.

2.1 Global climate models

Food production is an essential ecosystem service that is driven by a mixture of natural phenomena and human activity. Complex interactions between agro-climatic conditions and technological drivers such as nutrient application, irrigation, and seed selection determine food availability and quality. As warned by the IPCC in the introduction to this paper, anthropogenic activities have begun to change the climate in ways that may warrant a significant modification to existing agricultural knowledge and practices. Consequently, it is of critical concern to farmers, agricultural extension agents, and agronomists, as well as to government planners, national and international agricultural research institutes, and the general donor community to clarify the extent to which climate change and higher climate variability will impact agro-ecological production systems worldwide.

Rapidly rising levels of carbon dioxide and other GHGs in the atmosphere have direct effects on agricultural systems due to increased CO_2 and ozone levels[3], seasonal changes in rainfall and temperature, as well as modified pest, weed, and disease populations. In general, the flux of agro-climatic conditions can alter the length of growing seasons, and planting and harvesting calendars. It can also impact water availability and water usage rates, along with a host of plant physiological functions including evapotranspiration, photosynthesis and biomass production, and land suitability. Ongoing research has demonstrated a positive response to increased levels of CO_2 in controlled experiments for a number of staples (e.g. Kimball *et al.*, 2002; Ainsworth and Long, 2005), albeit in the absence of climate change. These results and those from regional crop models are helping to characterize what could plausibly be the future impact of climate change on agriculture. Due to the number of variables involved and the chaotic nature of weather systems, predictions are not meant to be taken as a confirmation of what will happen, but rather describe the range of possible outcomes that can be expected.

Model-based frameworks have been developed that forecast short- and long-term impacts on food systems. The majority of models investigate regional impacts, especially in North America and Europe, with relatively fewer mod-

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[3] Atmospheric ozone has been shown to depress plant productivity and greatly inhibit the ability of biomass to sequester carbon (e.g. Sitch *et al.*, 2007).

els dedicated to predicting impacts on developing country agriculture. A number of global models have been developed and are integral to highlighting the risk disparities between developed and developing countries (Fischer *et al.*, 2005).

A characterization of the possible effects of climate change on crop yields and production, as well as the corresponding impacts on food prices and food security, requires a number of specific modeling applications. Generally, a combination of a crop model, a climate simulation model, and a world food trade model is implemented, using various estimations for greenhouse gas emission rates and socio-economic development. The end result is an integrated physiological-economic model.

2.2 Future impacts

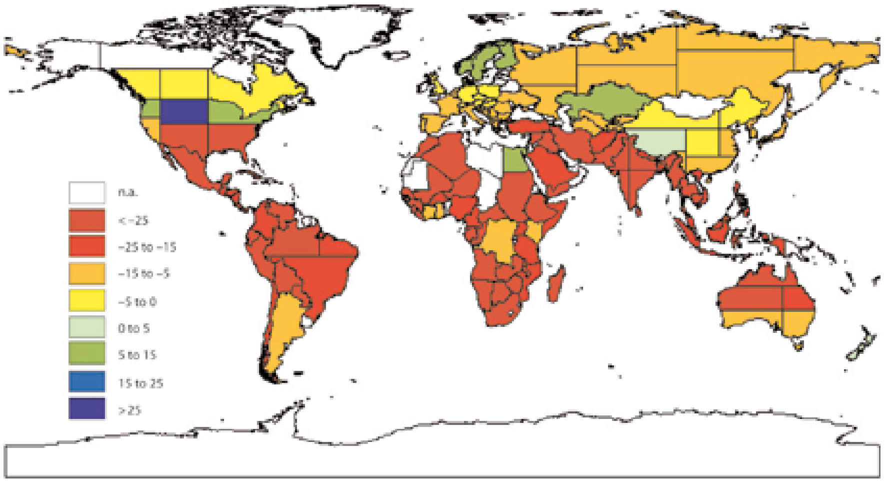
This section presents results from leading models related to agricultural system functioning and yield, plus associated impacts on prices, trade, and food security. In addition, the offsetting impacts of the carbon fertilization effect and adaptation at the farm level, such as irrigation and planting date changes, are reviewed.

