Climate Change and Asian Agriculture

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ABSTRACT

Asian and global agriculture will be under significant pressure to meet the demands of rising populations, using finite and often degraded soil and water resources that are predicted to be further stressed by the impacts of climate change. In addition, agriculture and land use change are prominent sources of global greenhouse gas (GHG) emissions. Fertilizer application, livestock rearing, and land management affect levels of GHG in the atmosphere and the amount of carbon storage and sequestration potential. Therefore, while some impending climatic changes will have negative effects on agricultural production in parts of Asia, and especially on resource-poor farmers, the sector also presents opportunities for emission reductions. Warming across the Asian continent will be unevenly distributed, but will certainly lead to crop yield losses in much of the region and subsequent impacts on prices, trade, and food security—disproportionately affecting poor people. Most projections indicate that agriculture in South, Central, and West Asia will be hardest hit.

This paper discusses two approaches to responding to the impacts of climate change: mitigation and adaptation. Mitigation—or the reduction of GHG emissions—is essential to slow climate change. The primary opportunities for pro-poor mitigation in the agriculture sector in Asia involve soil carbon sequestration, rice cultivation, and grazing land management. China and India, the world's largest producers of rice, also account for the vast majority of global methane emissions from rice. Potential exists for low- and no-cost mitigation policies in this sector. But significant reforms in the international climate policy framework and in implementation of carbon mitigation are needed to reduce transactions costs and increase the incentives for small farmer participation.

In addition, as climate change has already begun, adaptation—or the modification of agricultural practices and production—will be imperative if the growing food demands of modern society are to be met. However, many developing countries lack sufficient adaptive capacity. National governments, nongovernment organizations (NGOs), and international institutions therefore have a large role to play in building the necessary adaptive capacity and risk management structures. Significantly, mitigation and adaptation must be pursued in tandem. The greater the level of mitigation that can be achieved at affordable cost, the smaller the burdens placed on adaptation.

INTRODUCTION

Asian and global agriculture will be under significant pressure to meet the demands of rising populations, using finite and often degraded soil and water resources that are predicted to be further stressed by the impacts of climate change. In addition, agriculture and land use change are prominent sources of global greenhouse gas (GHG) emissions. Fertilizer application, livestock rearing, and land management affect levels of GHG in the atmosphere and the amount of carbon storage and sequestration potential. Therefore, while some impending climatic changes will have negative effects on agricultural production in parts of Asia, the sector also presents opportunities for emission reductions.

Even if emissions were reduced to zero from all sectors, warming of the climate would continue for decades to come. Hence, it is critical for stakeholders in the agriculture sector to understand the impacts that climate change will have on food and crop production. There will undoubtedly be shifts in agroecological conditions that will warrant changes in processes and practices to meet daily food requirements. In addition, for those populations in net food importing countries who continue to struggle to meet daily food requirements, climate change will become more salient as a production constraint.

This assessment presents two approaches to responding to the impacts of climate change: mitigation and adaptation. Mitigation—or the decline in the release of stored carbon and other GHG—must happen. There are opportunities for mitigation in the agriculture sector to reduce its impact on climate change, and there is significant room to promote pro-poor mitigation methods. In addition, as climate change has already begun, adaptation—or the modification of agricultural practices and production—is imperative if the growing food demands of modern society are to be met. Both mitigation and adaptation will require the attention of governments and policymakers for coordinating and leading initiatives. Principally, it is apparent that a system of regulations to ensure the economic value of carbon sequestration will be an important policy development in the agriculture sector.

This paper reviews the impacts of climate change on production and the opportunities for emission reductions, with a focus on Asia, including implications for food security and poor livelihoods. Centering on specific on-farm and soil management practices and adaptation strategies, this paper highlights emissions and impacts related to food production—mainly crop and livestock production—and their related mitigation and adaptation strategies. Following the introduction, the first part considers how the release of carbon and GHG will affect the agriculture sector, drawing heavily on future climate projections. The second part discusses the impacts of agricultural production on global warming, including possibilities for mitigation. Part three discusses the adaptation strategies of individuals and governments and their capacity to respond to increasing climate variability. Part four provides the conclusion and policy considerations. The objective is to provide a synthesis of the evidence on the impacts of agriculture on climate change, as well as the impacts that climate change is projected to have on this sector. The intention is to signal to development practitioners and policymakers the importance of coping with the threats, as well as of understanding the opportunities surrounding climate change.

IMPACTS OF CLIMATE CHANGE ON AGRICULTURE, WITH AN EMPHASIS ON ASIA

Even considering sufficient mitigation measures, the current scientific consensus holds that GHG emissions and atmospheric concentrations will increase for some decades. Consequently, global mean surface temperature will continue to rise long after the peak of emissions has passed. The predicted changes in temperature and other climate functions will have an impact on agroecological conditions and food production. Farmers will thus need to adjust technologies and practices to continue to meet 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, such as access to weather forecasts or better seed varieties, may result in further food insecurity. To better prepare vulnerable regions, climate scientists and economists are using integrated assessment models to identify high-risk regions and crops, as well as the resulting socioeconomic impacts. In this section, the model results are presented, along with the key uncertainties.

Impacts on Food Production Systems

Food production is an essential ecosystem service that is driven by a mixture of natural phenomena and human activity. The complex interactions between agroclimatic conditions and technological drivers such as nutrient application, irrigation, and seed selection determine food availability and quality. Anthropogenic activities have begun to change climate in ways that may warrant significant modification of existing agricultural knowledge and practices. As a result, 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 elucidate the extent to which climate change and the greater variability of the climate will impact agroecological production systems worldwide.

Rapidly rising levels of carbon dioxide (CO_2)[1] and other GHG in the atmosphere have direct effects on agricultural systems due to

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[1] Increased CO_2 levels lead to a positive growth response in a number of staples under controlled conditions, also known as the "carbon fertilization effect."

increased CO_2 and ozone levels, seasonal changes in rainfall and temperature, and modified pest, weed, and disease populations. In general, the flux of agroclimatic conditions can alter the length of growing seasons, planting and harvesting calendars, 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 in controlled experiments has demonstrated a positive response to increased levels of CO_2 in 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 of regional crop models are helping to characterize the plausible future climate impacts on agriculture. Due to the number of variables involved and the chaotic nature of weather systems, predictions are not meant to be taken as what will happen. Rather, they describe the range of possible outcomes.

Integrated Assessment Models for Food Systems under Climate Change

Model-based frameworks have been developed that forecast short- and long-term impacts on food systems. The majority of models investigate regional impacts, although relatively fewer models are dedicated to predicting impacts on developing country agriculture. A number of global models have been developed and are integral in highlighting risk disparities between developed and developing countries (Rosenzweig and Parry 1994; Parry et al. 1999; Parry et al. 2004; Fischer et al. 2005).

Characterizing the possible effects of climate change on crop yield and production, and the subsequent impacts on food prices and food security, requires several specific modeling applications. Generally, a combination of a crop model, climate simulation model, and world food trade model is implemented under predictions of GHG emission rates and socioeconomic development. These component models combine to create integrated physiological-economic models.

Future Impacts

Warming across the Asian continent is anticipated but will be unevenly distributed. The general trajectory will depend on global emissions scenarios, but impacts will depend critically on local manifestations. The average results across a collection of global circulation models in terms of global averages and the associated global distributions for three SRES (Special Report on Emission Scenarios) scenarios for the 2020s and the 2090s were analyzed (IPCC 2007). These temperature portraits were translated into subjective judgments of sectoral vulnerabilities for sub-continental regions distributed across Asia, as shown in Table 1 (IPCC 2007).

Impacts on yield and production. This section presents the results from leading models related to agricultural system functioning and yield, as well as the resulting 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.

Easterling et al. (2007) created a graphical summary based on a synthesis of 69 model-based results that demonstrates the relative impacts of temperature and carbon fertilization on changes in cereal yield. Figure 1 depicts the sensitivity of cereal yield to climate change for maize, wheat, and rice over a range of latitudes. Each of the studies included has been calibrated to reflect yield changes in response to mean

Table 1. Sectoral vulnerability for key sectors for sub-continental regions in Asia.

Sub-region	Food and fiber	Biodiversity	Water resources	Coastal ecosystem	Human health	Settlements	Land degradation
North Asia	+1/H	-2/M	+1/M	-1/M	-1/M	-1/M	-1/M
Central Asia and West Asia	-2/H	-1/M	-2/VH	-1/L	-2/M	-1/M	-2/H
Tibetan Plateau	+1/L	-2/M	-1/M	N/A	No info	No info	-1/L
East Asia	-2/VH	-2/H	-2/H	-2/H	-1/H	-1/H	-2/H
South Asia	-2/H	-2/H	-2/H	-2/H	-2/M	-1/M	-2/H
Southeast Asia	-2/H	-2/H	-1/H	-2/H	-2/H	-1/M	-2/H

Vulnerability:
-2 = Highly vulnerable
-1 = Moderately vulnerable
0 = Slightly or not vulnerable
+1 = Moderately resilient
+2 = Most resilient

Level of confidence:
VH = Very high
H = High
M = Medium
L = Low
VL = Very low

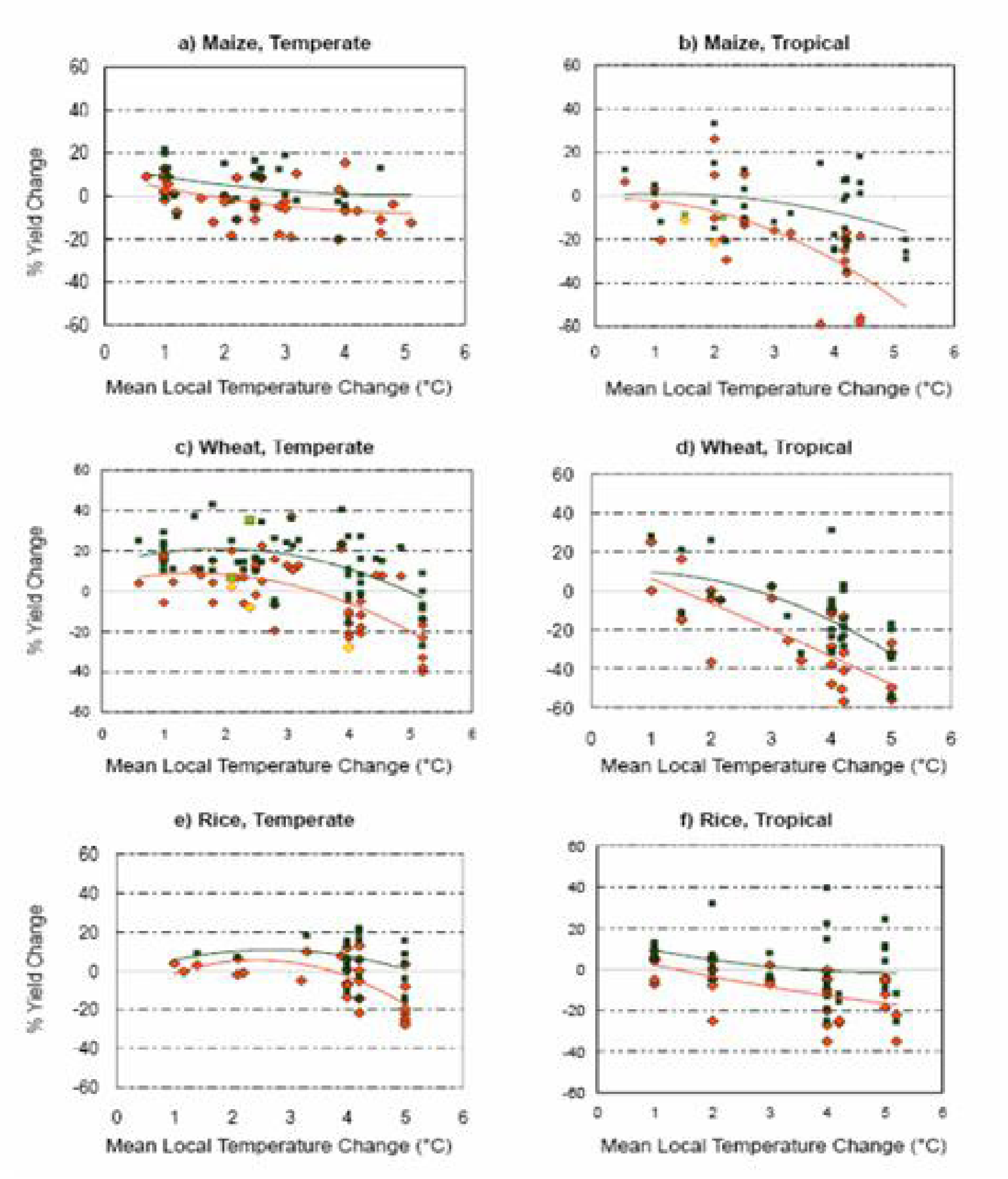
Source: IPCC 2007

local temperature changes, however, overall methodologies, scenarios, and geographic region of focus were varied.

