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Agriculture

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EXECUTIVE SUMMARY

Agricultural lands (lands used for agricultural production, consisting of cropland, managed grassland and permanent crops including agro-forestry and bio-energy crops) occupy about 40-50% of the Earth's land surface.

Agriculture accounted for an estimated emission of 5.1 to 6.1 $GtCO_2$-eq/yr in 2005 (10-12% of total global anthropogenic emissions of greenhouse gases (GHGs)). CH_4 contributes 3.3 $GtCO_2$-eq/yr and N_2O 2.8 $GtCO_2$-eq/yr. Of global anthropogenic emissions in 2005, agriculture accounts for about 60% of N_2O and about 50% of CH_4 (*medium agreement, medium evidence*). Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is estimated to be approximately balanced, with CO_2 emissions around 0.04 $GtCO_2$/yr only (emissions from electricity and fuel use are covered in the buildings and transport sector, respectively) (*low agreement, limited evidence*).

Globally, agricultural CH_4 and N_2O emissions have increased by nearly 17% from 1990 to 2005, an average annual emission increase of about 60 $MtCO_2$-eq/yr. During that period, the five regions composed of Non-Annex I countries showed a 32% increase, and were, by 2005, responsible for about three-quarters of total agricultural emissions. The other five regions, mostly Annex I countries, collectively showed a decrease of 12% in the emissions of these gases (*high agreement, much evidence*).

A variety of options exists for mitigation of GHG emissions in agriculture. The most prominent options are improved crop and grazing land management (e.g., improved agronomic practices, nutrient use, tillage, and residue management), restoration of organic soils that are drained for crop production and restoration of degraded lands. Lower but still significant mitigation is possible with improved water and rice management; set-asides, land use change (e.g., conversion of cropland to grassland) and agro-forestry; as well as improved livestock and manure management. Many mitigation opportunities use current technologies and can be implemented immediately, but technological development will be a key driver ensuring the efficacy of additional mitigation measures in the future (*high agreement, much evidence*).

Agricultural GHG mitigation options are found to be cost competitive with non-agricultural options (e.g., energy, transportation, forestry) in achieving long-term (i.e., 2100) climate objectives. Global long-term modelling suggests that non-CO_2 crop and livestock abatement options could cost-effectively contribute 270–1520 $MtCO_2$-eq/yr globally in 2030 with carbon prices up to 20 US\$/tCO_2-eq and 640–1870 $MtCO_2$-eq/yr with C prices up to 50 US\$/tCO_2-eq Soil carbon management options are not currently considered in long-term modelling (*medium agreement, limited evidence*).

Considering all gases, the global technical mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030 is estimated to be ~5500-6,000 $MtCO_2$-eq/yr (*medium agreement, medium evidence*). Economic potentials are estimated to be 1500-1600, 2500-2700, and 4000-4300 $MtCO_2$-eq/yr at carbon prices of up to 20, 50 and 100 US\$/tCO_2-eq, respectively About 70% of the potential lies in non-OECD/EIT countries, 20% in OECD countries and 10% for EIT countries (*medium agreement, limited evidence*).

Soil carbon sequestration (enhanced sinks) is the mechanism responsible for most of the mitigation potential (*high agreement, much evidence*), with an estimated 89% contribution to the technical potential. Mitigation of CH_4 emissions and N_2O emissions from soils account for 9% and 2%, respectively, of the total mitigation potential (*medium agreement, medium evidence*). The upper and lower limits about the estimates are largely determined by uncertainty in the per-area estimate for each mitigation measure. Overall, principal sources of uncertainties inherent in these mitigation potentials include: a) future level of adoption of mitigation measures (as influenced by barriers to adoption); b) effectiveness of adopted measures in enhancing carbon sinks or reducing N_2O and CH_4 emissions (particularly in tropical areas; reflected in the upper and lower bounds given above); and c) persistence of mitigation, as influenced by future climatic trends, economic conditions, and social behaviour (*medium agreement, limited evidence*).

The role of alternative strategies changes across the range of prices for carbon. At low prices, dominant strategies are those consistent with existing production such as changes in tillage, fertilizer application, livestock diet formulation, and manure management. Higher prices elicit land-use changes that displace existing production, such as biofuels, and allow for use of costly animal feed-based mitigation options. A practice effective in reducing emissions at one site may be less effective or even counterproductive elsewhere. Consequently, there is no universally applicable list of mitigation practices; practices need to be evaluated for individual agricultural systems based on climate, edaphic, social setting, and historical patterns of land use and management (*high agreement, much evidence*).

GHG emissions could also be reduced by substituting fossil fuels with energy produced from agricultural feed stocks (e.g., crop residues, dung, energy crops), which would be counted in sectors using the energy. The contribution of agriculture to the mitigation potential by using bioenergy depends on relative prices of the fuels and the balance of supply and demand. Using top-down models that include assumptions on such a balance the economic mitigation potential for agriculture in 2030 is estimated to be 70-1260 $MtCO_2$-eq/yr at up to 20 US\$/tCO_2-eq, and 560-2320 $MtCO_2$-eq/yr at up to 50 US\$/tCO_2-eq There are no estimates for the additional potential from top down models at carbon prices up to 100 US\$/tCO_2-eq, but the estimate for prices above 100 US\$/tCO_2-eq is 2720 $MtCO_2$-eq/yr. These potentials represent mitigation of 5-80%, and 20-90% of all

other agricultural mitigation measures combined, at carbon prices of up to 20, and up to50 US$/t$CO_2$-eq, respectively. An additional mitigation of 770 MtCO_2-eq/yr could be achieved by 2030 by improved energy efficiency in agriculture, though the mitigation potential is counted mainly in the buildings and transport sectors (*medium agreement, medium evidence*).

Agricultural mitigation measures often have synergy with sustainable development policies, and many explicitly influence social, economic, and environmental aspects of sustainability. Many options also have co-benefits (improved efficiency, reduced cost, environmental co-benefits) as well as trade-offs (e.g., increasing other forms of pollution), and balancing these effects will be necessary for successful implementation (*high agreement, much evidence*).

There are interactions between mitigation and adaptation in the agricultural sector, which may occur simultaneously, but differ in their spatial and geographic characteristics. The main climate change benefits of mitigation actions will emerge over decades, but there may also be short-term benefits if the drivers achieve other policy objectives. Conversely, actions to enhance adaptation to climate change impacts will have consequences in the short and long term. Most mitigation measures are likely robust to future climate change (e.g., nutrient management), but a subset will likely be vulnerable (e.g., irrigation in regions becoming more arid). It may be possible for a vulnerable practice to be modified as the climate changes and to maintain the efficacy of a mitigation measure (*low agreement, limited evidence*).

In many regions, non-climate policies related to macro-economics, agriculture and the environment, have a larger impact on agricultural mitigation than climate policies (*high agreement, much evidence*). Despite significant technical potential for mitigation in agriculture, there is evidence that little progress has been made in the implementation of mitigation measures at the global scale. Barriers to implementation are not likely to be overcome without policy/economic incentives and other programmes, such as those promoting global sharing of innovative technologies.

Current GHG emission rates may escalate in the future due to population growth and changing diets (*high agreement, medium evidence*). Greater demand for food could result in higher emissions of CH_4 and N_2O if there are more livestock and greater use of nitrogen fertilizers (*high agreement, much evidence*). Deployment of new mitigation practices for livestock systems and fertilizer applications will be essential to prevent an increase in emissions from agriculture after 2030. In addition, soil carbon may be more vulnerable to loss with climate change and other pressures, though increases in production will offset some or all of this carbon loss (*low agreement, limited evidence*).

Overall, the outlook for GHG mitigation in agriculture suggests that there is significant potential (*high agreement, medium evidence*). Current initiatives suggest that synergy between climate change policies, sustainable development and improvement of environmental quality will likely lead the way forward to realize the mitigation potential in this sector.

8.1 Introduction

Agriculture releases to the atmosphere significant amounts of CO_2, CH_4, and N_2O (Cole *et al.*, 1997; IPCC, 2001a; Paustian *et al.*, 2004). CO_2 is released largely from microbial decay or burning of plant litter and soil organic matter (Smith, 2004b; Janzen, 2004). CH_4 is produced when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion by ruminant livestock, from stored manures, and from rice grown under flooded conditions (Mosier *et al.* 1998). N_2O is generated by the microbial transformation of nitrogen in soils and manures, and is often enhanced where available nitrogen (N) exceeds plant requirements, especially under wet conditions (Oenema *et al.*, 2005; Smith and Conen, 2004). Agricultural greenhouse gas (GHG) fluxes are complex and heterogeneous, but the active management of agricultural systems offers possibilities for mitigation. Many of these mitigation opportunities use current technologies and can be implemented immediately.

This chapter describes the development of GHG emissions from the agricultural sector (Section 8.2), and details agricultural practices that may mitigate GHGs (Section 8.4.1), with many practices affecting more than one GHG by more than one mechanism. These practices include: cropland management; grazing land management/pasture improvement; management of agricultural organic soils; restoration of degraded lands; livestock management; manure/bio-solid management; and bio-energy production.

It is theoretically possible to increase carbon storage in long-lived agricultural products (e.g., strawboards, wool, leather, bio-plastics) but the carbon held in these products has only increased from 37 to 83 MtC per year over the past 40 years. Assuming a first order decay rate of 10 to 20 % per year, this is estimated to be a global net annual removal of 3 to 7 $MtCO_2$ from the atmosphere, which is negligible compared to other mitigation measures. The option is not considered further here.

Smith *et al.* (2007a) recently estimated a global potential mitigation of 770 $MtCO_2$-eq/yr by 2030 from improved energy efficiency in agriculture (e.g., through reduced fossil fuel use), However, this is usually counted in the relevant user sector rather than in agriculture and so is not considered further here. Any savings from improved energy efficiency are discussed in the relevant sections elsewhere in this volume, according to where fossil fuel savings are made, for example, from transport fuels (Chapter 5), or through improved building design (Chapter 6).

8.2 Status of sector, development trends including production and consumption, and implications

Population pressure, technological change, public policies, and economic growth and the cost/price squeeze have been the main drivers of change in the agricultural sector during the last four decades. Production of food and fibre has more than kept pace with the sharp increase in demand in a more populated world. The global average daily availability of calories per capita has increased (Gilland, 2002), with some notable regional exceptions. This growth, however, has been at the expense of increased pressure on the environment, and depletion of natural resources (Tilman *et al.*, 2001; Rees, 2003), while it has not resolved the problems of food security and child malnutrition suffered in poor countries (Conway and Toenniessen, 1999).