2.2.1 Impacts on yield and production

Easterling *et al.*, (2007) have created a synthesis of 69 model-based results that demonstrates the relative impact of temperature and carbon fertilization on changes in cereal yield. Although a wide range of variability in yield changes across the studies is found, some trends can be observed. In mid- to high latitudes, increases in temperature produce increases in yields, but with diminishing effect when temperature changes are greater than 3 degrees. Yet stronger yield-depressing effects are found in tropical and sub-tropical regions for all crops, which reflect a lower growing temperature threshold capacity in these areas.

Offsetting results have been confirmed by the positive physiological response in cereal crop yield witnessed un-

Fig. 7



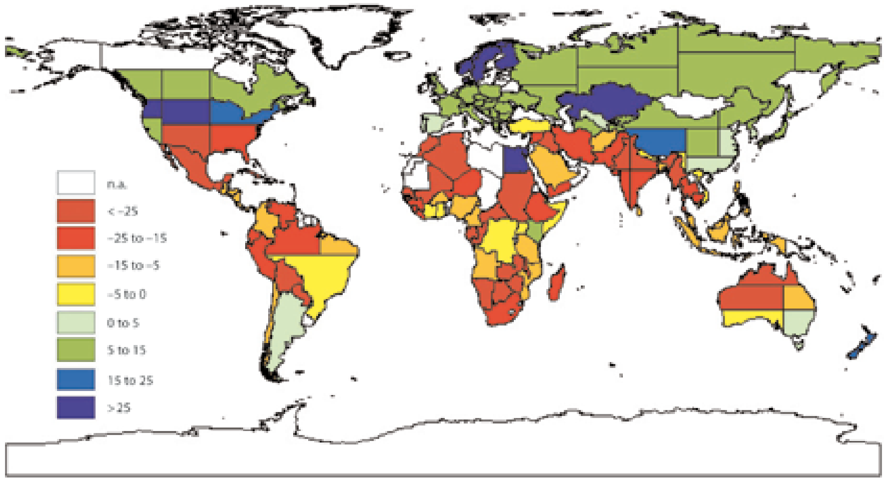
Impact on agricultural productivity without carbon fertilization (%)

Source: Cline (2007)

der higher concentrations of CO_2 (Kimball *et al.*, 2002; Gifford, 2004). However, the magnitude of these yield increases is debated (Long *et al.*, 2006; Tubiello *et al.*, 2007). Despite observed inconsistencies, the yield-enhancing effects of carbon fertilization have been incorporated into leading models. This consideration of the carbon fertilization effect greatly varies the results of global food production models. Discounting this effect, Parry *et al.* (2004) have estimated that cereal production is expected to decrease by between 200 to nearly 450 million tons by 2080, depending on the scenario employed. Yet, carbon fertilization effects could reduce this range to between 30 to 90 million tons, under differing scenarios. Similarly, Cline (2007) has found that a 16 percent decline in global agricultural production capacity can be expected if carbon fertilization is not considered, versus 3 percent if it is considered.

Cline (2007) additionally demonstrates the effect of carbon fertilization on agricultural productivity - measured in net revenue changes - for disaggregated global regions (Figures 7 and 8). Overall, agricultural productivity in developing countries is expected to decline by between 9 to 21 percent due to global warming. Meanwhile, agricultural productivity in industrialized countries is foreseen declining by up to 6 percent or increasing by up to 8 percent, depending on carbon fertilization. These estimates do not consider the effects of increased losses due to insect pests, more frequent extreme weather events such as droughts or floods, and increased water scarcity for irrigation. While these multiple stressors are expected to compound the impact of climate change on agriculture, studies conducted to date have tended to investigate each phenomenon separately, making the prediction of aggregate impacts difficult. For example, water resources are expected to decline in quantity and quality (Kundezewicz *et al.*, 2007). However, when they are available for irrigation, farmers' resilience to climate change improves, and productivity may even be enhanced, compared to a situation of no irrigation (Kurukulasuriya and Mendelsohn, 2006). As the next generation of global models improve, the combined effects of these stressors will become clearer.