The charts represent a wide range of variability in yield changes due to temperature across the 69 studies. As a result, it is difficult to draw specific conclusions; however, trends are observed. In mid- to high latitudes, increases in temperature of 1-2^0 C produce increases in yields, with flat to negative effects for temperature changes greater than that (Figure 1, charts a, c, and e). However, for tropical and sub-tropical regions for all crops, any increase in temperature depresses yields.

Cline (2007) shows strongly negative impacts on most developing countries and also demonstrates the effect of carbon fertilization on agricultural productivity—measured in net revenue changes—by regions (Figures 2 and 3). Overall, developing countries will have a 9-21 percent decline in overall agricultural productivity due to global warming, while industrialized countries will face a 6 percent decline to an 8-percent increase, 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 increases in water scarcity for irrigation.

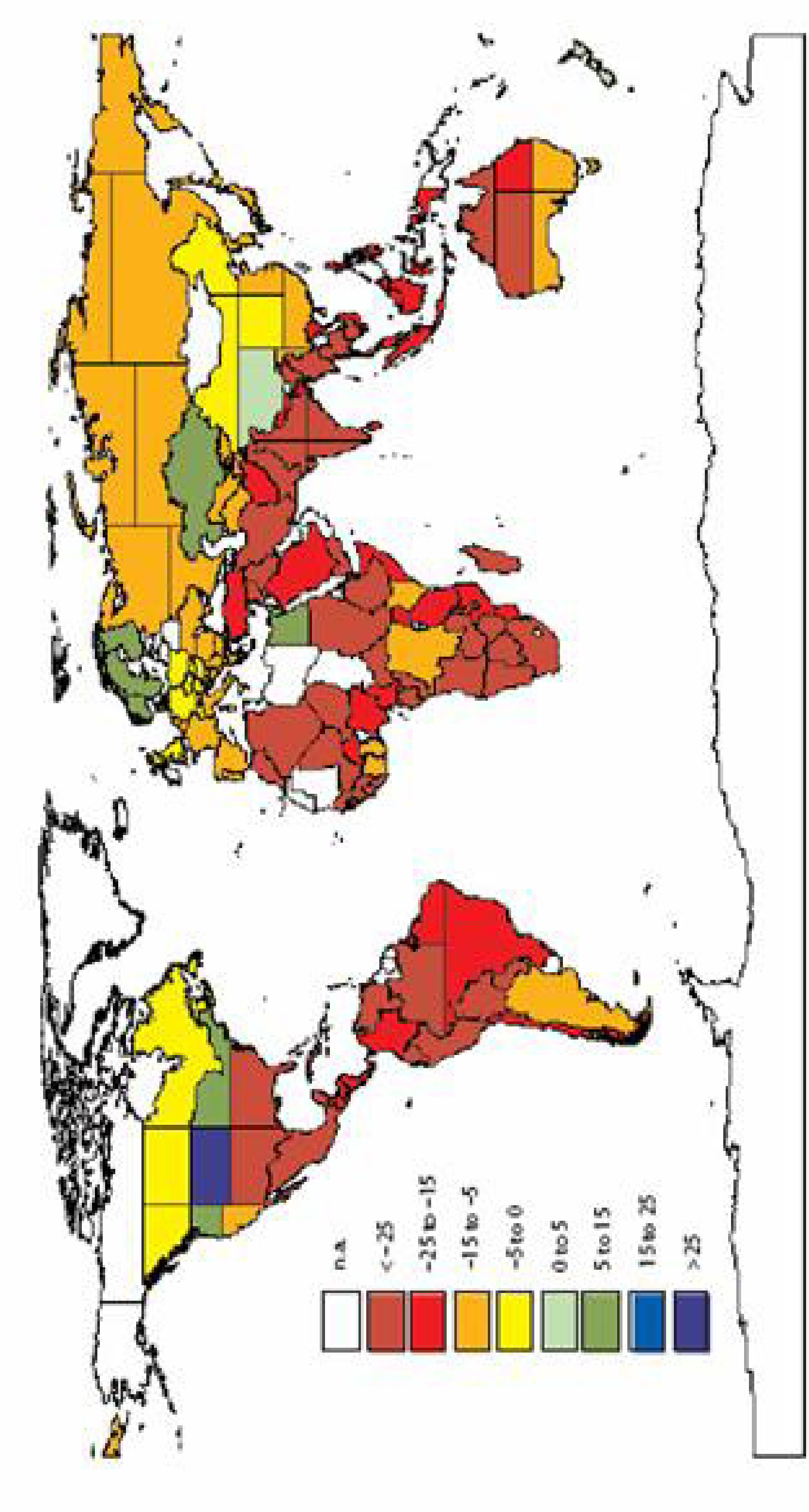
India may actually face agricultural losses of almost 40 percent without carbon fertilization, although this can be reduced to 29 percent with CO_2 fertilization in 2080. The northeast part of the country is in a much worse scenario as agricultural productivity can decline to as much as 44 percent if CO_2 fertilization does not materialize. On the other hand, China is in a better position. The south central region needs to address a 15-percent drop in agricultural productivity without fertilization, although the aggregate effects at the national scale will be about negative 7 to 7 percent. Table 2 presents the change in agricultural productivity with and without CO_2 fertilization in 2080.



Notes: Lighter filled dots (charts b and c) represent responses from rain-fed crops under decreased precipitation. Responses with no adaptation and those with adaptation, such as irrigation adoption, planting timing variation and cultivar modification, are represented by red and green dots, respectively. Lines represent best-fit polynomials.

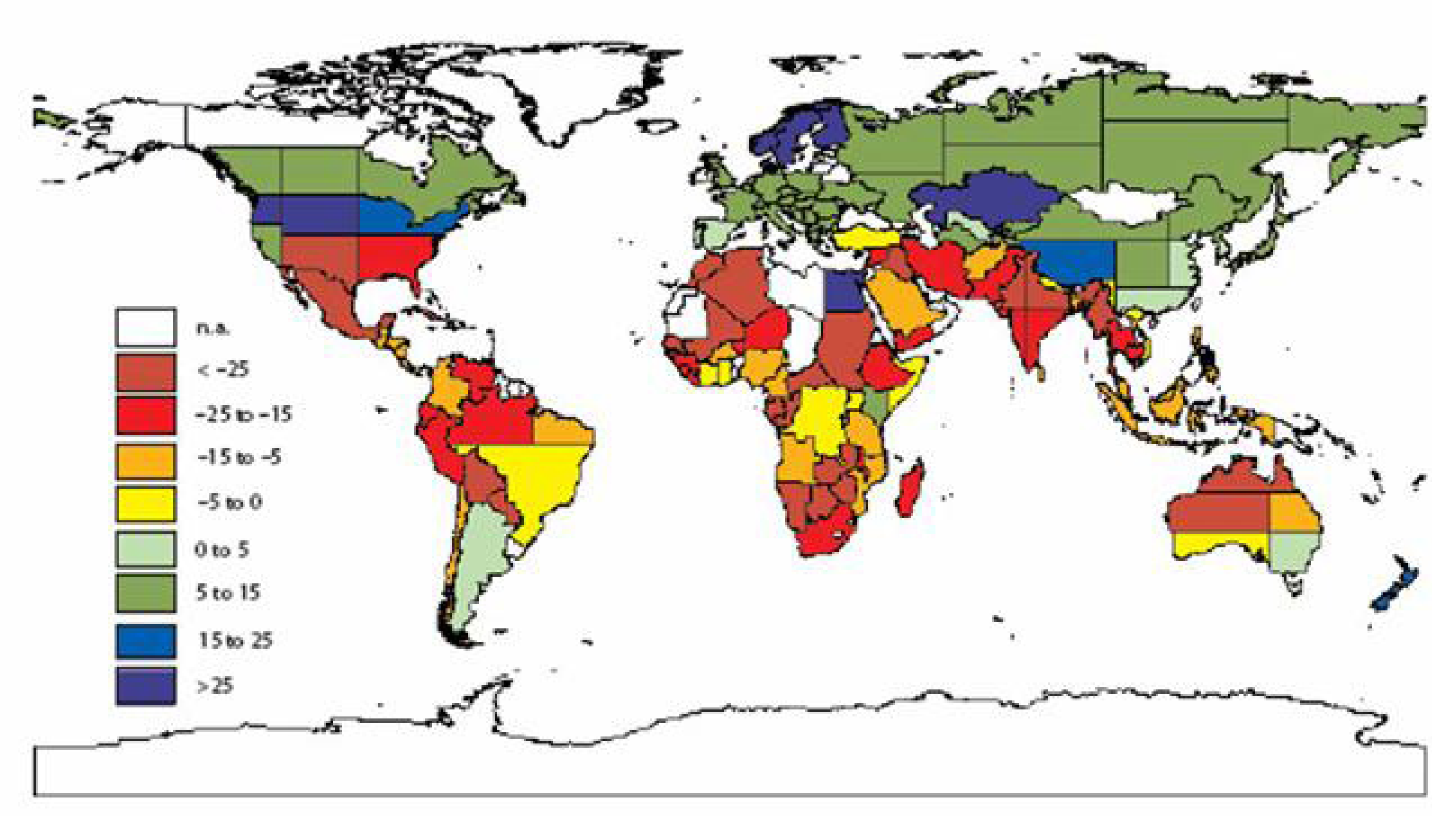
Source: Easterling et al. 2007

Figure 1. Sensitivity of crop yields to changes in local temperature with and without adaptation



Source: Cline (2007)

Figure 2. Impact on agricultural productivity without carbon fertilization (%)



Source: Cline (2007)

Figure 3. Impact on agricultural productivity with carbon fertilization (%)

Table 2. Agricultural impacts in Asia with and without carbon fertilization, 2080.

	Base Output (US$ billion 2003)	Population (million)	Change in Agricultural Potential (%)	
			Without carbon fertilization	With carbon fertilization
Asia	500	3,362	-19.3	-7.2
China	213	1,288	-7.2	6.8
India	132	1,604	-38.1	-28.8
Indonesia	35	215	-17.9	-5.6

Source: Warren 2006

IFPRI's work simultaneously assesses the impacts of climate change on food production and food prices. Figure 4a shows the percentage change in wheat yield in 2050 as a result of climate change, assuming the HadCM3-SRES B2 climate change scenario projected by the IMPACT[2] global food and water model. Wheat yield in most regions of the US and China is projected to benefit from climate change, while substantial reductions are expected in India. These reductions will occur despite significant increases in wheat prices due to climate change (Figure 4b). By 2050, the world wheat price under climate change is projected to be about 40 percent higher than the reference scenario, assuming climate change does not take place. Consumers will therefore absorb much of the impact of climate change.