Agricultural land occupied 5023 Mha in 2002 (FAOSTAT, 2006). Most of this area was under pasture (3488 Mha, or 69%)

Table 8.1. *Agricultural land use in the last four decades.*

	Area (Mha)					Change 2000s/1960s	
	1961-70	1971-80	1981-90	1991-00	2001-02	%	Mha
1. World							
Agricultural land	4,562	4,684	4,832	4,985	5,023	+10	461
Arable land	1,297	1,331	1,376	1,393	1,405	+8	107
Permanent crops	82	92	104	123	130	+59	49
Permanent pasture	3,182	3,261	3,353	3,469	3,488	+10	306
2. Developed countries							
Agricultural land	1,879	1,883	1,877	1,866	1,838	-2	-41
Arable land	648	649	652	633	613	-5	-35
Permanent crops	23	24	24	24	24	+4	1
Permanent pasture	1,209	1,210	1,201	1,209	1,202	-1	-7
3. Developing countries							
Agricultural land	2,682	2,801	2,955	3,119	3,184	+19	502
Arable land	650	682	724	760	792	+22	142
Permanent crops	59	68	80	99	106	+81	48
Permanent pasture	1,973	2,051	2,152	2,260	2,286	+16	313

Source: FAOSTAT, 2006.

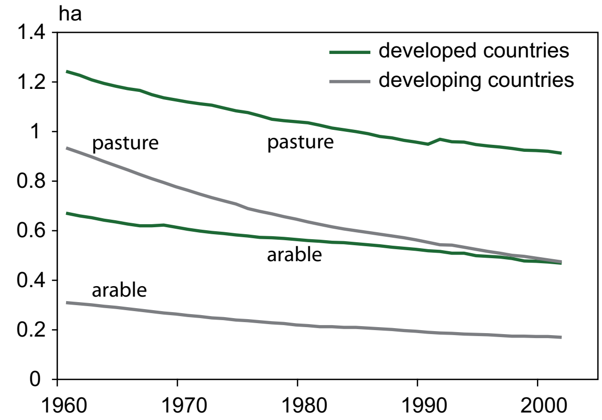

Figure 8.1. *Per-capita area of arable land and pasture, in developed and developing countries.*
Source: FAOSTAT, 2006.

and cropland occupied 1405 Mha (28%). During the last four decades, agricultural land gained almost 500 Mha from other land uses, a change driven largely by increasing demands for food from a growing population. Every year during this period, an average 6 Mha of forestland and 7 Mha of other land were converted to agriculture, a change occurring largely in the developing world (Table 8.1). This trend is projected to continue into the future (Huang *et al*., 2002; Trewavas, 2002; Fedoroff and Cohen, 1999; Green *et al*., 2005), and Rosegrant *et al*., (2001) project that an additional 500 Mha will be converted to agriculture during 1997-2020, mostly in Latin America and Sub-Saharan Africa.

Technological progress has made it possible to achieve remarkable improvements in land productivity, increasing per-capita food availability (Table 8.2), despite a consistent decline in per-capita agricultural land (Figure 8.1). The share of animal products in the diet has increased consistently in the developing countries, while remaining constant in developed countries (Table 8.2). Economic growth and changing lifestyles in some developing countries are causing a growing demand for meat and dairy products, notably in China where current demands are low. Meat demand in developing countries rose from 11 to 24 kg/capita/yr during the period 1967-1997, achieving an annual growth rate of more than 5% by the end of that period. Rosegrant *et al.* (2001) forecast a further increase of 57% in global meat demand by 2020, mostly in South and Southeast Asia, and Sub-Saharan Africa. The greatest increases in demand are expected for poultry (83 % by 2020; Roy *et al.*, 2002).

Annual GHG emissions from agriculture are expected to increase in coming decades (included in the baseline) due to escalating demands for food and shifts in diet. However, improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or of protein) produced. The main trends in the agricultural sector with the implications for GHG emissions or removals are summarized as follows:

- Growth in land productivity is expected to continue, although at a declining rate, due to decreasing returns from further technological progress, and greater use of marginal land with lower productivity. Use of these marginal lands increases the risk of soil erosion and degradation, with highly uncertain consequences for CO_2 emissions (Lal, 2004a; Van Oost *et al.*, 2004).
- Conservation tillage and zero-tillage are increasingly being adopted, thus reducing the use of energy and often increasing carbon storage in soils. According to FAO (2001), the worldwide area under zero-tillage in 1999 was approximately 50 Mha, representing 3.5% of total arable land. However, such practices are frequently combined with periodical tillage, thus making the assessment of the GHG balance highly uncertain.
- Further improvements in productivity will require higher use of irrigation and fertilizer, increasing the energy demand (for moving water and manufacturing fertilizer; Schlesinger, 1999). Also, irrigation and N fertilization can increase GHG emissions (Mosier, 2001).
- Growing demand for meat may induce further changes in land use (e.g., from forestland to grassland), often increasing CO_2 emissions, and increased demand for animal

Table 8.2: *Per capita food supply in developed and developing countries*

						Change 2000s/1960s	
	1961-70	1971-80	1981-90	1991-00	2001-02	%	cal/d or g/d
1. Developed countries							
Energy, all sources (cal/day)	3049	3181	3269	3223	3309	+9	261
% from animal sources	27	28	28	27	26	-2	--
Protein, all sources (g/day)	92	97	101	99	100	+9	8
% from animal sources	50	55	57	56	56	+12	--
2. Developing countries							
Energy, all sources (cal/day)	2032	2183	2443	2600	2657	+31	625
% from animal sources	8	8	9	12	13	+77	--
Protein, all sources (g/day)	9	11	13	18	21	+123	48
% from animal sources	18	20	22	28	30	+67	--

Source: FAOSTAT, 2006.

feeds (e.g., cereals). Larger herds of beef cattle will cause increased emissions of CH_4 and N_2O, although use of intensive systems (with lower emissions per unit product) is expected to increase faster than growth in grazing-based systems. This may attenuate the expected rise in GHG emissions.
- Intensive production of beef, poultry, and pork is increasingly common, leading to increases in manure with consequent increases in GHG emissions. This is particularly true in the developing regions of South and East Asia, and Latin America, as well as in North America.
- Changes in policies (e.g., subsidies), and regional patterns of production and demand are causing an increase in international trade of agricultural products. This is expected to increase CO_2 emissions, due to greater use of energy for transportation.
- There is an emerging trend for greater use of agricultural products (e.g., bio-plastics bio-fuels and biomass for energy) as substitutes for fossil fuel-based products. This has the potential to reduce GHG emissions in the future.

8.3 Emission trends (global and regional)

With an estimated global emission of non-CO_2 GHGs from agriculture of between 5120 $MtCO_2$-eq/yr (Denman *et al.*, 2007) and 6116 $MtCO_2$-eq/yr (US-EPA, 2006a) in 2005, agriculture accounts for 10-12 % of total global anthropogenic emissions of GHGs. Agriculture contributes about 47% and 58% of total anthropogenic emissions of CH_4 and N_2O, respectively, with a wide range of uncertainty in the estimates of both the agricultural contribution and the anthropogenic total. N_2O emissions from soils and CH_4 from enteric fermentation constitute the largest sources, 38% and 32% of total non-CO_2 emissions from agriculture in 2005, respectively (US-EPA, 2006a). Biomass burning (12%), rice production (11%), and manure management (7%) account for the rest. CO_2 emissions from agricultural soils are not normally estimated separately, but are included in the land use, land use change and forestry sector (e.g., in national GHG inventories). So there are few comparable estimates of emissions of this gas in agriculture. Agricultural lands generate very large CO_2 fluxes both to and from the atmosphere (IPCC, 2001a), but the *net* flux is small. US-EPA, 2006b) estimated a net CO_2 emission of 40 $MtCO_2$-eq from agricultural soils in 2000, less than 1% of global anthropogenic CO_2 emissions.

Both the magnitude of the emissions and the relative importance of the different sources vary widely among world regions (Figure 8.2). In 2005, the group of five regions mostly consisting of non-Annex I countries was responsible for 74% of total agricultural emissions.

In seven of the ten regions, N_2O from soils was the main source of GHGs in the agricultural sector in 2005, mainly associated with N fertilizers and manure applied to soils. In the other three regions - Latin America and The Caribbean, the countries of Eastern Europe, the Caucasus and Central Asia, and OECD Pacific - CH_4 from enteric fermentation was the dominant source (US-EPA, 2006a). This is due to the large livestock population in these three regions which, in 2004, had a combined stock of cattle and sheep equivalent to 36% and 24% of world totals, respectively (FAO, 2003).

Emissions from rice production and burning of biomass were heavily concentrated in the group of developing countries, with 97% and 92% of world totals, respectively. While CH_4 emissions from rice occurred mostly in South and East Asia, where it is a dominant food source (82% of total emissions), those from biomass burning originated in Sub-Saharan Africa and Latin America and the Caribbean (74% of total). Manure management was the only source for which emissions where higher in the group of developed regions (52%) than in developing regions (48%; US-EPA, 2006a).

The balance between the large fluxes of CO_2 emissions and removals in agricultural land is uncertain. A study by US-EPA (2006b) showed that some countries and regions have net emissions, while others have net removals of CO_2. Except for the countries of Eastern Europe, the Caucasus and Central Asia, which had an annual emission of 26 $MtCO_2$/yr in 2000, all other countries showed very low emissions or removals.

8.3.1 Trends since 1990

Globally, agricultural CH_4 and N_2O emissions increased by 17% from 1990 to 2005, an average annual emission increase of 58 $MtCO_2$-eq/yr (US-EPA, 2006a). Both gases had about the same share of this increase. Three sources together explained 88% of the increase: biomass burning (N_2O and CH_4), enteric fermentation (CH_4) and soil N_2O emissions (US-EPA, 2006a).

During that period, according to US-EPA (2006a; Figure 8.2), the five regions composed of Non-Annex I countries showed a 32% increase in non-CO_2 emissions (equivalent to 73 $MtCO_2$-eq/yr).The other five regions, with mostly Annex I countries, collectively showed a decrease of 12% (equivalent to 15 $MtCO_2$-eq/yr). This was mostly due to non-climate macroeconomic policies in the Central and Eastern European and the countries of Eastern Europe, the Caucasus and Central Asia (see Section 8.7.1 and 8.7.2).