Fig. 8



Impact on agricultural productivity with carbon fertilization (%)

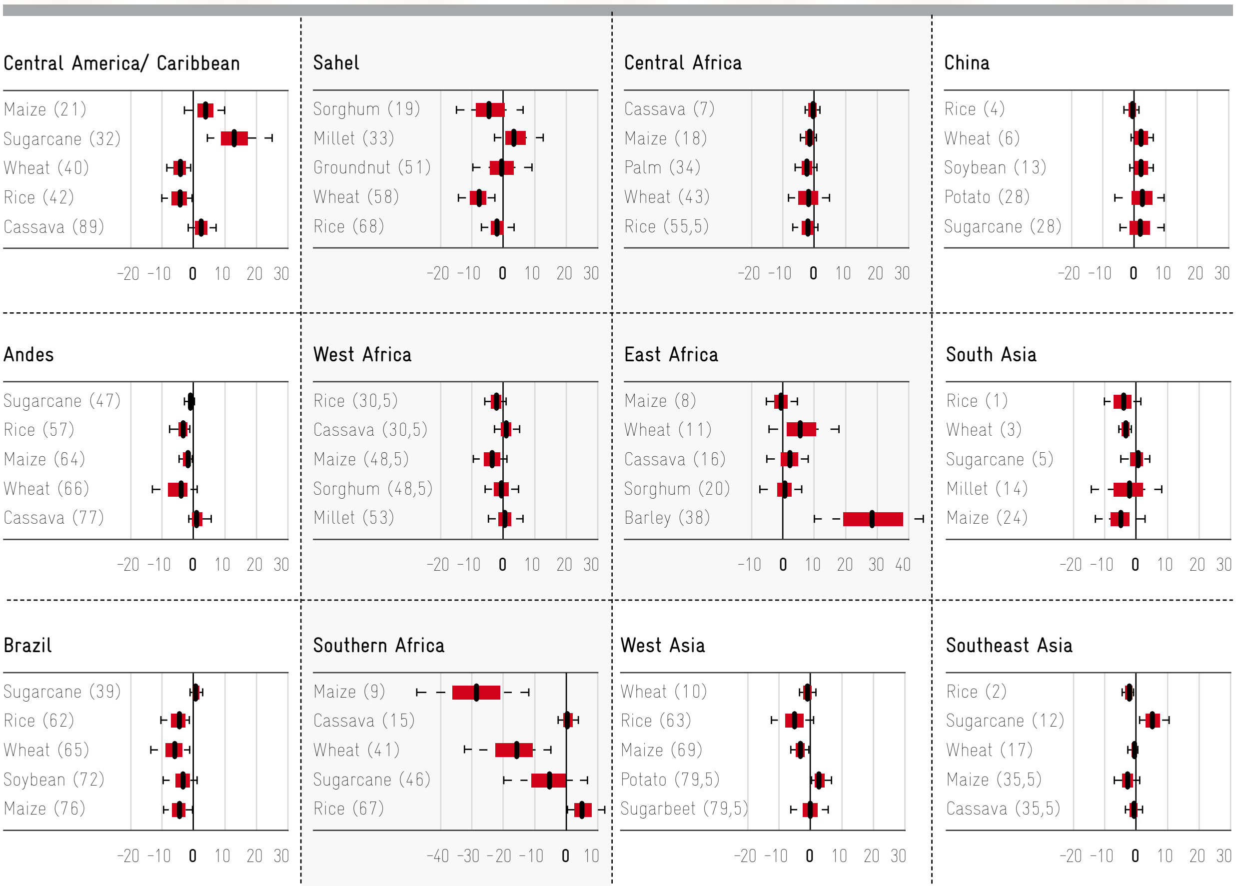
Source: Cline (2007)

2.2.2 Socioeconomic and Food Security Implications

The spatial differences between low, middle and high latitudes highlighted above allude to the great regional variation that climate change is expected to have on agriculture. As a result of differences in predicted production capabilities, some regions will benefit from increases in yield while others will be left to importing an increasing amount of food to help meet demand. Fischer *et al.* (2002), estimate that cereal imports in developing countries will increase by between 10 to 40 percent by 2080. Economies that derive a large share of GDP from agriculture will be most vulnerable, in terms of affected food production systems. Of most concern is the fact that developing countries are overwhelmingly geographically low latitude economies; ones already facing significant development challenges.

Future food availability depends on a number of factors and not only climate impacts on production, including trade policy, food-aid, and storage capacity. Food security

Fig. 9



Projected impacts of climate change by 2030 for five major crops in each region

Notes: For each crop, the dark vertical line indicates the middle value obtained from 100 separate model projections – boxes extend from the 25th to 75th percentiles, and horizontal lines extend from the 5th to 95th percentiles. The number in parentheses is the overall rank of the crop in terms of importance to food security, as calculated by multiplying the number of malnourished in the region by the percentage of calories derived from the crop concerned.