Impacts on yield and production in sub-regions of Asia. Asia has considerable inter- and intra-annual climate variation, with agriculture in many regions relying primarily on monsoon rainfall. Certain areas of Asia are projected to be vulnerable to climate change, with less rainfall in the future. Low latitude regions are also more likely to experience crop yield losses due to higher temperatures than regions at higher latitudes.

Warren (2006) studied the impacts of climate change on cereal yields for sub-regions in Asia. He conducted a simulation of percentage reductions in major crop yields in the presence or absence of CO_2 fertilization and under increased temperature using data assembled from Parry et al. (2004). Analysis showed that wheat yields will decline 30–40 percent in Western Asia at a temperature rise of 3–4^0 C globally above 1990 levels, should CO_2 fertilization not occur. Losses occur at 20–30 percent in Central Asia and East Asia, and at 10–20 percent in South Asia. With CO_2 fertilization, losses are roughly 50 percent smaller.

For rice yields, without CO_2 fertilization, Central Asia will lose 20–25 percent, while South and East Asia will lose 10–20 percent at a temperature rise of 3–4^0 C above 1990 levels. With CO_2 fertilization, increases in yield of 1-2 percent could occur at a temperature rise of 2–3^0 C in many regions, except Africa and Central Asia, where losses would still occur. However, at a higher temperature increase of

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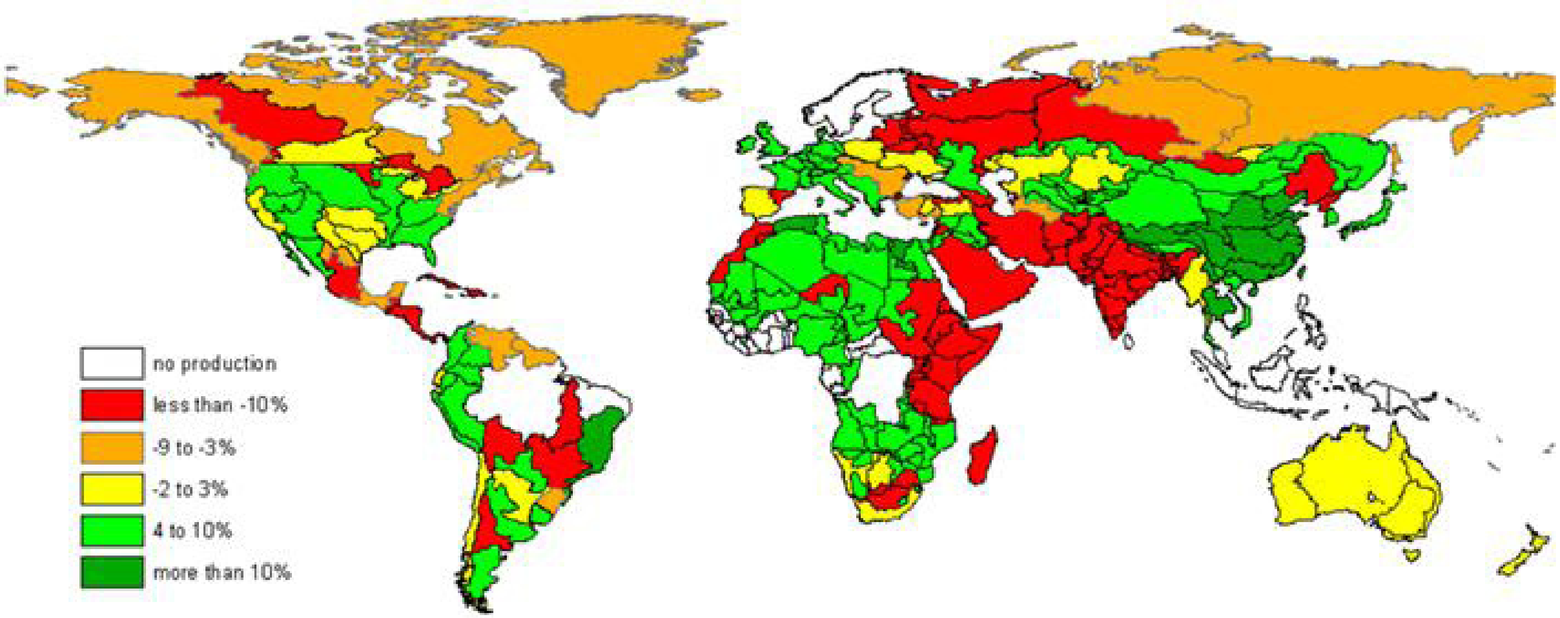
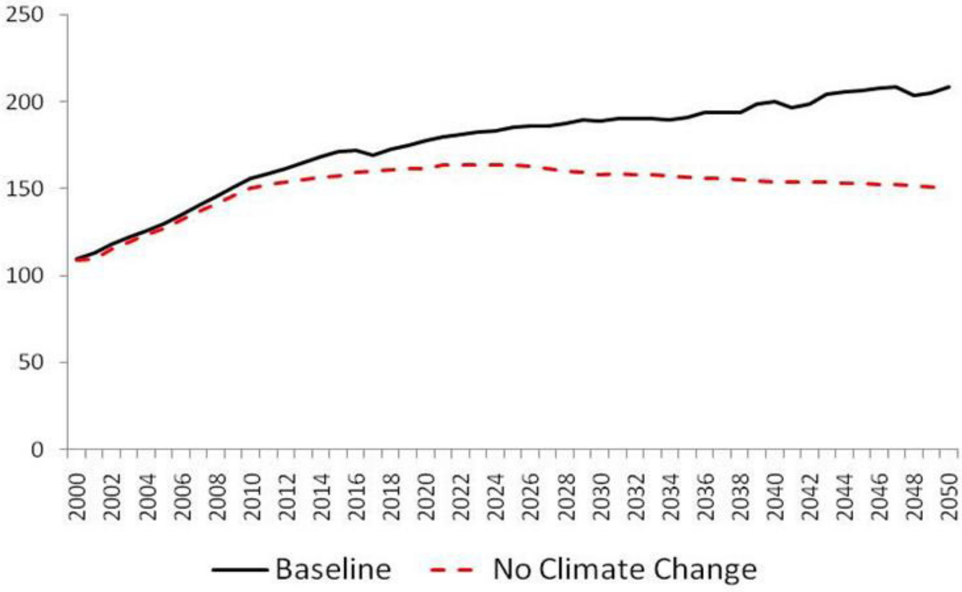
[2] IMPACT – International Model for Policy Analysis of Agricultural Commodities and Trade. Details can be found in Rosegrant et al. (2002).



Source: IFPRI IMPACT Projection 2008. IFPRI IMPACT simulations for HadCM3/SRESB2 scenario (with IMAGE temperature and CO_2 fertilization effects)

Figure 4a. Projected percentage change of wheat yield in 2050 due to climate change



Source: IFPRI IMPACT Projection 2008. IFPRI IMPACT simulations for HadCM3/SRESB2 scenario (with IMAGE temperature and CO_2 fertilization effects)

Figure 4b. World prices of wheat under baseline and the scenario assuming no climate change

3–4°C, global yield reductions of around 3 percent would occur as temperature effects trump those of CO_2 fertilization. Central, South, and West Asia would have a 20–30-percent decline in maize yields, while East Asia would experience a 10-20-percent decrease at a 3–4 ^{o}C temperature increase without CO_2 fertilization. A 16-percent reduction in yields was estimated in Central Asia, even with CO_2 fertilization. (Maize is a C4 plant and thus responds less to CO_2 fertilization.)

Impacts on yield and production in China and India. As the two countries with the largest populations and areas in Asia, China and India may significantly impact the rest of the countries in Asia and the world through international trade of agricultural commodities as climate change affects their agricultural production. A number of studies have evaluated agricultural production in the two countries under climate change.

China. Tang et al. (2000) found that average land productivity grew by 1.5-7 percent under irrigated conditions, and 1.1-12.6 percent in rainfed conditions from the 2020s to 2080s using HadCM2, CGCM1, and ECHAM4 scenarios. Another study looked at the impact on cereal yield using PRECIS (Providing Regional Climates for Impact Studies) of the Hadley Center. Assuming an absence of land use pattern, water supply, and pest and disease turbulence, results indicate that without CO_2 effects, the yield of all rainfed crops would decline by 2050 (wheat, 12–20%; maize, 15–22%; and rice, 8–14%) compared with baseline rainfed crops. With irrigation, a lesser decline will take place: wheat, 3–7 percent; maize, 1–11 percent; and rice, 5–12 percent (Ju et al. 2005; Xiong et al. 2005).

Lin et al. (2006) studied the monetary value of climate change impacts on rice, wheat, and maize. Considering changes in the inflation rate and agricultural product price trends since the 1980s, the assumption was made that in the next 15 years, price indices of rice, wheat, and maize will remain at around 105 percent (104-106 percent), and so will the current crop planting time and planting varieties. Given these conditions, the corresponding economic impact estimations of changes due to climate change in average crop production by 2020 compared with the base period of 1961–1990 are given in Tables 3, 4, and 5. Without CO_2 fertilization, outputs of the three crops will diminish under the A2 and B2 scenarios due to climate change, while lower outputs will be produced under rainfed conditions. For the B2 scenario under rainfed conditions, rice, maize, and wheat production will decrease by 5.3 percent, 11.3 percent, and 10.2 percent, respectively, without CO_2 fertilization. This corresponds to direct economic losses of ¥24.7 billion for rice, ¥19.9 billion for maize, and ¥21.3 billion for wheat, accounting for 1.84 percent of GDP in 2020.

India. Govindasamy et al. (2003) assessed the effect of heat due to climate change on wheat yields in India, with a doubling of CO_2. Under this scenario, they found a 51-percent decrease in wheat yield under the most favorable and high yielding regions due to heat stress, thereby leading to likely wheat yield losses. Roy (2006) analyzed the impacts of climate change using RCM (regional climate model), SWAT (soil and water assessment tool), and BIOME4 (biogeochemistry-biogeography model) models[3]. Some results of simulations on cereal crops (Table 6) show a small positive effect on rice, with a 20-percent yield increase in South India (Saseendran et al. 1999). The same result was found by Roy (2006), where rice has higher yield increases of 5–20 percent until 2070, due to a large increase in CO_2 compared with a relatively small reduction in yield during summer (0.10–0.30oC increase in temperature). Moreover, Roy (2006) found that wheat yield changes could be positive (increases of up to 25%) or negative (declines of up to 30%), depending on the magnitude of change in CO_2 and temperature. Productivity of wheat and other winter crops would considerably decrease with higher temperatures during the winter months. Since wheat is a winter crop, temperature fluctuations would affect its production more than rice production.

Socioeconomic and food security implications. The spatial differences highlighted above between low, middle, and high latitudes point to the great regional variation that climate change is expected to have on agriculture. As a result of these differentials in predicted production capabilities, some regions would benefit from increases in yield, while others would be compelled to increase food imports to meet demand. Fischer et al. (2002) estimate that cereal imports will increase in developing countries by 10-40 percent by 2080. Economies that derive a large share of GDP from agriculture would be most vulnerable to the affected food production systems. Most troubling is that developing economies are overwhelmingly low latitude countries and already face significant development challenges.