8.3.2 Future global trends

Agricultural N_2O emissions are projected to increase by 35-60% up to 2030 due to increased nitrogen fertilizer use and increased animal manure production (FAO, 2003). Similarly, Mosier and Kroeze (2000) and US-EPA (2006a; Figure 8.2) estimated that N_2O emissions will increase by about 50% by 2020 (relative to 1990). If demands for food increase, and diets shift as projected, then annual emissions of GHGs from agriculture may escalate further. But improved management

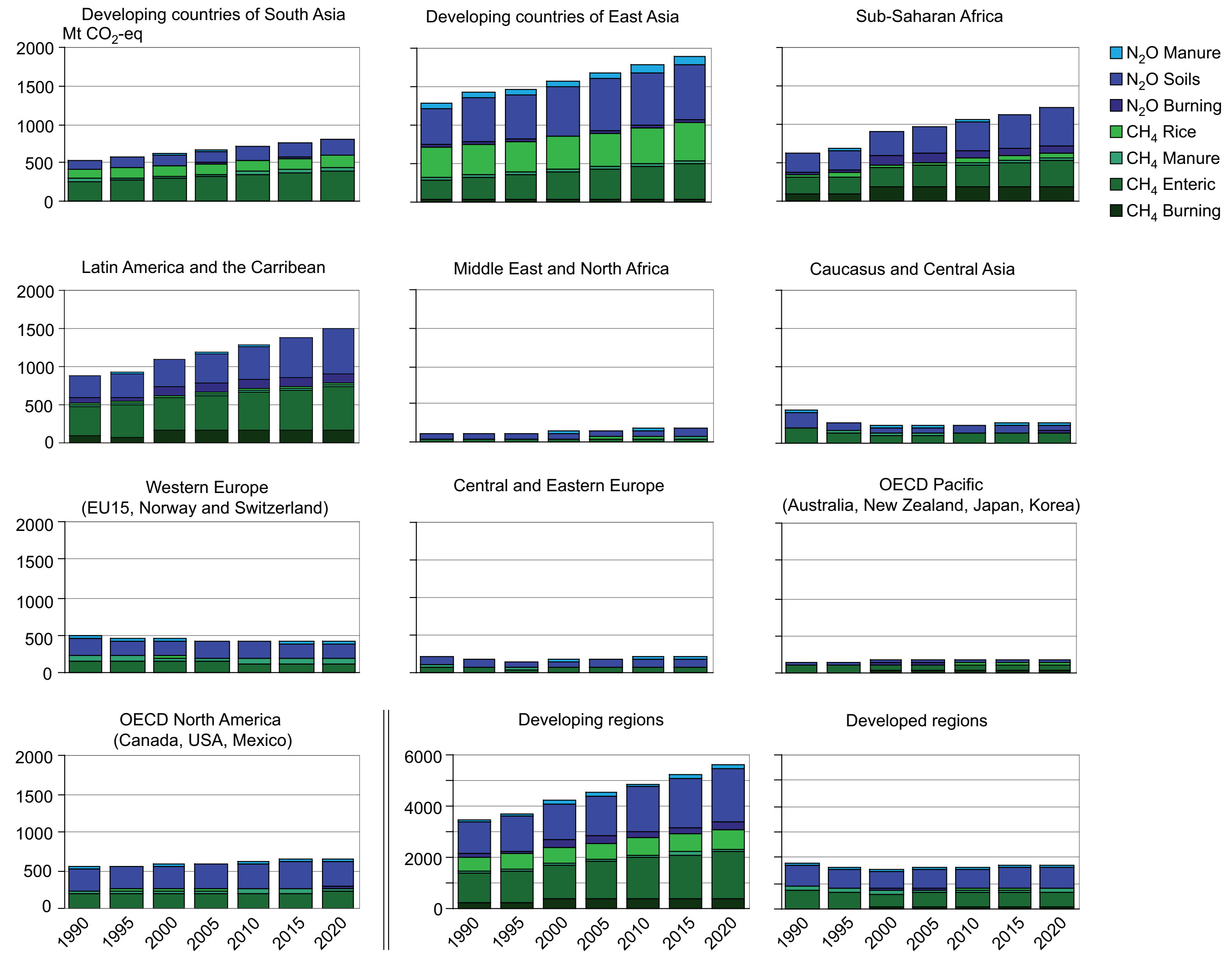

Figure 8.2: *Estimated historical and projected N_2O and CH_4 emissions in the agricultural sector of the ten world regions during the period 1990-2020. Source: Adapted from US-EPA, 2006a.*

practices and emerging technologies may permit a reduction in emissions per unit of food (or protein) produced, and perhaps also a reduction in emissions per capita food consumption.

If CH_4 emissions grow in direct proportion to increases in livestock numbers, then global livestock-related methane production is expected to increase by 60% up to 2030 (FAO, 2003). However, changes in feeding practices and manure management could ameliorate this increase. US-EPA (2006a) forecast that combined methane emissions from enteric fermentation and manure management will increase by 21% between 2005 and 2020.

The area of rice grown globally is forecast to increase by 4.5% to 2030 (FAO, 2003), so methane emissions from rice production would not be expected to increase substantially. There may even be reductions if less rice is grown under continuous flooding (causing anaerobic soil conditions) as a result of scarcity of water, or if new rice cultivars that emit less methane are developed and adopted (Wang *et al.*, 1997). However, US-EPA (2006a) projects a 16% increase in CH_4 emissions from rice crops between 2005 and 2020, mostly due to a sustained increase in the area of irrigated rice.

No baseline agricultural non-CO_2 GHG emission estimates for the year 2030 have been published, but according to US-EPA (2006a), aggregate emissions are projected to increase by ~13% during the decades 2000-2010 and 2010-2020. Assuming similar rates of increase (10-15%) for 2020-2030, agricultural emissions might be expected to rise to 8000–8400, with a mean of 8300 $MtCO_2$-eq by 2030. The future evolution of CO_2 emissions from agriculture is uncertain. Due to stable or declining deforestation rates (FAO, 2003), and increased adoption of conservation tillage practices (FAO, 2001), these emissions are likely to decrease or remain at low levels.

8.3.3 Regional trends

The Middle East and North Africa, and Sub-Saharan Africa have the highest projected growth in emissions, with a combined 95% increase in the period 1990 to 2020 (US-EPA, 2006a). Sub-Saharan Africa is the one world region where per-capita food production is either in decline, or roughly constant at a level that is less than adequate (Scholes and Biggs, 2004). This trend is linked to low and declining soil fertility (Sanchez, 2002), and inadequate fertilizer inputs. Although slow, the rising wealth of urban populations is likely to increase demand for livestock products. This would result in intensification of agriculture and expansion to still largely unexploited areas, particularly in South and Central Africa (including Angola, Zambia, DRC, Mozambique and Tanzania), with a consequent increase in GHG emissions.

East Asia is projected to show large increases in GHG emissions from animal sources. According to FAO (FAOSTAT, 2006), total production of meat and milk in Asian developing countries increased more than 12 times and 4 times, respectively, from 2004 to 1961. Since the per-capita consumption of meat and milk is still much lower in these countries than in developed countries, increasing trends are expected to continue for a relatively long time. Accordingly, US-EPA (2006a) forecast increases of 153% and 86% in emissions from enteric fermentation and manure management, respectively, from 1990 to 2020. In South Asia, emissions are increasing mostly because of expanding use of N fertilizers and manure to meet demands for food, resulting from rapid population growth.

In Latin America and the Caribbean, agricultural products are the main source of exports. Significant changes in land use and management have occurred, with forest conversion to cropland and grassland being the most significant, resulting in increased GHG emissions from soils (CO_2 and N_2O). The cattle population has increased linearly from 176 to 379 Mhead between 1961 and 2004, partly offset by a decrease in the sheep population from 125 to 80 Mhead. All other livestock categories have increased in the order of 30 to 600% since 1961. Cropland areas, including rice and soybean, and the use of N fertilizers have also shown dramatic increases (FAOSTAT, 2006). Another major trend in the region is the increased adoption of no-till agriculture, particularly in the Mercosur area (Brazil, Argentina, Paraguay, and Uruguay). This technology is used on ~30 Mha every year in the region, although it is unknown how much of this area is under permanent no-till.

In the countries of Central and Eastern Europe, the Caucasus and Central Asia, agricultural production is, at present, about 60-80% of that in 1990, but is expected to grow by 15-40% above 2001 levels by 2010, driven by the increasing wealth of these countries. A 10-14% increase in arable land area is forecast for the whole of Russia due to agricultural expansion. The widespread application of intensive management technologies could result in a 2 to 2.5-fold rise in grain and fodder yields, with a consequent reduction of arable land, but may increase N fertilizer use. Decreases in fertilizer N use since 1990 have led to a significant reduction in N_2O emissions. But, under favourable economic conditions, the amount of N fertilizer applied will again increase, although unlikely to reach pre-1990 levels in the near future. US-EPA (2006a) projected a 32% increase in N_2O emissions from soils in these two regions between 2005 and 2020, equivalent to an average rate of increase of 3.5 $MtCO_2$-eq/yr.

OECD North America and OECD Pacific are the only developed regions showing a consistent increase in GHG emissions in the agricultural sector (18% and 21%, respectively between 1990 and 2020; Figure 8.2). In both cases, the trend is largely driven by non-CO_2 emissions from manure management and N_2O emissions from soils. In Oceania, nitrogen fertilizer use has increased exponentially over the past 45 years with a 5 and 2.5 fold increase since 1990 in New Zealand and Australia, respectively. In North America, in contrast, nitrogen fertilizer use has remained stable; the main driver for increasing emissions is management of manure from cattle, poultry and swine production, and manure application to soils. In both regions, conservation policies have resulted in reduced CO_2 emissions from land conversion. Land clearing in Australia has declined by 60% since 1990 with vegetation management policies restricting further clearing, while in North America, some marginal croplands have been returned to woodland or grassland.

Western Europe is the only region where, according to US-EPA (2006a), GHG emissions from agriculture are projected to decrease to 2020 (Figure 8.2). This is associated with the adoption of a number of climate-specific and other environmental policies in the European Union, as well as economic constraints on agriculture, as discussed in Sections 8.7.1 and 8.7.2.