Source: Lobell et al. (2008).

futures are predicted by making assumptions about trade policy and other aspects of socio-economic development, and by integrating these with the results of crop and general circulation models. To date, however, only one economic model has been used to predict impacts on food security, albeit under differing crop models (Schmidhuber and Tubiello, 2007). Schmidhuber and Tubiello synthesize the results of these models and estimate that an additional 5 to 170 million people will become malnourished, depending on the scenario employed. In addition, Africa will likely become the region with the highest population of food insecure, accounting for up to 75 percent of the world total by 2080 (Schmidhuber and Tubiello 2007). Yet, Parry *et al.* (2005) have shown that regional variation in the number of food insecure is better explained by population changes than climate impacts on food availability. As a result, economic and other development policies will be critical to influencing future human well-being.

While not considering the full economic effects of production and consumption, Lobell *et al.* (2008) identify crops and regions that may be "climate risk hot spots" based on predicted yield changes due to climate change and important diet considerations (Figure 9). The authors identify the top five crops required for food security (based on calorie intake and population) and then synthesize results from various crop models. Probabilities are given for a range of crop yield changes. For example, 95 percent of the models predict that climate change will to some extent depress yields for South Asian wheat, South-East Asian rice, and Southern African maize. These are also the "more important" regions and crops in terms of possible threats to food security.

2.3 Impact of farm-level adaptation

The effects of farm-level management changes in response to climate change — referred to in the literature as "adaptation"— have been considered in a number of model predictions. Adaptation measures generally considered are listed in Table 3, and the potential of each will be discussed further in the following section. In general, model-based results are not able to consider the decision-making capability of farmers, but rather the overall impact that such management decisions could have on diminishing the effects of global warming.[4]

Tab. 3

Adaptation	Adjustment time (years)
Variety adoption	3-14
Variety development	8-15
Tillage systems	10-12
New crop adoption: soybeans	15-30
Opening new lands	3-10
Irrigation equipment	20-25
Fertilizer adoption	10

Farm-level adaptation responses and speed of adoption
Source: adapted from Reilly (1995)

The meta-analysis conducted by Easterling *et al.* (2007) is again useful for considering the effects of adaptation in mitigating climate effects on yields for major staples. In general, on-farm adaptation has a positive effect on yields, and is estimated to have an overall 10 percent yield benefit, as compared to yields generated in the absence of adaptation. While these estimates may point to the ability farmers have to avoid the negative impact of climate change on food production, model-based results are not able to capture the probability of an individual farmer embracing adaptation in the face of perceived climatic variations. Each farmer would weigh the risks, costs, and potential benefits of changing management practices. In addition, many farmers may be ill-equipped to adapt or may not understand the risks that climate change imposes. As a result, information sharing, such as that involving climate forecasting, will likely play an integral part in managing climate change risk. In the next section, adaptation capacity, strategies, and policy will be discussed in further detail to help characterize the role that adaptation can play in diminishing the negative effects of climate change.

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[4] Mendelsohn and others examine the profit maximizing behavior of farmers when deciding whether to adapt to perceived climate change in a number of microeconomic studies (e.g. Seo and Mendelsohn, 2008)

3.

Adaptation in agriculture

Formally defined, adaptation to climate change is an adjustment made to a human, ecological or physical system in response to a perceived vulnerability (Adger *et al.*, 2007). Adaptation responses can be categorized by the level of ownership of the adaptation measure or strategy. Individual level or *autonomous adaptations* are considered to be those that take place in reaction to climatic stimuli (after manifestation of initial impact), that is, as a matter of course and without the directed intervention of any public agency (Smit and Pilifosova, 2001). Autonomous adaptations are widely interpreted to be initiatives by private actors rather than by governments, usually triggered by market or welfare changes induced by actual or anticipated climate change (Leary, 1999). *Policy-driven or planned adaptation* is often interpreted as being the result of a deliberate policy decision on the part of a public agency, based on an awareness that conditions are about to change or have changed, and that action is required to minimize losses or benefit from opportunities (Pittock and Jones, 2000). Thus, autonomous and policy-driven adaptation largely correspond to private and public adaptation, respectively (Smit and Pilifosova, 2001). Table 4 provides examples of autonomous and policy-driven adaptation strategies for agriculture.