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[3] See Roy 2006 for detailed discussions of the models.

Table 3. China's rice output change and the average value change in the 2020s.

		With CO_2 fertilization		Without CO_2 fertilization	
		Average yield change (%)	Value change (¥ billion)	Average yield change (%)	Value change (¥ billion)
A2[4]	Rainfed	2.1	9.8	-12.9	-60.1
A2	Irrigated	3.8	17.7	-8.9	-41.4
B2[5]	Rainfed	0.2	0.9	-5.3	-24.7
B2	Irrigated	-0.4	-1.9	-1.1	-5.1

Source: Lin et al. 2006

Table 4. China's maize output change and the average value change in the 2020s.

		With CO_2 fertilization		Without CO_2 fertilization	
		Average yield change (%)	Value change (¥ billion)	Average yield change (%)	Value change (¥ billion)
A2	Rainfed	9.8	17.2	-10.3	-18.1
A2	Irrigated	-0.6	-1.1	-5.3	-9.3
B2	Rainfed	1.1	1.9	-11.3	-19.9
B2	Irrigated	-0.1	-0.2	0.2	0.4

Source: Lin et al. 2006

Table 5. China's wheat output change and the average value change in the 2020s.

		With CO_2 fertilization		Without CO_2 fertilization	
		Average yield change (%)	Value change (¥ billion)	Average yield change (%)	Value change (¥ billion)
A2	Rainfed	15.4	32.1	-18.5	-38.6
A2	Irrigated	13.3	27.7	-5.6	-11.7
B2	Rainfed	4.5	9.4	-10.2	-21.3
B2	Irrigated	11	22.9	-0.5	-1

Source: Lin et al. 2006

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[4] One of the two major emissions scenarios in IPCC SRES: Uneven global economic development, increasing world population, and medium-high levels of GHG emissions.

[5] One of the two major emissions scenarios in IPCC SRES: Regional sustainable development, slowly increasing world population, and low-medium levels of GHG emissions.

Table 6. Climate models and predictions in India.

	Assumption	Impact	Strength/ Weakness	Source
Aggregate agriculture	Temperature change 2.7–5.4°C	Losses up to $87 billion; loss of half of agricultural GDP	Price change effect ignored; CO_2 fertilization not considered	Mendelsohn (2005)
Rice and wheat yields	A2, B2 scenarios	Decline		Shukla et al. (2002)
	Temperature rise 2.5°C–4.9°C	Losses between 15%–42% and 25%–55%	CO_2 fertilization ignored	Kumar and Parikh (1998)
Rice yield	1.5°C rise in temperature and a 2 mm/day increase in precipitation	Decrease by 3–15%	CO_2 fertilization ignored	Saseendran et al. (1999)
	1.5°C rise + 2 mm rainfall rise + 460 ppm CO_2	+12% in South India		Saseendran et al. (1999)
Wheat yield	2°C rise + 425 ppm CO_2	-10% (Punjab, Haryana)		Kumar and Parikh (1998)
Soybean yield	+2 and +4°C change in temperature; ± 20 and ± 40% change in precipitation	- 22% to 18%	CO_2 fertilization ignored	Lal et al. 1998
Farm-level net revenue	Temperature rise 2.0–3.5°C , farm-level adaptation	Losses of 9–25%	Considers imperfect land market and administered price	Kumar and Parikh (1998)
GDP		Drop between 1.8–3.4%	CO_2 fertilization ignored	Kumar and Parikh (1998)
Agricultural relative to nonagricultural prices		Increase by 7–18%;	CO_2 fertilization ignored	Kumar and Parikh (1998)
		Losses in the same direction but somewhat smaller	With carbon fertilization effects	
Farm-level total net revenue	+2°C and accompanying precipitation change of +7% with adaptation by farmers of cropping patterns and inputs	Fall by 9%	With adaptation by farmers of cropping patterns and inputs	Kumar and Parikh (1998)
Farm level total net revenue	+3.5°C and precipitation change of + 15%,	Fall nearly 25%		
Agricultural net revenue	2° C rise in mean temperature and a 7% increase in mean precipitation	Reduce by 12.3%	Includes adaptation options	Sanghi et al. (1998)

Source: Roy 2006

Future food availability depends on a number of factors in addition to climate impacts on production, including trade policy, food aid, and storage capacity. Food security futures are predicted by making assumptions about trade policy and other aspects of socioeconomic development and integrating them with the results of crop and general circulation models. Currently, however, only one economic model has been used to predict impacts on food security, albeit under different crop models (Schmidhuber and Tubiello 2007). These different crop model results are presented in Fischer et al. (2005) and Parry et al. (2005), both using the Basic Linked System of National Agricultural Policy Models (BLS). Schmidhuber and Tubiello (2007) synthesized the results of these models and estimated that an additional 5-170 million people will be malnourished by 2080, depending on the SRES scenario. On the other hand, Parry et al. (2005) showed that the regional variation in the number of food insecure people is better explained by population changes than climate impacts on food availability. As a result, economic and other development policies will be critical in influencing future human well-being.

While not considering the full economic effects of production and consumption, Lobell et al. (2008) identified crops and regions that may be "climate risk hot spots" based on predicted yield changes due to climate change and diet importance. The authors identified the top five crops for food security (based on calorie intake and population) and synthesized the results from crop models. Probabilities are given over a range of crop yield changes. For example, 95 percent of models predict that climate change will depress yields to some extent for South Asian wheat, Southeast Asian rice, and Southern Africa maize -- regions and crops that are also more vulnerable to threats to food security.

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. Table 7 lists these adaptation measures. In general, model-based results are not able to consider the decision-making capability of farmers, but rather the overall impacts that such management decisions could have in diminishing the effects of global warming.[6]

The meta-analysis conducted by Easterling et al. (2007) is again useful for considering the effects of adaptation in mitigating climate effects on yield for major staples (Figure 1). These effects are shown by the differences between the red (no adaptation) and green (with adaptation) best-fit polynomials. In general, on-farm adaptation has a positive effect on yields and can be approximated as having an overall 10-percent yield benefit when compared with yields of no adaptation. In addition, charts (b), (c), and (e) demonstrate the increasing returns to adaptation up to approximately three degrees (the inflection point in the curve).

While these estimates reveal that farmers can partially avoid the negative impacts of climate change on food production, the model-based results are not able to capture the probability that an individual farmer would adapt in the face of perceived climatic variations. Each farmer will weigh the risks, costs, and potential benefits of changing management practices. In addition,

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[6] Mendelsohn and others examined the profit-maximizing behavior of farmers in deciding whether or not to adapt to perceived climate change in a number of microeconomic studies (e.g., Seo and Mendelsohn, 2008).

Table 7. Farm-level adaptation responses and speed of adoption.

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

Source: Adapted from Reilly 1995

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 climate forecasting—will play an integral part in managing climate change risks.

Summary of Impacts

The clearest conclusion is that climate change will have highly varying and unpredictable impacts on agricultural production in Asia. The estimated impacts depend on the crop, the degree of warming, the assumptions regarding the degree of carbon fertilization and adaptation, and the modeling approach taken. Despite the uncertainty, the weight of evidence indicates that the impact on agricultural production is likely to be most negative in South, Central, and Western Asia. Other regions in Asia will likely face declines in wheat, rice, and maize yields, although these will be smaller than in South Asia. On the other hand, parts of China and East Asia may have slight increases in production for some crops. Globally, agricultural production will likely decline due to climate change, resulting in higher food prices. Consequently, food consumers will face higher prices and poor consumers especially will experience reductions in food security and well-being.

MITIGATION AND SEQUESTRATION POTENTIAL

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

GHG emissions from agriculture

- The share of agricultural emissions in total GHG emissions in 2000 was 13 percent. In developing countries, emissions are expected to rise in the coming decades due to population and income growth, among other factors.

- Within the agriculture sector, emissions from fertilizer application, livestock and manure management, rice cultivation, and savanna burning are the major emission sources.

Mitigation potential and options

- Overall, opportunities for emissions mitigation in the agriculture sector at no or low cost are modest. As shown below, the potential for soil carbon sequestration is significantly higher than that of emissions mitigation.

- India has the lowest economic potential, contributing only 3.4 percent to the total potential reductions at carbon prices of US$30 per tCO_2-eq or less. China and South and Southeast Asia have higher potential, contributing together over 40 percent of reductions at carbon prices of US$30 per tCO_2-eq or less.

- Rice cultivation mitigation strategies have the highest economic potential in developing countries for emissions reduction.

Conditions for realizing mitigation potential

- Agriculture in developing countries can play a significant role in GHG mitigation, but incentives to date are not conducive to investing in mitigation. At the same time, aligning growing demand for agricultural products with sustainable and emissions-saving development paths will prove challenging.

- The carbon market for the agriculture sector is underdeveloped. This is in part for good reason, as verification, monitoring, and transaction costs are rather high. However, the carbon market could be stimulated through different rules of access and operational rules in carbon trading, as well as capacity-building and advances in measurement and monitoring.

- Policies focused on mitigating GHG emissions, if carefully designed, can help create a new development strategy that encourages the creation of more valuable pro-poor investments by increasing the profitability of environmentally sustainable practices.

Emissions Trends

Climate change is the result of an increase in the concentration of GHG, such as CO_2, nitrous oxide (N_2O), and methane (CH_4). Rising GHG emissions are associated with economic activities such as energy, industry, transport, and patterns of land use, including agricultural production and deforestation. Agriculture—together with related emissions from land use change and forestry (LUCF)—account for nearly one-third of global GHG emissions. Industrial processes, energy, and waste contribute 3 percent each (WRI 2008).

Agriculture alone contributed 13 percent of total global GHG emissions in 2000, or 5,729 $MtCO_2$-equivalents.[7] Emissions from this sector are primarily CH_4 and N_2O, making the agriculture sector the largest producer of non-CO_2 emissions, accounting for 60 percent of the world total in 2000 (WRI 2008). While agricultural lands also generate very large CO_2 fluxes both to and from the atmosphere via photosynthesis and respiration, this flux is nearly balanced on existing agriculture lands. Significant carbon release, however, results from the conversion of forested land, which is

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[7] One million metric tons (MMt) of CH_4 emissions equal 21 million metric tons of 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 potentials of CH_4 and N_2O are higher than CO_2 because they exist longer in the atmosphere. Yet, due to their significantly smaller concentrations, the actual radioactive forcing of CH_4 and N_2O are one-third and one-tenth of CO_2, respectively.

included under the LUCF category.[8] Finally, other agricultural activities related to GHG emissions are included in other sectors, such as the upstream manufacture of equipment, fertilizers, and pesticides; the on-farm use of fuels; and the transport of agricultural products.

Regional variations in emissions from agricultural sources (non-CO_2) indicate that non-OECD countries emit nearly 75 percent of global emissions, as shown in Table 8 (WRI 2008). Hence, the theoretical potential for mitigation in the agriculture sector is greater in developing countries than in industrialized nations. Asian countries account for 37 percent of total world emissions from agricultural production. Latin America and Europe are 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 is responsible for nearly 10 percent of agricultural emissions in Latin America (WRI 2008).

Emissions from agriculture come from four principal sectors: agricultural soils, livestock and manure management, rice cultivation, and the burning of agricultural residues and savanna for land clearing. Figure 5 presents the share of and pollutant(s) from each of these sectors. The largest shares of emissions originate from agricultural soils (N_2O) and enteric fermentation and manure management (CH_4) associated with livestock production. Emissions from agriculture are expected to rise due to increased demand for agricultural production from growing populations and improved nutrition and changes in diet preferences that favor larger shares of meat and dairy products (e.g., Delgado et al. 1999). This leads to increased pressure on forests due to agricultural expansion. Figure 6 presents the projected growth in emissions from each source from 1990 to 2020.