8.4 Description and assessment of mitigation technologies and practices, options and potentials, costs and sustainability

8.4.1 Mitigation technologies and practices

Opportunities for mitigating GHGs in agriculture fall into three broad categories[1], based on the underlying mechanism:

a. Reducing emissions: Agriculture releases to the atmosphere significant amounts of CO_2, CH_4, or N_2O (Cole *et al.*, 1997; IPCC, 2001a; Paustian *et al.*, 2004). The fluxes

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[1] Smith *et al.* (2007a) have recently reviewed mechanisms for agricultural GHG mitigation. This section draws largely from that study.

of these gases can be reduced by more efficient management of carbon and nitrogen flows in agricultural ecosystems. For example, practices that deliver added N more efficiently to crops often reduce N_2O emissions (Bouwman, 2001), and managing livestock to make most efficient use of feeds often reduces amounts of CH_4 produced (Clemens and Ahlgrimm, 2001). The approaches that best reduce emissions depend on local conditions, and therefore, vary from region to region.

b. Enhancing removals: Agricultural ecosystems hold large carbon reserves (IPCC, 2001a), mostly in soil organic matter. Historically, these systems have lost more than 50 Pg C (Paustian *et al.*, 1998; Lal, 1999, 2004a), but some of this carbon lost can be recovered through improved management, thereby withdrawing atmospheric CO_2. Any practice that increases the photosynthetic input of carbon and/or slows the return of stored carbon to CO_2 via respiration, fire or erosion will increase carbon reserves, thereby 'sequestering' carbon or building carbon 'sinks'. Many studies, worldwide, have now shown that significant amounts of soil carbon can be stored in this way, through a range of practices, suited to local conditions (Lal, 2004a). Significant amounts of vegetative carbon can also be stored in agro-forestry systems or other perennial plantings on agricultural lands (Albrecht and Kandji, 2003). Agricultural lands also remove CH_4 from the atmosphere by oxidation (but less than forests; Tate *et al.*, 2006), but this effect is small compared to other GHG fluxes (Smith and Conen, 2004).

c. Avoiding (or displacing) emissions: Crops and residues from agricultural lands can be used as a source of fuel, either directly or after conversion to fuels such as ethanol or diesel (Schneider and McCarl, 2003; Cannell, 2003). These bio-energy feedstocks still release CO_2 upon combustion, but now the carbon is of recent atmospheric origin (via photosynthesis), rather than from fossil carbon. The net benefit of these bio-energy sources to the atmosphere is equal to the fossil-derived emissions displaced, less any emissions from producing, transporting, and processing. GHG emissions, notably CO_2, can also be avoided by agricultural management practices that forestall the cultivation of new lands now under forest, grassland, or other non-agricultural vegetation (Foley *et al.*, 2005).

Many practices have been advocated to mitigate emissions through the mechanisms cited above. Often, a practice will affect more than one gas, by more than one mechanism, sometimes in opposite ways, so the net benefit depends on the combined effects on all gases (Robertson and Grace, 2004; Schils *et al.*, 2005; Koga *et al.*, 2006). In addition, the temporal pattern of influence may vary among practices or among gases for a given practice; some emissions are reduced indefinitely, other reductions are temporary (Six *et al.*, 2004; Marland *et al.*, 2003a). Where a practice affects radiative forcing through other mechanisms such as aerosols or albedo, those impacts also need to be considered (Marland *et al.*, 2003b; Andreae *et al.*, 2005).

The impacts of the mitigation options considered are summarized qualitatively in Table 8.3. Although comprehensive life-cycle analyses are not always possible, given the complexity of many farming systems, the table also includes estimates of the confidence based on expert opinion that the practice can reduce overall net emissions at the site of adoption. Some of these practices also have indirect effects on ecosystems elsewhere. For example, increased productivity in existing croplands could avoid deforestation and its attendant emissions (see also Section 8.8). The most important options are discussed in Section 8.4.1.

8.4.1.1 Cropland management

Because often intensively managed, croplands offer many opportunities to impose practices that reduce net GHG emissions (Table 8.3). Mitigation practices in cropland management include the following partly-overlapping categories:

a. Agronomy: Improved agronomic practices that increase yields and generate higher inputs of carbon residue can lead to increased soil carbon storage (Follett, 2001). Examples of such practices include: using improved crop varieties; extending crop rotations, notably those with perennial crops that allocate more carbon below ground; and avoiding or reducing use of bare (unplanted) fallow (West and Post, 2002; Smith, 2004a, b; Lal, 2003, 2004a; Freibauer *et al.*, 2004). Adding more nutrients, when deficient, can also promote soil carbon gains (Alvarez, 2005), but the benefits from N fertilizer can be offset by higher N_2O emissions from soils and CO_2 from fertilizer manufacture (Schlesinger, 1999; Pérez-Ramírez *et al.*, 2003; Robertson, 2004; Gregorich *et al.*, 2005). Emissions per hectare can also be reduced by adopting cropping systems with reduced reliance on fertilizers, pesticides and other inputs (and therefore, the GHG cost of their production: Paustian *et al.*, 2004). An important example is the use of rotations with legume crops (West and Post, 2002; Izaurralde *et al.*, 2001), which reduce reliance on external N inputs although legume-derived N can also be a source of N_2O (Rochette and Janzen, 2005). Another group of agronomic practices are those that provide temporary vegetative cover between successive agricultural crops, or between rows of tree or vine crops. These 'catch' or 'cover' crops add carbon to soils (Barthès *et al.*, 2004; Freibauer *et al.*, 2004) and may also extract plant-available N unused by the preceding crop, thereby reducing N_2O emissions.

b. Nutrient management: Nitrogen applied in fertilizers, manures, biosolids, and other N sources is not always used efficiently by crops (Galloway *et al.*, 2003; Cassman *et al.*, 2003). The surplus N is particularly susceptible to emission

Table 8.3: *Proposed measures for mitigating greenhouse gas emissions from agricultural ecosystems, their apparent effects on reducing emissions of individual gases where adopted (mitigative effect), and an estimate of scientific confidence that the proposed practice can reduce overall net emissions at the site of adoption.*

		Mitigative effects[a]			Net mitigation[b] (confidence)	
Measure	**Examples**	**CO_2**	**CH_4**	**N_2O**	**Agreement**	**Evidence**
Cropland management	Agronomy	+		+/-	***	**
	Nutrient management	+		+	***	**
	Tillage/residue management	+		+/-	**	**
	Water management (irrigation, drainage)	+/-		+	*	*
	Rice management	+/-	+	+/-	**	**
	Agro-forestry	+		+/-	***	*
	Set-aside, land-use change	+	+	+	***	***
Grazing land management/ pasture improvement	Grazing intensity	+/-	+/-	+/-	*	*
	Increased productivity (e.g., fertilization)	+		+/-	**	*
	Nutrient management	+		+/-	**	**
	Fire management	+	+	+/-	*	*
	Species introduction (including legumes)	+		+/-	*	**
Management of organic soils	Avoid drainage of wetlands	+	-	+/-	**	**
Restoration of degraded lands	Erosion control, organic amendments, nutrient amendments	+		+/-	***	**
Livestock management	Improved feeding practices		+	+	***	***
	Specific agents and dietary additives		+		**	***
	Longer term structural and management changes and animal breeding		+	+	**	*
Manure/biosolid management	Improved storage and handling		+	+/-	***	**
	Anaerobic digestion		+	+/-	***	*
	More efficient use as nutrient source	+		+	***	**
Bio-energy	Energy crops, solid, liquid, biogas, residues	+	+/-	+/-	***	**

Notes:

[a] + denotes reduced emissions or enhanced removal (positive mitigative effect);
- denotes increased emissions or suppressed removal (negative mitigative effect);
+/- denotes uncertain or variable response.

[b] A qualitative estimate of the confidence in describing the proposed practice as a measure for reducing net emissions of greenhouse gases, expressed as CO_2-eq: Agreement refers to the relative degree of consensus in the literature (the more asterisks, the higher the agreement); Evidence refers to the relative amount of data in support of the proposed effect (the more asterisks, the more evidence).

Source: adapted from Smith et al., 2007a.

of N_2O (McSwiney and Robertson, 2005). Consequently, improving N use efficiency can reduce N_2O emissions and indirectly reduce GHG emissions from N fertilizer manufacture (Schlesinger, 1999). By reducing leaching and volatile losses, improved efficiency of N use can also reduce off-site N_2O emissions. Practices that improve N use efficiency include: adjusting application rates based on precise estimation of crop needs (e.g., precision farming); using slow- or controlled-release fertilizer forms or nitrification inhibitors (which slow the microbial processes leading to N_2O formation); applying N when least susceptible to loss, often just prior to plant uptake (improved timing); placing the N more precisely into the soil to make it more accessible to crops roots; or avoiding N applications in excess of immediate plant requirements (Robertson, 2004; Dalal *et al.*, 2003; Paustian *et al.*, 2004; Cole *et al.*, 1997; Monteny *et al.*, 2006).

c. Tillage/residue management: Advances in weed control methods and farm machinery now allow many crops to be grown with minimal tillage (reduced tillage) or without tillage (no-till). These practices are now increasingly used throughout the world (e.g., Cerri *et al.*, 2004). Since soil disturbance tends to stimulate soil carbon losses through enhanced decomposition and erosion (Madari *et al.*, 2005), reduced- or no-till agriculture often results in soil carbon gain, but not always (West and Post, 2002; Ogle *et al.*, 2005; Gregorich *et al.*, 2005; Alvarez 2005). Adopting reduced- or no-till may also affect N_2O, emissions but the net effects are inconsistent and not well-quantified globally (Smith and Conen, 2004; Helgason *et al.*, 2005; Li *et al.*, 2005; Cassman *et al.*, 2003). The effect of reduced tillage on N_2O emissions may depend on soil and climatic conditions. In some areas, reduced tillage promotes N_2O emissions, while elsewhere it may reduce emissions or have no measurable influence (Marland *et al.*, 2001). Further, no-tillage systems can reduce CO_2 emissions from energy use (Marland *et al.*, 2003b; Koga *et al.*, 2006). Systems that retain crop residues also tend to increase soil carbon because these residues are the precursors for soil organic matter, the main carbon store in soil. Avoiding the burning of residues (e.g., mechanising sugarcane harvesting, eliminating the need for pre-harvest burning (Cerri *et al.*, 2004)) also avoids emissions of aerosols and GHGs generated from fire, although CO_2 emissions from fuel use may increase.

d. Water management: About 18% of the world's croplands now receive supplementary water through irrigation (Millennium Ecosystem Assessment, 2005). Expanding this area (where water reserves allow) or using more effective irrigation measures can enhance carbon storage in soils through enhanced yields and residue returns (Follett, 2001; Lal, 2004a). But some of these gains may be offset by CO_2 from energy used to deliver the water (Schlesinger 1999; Mosier *et al.,* 2005) or from N_2O emissions from higher moisture and fertilizer N inputs (Liebig *et al.* 2005), The latter effect has not been widely measured. Drainage of croplands lands in humid regions can promote productivity (and hence soil carbon) and perhaps also suppress N_2O emissions by improving aeration (Monteny *et al.,* 2006). Any nitrogen lost through drainage, however, may be susceptible to loss as N_2O.(Reay *et al.* 2003).

e. Rice management: Cultivated wetland rice soils emit significant quantities of methane (Yan *et al.*, 2003). Emissions during the growing season can be reduced by various practices (Yagi *et al.*, 1997; Wassmann *et al.*, 2000; Aulakh *et al.*, 2001). For example, draining wetland rice once or several times during the growing season reduces CH_4 emissions (Smith and Conen, 2004; Yan *et al.*, 2003; Khalil and Shearer, 2006). This benefit, however, may be partly offset by increased N_2O emissions (Akiyama *et al.* 2005), and the practice may be constrained by water supply. Rice cultivars with low exudation rates could offer an important methane mitigation option (Aulakh *et al.*, 2001). In the off-rice season, methane emissions can be reduced by improved water management, especially by keeping the soil as dry as possible and avoiding water logging (Cai *et al.*, 2000 2003; Kang *et al.*, 2002; Xu *et al.*, 2003). Increasing rice production can also enhance soil organic carbon stocks (Pan *et al.*, 2006). Methane emissions can be reduced by adjusting the timing of organic residue additions (e.g., incorporating organic materials in the dry period rather than in flooded periods; Xu *et al.*, 2000; Cai and Xu, 2004), by composting the residues before incorporation, or by producing biogas for use as fuel for energy production (Wang and Shangguan, 1996; Wassmann *et al.*, 2000).