As implied in the previous section, autonomous adaptation responses will be evaluated by individual farmers in terms of costs and benefits. It is anticipated that farmers will adapt “efficiently”, and that markets alone can encourage efficient adaptation in traded agricultural goods (Mendelsohn, 2006). Yet, in situations where market imperfections exist, such as the absence of information on climate change or land tenure insecurity, climate change will further reduce the capacity of individual farmers to manage risk effectively. Moreover, responses at the individual level tend to be costly to poor producers and often create excessive burdens. As a result, an appropriate bal-

Tab. 4

Type of response	Autonomous	Policy-driven
Short-run	Crop choice, crop area, planting date Risk-pooling insurance	Improved forecasting Research for improved understanding of climate risk
Long-run	Private investment (on-farm irrigation) Private crop research	Large-scale public investment (water, storage, roads) Crop research
Issues	Costly to poor Social safety nets Trade-offs with integration	Uncertain returns on investment Costs

Adaptation responses and issues

Source: Authors

ance between public sector efforts and incentives, such as capacity building, creation of risk insurance and private investment, needs to be struck so that the burden can shift away from poor producers.

Key points on adaptation in summary:

- Adaptation is defined as an adjustment made to a human, ecological or physical system in response to a perceived vulnerability.
- Changes in tillage practices or adjusted livestock breeds are short-term measures.
- Longer-term measures, such as improved water management or the building of irrigation systems, can help in adapting to a changing climate.
- Supporting policies that promote adaptation measures can help towards more effective implementation.
- Modes of external assistance range from allocating information, advice, and training on adaptation measures, to developing institutional capacities and policies.
- Adaptation is not a stand-alone activity, and its integration into development projects, plans, policies, and strategies will be crucial.
- Synergies between mitigation and adaptation should be maximized.

3.1 Role of adaptation policy

Decisions about what adaptation measures to adopt are not taken in isolation by rural agricultural individuals, households or communities, but within the context of a wider society and political economy (Burton and Lim, 2005). End choices are thus shaped by public policy, which can either be supportive or which can at times provide barriers or disincentives to adaptation. Possible supporting policies to help promote adaptation measures are shown in Table 5.

Adaptation policy is in many cases an extension of development policy that seeks to eradicate the structural causes of poverty and food insecurity. The complementarities between the two will enable a streamlined approach towards achieving both adaptation and poverty alleviation goals. General policies that should be supported include those: promoting growth and diversification; strengthening institutions; protecting natural resources; investing in research and development, education and health; creating markets in water and environmental services; improving the international trade system; enhancing resilience to disasters and improving disaster management; and policies promoting risk-sharing, including social safety nets and weather insurance.

Adaptation options and their supporting policies should be adopted by the appropriate level of government and im-

Tab. 5

Adaptation Option	Supporting Policies
Short-term	
Crop insurance for risk coverage	Improved access, risk management, revise pricing incentives, etc
Crop/livestock diversification to increase productivity and protect against diseases	Availability of extension services, financial support, etc.
Adjust timing of farm operations to reduce risks of crop damage	Extension services, pricing policies, etc
Change cropping intensity	Improved extension services, pricing policy adjustments
Livestock management to adjust to new climate conditions	Provision of extension services
Changes in tillage practices	Extension services to support activities, pricing incentives
Temporary mitigation for risk diversification to withstand climate shocks	Employment/training opportunities
Food reserves and storage as temporary relief	
Changing crop mix	Improving access and affordability, revising pricing, etc.
Modernization of farm operations	Promote adoption of technologies
Permanent migration to diversify income opportunities	Education and training
Defining land-use and tenure rights for investments	Legal reform and enforcement
Both short- and long-term	
Development of crop and livestock technology adapted to climate change stress: drought and heat tolerance, etc.	Agricultural research (crop and livestock trait development), agricultural extension services
Develop market efficiency	Invest in rural infrastructure, remove market barriers, property rights, etc
Irrigation and water storage expansion	Investment by public and private sectors
Efficient water use	Water pricing reforms, clearly defined property rights, etc
Promoting international trade	Pricing and exchange rate policies
Improving forecasting mechanisms	Information needs to be distributed across all sectors, etc
Institutional strengthening and decision-making structures	Reform existing institutions on agriculture, etc

Adaptation options and supporting policies given climate change

Source: Adapted from Kurukulasuriya and Rosenthal (2003) plemented by institutions in direct contact with beneficiaries. For example, adaptation responses such as changing planting dates and tillage practices may require technical services provided by local extension agents, which are coordinated by regional universities and research institutions. Agricultural research, including crop breeding to develop drought and heat tolerant crop varieties, will require both public and private investment. Structural adaptation measures, such as creating water markets and price incentives, will need to be implemented on a national level, most likely in partnership with economic cooperation unions.