Globally, agricultural emissions increased by 14 percent from 1990 to 2005 and are expected to rise by 38 percent from 1990 to 2020. Figure 7 illustrates the share of expected growth of emissions from developing countries in each sector. Agricultural emissions in developing countries will increase by 58 percent in 2020, while emissions from the burning of agricultural residues and savanna and N_2O from soils will grow by over 40 percent from 1990 levels. From a mitigation perspective, one of the largest challenges will be to align increasing demands for food, shifts in diets, and demand for agricultural commodities for non-food uses with sustainable and low-emitting development paths.

Smith et al. (2007a) further analyzed the contributions of agriculture to GHG emissions by sector in 2005, regionally and at the global level (Table 9). At the sectoral level, N_2O from soils had the highest emission level, at 44 percent of Asia's total, followed by CH_4 from enteric fermentation at 31 percent. Fertilizer and manure applied to soil were the main sources of N_2O, whereas the large livestock population contributed to the high enteric fermentation that releases CH_4 gas (USEPA 2006b). Most developing countries are agriculture based; thus, N_2O from soil ranked as the top emitter of GHG (Table 9). On the other hand, CH_4 from enteric fermentation placed second and is highest in Latin America and the Caribbean (LAC) due to the combined population of cattle, sheep, and other livestock (Smith et al. 2007a). In addition, CH_4 from rice was found to be highest

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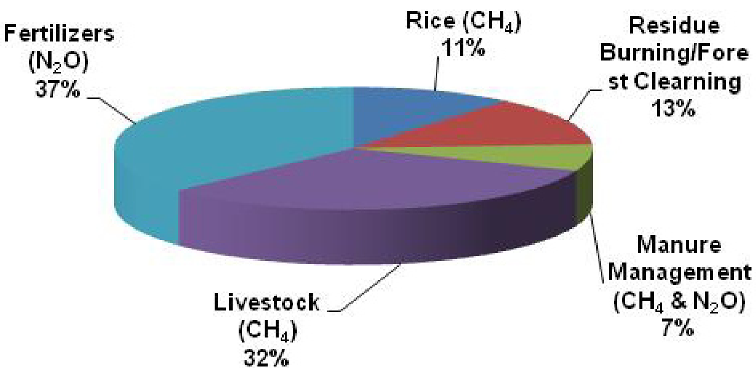
[8] Total LUCF emissions, which include biomass clearing and burning for agriculture and urban expansion, as well as timber and fuel wood harvesting, were nearly 18 percent of total GHG emissions in 2000, equivalent to 7,618 Mt CO_2. Concerning food production specifically, estimates of the amount of total emissions in this sector that are due to land conversion for agricultural extensification are difficult to make. However, one estimate attributes 9 percent of total global emissions—one half of LUCF emissions—to expansion into forests for feed crop and livestock production (Steinfeld et al. 2006).

Table 8. Agricultural emissions by region, 1990 to 2020 (MtCO$_2$-eq).

Country	1990	2000	2010	2020
Africa	664	934	1,098	1,294
China/CPA	1,006	1,159	1,330	1,511
Latin America	890	1,097	1,284	1,505
Middle East	62	74	99	125
Non-EU Eastern Europe	21	19	21	24
Non-EU FSU	410	217	246	279
OECD90 & EU	1,346	1,283	1,306	1,358
South and SE Asia	823	946	1,084	1,214
World Total	**5,223**	**5,729**	**6,468**	**7,311**

Source: Drawn from data used in USEPA 2006a



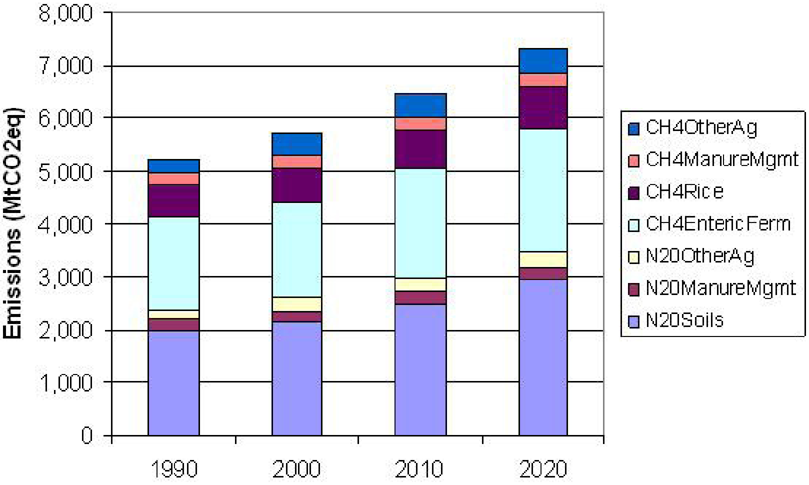
Source: Drawn from data presented in USEPA 2006a

Figure 5. Sources of emissions from the agriculture sector, 2000

in East and South Asia, at 29 and 13 percent of the region's total, respectively. China and India are the two top rice producing countries at the global scale (Maclean et al. 2002) and thus produce elevated levels of CH_4 emissions.

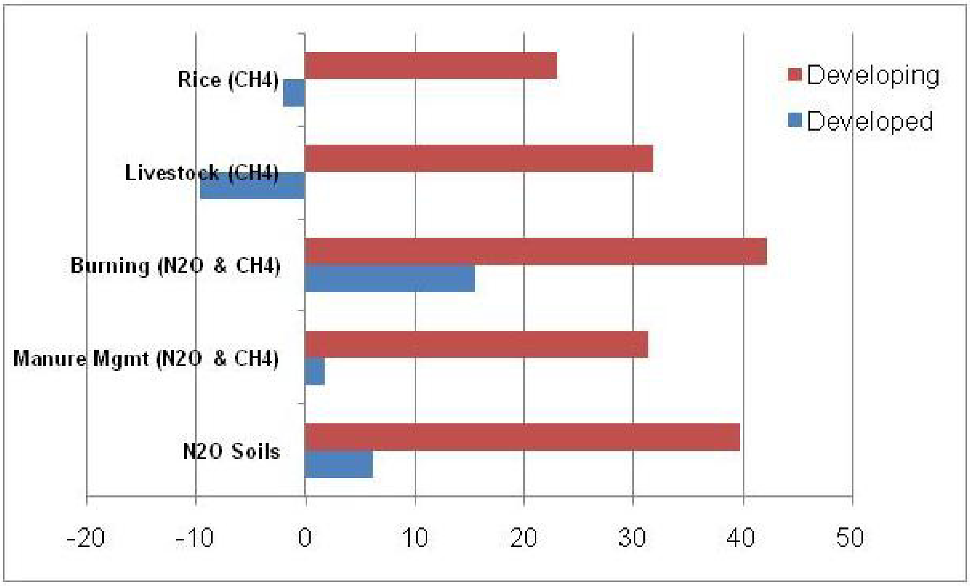
Agricultural Soils

Nitrous oxide (N_2O) is the largest source of GHG emissions from agriculture, accounting for 38 percent of the share globally. N_2O is produced naturally in soils through the processes of nitrification and denitrification. Activities may add nitrogen to soils either directly or indirectly. Direct additions occur through nitrogen fertilizer use, application of managed livestock manure and sewage sludge, production of nitrogen-fixing crops and forages, retention of crop residues, and cultivation soils with high organic-matter content. Indirect emissions occur through volatilization and subsequent atmospheric deposition of applied



Source: Drawn from data used in USEPA 2006a

Figure 6. Projected agricultural emissions by sector, 1990–2020



Source: Drawn from data presented in USEPA 2006a

Figure 7. Percent change in sector emissions in developed and developing country groups, 1990–2020

Table 9. GHG emissions by main sources in the agriculture sector in different regions, 2005.

Region	N_2O soils	CH_4 enteric	CH_4 rice	CH_4, N_2O manure	CH_4, N_2O burning	Total
South Asia						
Mt CO_2-eq/yr	536	275	129	40	24	1,005
% of region's total	53	27	13	4	4	100
% of source's world total	20	15	20	9	3	17
East Asia						
Mt CO_2-eq/yr	600	294	432	127	53	1,505
% of region's total	40	20	29	8	4	100
% of source's world total	23	16	68	29	14	25
LAC						
Mt CO_2-eq/yr	359	446	25	25	141	996
% of region's total	36	45	3	3	14	100
% of source's world total	14	24	4	6	37	17
SSA						
Mt CO_2-eq/yr	350	244	21	16	143	775
% of region's total	45	32	3	2	18	100
% of source's world total	13	13	3	4	37	13
MENA						
Mt CO_2-eq/yr	101	41	10	3	2	157
% of region's total	64	26	6	3	2	100
% of source's world total	4	2	2	1	0	3
Subtotal (developing regions)						
Mt CO_2-eq/yr	1,946	1,300	617	211	363	4,438
% of region's total	44	29	14	5	8	100
% of source's world total	74	70	97	48	92	74
Subtotal (developed regions)						
Mt CO_2-eq/yr	700	554	20	225	32	1,531
% of region's total	46	36	1	15	2	100
% of source's world total	26	30	3	52	8	26
TOTAL						
Mt CO_2-eq/yr	2,646	1854	637	436	395	5,969
% of region's total	44	31	11	7	7	100
% of source's world total	100	100	100	100	100	100

Source: Adapted from USEPA 2006b

nitrogen, as well as through surface runoff and leaching of applied nitrogen into groundwater and surface water (USEPA 2006b).

Direct application of nitrogen-based fertilizers, both synthetic and organic, will 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 to 2020 indicate that emissions will remain relatively static in the OECD, with major increases coming from China (50-percent increase), Africa, Latin America, and the Middle East (100-percent increase). The sharpest increase in fertilizer application is expected in developing countries, which are expected to use 36 million tons more than developed countries by 2020 (Bumb and Baanante 1996).

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 and is the second largest source of total emissions from agriculture, at 34 percent globally. 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. CH_4 is produced from the anaerobic breakdown of manure. N_2O results from handling the 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 in the developing world. By 2020, over 60 percent of meat and milk consumption will take place in the developing world, and the production of beef, poultry, pork, and milk will at least double from 1993 levels (Delgado et al. 1999). As a result, CH_4 emissions from enteric fermentation are projected to increase by 32 percent by 2020, with China, Brazil, India, the US, and Pakistan as the top sources. In addition, CH_4 and N_2O emissions from manure management are expected to increase by an estimated 21 and 30 percent, respectively, again with large shares from China and Brazil.

Rice Cultivation

Flooded rice fields are the third largest source of agricultural emissions, contributing 11 percent in the form of CH_4 resulting from anaerobic decomposition of organic matter. China and Southeast Asian countries produce the lion's share of CH_4 emissions from rice, accounting for over 90 percent in 1990. Due to population growth in these countries, emissions are expected to increase by 36 percent in Southeast Asia and 10 percent in China by 2020 (USEPA 2006a).

Options for Mitigation in Agriculture

The biological processes associated with agriculture are natural sources of GHG. Anthropogenic activities have the potential to impact the quantity of emissions through the management of carbon and nitrogen flows and thus can be directed to mitigate GHG emissions. There are two categories of mitigation methods in agriculture: carbon sequestration into soils and on-farm emissions reductions. Another mitigation strategy considered is bioenergy production, which displaces GHG emissions from fossil fuel use. These three options for mitigation in agriculture are further discussed below.