f. Agro-forestry: Agro-forestry is the production of livestock or food crops on land that also grows trees for timber, firewood, or other tree products. It includes shelter belts and riparian zones/buffer strips with woody species. The standing stock of carbon above ground is usually higher than the equivalent land use without trees, and planting trees may also increase soil carbon sequestration (Oelbermann *et al.*, 2004; Guo and Gifford, 2002; Mutuo *et al.*, 2005; Paul *et al.*, 2003). But the effects on N_2O and CH_4 emissions are not well known (Albrecht and Kandji, 2003).

g. Land cover (use) change: One of the most effective methods of reducing emissions is often to allow or encourage the reversion of cropland to another land cover, typically one similar to the native vegetation. The conversion can occur over the entire land area ('set-asides'), or in localized spots, such as grassed waterways, field margins, or shelterbelts (Follett, 2001; Freibauer *et al.*, 2004; Lal, 2004b; Falloon *et al.*, 2004; Ogle *et al.*, 2003). Such land cover change often increases carbon storage. For example, converting arable cropland to grassland typically results in the accrual of soil carbon because of lower soil disturbance and reduced carbon removal in harvested products. Compared to cultivated lands, grasslands may also have reduced N_2O emissions from lower N inputs, and higher rates of CH_4 oxidation, but recovery of oxidation may be slow (Paustian *et al.*, 2004). Similarly, converting drained croplands back to wetlands can result in rapid accumulation of soil carbon (removal of atmospheric CO_2). This conversion may stimulate CH_4 emissions because water logging creates anaerobic conditions (Paustian *et al.*, 2004). Planting trees can also reduce emissions. These practices are considered under agro-forestry (Section 8.4.1.1f); afforestation (Chapter 9), and reafforestation (Chapter 9). Because land cover (or use) conversion comes at the expense of lost agricultural productivity, it is usually an option only on surplus agricultural land or on croplands of marginal productivity.

8.4.1.2 Grazing land management and pasture improvement

Grazing lands occupy much larger areas than croplands (FAOSTAT, 2006) and are usually managed less intensively. The following are examples of practices to reduce GHG emissions and to enhance removals:

a. Grazing intensity: The intensity and timing of grazing can influence the removal, growth, carbon allocation, and flora of grasslands, thereby affecting the amount of carbon accrual in soils (Conant *et al.*, 2001; 2005; Freibauer *et al.*, 2004; Conant and Paustian, 2002; Reeder *et al.*, 2004). Carbon accrual on optimally grazed lands is often greater than on ungrazed or overgrazed lands (Liebig *et al.*, 2005; Rice and Owensby, 2001). The effects are inconsistent, however, owing to the many types of grazing practices employed and the diversity of plant species, soils, and climates involved (Schuman *et al.*, 2001; Derner *et al.*, 2006). The influence of grazing intensity on emission of non-CO_2 gases is not well-established, apart from the direct effects on emissions from adjustments in livestock numbers.

b. Increased productivity: (including fertilization): As for croplands, carbon storage in grazing lands can be improved by a variety of measures that promote productivity. For instance, alleviating nutrient deficiencies by fertilizer or organic amendments increases plant litter returns and, hence, soil carbon storage (Schnabel *et al.*, 2001; Conant *et al.*, 2001). Adding nitrogen, however, often stimulates N_2O emissions (Conant *et al.*, 2005) thereby offsetting some of the benefits. Irrigating grasslands, similarly, can promote soil carbon gains (Conant *et al.*, 2001). The net effect of this practice, however, depends also on emissions from energy use and other activities on the irrigated land (Schlesinger, 1999).

c. Nutrient management: Practices that tailor nutrient additions to plant uptake, such as those described for croplands, can reduce N_2O emissions (Dalal *et al.*, 2003; Follett *et al.*, 2001). Management of nutrients on grazing lands, however, may be complicated by deposition of faeces and urine from livestock, which are not as easily controlled nor as uniformly applied as nutritive amendments in croplands (Oenema *et al.*, 2005).

d. Fire management: On-site biomass burning (not to be confused with bio-energy, where biomass is combusted off-site for energy) contributes to climate change in several ways. Firstly, it releases GHGs, notably CH_4 and, and to a lesser extent, N_2O (the CO_2 released is of recent origin, is absorbed by vegetative regrowth, and is usually not included in GHG inventories). Secondly, it generates hydrocarbon and reactive nitrogen emissions, which react to form tropospheric ozone, a powerful GHG. Thirdly, fires produce a range of smoke aerosols which can have either warming or cooling effects on the atmosphere; the *net* effect is thought to be positive radiative forcing (Andreae *et al.*, 2005; Jones *et al.*, 2003; Venkataraman *et al.*, 2005; Andreae, 2001; Andreae and Merlet, 2001; Anderson *et al.*, 2003; Menon *et al.*, 2002). Fourth, fire reduces the albedo of the land surface for several weeks, causing warming (Beringer *et al.,* 2003). Finally, burning can affect the proportion of woody versus grass cover, notably in savannahs, which occupy about an eighth of the global land surface. Reducing the frequency or intensity of fires typically leads to increased tree and shrub cover, resulting in a CO_2 sink in soil and biomass (Scholes and van der Merwe, 1996). This woody-plant encroachment mechanism saturates over 20-50 years, whereas avoided CH_4 and N_2O emissions continue as long as fires are suppressed.

Mitigation actions involve reducing the frequency or extent of fires through more effective fire suppression; reducing the fuel load by vegetation management; and burning at a time of year when less CH_4 and N_2O are emitted (Korontzi *et al.*, 2003). Although most agricultural-zone fires are ignited by humans, there is evidence that the area burned is ultimately under climatic control (Van Wilgen *et al.*, 2004). In the absence of human ignition, the fire-prone ecosystems would still burn as a result of climatic factors.

e. Species introduction: Introducing grass species with higher productivity, or carbon allocation to deeper roots, has been shown to increase soil carbon. For example, establishing deep-rooted grasses in savannahs has been reported to yield very high rates of carbon accrual (Fisher *et al.*, 1994), although the applicability of these results has not been widely confirmed (Conant *et al.*, 2001; Davidson *et al.*, 1995). In the Brazilian Savannah (Cerrado Biome), integrated crop-livestock systems using Brachiaria grasses and zero tillage are being adopted (Machado and Freitas, 2004). Introducing legumes into grazing lands can promote soil carbon storage (Soussana *et al.*, 2004), through enhanced productivity from the associated N inputs, and perhaps also reduced emissions from fertilizer manufacture if biological N_2 fixation displaces applied N fertilizer N (Sisti *et al.*, 2004; Diekow *et al.*, 2005). Ecological impacts of species introduction need to be considered.

Grazing lands also emit GHGs from livestock, notably CH_4 from ruminants and their manures. Practices for reducing these emissions are considered under Section 8.4.1.5: Livestock management.

8.4.1.3 Management of organic/peaty soils

Organic or peaty soils contain high densities of carbon accumulated over many centuries because decomposition is suppressed by absence of oxygen under flooded conditions. To be used for agriculture, these soils are drained, which aerates the soil, favouring decomposition and therefore, high CO_2 and N_2O fluxes. Methane emissions are usually suppressed after draining, but this effect is far outweighed by pronounced increases in N_2O and CO_2 (Kasimir-Klemedtsson *et al.*, 1997). Emissions from drained organic soils can be reduced to some extent by practices such as avoiding row crops and tubers, avoiding deep ploughing, and maintaining a shallower water table. But the most important mitigation practice is avoiding the drainage of these soils in the first place or re-establishing a high water table (Freibauer *et al.*, 2004).

8.4.1.4 Restoration of degraded lands

A large proportion of agricultural lands has been degraded by excessive disturbance, erosion, organic matter loss, salinization, acidification, or other processes that curtail productivity (Batjes, 1999; Foley *et al.*, 2005; Lal, 2001a, 2003, 2004b). Often, carbon storage in these soils can be partly restored by practices that reclaim productivity including: re-vegetation (e.g., planting grasses); improving fertility by nutrient amendments; applying organic substrates such as manures, biosolids, and composts; reducing tillage and retaining crop residues; and conserving water (Lal, 2001b; 2004b; Bruce *et al*., 1999; Olsson and Ardö, 2002; Paustian *et al*., 2004). Where these practices involve higher nitrogen amendments, the benefits of carbon sequestration may be partly offset by higher N_2O emissions.

8.4.1.5 Livestock management

Livestock, predominantly ruminants such as cattle and sheep, are important sources of CH_4, accounting for about one-third of global anthropogenic emissions of this gas (US-EPA, 2006a). The methane is produced primarily by enteric fermentation and voided by eructation (Crutzen, 1995; Murray *et al.*, 1976; Kennedy and Milligan, 1978). All livestock generate N_2O emissions from manure as a result of excretion of N in urine and faeces. Practices for reducing CH_4 and N_2O emissions from this source fall into three general categories: improved feeding practices, use of specific agents or dietary additives; and longer-term management changes and animal breeding (Soliva *et al*., 2006; Monteny *et al.,* 2006).

a. Improved feeding practices: Methane emissions can be reduced by feeding more concentrates, normally replacing forages (Blaxter and Claperton, 1965; Johnson and Johnson, 1995; Lovett *et al.*, 2003; Beauchemin and McGinn, 2005). Although concentrates may increase daily methane emissions per animal, emissions per kg-feed intake and per kg-product are almost invariably reduced. The magnitude of this reduction per kg-product decreases as production increases. The net benefit of concentrates, however, depends on reduced animal numbers or younger age at slaughter for beef animals, and on how the practice affects land use, the N content of manure and emissions from producing and transporting the concentrates (Phetteplace *et al.*, 2001; Lovett *et al.*, 2006). Other practices that can reduce CH_4 emissions include: adding certain oils or oilseeds to the diet (e.g., Machmüller *et al.*, 2000; Jordan *et al.*, 2006c); improving pasture quality, especially in less developed regions, because this improves animal productivity, and reduces the proportion of energy lost as CH_4 (Leng, 1991; McCrabb *et al.*, 1998; Alcock and Hegarty, 2006); and optimizing protein intake to reduce N excretion and N_2O emissions (Clark *et al.*, 2005).