3.2 Evaluating adaptation options

Selecting appropriate adaptation measures to pursue is context and project specific. Criteria to consider include the: net economic benefit; timing of benefits; distribution of benefits; consistency with development objectives; consistency with other government policies; costs involved; environmental impacts; spill-over effects; implementation/implementing capacity; and social, economic and technical barriers (Leary *et al.*, 2007). Once an adaptation strategy has been evaluated, the measure that yields the greatest net benefit should be chosen.

Methods presented by Fankhauser (1997), Calloway *et al.*, (1999), and Calloway (2003) have been integral to developing the benefit-cost analysis for adaptation strategies. Using these methods, Calloway *et al.*, (2006) developed a policy-planning model to evaluate the benefits, costs and risks of avoiding detrimental climate change due to inefficient water allocation to competing users in the Berg River basin area of South Africa. Their study found that switching to allocation by water markets provided net benefits of between 10 to 20 percent over a no adaptation scenario in the area concerned.

Technical capabilities of changing and/or improving agricultural practices can be assessed by determining their agronomic potential. Crop production in Mali has been found to be responsive to the adoption of heat resistant cultivars, but not to changes in planting dates (Butt *et al.*, 2005). In Gambia, however, technologically feasible drought resistant cultivars were found to be impractical due to the high economic costs incurred in related research and development (Njie *et al.*, 2006). Therefore, multiple criteria should be used in order to make a judicious selection of adaptation measures from environmental, technical, social, and economic standpoints.

The methods discussed above emphasize a project specific decision-making framework, mainly because adaptation would take place locally. Yet, comprehensive economic assessments of multi-sectoral and regional adaptation costs and benefits are "currently lacking" (Adger *et al.*, 2007). Global scale assessments will likely be integral to highlighting intra-regional variation in the benefits accrued from adaptation. These, in turn, would enable more and better targeting of funds. For example, recent research has helped to identify potentially food insecure regions as a means of prioritizing investment needs (Lobell *et al.*, 2008). Moreover, as indicated by the Mali and Gambia studies, many low-cost adaptation strategies are likely to be insufficient in terms of minimizing risk. As a result, it can be concluded that further evaluation criteria need to be developed in order to direct necessary external assistance.

3.3 Enabling adaptation

It is clear that there will be an important role for public policy in assisting adaptation to climate change (Adger *et al.*, 2007). Planning for adaptation and implementing a well-targeted adaptation policy will require resources beyond the capacity of most governments in developing regions. In addition, lack of awareness or even reluctance to take action present further barriers to adaptation. Incentives and investments will be necessary for creating and diffusing improved technology and management techniques. As a result, national governments, NGOs and the international community all have a role to play in creating the means and cooperation required for adaptation.

Policy driven or planned adaptation strategies need to address high priority areas such as irreversible and catastrophic climate change impacts (i.e. where reactive measures are not enough), long-term investments (e.g. irrigation infrastructure), and unfavorable trends, such as soil quality degradation and water scarcity (Smith and Lenhart, 1996). In general, climate change should be considered in long-term planning (Easterling *et al.*, 2004) in order to maximize adaptive capacity. Specific policy driven measures for the agricultural sector include: drought contingency plans; efficient water allocation; seed research and development; the elimination of subsidies and taxes; efficient irrigation; conservation management practices; and trade liberalization (Smith and Lenhart, 1996).

3.3.1 Moving the adaptation agenda forward: Three suggestions

Clearly the adaptation agenda is very large. Much of the action required is at the local level, and its precise nature would depend a lot on local circumstances. Specific problems in particular areas call for explicit remedies. There is also much that can be done at the national level with international support to facilitate and promote adaptation at the local level. Three actions could be undertaken at the national and international levels that would move adaptation forward.