Technical Potential for Mitigation

The technical potential is the theoretical amount of emissions that can be reduced and the amounts of carbon that can be sequestered given the full application of current technologies, without considering the costs of implementation. It describes the order of magnitude that current methods of mitigation may allow, instead of providing realistic estimates of the amount of carbon that will be reduced under current policy and economic conditions. In general, they do not consider trade-offs with other goals, such as income generation or food security, nor do they consider the heterogeneity in management capacity or cultural appropriateness.

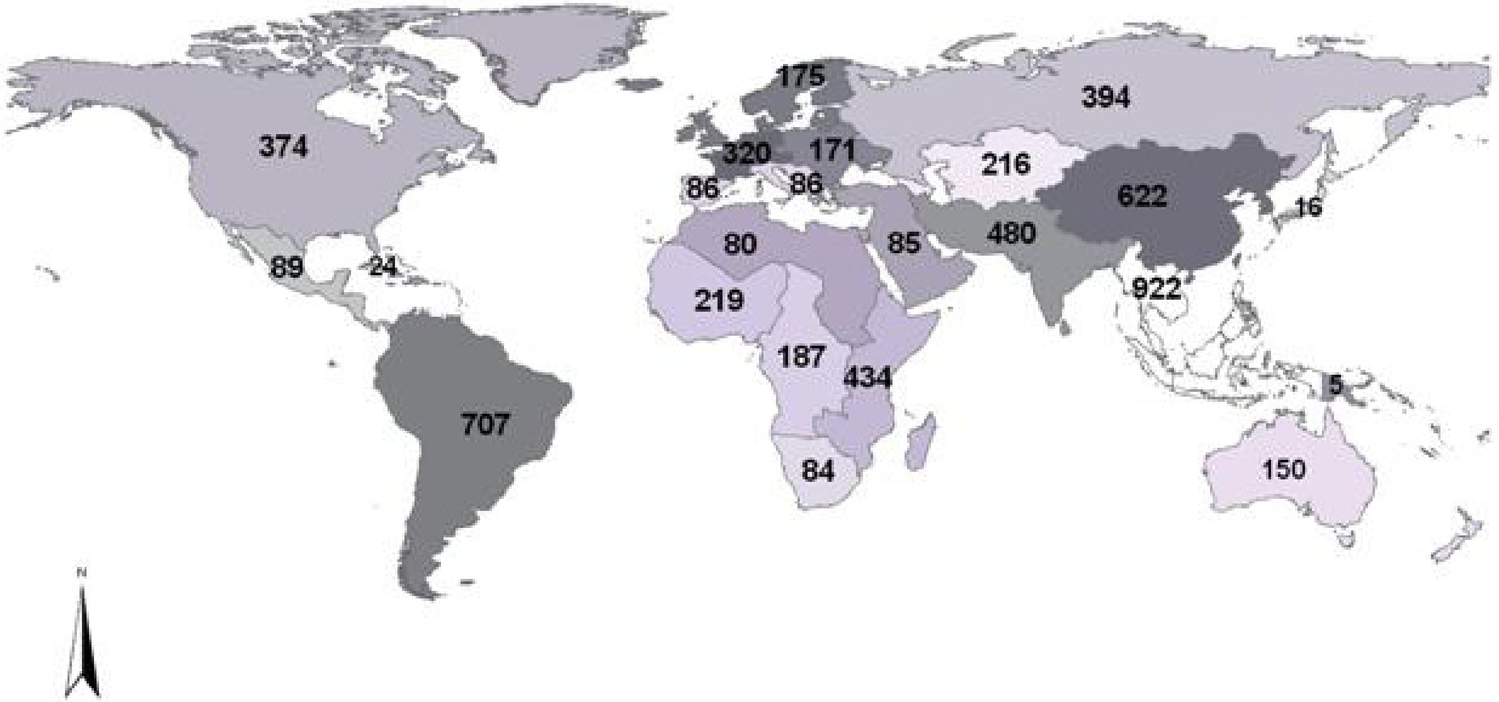
Smith et al. (2007a) estimated the global technical potential for mitigation options in agriculture per region by 2030 (Figure 8). They reported that considering all gases, Caldeira et al. in 2004 estimated about 4,500 Mt CO_2-eq/yr, which further increased to 5,500-6,000 Mt CO_2-eq/yr. At the regional level, Asia has the highest potential for mitigation options among the regions at 45 percent. It was followed by LAC and Europe, 14 percent each; Sub-Saharan Africa (SSA), 12 percent; North America and the Middle East and North Africa (MENA), 6 percent each; and Australia, 2 percent.

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 that retard the release of stored carbon into the atmosphere through burning, tillage, and soil erosion. Sequestered carbon is stored in soils, resulting in increases in soil organic carbon (SOC). SOC is expected to approach a new equilibrium over a 30–50 year period and is ultimately limited by saturation. In addition, there is potential for the re-release of SOC into the atmosphere through fire or tillage, which raises concerns of the "permanence" of SOC storage. On the other hand, emissions abatement through improved farm management practices could be sustained indefinitely. Despite these limitations, soil carbon sequestration is estimated to account for 89 percent of the technical mitigation potential in agriculture, compared with 11 percent for emissions abatement (Smith et al. 2007a). Figure 9 shows the dominance of soil carbon sequestration (CO_2) in technical mitigation potential.

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, irrigating, rotating crop and forage, and practicing no-till agriculture (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). The literature highlights no-till agriculture as having a high mitigation potential. 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.

SOC can be also increased through grazing land management, which improves the cover of high-productivity grasses and overall grazing intensity. In Asia, large potential exists in India, which has one of the world's largest grazing land areas.

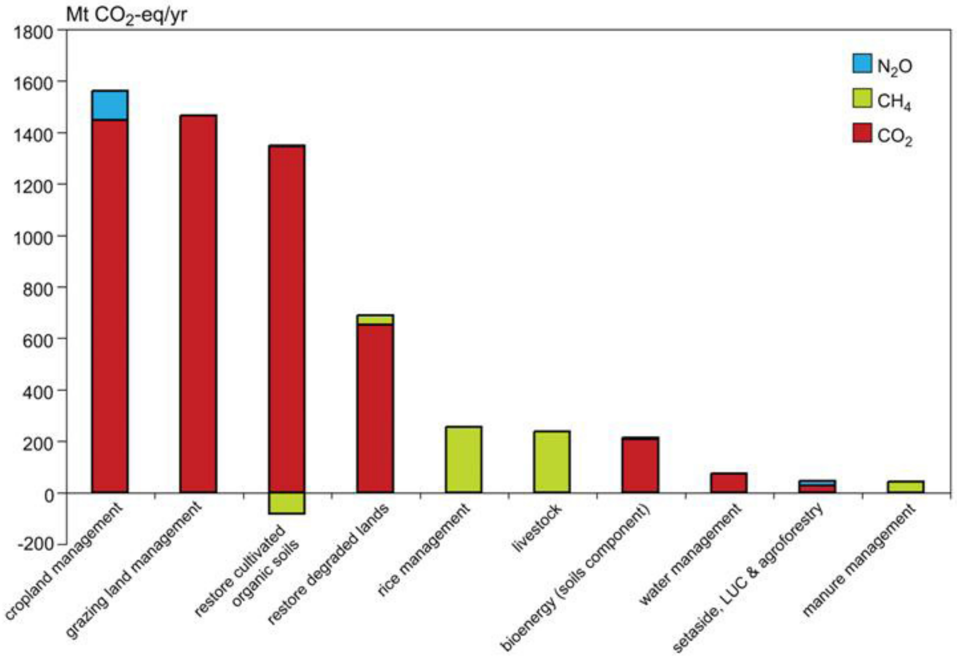
Bioenergy. The production of liquid fuels from dedicated energy crops (e.g., grains and oilseeds) is being evaluated for use as



Note: Technical mitigation potential includes all practices, GHGs, and Mt CO_2-eq/yr. The above figure is based on the B2 scenario, although the pattern is similar for all SRES scenarios.

Source: Smith et al. 2007a

Figure 8. Total technical mitigation potentials for each region by 2030



Source: Smith et al. 2007a

Figure 9. Global technical mitigation potential by 2030 of each agricultural management practice showing the impacts of each practice in GHG

transportation fuel 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 on 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 with traditional fossil fuels is being challenged by 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 for agricultural soil emissions, bioenergy production is estimated to have a technical potential of approximately 200 Mt CO_2-eq/year in 2030 (Figure 9). But the potential for GHG savings is much higher when the offsetting potential from displacement of fossil fuels is considered. It is estimated that 5-30 percent of cumulative carbon emissions would be abated if bioenergy supplied 10-25 percent of world global energy in 2030 (Ferrentino 2007). But rapid expansion in bioenergy of this magnitude would have significant tradeoffs with food security, as has already been seen in the past few years, and have significant negative impacts on food production and biodiversity. A careful assessment of these tradeoffs, as well as of net GHG gains including land use change effects, needs to be undertaken for alternative bioenergy technologies as they develop.

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

Enteric Fermentation. Methods to reduce CH_4 emissions from enteric fermentation include improving digestive efficiency of livestock with improved feeding practices and dietary additives. The efficacy of these methods depends on feed quality, livestock breed and age, and whether the livestock is grazing or stall fed. Developing countries, compared with developed countries, are assumed to provide lower quality feed to livestock, which raises the emissions rate per animal. The technical potential to mitigate livestock emissions in 2030 is 300 Mt CO_2-eq/yr (Figure 9).

Manure Management. In manure management, cooling and using solid covers for storage tanks and lagoons, separating solids from slurry, and capturing the CH_4 emitted are effective techniques. In developing countries, however, applying this type 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 75 Mt CO_2-eq/yr (Figure 9).

Fertilizer Management. Improving the efficiency of fertilizer application or switching to organic production can decrease the nutrient load and N_2O emissions. However, overall benefits will need to be weighed against potential impacts on yield. Fertilizer reductions of 90 percent in rainfed maize fields were shown to reduce yields by 8.4 and 10.5 percent over the baseline in Brazil and China, respectively (USEPA 2006a). In addition, the lack of access to soil nutrients to improve the quality of degraded soils in many parts of the developing world is a hindrance to achieving food security (Gruhn et al. 2000). Overall, cropland management could reduce emissions in 2030 up to 150 Mt CO_2-eq/yr (Figure 9).

Rice Cultivation. Improving water management in high-emitting, irrigated rice systems through mid-season drainage or alternate wetting and drying has shown substantial reductions in CH_4 emissions in Asia. However, these effects may be partially offset because the amount of N_2O emitted increases (Wassman et al. 2006). The technical potential of improved rice management is 300 Mt CO_2-eq/yr (Figure 9).

Aggregate estimates of the global technical potential of both on-farm and sequestration techniques are presented by the Intergovernmental Panel on Climate Change (IPCC); they reveal a maximum global mitigation potential of 4.5-6 Pg (4,500–6,000 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. Emission estimates presented in earlier sections do not consider sequestration potential in calculating net emissions. Therefore, given that these savings are close to current emissions from agriculture, agriculture could be emissions neutral. While these figures give an order of magnitude, such global estimates should be interpreted with caution. The biophysical capability to sequester carbon will vary across highly heterogeneous agroecological conditions. In addition, the technical potentials in general are not realistic because they do not consider the effects on food security, heterogeneity in management capacity, or the costs of mitigation. As a result, the economic potential is often preferred and is discussed below.

Economic Potential

Calculations of economic potential come from two main sources: Smith et al. (2007b) and USEPA (2006a,b). This paper uses both sources. The results from USEPA (2006a) are preferred for non-CO2 emissions abatement due to a finer level of regional disaggregation, which enables explicit examination of the economic potential of developing countries. Smith et al. (2007a) conducted a comparison of Smith et al. (2007b) and USEPA (2006b) and found consistent results across emissions sources. Smith et al. (2007a,b), however, provide a more comprehensive assessment of the potential for soil carbon sequestration.