b. Specific agents and dietary additives: A wide range of specific agents, mostly aimed at suppressing methanogenesis, has been proposed as dietary additives to reduce CH_4 emissions:
   - Ionophores are antibiotics that can reduce methane emissions (Benz and Johnson, 1982; Van Nevel and Demeyer, 1996; McGinn *et al.*, 2004), but their effect may be transitory (Rumpler *et al.*, 1986); and they have been banned in the EU.
   - Halogenated compounds inhibit methanogenic bacteria (Wolin *et al.*, 1964; Van Nevel and Demeyer, 1995) but their effects, too, are often transitory and they can have side-effects such as reduced intake.
   - Novel plant compounds such as condensed tannins (Pinares-Patiño *et al*., 2003; Hess *et al*., 2006), saponins (Lila *et al*., 2003) or essential oils (Patra *et al*., 2006; Kamra *et al.*, 2006) may have merit in reducing methane emissions, but these responses may often be obtained through reduced digestibility of the diet.
   - Probiotics, such as yeast culture, have shown only small, insignificant effects (McGinn *et al.*, 2004), but selecting strains specifically for methane-reducing ability could improve results (Newbold and Rode, 2006).
   - Propionate precursors such as fumarate or malate reduce methane formation by acting as alternative hydrogen acceptors (Newbold *et al.*, 2002). But as response is elicited only at high doses, propionate precursors are, therefore, expensive (Newbold *et al.*, 2005).
   - Vaccines against methanogenic bacteria are being developed but are not yet available commercially (Wright *et al.*, 2004).
   - Bovine somatotropin (bST) and hormonal growth implants do not specifically suppress CH_4 formation, but by improving animal performance (Bauman, 1992; Schmidely, 1993), they can reduce emissions per-kg of animal product (Johnson *et al.*, 1991; McCrabb, 2001).

c. Longer-term management changes and animal breeding: Increasing productivity through breeding and better management practices, such as a reduction in the number of replacement heifers, often reduces methane output per unit of animal product (Boadi *et al.*, 2004). Although selecting cattle directly for reduced methane production has been proposed (Kebreab *et al.*, 2006), it is still impractical due to difficulties in accurately measuring methane emissions at a magnitude suitable for breeding programmes. With improved efficiency, meat-producing animals reach slaughter weight at a younger age, with reduced lifetime emissions (Lovett and O'Mara, 2002). However, the whole-system effects of such practices may not always lead to reduced emissions. For example in dairy cattle, intensive selection for higher yield may reduce fertility, requiring more replacement heifers in the herd (Lovett *et al.*, 2006).

8.4.1.6 Manure management

Animal manures can release significant amounts of N_2O and CH_4 during storage, but the magnitude of these emissions varies. Methane emissions from manure stored in lagoons or tanks can be reduced by cooling, use of solid covers, mechanically separating solids from slurry, or by capturing the CH_4 emitted (Amon *et al.* 2006; Clemens and Ahlgrimm, 2001; Monteny *et al.* 2001, 2006; Paustian *et al.*, 2004). The manures can also be digested anaerobically to maximize CH_4 retrieval as a renewable energy source (Clemens and Ahlgrimm, 2001; Clemens *et al.*, 2006). Handling manures in solid form (e.g., composting) rather than liquid form can suppress CH_4 emissions, but may increase N_2O formation (Paustian *et al.*, 2004). Preliminary evidence suggests that covering manure heaps can reduce N_2O emissions, but the effect of this practice on CH_4 emissions is variable (Chadwick, 2005). For most animals, worldwide there is limited opportunity for manure management, treatment, or storage; excretion happens in the field and handling for fuel or fertility amendment occurs when it is dry and methane emissions are negligible (Gonzalez-Avalos and Ruiz-Suarez, 2001). To some extent, emissions from manure might be curtailed by altering feeding practices (Külling *et al.*, 2003; Hindrichsen *et al.*, 2006; Kreuzer and Hindrichsen, 2006), or by composting the manure (Pattey *et al.*, 2005; Amon *et al.*, 2001), but if aeration is inadequate CH_4 emissions during composting can still be substantial (*Xu et al.*, 2007). All of these practices require further study from the perspective of their impact on whole life-cycle GHG emissions.

Manures also release GHGs, notably N_2O, after application to cropland or deposition on grazing lands. Practices for reducing these emissions are considered in Subsection 8.4.1.1: Cropland management and Subsection 8.4.1.2: Grazing land management.

8.4.1.7 Bioenergy

Increasingly, agricultural crops and residues are seen as sources of feedstocks for energy to displace fossil fuels. A wide range of materials have been proposed for use, including grain, crop residue, cellulosic crops (e.g., switchgrass, sugarcane), and various tree species (Edmonds, 2004; Cerri *et al.*, 2004; Paustian *et al.*, 2004; Sheehan *et al.*, 2004; Dias de Oliveira *et al.*, 2005; Eidman, 2005). These products can be burned directly, but can also be processed further to generate liquid fuels such as ethanol or diesel fuel (Richter, 2004). Such fuels release CO_2 when burned, but this CO_2 is of recent atmospheric origin (via photosynthetic carbon uptake) and displaces CO_2 which otherwise would have come from fossil carbon. The net benefit to atmospheric CO_2, however, depends on energy used in growing and processing the bioenergy feedstock (Spatari *et al.*, 2005).

The competition for other land uses and the environmental impacts need to be considered when planning to use energy crops (e.g., European Environment Agency, 2006). The interactions of an expanding bioenergy sector with other land uses, and impacts on agro-ecosystem services such as food production, biodiversity, soil and nature conservation, and carbon sequestration have not yet been adequately studied, but bottom-up approaches (Smeets *et al.*, 2007) and integrated assessment modelling (Hoogwijk *et al.*, 2005; Hoogwijk, 2004) offer opportunities to improve understanding. Latin America, Sub-Saharan Africa, and Eastern Europe are promising regions for bio-energy, with additional long-term contributions from Oceania and East and Northeast Asia. The technical potential for biomass production may be developed at low production costs in the range of 2 US$/GJ (Hoogwijk, 2004; Rogner *et al.*, 2000).

Major transitions are required to exploit the large potential for bioenergy. Improving agricultural efficiency in developing countries is a key factor. It is still uncertain to what extent, and how fast, such transitions could be realized in different regions. Under less favourable conditions, the regional bio-energy potential(s) could be quite low. Also, technological developments in converting biomass to energy, as well as long distance biomass supply chains (e.g., those involving intercontinental transport of biomass derived energy carriers) can dramatically improve competitiveness and efficiency of bio-energy (Faaij, 2006; Hamelinck *et al.*, 2004).

8.4.2 Mitigation technologies and practices: per-area estimates of potential

As mitigation practices can affect more than one GHG[2], it is important to consider the impact of mitigation options on all GHGs (Robertson *et al,.* 2000; Smith *et al.*, 2001; Gregorich *et al.*, 2005). For non-livestock mitigation options, ranges for per-area mitigation potentials of each GHG are provided in Table 8.4 (tCO_2-eq/ha/yr).

Mitigation potentials for CO_2 represent the *net* change in soil carbon pools, reflecting the accumulated difference between carbon inputs to the soil after CO_2 uptake by plants, and release of CO_2 by decomposition in soil. Mitigation potentials for N_2O and CH_4 depend solely on emission reductions. Soil carbon stock changes were derived from about 200 studies, and the emission ranges for CH_4 and N_2O were derived using the DAYCENT and DNDC simulation models (IPCC, 2006; US-EPA, 2006b; Smith *et al.*, 2007b; Ogle *et al.*, 2004, 2005).

Table 8.5 presents the mitigation potentials in livestock (dairy cows, beef cattle, sheep, dairy buffalo and other buffalo) for reducing enteric methane emissions via improved feeding practices, specific agents and dietary additives, and longer term structural and management changes/animal breeding. These estimates were derived by Smith *et al.* (2007a) using a model similar to that described in US-EPA (2006b).

Some mitigation measures operate predominantly on one GHG (e.g., dietary management of ruminants to reduce CH_4 emissions) while others have impacts on more than one GHG (e.g., rice management). Moreover, practices may benefit more

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[2] Smith *et al.* (2007a) have recently collated per-area estimates of agricultural GHG mitigation options. This section draws largely from that study.

Table 8.4: *Annual mitigation potentials in each climate region for non-livestock mitigation options*