Promoting adaptation strategies and integration into development planning

All countries, as part of their responsibilities under the Convention could make national adaptation strategies. This would involve taking a broad strategic view of the future development path of a country and considering how it could best be designed or modified in the light of expected climate change. Within such a strategic view, policies for sectors and regions could be examined and adjusted to take account of climate change. Sectoral policies would likely include those for agriculture, forests and fisheries, water and other natural resources, health, infrastructure, and ecosystems. In addition to the sectoral approach, policy review could cover the management of extreme events such as droughts, storms and floods, and areas of particular risk, for example, exposed coastal zones, steep mountain slopes etc. Specific adaptation measures could then be evaluated and selected within the context of a climate-sensitive strategy and set of policies. Related documents should be integrated with national development planning in order to be effective.

Ensuring finance

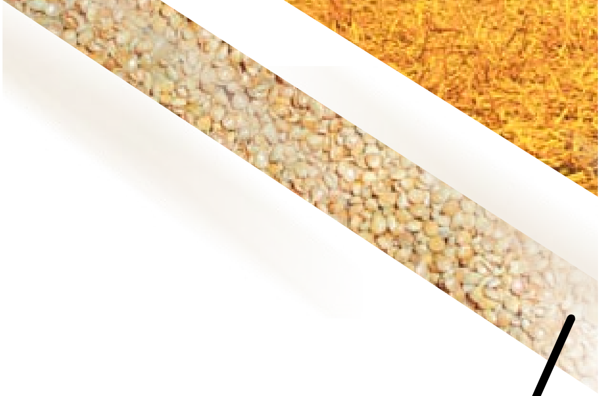
A common concern of developing countries has been that their participation in multilateral environmental agreements imposes costs in terms of undertaking new obligations to address the global environmental problems largely created by industrialized countries. Climate change is a salient issue of this kind. It seems realistic, therefore, to suggest that developed countries should scale up their support to developing countries for adapting to climate change. This would not only help ensure that climate issues are adequately considered in national development plans and sectoral policies, but also reassure donors and investors that climate change adaptation measures are well-conceived and represent good investment.

Promoting insurance

A further suggestion concerns the provision of insurance against climate risks. Countries, communities and individuals in most developing countries have little or no insurance coverage against the extreme weather events linked to climate change. The private insurance industry is poorly developed in many cases, and a fear that large catastrophe-related losses are unlikely to be covered by insurance premium income poses a significant deterrence to its growth.

3.3.2 Synergies between adaptation and mitigation

A final comment should be made on the synergies between adaptation and mitigation. Practices that increase the resilience of production systems may also reduce emissions or sequester carbon. In general, strategies to conserve soil and water resources (such as restoring degraded soils, agro-forestry, and biogas recovery) also enhance ecosystem functioning, providing resilience against droughts, pests, and other climatic threats. However, adaptation can also come at the expense of mitigation, for example, when increased nitrogen fertilizer usage for increased food production also expands nitrous oxide emissions. In order to maximize synergies and reduce trade-offs, mitigation and adaptation strategies should be developed together, recognizing that in some cases hard decisions will need to be made between competing goals.



4.

Conclusions and policy considerations

In this paper, the state of knowledge on climate change and agriculture has been reviewed. In general, agriculture impacts climate change significantly through livestock production and the conversion of forest to land cover that has low carbon sink or sequestration potential. Nitrous oxide emissions from crop production and methane from rice production are also significant. Mitigation options that are the most technically and economically feasible include better rice, crop- and pastureland management.

Although there are viable mitigation technologies in the agricultural sector, particularly in developing countries, some key constraints need to be overcome. First, rules of access — which still do not credit developing countries for reducing emissions by avoiding deforestation or improving soil carbon sequestration — must be changed. Second, operational rules, with their high transaction costs for developing countries and small farmers and foresters in particular, must be streamlined.

Climate change is also likely to have a significant negative impact on agricultural production, prompting output reductions that will greatly affect parts of the developing world. Adaptation, including crop choice and timing, has the ability to partially compensate for production declines in all regions. While a number of models have predicted this development, there is still a range of specific regional effects to be considered. Furthermore, insufficient attention has been given to multiple stressors, like extreme weather events, pests, and diseases. In addition, to date, only a limited number of studies have focused on the climate change and carbon fertilization effects related to crops of importance to the rural poor, such as root crops and millet.