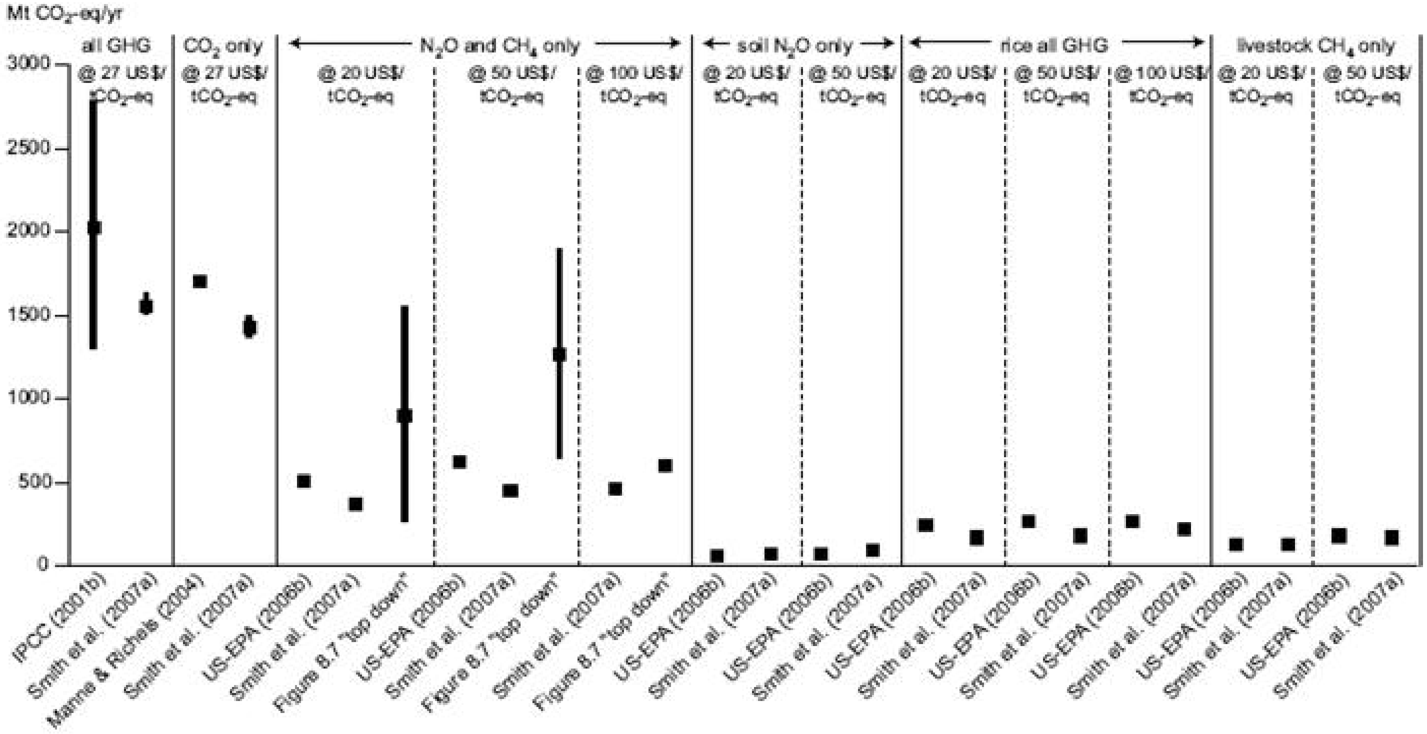
The USEPA (2006a) provides estimates for three categories of emissions mitigation and sequestration: cropland management (including N_2O from fertilizer reductions, soil carbon sequestration through no tillage—but not through other management and policy changes—and split fertilization, each under both rainfed and irrigated conditions for rice, soybeans, and wheat); rice cultivation; and livestock and manure management. Marginal abatement curves are constructed for the years 2010, 2020, and 2030 to determine the relationship between carbon price and quantitative emissions reductions.

Smith et al. (2007a) estimated global economic potential for agricultural mitigation using top-down and bottom-up modeling. Bottom-up mitigation responses described typical constraints to input management (such as fertilizer quantity or type of livestock feed) as well as cost estimates (partial equilibrium, where input and output market prices are fixed like acreage or production). On the other hand, the top-down mitigation responses add more generic input management responses as well as changes in output (e.g., shifts from cropland to forest) and market prices (e.g., decreases in land prices with rising production costs due to a carbon tax). Figure 10 presents the global estimates of economic potential for agricultural mitigation from various studies at differently assumed carbon prices in 2030.

Cropland management (N_2O and CO_2). Compared with 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 US\$30/tCO_2-eq. Beyond this point, abatement costs rise exponentially. These results are similar for all years considered.

The largest zero- and low-cost potential (up to \$30 t/CO_2-eq) is in the Russian Federation (31.7 percent reductions over the baseline in 2020), followed by the US and Australia/New Zealand (26.5 and 26.1 percent, respectively). The least amount of potential is in China, South and Southeast Asia, and India (7.3, 11, and 11.5 percent, respectively). Results from other developing countries indicate modest zero-cost potential in Africa and Mexico (13.5- and 23.2-percent reductions over the baseline in 2020, respectively).

Existing low levels of fertilizer usage or the effect of sub-optimal nutrient application on yields may be some of the reasons that fertilizer reductions do not have a strong mitigation potential for developing countries. On the other hand, across the US, EU, Brazil, China, and India, converting from conventional tillage to no till resulted in yield increases for each crop considered. This indicates a large potential for this practice as a negative cost option or "no-regret" scenario. Yet, the observation that



Notes: USEPA (2006b) figures are for 2020 rather than 2030. Values for top-down models are taken from ranges given in Figure 8.7 of Smith et al. 2007a
Source: Smith et al. 2007a

Figure 10. Global estimates of economic mitigation potential for agricultural mitigation at different carbon prices at 2030

farmers in these regions are not adopting no-tillage practices indicates that cost barriers are not captured, which may include profit variability or complex management requirements (USEPA 2006b).

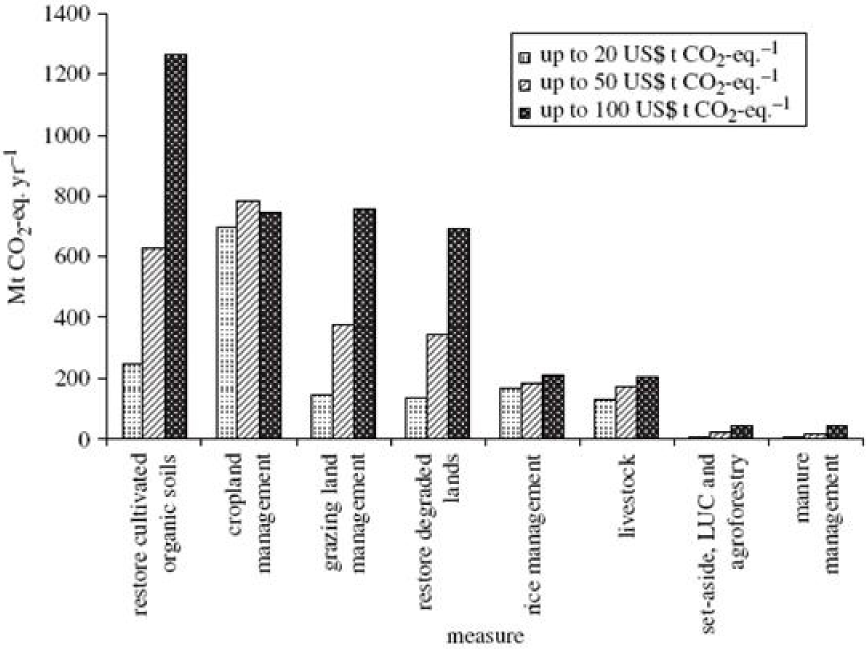
Smith et al. (2007a) expanded the treatment of cropland management for soil carbon sequestration to include a broader range of practices, such as reducing bare fallow and residue management. Considering a broader spectrum, the economic potential for soil carbon sequestration increases up to 800 Mt CO_2-eq in 2030 at carbon prices of up to US$20 tCO_2-eq (Figure 11). Given that 70 percent of total emissions abatement could come from developing countries, soil carbon sequestration will be an important management practice.

Bioenergy. Neither Smith et al. (2007a) nor the USEPA (2006a, b) calculated the marginal abatement costs of bioenergy cultivation related to agricultural soils. Estimates do exist, however, for their potential displacement of fossil fuels. Specifically for the transportation sector, liquid biofuels are predicted to reach 3 percent of demand under the baseline scenario, increasing up to 13-25 percent of demand under alternative scenarios in 2030 (IEA 2006). This could reduce emissions by 1.8-2.3 Gt CO_2, corresponding to between 5.6 and 6.4 percent of total emissions reductions across all sectors at carbon prices greater than US$25 tCO_2 (Ferrentino 2007).

Rice cultivation. At zero cost, only 3 percent of emissions from rice cultivation can be abated in 2000, jumping to 11 percent in 2010. Also in 2010, 22 percent of global emissions at US$30/$tCO_2$-eq could be abated. South and Southeast Asia and China could contribute the most reductions at the lowest cost (60.6 $MtCO_2$-eq at no cost and 97.9 $MtCO_2$-eq at US$30 per tCO_2-eq in South and Southeast Asia for the year 2010, or about 55 and 43 percent, respectively). This is not surprising, given that China and South and Southeast 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 US$30/$tCO_2$-eq. Annex 1 and OECD countries have the highest least-cost economic potential, while Africa and Mexico have the least. Moreover, the countries with the highest herd numbers, such as India and Brazil, also have low to moderate economic potential. For example, Brazil could only contribute 9 percent of total global livestock emissions reductions in 2020 at carbon prices of US$30 tCO_2-eq. In comparison, Annex 1 countries could contribute approximately 50 percent.

Table 10 provides regional contributions to the total economic potential of mitigation through emissions abatement. Africa has the lowest economic potential, contributing only 3.4 percent to the total potential reductions at carbon prices of US$30 tCO_2-eq. Similar results are found for Brazil and India. China and South and Southeast Asia, on the other hand, have a higher potential, contributing together over 40 percent of reductions at carbon prices of US$30 per tCO_2-eq. Based on these results, rice cultivation mitigation strategies have the highest economic potential in developing countries, while there is moderate mitigation potential for no-till agriculture in Africa, and improved livestock management in India and Brazil. In addition, the consideration of expanded practices of soil carbon sequestration by Smith et al. (2007b) indicates that no-tillage and other sequestration methods could have significant economic potential in developing countries.



Source: Smith et al. 2007b

Figure 11. Economic potential for GHG agricultural mitigation by 2030 at a range of prices of CO_2-eq

Table 10. Percent emission reductions over the baseline at different carbon prices ($/t$CO_2$-eq) by region.

	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**

Source: USEPA 2006b

The highest mitigation potential from emissions abatement is in the US and Annex 1 countries, despite the fact that emissions are significantly higher and predicted to rise most in developing countries over the next 10-15 years (Table 8). This indicates significant barriers to mitigation in the developing countries. These barriers may include property rights, higher production costs for sustainable practices, and lack of access to inputs and technical assistance. Hence, policy interventions are needed to create pro-poor mitigation strategies. Moreover, policy design will need to maximize synergies with sustainable rural development and adaptation. For example, reducing tillage has been shown to increase soil moisture, which can lead to improved drought resistance. While this does not mitigate emissions per se, it is an adaptation strategy that enhances ecosystem resilience to further climatic variability. When soil carbon sequestration is taken into account, the mitigation potential in developing countries is considerably higher, with an estimated 70 percent of the economic potential in non-OECD and transitioning economies (Smith et al. 2007a). Nevertheless to reach or expand this economic potential in developing countries will require significant policy reforms.