			CO_2 (tCO_2/ha/yr)			CH_4 (tCO_2-eq/ha/yr)			N_2O (tCO_2-eq/ha/yr)			All GHG (tCO_2-eq/ha/yr)		
Climate zone	**Activity**	**Practice**	**Mean estimate**	**Low**	**High**	**Mean estimate**	**Low**	**High**	**Mean estimate**	**Low**	**High**	**Mean estimate**	**Low**	**High**
Cool-dry	Croplands	Agronomy	0.29	0.07	0.51	0.00	0.00	0.00	0.10	0.00	0.20	0.39	0.07	0.71
	Croplands	Nutrient management	0.26	-0.22	0.73	0.00	0.00	0.00	0.07	0.01	0.32	0.33	-0.21	1.05
	Croplands	Tillage and residue management	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
	Croplands	Water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	Set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	2.30	0.00	4.60	3.93	-0.07	7.90
	Croplands	Agro-forestry	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
	Grasslands	Grazing, fertilization, fire	0.11	-0.55	0.77	0.02	0.01	0.02	0.00	0.00	0.00	0.13	-0.54	0.79
	Organic soils	Restoration	36.67	3.67	69.67	-3.32	-0.05	-15.30	0.16	0.05	0.28	33.51	3.67	54.65
	Degraded lands	Restoration	3.45	-0.37	7.26	0.08	0.04	0.14	0.00	0.00	0.00	3.53	-0.33	7.40
	Manure/ biosolids	Application	1.54	-3.19	6.27	0.00	0.00	0.00	0.00	-0.17	1.30	1.54	-3.36	7.57
	Bioenergy	Soils only	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
Cool-moist	Croplands	Agronomy	0.88	0.51	1.25	0.00	0.00	0.00	0.10	0.00	0.20	0.98	0.51	1.45
	Croplands	Nutrient management	0.55	0.01	1.10	0.00	0.00	0.00	0.07	0.01	0.32	0.62	0.02	1.42
	Croplands	tillage and residue management	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	Croplands	Water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	Set-aside and LUC	3.04	1.17	4.91	0.02	0.00	0.00	2.30	0.00	4.60	5.36	1.17	9.51
	Croplands	Agro-forestry	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	Grasslands	Grazing, fertilization, fire	0.81	0.11	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.11	1.50
	Organic soils	Restoration	36.67	3.67	69.67	-3.32	-0.05	-15.30	0.16	0.05	0.28	33.51	3.67	54.65
	Degraded lands	Restoration	3.45	-0.37	7.26	1.00	0.69	1.25	0.00	0.00	0.00	4.45	0.32	8.51
	Manure/ biosolids	Application	2.79	-0.62	6.20	0.00	0.00	0.00	0.00	-0.17	1.30	2.79	-0.79	7.50
	Bioenergy	Soils only	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
Warm-dry	Croplands	Agronomy	0.29	0.07	0.51	0.00	0.00	0.00	0.10	0.00	0.20	0.39	0.07	0.71
	Croplands	Nutrient management	0.26	-0.22	0.73	0.00	0.00	0.00	0.07	0.01	0.32	0.33	-0.21	1.05
	Croplands	Tillage and residue management	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	Croplands	Water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	Set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	2.30	0.00	4.60	3.93	-0.07	7.90
	Croplands	Agro-forestry	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	Grasslands	Grazing, fertilization, fire	0.11	-0.55	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.11	-0.55	0.77
	Organic soils	Restoration	73.33	7.33	139.33	-3.32	-0.05	-15.30	0.16	0.05	0.28	70.18	7.33	124.31
	Degraded lands	Restoration	3.45	-0.37	7.26	0.00	0.00	0.00	0.00	0.00	0.00	3.45	-0.37	7.26
	Manure/ biosolids	Application	1.54	-3.19	6.27	0.00	0.00	0.00	0.00	-0.17	1.30	1.54	-3.36	7.57
	Bioenergy	Soils only	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
Warm-moist	Croplands	Agronomy	0.88	0.51	1.25	0.00	0.00	0.00	0.10	0.00	0.20	0.98	0.51	1.45
	Croplands	Nutrient management	0.55	0.01	1.10	0.00	0.00	0.00	0.07	0.01	0.32	0.62	0.02	1.42
	Croplands	Tillage and residue management	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89
	Croplands	Water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	Set-aside and LUC	3.04	1.17	4.91	0.02	0.00	0.00	2.30	0.00	4.60	5.36	1.17	9.51
	Croplands	Agro-forestry	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89
	Grasslands	Grazing, fertilization, fire	0.81	0.11	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.11	1.50
	Organic soils	Restoration	73.33	7.33	139.33	-3.32	-0.05	-15.30	0.16	0.05	0.28	70.18	7.33	124.31
	Degraded lands	Restoration	3.45	-0.37	7.26	0.00	0.00	0.00	0.00	0.00	0.00	3.45	-0.37	7.26
	Manure/ biosolids	Application	2.79	-0.62	6.20	0.00	0.00	0.00	0.00	-0.17	1.30	2.79	-0.79	7.50
	Bioenergy	Soils only	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89

Notes:

The estimates represent average change in soil carbon stocks (CO_2) or emissions of N_2O and CH_4 on a per hectare basis. Positive values represent CO_2 uptake which increases the soil carbon stock, or a reduction in emissions of N_2O and CH_4.

Estimates of soil carbon storage (CO_2 mitigation) for all practices except management of organic soils were derived from about 200 studies (see IPCC, 2006, Grassland and Cropland Chapters of Volume IV, Annexes 5A and 6A) using a linear mixed-effect modelling approach, which is a standard linear regression technique with the inclusion of random effects due to dependencies in data from the same country, site and time series (Ogle et al., 2004, 2005; IPCC, 2006; Smith et al., 2007b). The studies were conducted in regions throughout the world, but temperate studies were more prevalent leading to smaller uncertainties than for estimates for warm tropical climates. Estimates represent annual soil carbon change rate for a 20-year time horizon in the top 30 cm of the soil. Soils under bio-energy crops and agro-forestry were assumed to derive their mitigation potential mainly from cessation of soil disturbance, and given the same estimates as no-till. Management of organic soils was based on emissions under drained conditions from IPCC guidelines (IPCC, 1997). Soil CH_4 and N_2O emission reduction potentials were derived as follows:

a) for organic soils, N_2O emissions were based on the median, low and high nutrient status organic soil N_2O emission factors from the IPCC GPG LULUCF (IPCC, 2003) and CH_4 emissions were based on low, high and median values from Le Mer and Roger (2001);

b) N_2O figures for nutrient management were derived using the DAYCENT simulation model, and include both direct emissions from nitrification/denitrification at the site, as well as indirect N_2O emissions associated with volatilization and leaching/runoff of N that is converted into N_2O following atmospheric deposition or in waterways, respectively (US-EPA, 2006b; assuming a N reduction to 80% of current application);

c) N_2O figures for tillage and residue management were derived using DAYCENT (US-EPA, 2006b; figures for no till);

d) Rice figures were taken directly from US-EPA (2006b) so are not shown here. Low and high values represent the range of a 95% confidence interval. Table 8.4 has mean and uncertainty for change in soil C, N_2O and CH_4 emissions at the climate region scale, and are not intended for use in assessments at finer scales such as individual farms.

Table 8.5: *Technical reduction potential (proportion of an animal's enteric methane production) for enteric methane emissions due to (i) improved feeding practices, (ii) specific agents and dietary additives and (iii) longer term structural/management change and animal breeding*[a]

AEZ regions	Improved feeding practices[b]					Specific agents and dietary additives[c]					Longer term structural/management change and animal breeding[d]				
	Dairy cows	Beef cattle	Sheep	Dairy buffalo	Non-dairy buffalo	Dairy cows	Beef cattle	Sheep	Dairy buffalo	Non-dairy buffalo	Dairy cows	Beef cattle	Sheep	Dairy buffalo	Non-dairy buffalo
Northern Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
Southern. Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
Western Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
Eastern. Europe	0.11	0.06	0.03			0.04	0.01	0.002			0.03	0.07	0.003		
Russian Federation	0.10	0.05	0.03			0.03	0.04	0.002			0.03	0.06	0.003		
Japan	0.17	0.11	0.04			0.08	0.09	0.004			0.03	0.03	0.003		
South Asia	0.04	0.02	0.02	0.04	0.02	0.01	0.01	0.0005	0.01	0.002	0.01	0.01	0.001	0.01	0.02
East Asia	0.10	0.05	0.03	0.10	0.05	0.03	0.05	0.002	0.03	0.012	0.03	0.06	0.003	0.03	0.07
West Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Southeast Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Central Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Oceania	0.22	0.14	0.06			0.08	0.08	0.004			0.05	0.03	0.004		
North America	0.16	0.11	0.04			0.11	0.09	0.004			0.03	0.03	0.003		
South America	0.06	0.03	0.02			0.03	0.02	0.001			0.02	0.03	0.002		
Central America	0.03	0.02	0.02			0.02	0.01	0.001			0.01	0.02	0.002		
East Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
West Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
North Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
South Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
Middle Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		

Notes:

[a] The proportional reduction due to application of each practice was estimated from reports in the scientific literature (see footnotes below). These estimates were adjusted for:
(i) proportion of the animal's life where the practice was applicable;
(ii) technical adoption feasibility in a region, such as whether farmers have the necessary knowledge, equipment, extension services, etc. to apply the practice (average dairy cow milk production in each region over the period 2000-2004 was used as an index of the level of technical efficiency in the region, and was used to score a region's technical adoption feasibility);
(iii) proportion of animals in a region that the measure can be applied (i.e. if the measure is already being applied to some animals as in the case of bST use in North America, it is considered to be only applicable to the proportion of animals not currently receiving the product;
(iv) Non-additivity of simultaneous application of multiple measures.
There is evidence in the literature that some measures are not additive when applied simultaneously, such as the use of dietary oils and ionophores, but this is probably not the case with most measures. However, the model used (as described in Smith *et al.*, 2007a) did account for the fact that once one measure is applied, the emissions base for the second measure is reduced, and so on, and a further 20% reduction in mitigation potential was incorporated to account for unknown non-additivity effects. Only measures considered feasible for a region were applied in that region (e.g., bST was not considered for European regions due to the ban on its use in the EU). It was assumed that total production of milk or meat was not affected by application of the practices, so that if a measure increased animal productivity, animal numbers were reduced in order to keep production constant.

[b] Includes replacing roughage with concentrate (Blaxter & Claperton, 1965; Moe & Tyrrell, 1979; Johnson & Johnson, 1995; Yan *et al.*, 2000; Mills *et al.*, 2003; Beauchemin & McGinn, 2005; Lovett *et al.*, 2006), improving forages/inclusion of legumes (Leng, 1991; McCrabb *et al.*, 1998; Woodward *et al.*, 2001; Waghorn *et al.*, 2002; Pinares-Patiño *et al.*, 2003; Alcock & Hegarty, 2006) and feeding extra dietary oil (Machmüller *et al.*, 2000; Dohme *et al.*, 2001; Machmüller *et al.*, 2003, Lovett *et al.*, 2003; McGinn *et al.*, 2004; Beauchemin & McGinn, 2005; Jordan *et al.*, 2006a; Jordan *et al.*, 2006b; Jordan *et al.*, 2006c).

[c] Includes bST (Johnson *et al.*, 1991; Bauman, 1992), growth hormones (McCrabb, 2001), ionophores (Benz & Johnson, 1982; Rumpler *et al.*, 1986; Van Nevel & Demeyer, 1996; McGinn *et al.*, 2004), propionate precursors (McGinn *et al.*, 2004; Beauchemin & McGinn, 2005; Newbold *et al.*, 2005; Wallace *et al.*, 2006).

[d] Includes lifetime management of beef cattle (Johnson *et al.*, 2002; Lovett & O'Mara, 2002) and improved productivity through animal breeding (Ferris *et al.*, 1999; Hansen, 2000; Robertson and Waghorn, 2002; Miglior *et al.*, 2005).

Source: adapted from Smith et al., 2007a.

than one gas (e.g., set-aside/headland management) while others involve a trade-off between gases (e.g., restoration of organic soils). The effectiveness of non-livestock mitigation options are variable across and within climate regions (see Table 8.4). Consequently, a practice that is highly effective in reducing emissions at one site may be less effective or even counter-productive elsewhere. Similarly, effectiveness of livestock options also varies regionally (Table 8.5). This means that there is no universally applicable list of mitigation practices, but that proposed practices will need to be evaluated for individual agricultural systems according to the specific climatic, edaphic, social settings, and historical land use and management. Assessments can be conducted to evaluate the effectiveness of practices in specific areas, building on findings from the global scale assessment reported here. In addition, such assessments could address GHG emissions associated with energy use and other inputs (e.g., fuel, fertilizers, and pesticides) in a full life cycle analysis for the production system.

The effectiveness of mitigation strategies also changes with time. Some practices, like those which elicit soil carbon gain, have diminishing effectiveness after several decades; others such as methods that reduce energy use may reduce emissions indefinitely. For example, Six et al. (2004) found a strong time dependency of emissions from no-till agriculture, in part because of changing influence of tillage on N_2O emissions.