As a result of changes in production, food security will be affected by climate change. Indeed, climate change alone is expected to increase the number of food insecure by an additional 5 to 170 million people by 2080, especially in Africa. Nevertheless, socio-economic policy, especially trade liberalization, can compensate for some of the negative impact here.

Even the most aggressive mitigation efforts that can reasonably be anticipated cannot be expected to make a significant difference in the short-term. This means that adaptation is an imperative. Yet, in the face of this imperative, many developing countries are lacking in sufficient adaptive capacity. As a result, there is a large role for national governments, NGOs, and international institutions to play in building the necessary adaptive capacity and risk management structures.

In order to facilitate these roles, global scale assessments should be conducted to help identify intra-regional variations in the effects of climate change. These studies would clarify the range of outcomes possible under plausible climate and adaptation scenarios, which would then assist in the targeting of high priority areas. Once areas of prioritization have been identified, evaluation criteria should be applied, that not only consider net economic benefits, but also environmental and social appropriateness. In addition, adaptation measures should maximize the complementarities between existing rural and sustainable development objectives.

Finally, climate change adaptation and mitigation have to proceed simultaneously. Since adaptation becomes costlier and less effective as the magnitude of climate changes increases, mitigation of climate change remains essential. The greater the level of mitigation that can be achieved at affordable costs, the smaller the burden placed on adaptation. Policies focused on mitigating GHG emissions, if carefully designed, can help generate a new development strategy; one that encourages the creation of new value in pro-poor investments by increasing the profitability of environmentally sustainable practices. To achieve this goal, it will be necessary to streamline the measurement and enforcement of offsets, financial flows, and carbon credits for investors. It will also be important to enhance global financial facilities and to reform their governance, namely to simplify rules and to increase the funding flows for mitigation in developing countries.

There has been a tendency to treat adaptation to climate change as a stand-alone activity, but this should be integrated into development projects, plans, policies, and strategies. Meanwhile, development policy issues must be addressed in association with the climate change community. A combined perspective is required to ensure the formulation and implementation of integrated approaches and processes that recognize how persistent poverty and environmental needs exacerbate the adverse consequences of climate change. Climate change will alter the set of appropriate investments and policies over time, both in type and in spatial location. Effective adaptation therefore requires a judicious selection of measures within a policy context and a strategic development framework, but must also explicitly counter the impact of climate change, particularly with respect to the poor.

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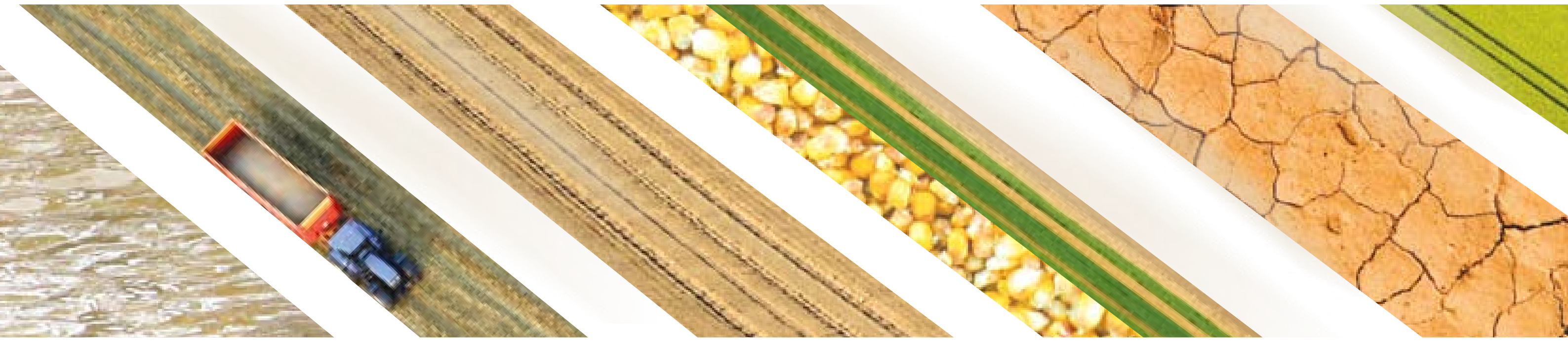

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