Expanding the Potential for Mitigation

To date, little progress has been made in implementing mitigation measures at the global scale. GHG mitigation potential would be enhanced with an appropriate international climate policy framework providing policy and economic incentives.

The emerging market for trading carbon emissions offers new possibilities for agriculture to benefit from land uses that sequester carbon or save 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, eligible activities under the CDM are limited to afforestation and reforestation and reduction of non-CO_2 gases in agriculture. Carbon sequestration activities, such as conservation tillage and the restoration of degraded soils, are not currently eligible under the CDM.

In mid-2008, 87 projects were registered under the agriculture sector, representing 6 percent of the CDM portfolio (CDM 2008). There was one afforestation/reforestation project, representing 0.07 percent. The majority of registered agriculture projects are in Latin America; only one project is located in Africa. The total emissions reduction from the 87 projects is estimated at 7.6 Mt CO_2-eq per year (CDM 2008). This is a reduction of approximately 0.1 percent of the reported emissions in the year 2000 from the agriculture sector.

Soil carbon sequestration has the highest technical potential for mitigation in the agriculture sector, so there is room to expand agriculture sector mitigation through CDM if carbon sequestration projects are included. However, there are feasibility issues in selling agricultural soil carbon within a market-based credit-trading program. The transaction costs in soil carbon sequestration include obtaining needed site-specific information to access the baseline stock of carbon and the potential to sequester carbon. The transaction costs per ton of carbon associated with negotiating contracts will decline as the size of the contract increases, and a market for carbon credits is likely to operate for large, standardized contracts (e.g., 100,000 tons). For a typical individual farmer who can sequester 0.5 ton per hectare per year, these transaction costs would be 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 while simultaneously reducing 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 the crop residue on the surface, conservation of between 0.2 and 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 in achieving economies of scale.

In addition to the crucial steps of including soil carbon offsets in CDM, a number of other advancements are needed. To ensure that these emerging carbon markets benefit developing countries, CDM rules should encourage the participation of small farmers and protect them against major livelihood risks, while still meeting investors' needs and rigorously ensured carbon goals. This can be supported by:

- *Promoting measures to reduce transaction costs.* Rigorous but simplified procedures should be adapted to developing-country carbon offset projects. Small-scale soil carbon sequestration projects should be eligible for simplified modalities to reduce the costs of these projects. 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.* The 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).

Finally, further investment in advanced measurement and monitoring can dramatically reduce transaction costs. Measurement and monitoring techniques have been improving rapidly, thanks to a growing body of field measurements and the use of statistics and computer modeling, remote sensing, global positional systems, and geographic information systems. As such, changes in stocks of carbon can now be estimated more accurately at a lower cost.

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. 2005). Adaptation responses can be categorized by the level of ownership of the adaptation measure or strategy. Individual-level or autonomous adaptations are those that take place—invariably as a reactive response (after initial impacts are manifest) to climatic stimuli—as a matter of course, without the directed intervention of a public agency (Smit and Pilifosova 2001). Autonomous adaptations are 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 the result of a deliberate policy decision by 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 adaptations largely correspond with private and public adaptation, respectively (Smit and Pilifosova 2001). Table 11 provides

Table 11. Adaptation responses and issues.

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

Source: Authors

examples of autonomous and policy-driven adaptation strategies for agriculture.

As explained in the previous section, autonomous adaptation responses will be evaluated by individual farmers based on costs and benefits. It is assumed 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 risks effectively. Individual-level responses tend to be costly for poor producers and often create excessive burdens. In this regard, there needs to be an appropriate balance between public sector efforts and incentives (such as capacity building), the creation of risk insurance, and private investment so that the burden can shift away from poor producers.

Role of Adaptation Policy

Decisions on which adaptation measures to adopt are not taken in isolation by rural and agricultural individuals, households, or communities, but in the context of the wider society and political economy (Burton and Lim 2005). The choices are thus shaped by public policy, which can be supportive or at times provide barriers or disincentives to adaptation. Possible supporting policies to stimulate adaptation measures are shown in Table 12.

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 toward achieving both adaptation and poverty alleviation goals. General policies that should be supported include promoting growth and diversification, strengthening institutions, protecting natural resources, creating markets in water and environmental services, improving the international trade system, enhancing resilience to disasters and improving disaster management, promoting risk sharing (including social safety nets and weather insurance), and investing in research and development, education, and health.

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

Table 12. Adaptation options and supporting policies given climate change.

Adaptation Options	Supporting Policies
Short term	
Crop insurance for risk coverage	Improve 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	Improve extension services, pricing policy adjustments
Livestock management to adjust to new climate conditions	Provide 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	Improve access and affordability, revise pricing, etc.
Modernize farm operations	Promote adoption of technologies
Permanent migration to diversify income opportunities	Education and training
Define land-use and tenure rights for investments	Legal reform and enforcement
(Both short and long term)	
Develop 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.
Expand irrigation and water storage	Investment from public and private sectors
Efficient water use	Water pricing reforms, clearly defined property rights, etc
Promote international trade	Pricing and exchange rate policies
Improve forecasting mechanisms	Distribute information across all sectors, etc.
Strengthen institutional and decision-making structures	Reform existing institutions on agriculture, etc.

Source: Adapted from Kurukulasuriya and Rosenthal 2003 local extension agents and 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.

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 policy costs, environmental impacts, spillover effects, implementation capacity, and social, economic and technical barriers (Leary et al. 2007). Once the adaptation strategy has been evaluated, the measure that yields the greatest net benefit should be chosen. Methods presented by Fankhauser (1997), Callaway et al. (1999), and Callaway (2003) have been integral in developing the cost–benefit analysis of adaptation strategies. Technical capabilities of changing and/or improving agricultural practices can be assessed by determining their agronomic potential. Therefore, multiple criteria should be used to make judicious selections of adaptation measures from environmental, technical, social, and economic standpoints.

The methods discussed above emphasize a project-specific decision-making framework, mainly since adaptation will take place locally. Yet, comprehensive economic assessments of multi-sectoral and regional adaptation costs and benefits are currently lacking (Adger et al. 2005). Global-scale assessments will be integral in highlighting intraregional variation in the benefits of adaptation, which in turn will enable more and better targeting of funds. For example, recent research has helped to identify potential food insecure regions as a means of prioritizing investment needs (Lobell et al. 2008). Evaluation criteria will need to be further developed to direct necessary external assistance.

Enabling Adaptation

Clearly, public policy has an important role in facilitating adaptation to climate change (Adger et al. 2005). Planning for adaptation and enacting well-targeted adaptation policies will require resources beyond the capacity of most governments in developing regions. In addition, the lack of awareness or even the reluctance to take action presents further barriers to adaptation. Incentives and investments to create and deploy improved technology and management techniques will be necessary. As such, national governments, NGOs, and the international community have a role to play in creating the means and cooperation for adaptation.

Policy-driven or planned adaptation strategies need to address high-priority areas, such as the irreversible and catastrophic impacts of climate change (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) to maximize adaptive capacity. Specific policy-driven measures for the agriculture sector include drought contingency plans, efficient water allocation, seed research and development, elimination of subsidies and taxes, efficient irrigation, conservation management practices, and trade liberalization (Smith and Lenhart 1996).

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 depends a lot on local circumstances. Specific problems in particular places 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 taken at 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 UNFCCC, should prepare national adaptation strategies. These plans would take a broad strategic view of the future development path of the country and consider how that could best be designed or modified in light of expected climate change. Within such a strategic view, policies for sectors and regions could be examined and adjusted to account for 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, the policy review could include the management of extreme events such as droughts, storms, and floods, and areas of particular risk such as exposed coastal zones, steep mountain slopes, and so forth. Specific adaptation measures could then be evaluated and selected within the context of a climate-sensitive strategy and set of policies. These documents should be integrated with national development planning to be effective.

Ensuring financing. A common concern of developing countries has been that their participation in multilateral environmental agreements imposes costs on them as they address global environmental problems created primarily by industrialized countries. It seems realistic therefore to suggest that developed countries should scale up their support to developing countries in adapting to climate change. This would not only help to ensure that climate is adequately considered in national development plans and sectoral policies, but also to reassure donors and investors that climate change adaptation measures are well-conceived and represent sound expenditures.

Promoting insurance. A further suggestion concerns providing insurance against climate risks. Countries, communities, and individuals in most developing countries have little or no insurance coverage against extreme climate-related weather events. The private insurance industry is poorly developed in many cases, and the fear of large losses in catastrophic events that are unlikely to be covered by income from insurance premiums is a significant deterrent.

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 (e.g., restoring degraded soils, agroforestry, 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 greater use of nitrogen fertilizer to increase food production also increases N_2O emissions. To maximize synergies and reduce trade-offs, mitigation and adaptation strategies should be developed together, recognizing that in some cases difficult decisions will need to be made between competing goals.

CONCLUSIONS AND POLICY CONSIDERATIONS

This paper reviewed the state of knowledge of climate change and agriculture. In general, agriculture contributes to climate change significantly through livestock production and the conversion of forest to land cover that has low carbon sink or sequestration potential. N_2O emissions from crop production and CH_4 from rice production are also significant. Mitigation options that are the most technically and economically feasible include better cropland and pasture management.

Climate change will also likely have significant negative impacts on agricultural production, with the greatest reductions being in parts of the developing world. Adaptation, including crop choice and timing, has the ability to partially compensate for production declines in all regions. While these predictions have been shown across a number of models, there is a range of specific regional effects and insufficient consideration of multiple stresses, such as extreme weather events, pests, and diseases. In addition, there have been no studies to date on some of the important crops for the rural poor, such as root crops and millet, regarding climate change and carbon fertilization effects.

The changes in production due to climate change are bound to affect food security; although socioeconomic policy, especially trade liberalization, can compensate for some of the negative impacts. Climate change alone is expected to increase the number of food-insecure people by 5-170 million more by 2080, especially in Africa.

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

Nonetheless, the most aggressive mitigation efforts that can be reasonably anticipated cannot be expected to make a significant difference in the short term. This prospect means that adaptation becomes imperative. However, many developing countries lack sufficient adaptive capacity. As such, there is a large role for national governments, NGOs, and international institutions to play in building the necessary adaptive capacity and risk management structures.

To facilitate these roles, global scale assessments should be conducted to identify intraregional variations in the effects of climate change. These studies will elucidate the range of outcomes possible under plausible climate and adaptation scenarios, which will assist in targeting high-priority areas. Once priority areas have been identified, evaluation criteria should be applied that consider not only the net economic benefits, but also the 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 change increases, mitigation remains essential. The greater the level of mitigation that can be achieved at affordable cost, the smaller the burdens placed on adaptation. Policies focused on mitigating GHG emissions, if carefully designed, can help create a new development strategy that encourages the creation of more valuable 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 is important to enhance global financial facilities and governance to simplify rules and increase funding flows for mitigation in developing countries.

The tendency has been to treat adaptation to climate change as a stand-alone activity, but it should be integrated into development projects, plans, policies, and strategies. Development policy issues must inform the work of the climate change community so that they combine their perspectives in 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 judicious selection of measures within a policy context and strategic development framework. More than this, it must also explicitly target the impacts of climate change, particularly on the poor.

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