8.4.3 Global and regional estimates of agricultural GHG mitigation potential

8.4.3.1 Technical potential for GHG mitigation in agriculture

There have been numerous attempts to assess the technical potential for GHG mitigation in agriculture. Most of these have focused on soil carbon sequestration. Estimates in the IPCC Second Assessment Report (SAR; IPCC, 1996) suggested that 400-800 MtC/yr (equivalent to about 1400-2900 $MtCO_2$-eq/yr) could be sequestered in global agricultural soils with a finite capacity saturating after 50 to100 years. In addition, SAR concluded that 300-1300 MtC (equivalent to about 1100-4800 $MtCO_2$-eq/yr) from fossil fuels could be offset by using 10 to15% of agricultural land to grow energy crops; with crop residues potentially contributing 100-200 MtC (equivalent to about 400-700 $MtCO_2$-eq/yr) to fossil fuel offsets if recovered and burned. Burning residues for bio-energy might increase N_2O emissions but this effect was not quantified.

SAR (IPCC, 1996) estimated that CH_4 emissions from agriculture could be reduced by 15 to 56%, mainly through improved nutrition of ruminants and better management of paddy rice, and that improved management could reduce N_2O

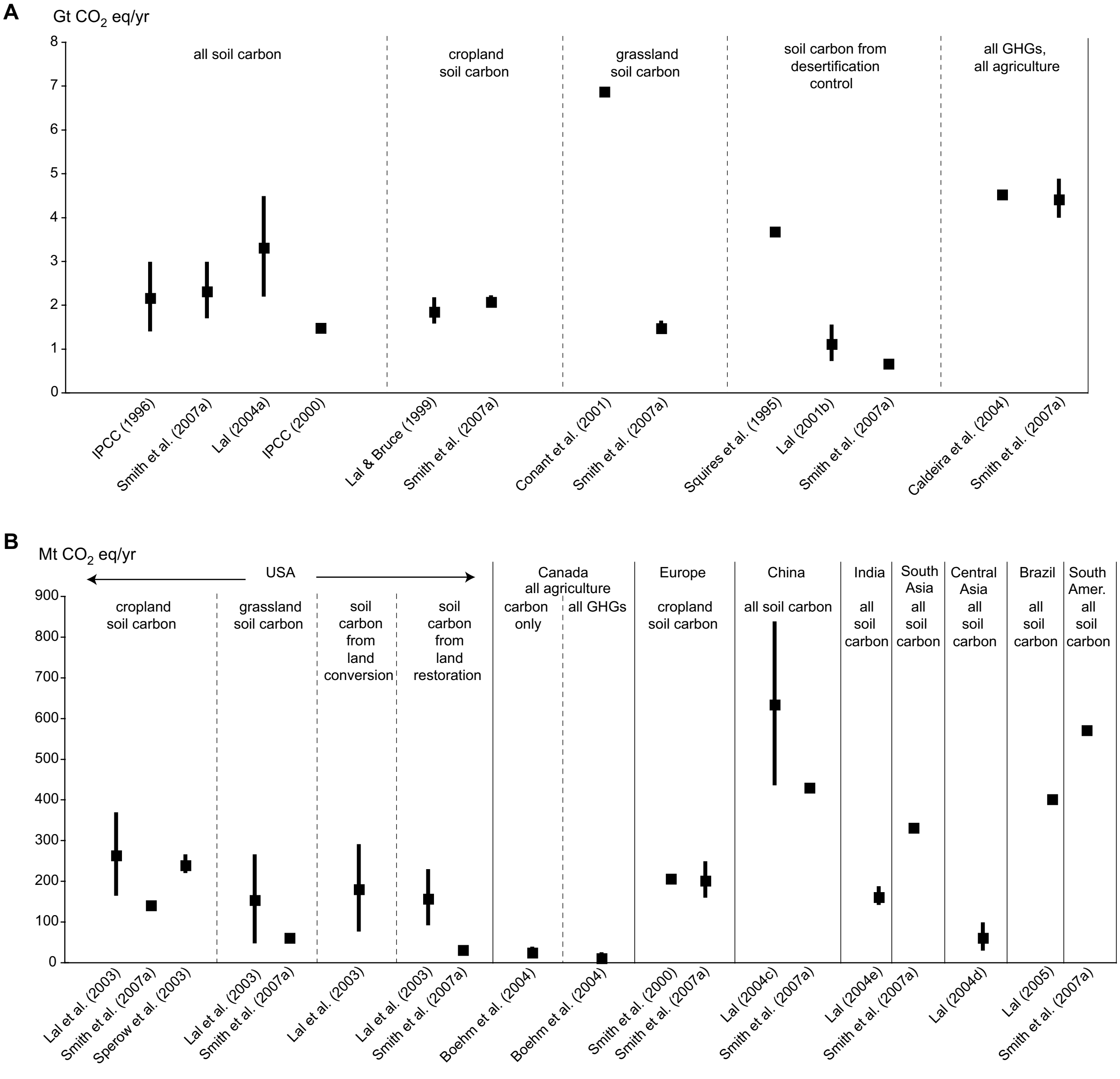

Figure 8.3: *Global (A) and regional (B) estimates of technical mitigation potential by 2030*

Note: Equivalent values for Smith et al. (2007a) are taken from Table 7 of Smith et al., 2007a.

emissions by 9-26%. The document also stated that GHG mitigation techniques will not be adopted by land managers unless they improve profitability but some measures are adopted for reasons other than climate mitigation. Options that both reduce GHG emissions and increase productivity are more likely to be adopted than those which only reduce emissions.

Of published estimates of technical potential, only Caldeira *et al.* (2004) and Smith *et al.* (2007a) provide global estimates considering all GHGs together, and Boehm *et al.* (2004) consider all GHGs for Canada only for 2008. Smith *et al.* (2007a) used per-area or per-animal estimates of mitigation potential for each GHG and multiplied this by the area available for that practice in each region. It was not necessary to use baseline emissions in calculating mitigation potential. US-EPA (2006b) estimated baseline emissions for 2020 for non-CO_2 GHGs as 7250 $MtCO_2$-eq in 2020 (see Chapter 11; Table 11.4). Non-CO_2 GHG emissions in agriculture are projected to increase by about 13% from 2000 to 2010 and by 13% from 2010 to 2020 (US-EPA, 2006b). Assuming a similar rate of increase as in the period from 2000 to 2020, global agricultural non-CO_2 GHG emissions would be around 8200 $MtCO_2$-eq in 2030.

The global technical potential for mitigation options in agriculture by 2030, considering all gases, was estimated to be ~4500 by Caldeira *et al.* (2004) and ~5500-6000 $MtCO_2$-eq/yr by Smith *et al.* (2007a) if considering no economic or other barriers. Economic potentials are considerably lower (see Section 8.4.3.2). Figure 8.3 presents global and regional estimates of agricultural mitigation potential. Of the technical potentials estimated by Smith *et al.* (2007a), about 89% is from soil carbon sequestration, about 9% from mitigation of methane and about 2% from mitigation of soil N_2O emissions (Figure 8.4). The total mitigation potential per region is presented in Figure 8.5.

The uncertainty in the estimates of the technical potential is given in Figure 8.6, which shows one standard deviation either side of the mean estimate (box), and the 95% confidence interval about the mean (line). The range of the standard deviation, and the 95% confidence interval about the mean of 5800 $MtCO_2$-eq/yr, are 3000-8700, and 300-11400 $MtCO_2$-eq/yr, respectively, and are largely determined by uncertainty in the per-area estimate for the mitigation measure. For soil carbon sequestration (89% of the total potential), this arises from the mixed linear effects model used to derive the mitigation potentials. The most appropriate mitigation response will vary among regions, and different portfolios of strategies will be developed in different regions, and in countries within a region.

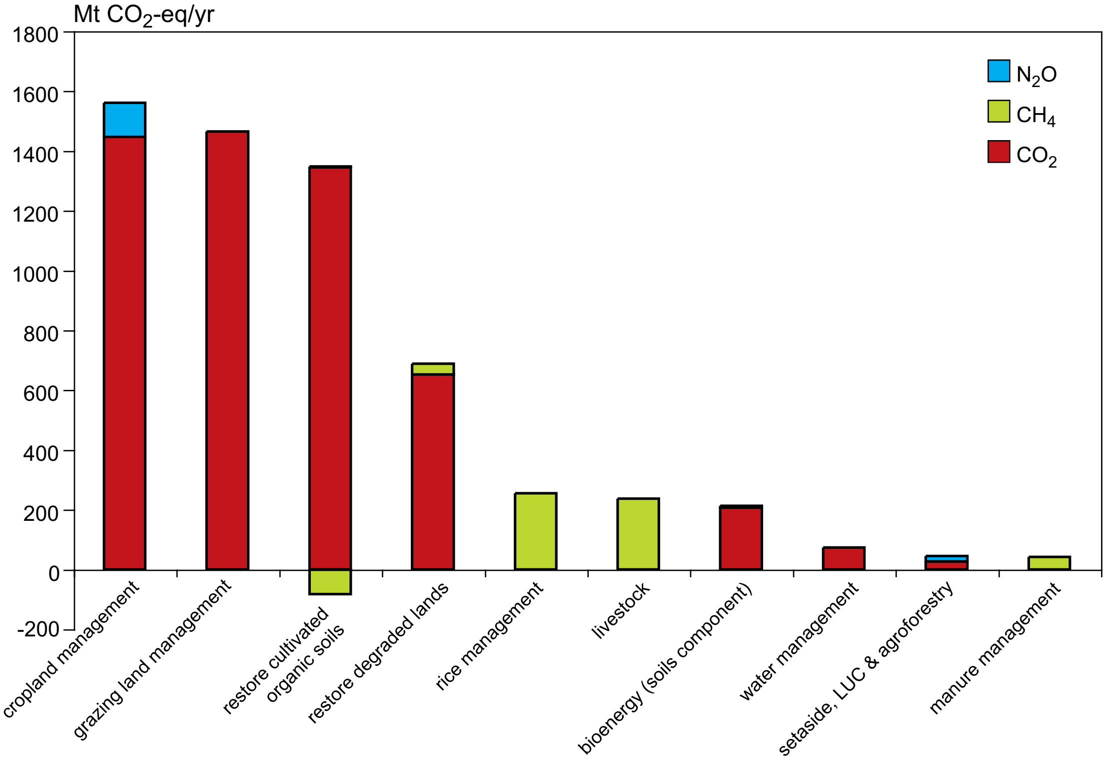

Figure 8.4: *Global technical mitigation potential by 2030 of each agricultural management practice showing the impacts of each practice on each GHG.*

Note: based on the B2 scenario though the pattern is similar for all SRES scenarios.

Source: Drawn from data in Smith et al., 2007a.

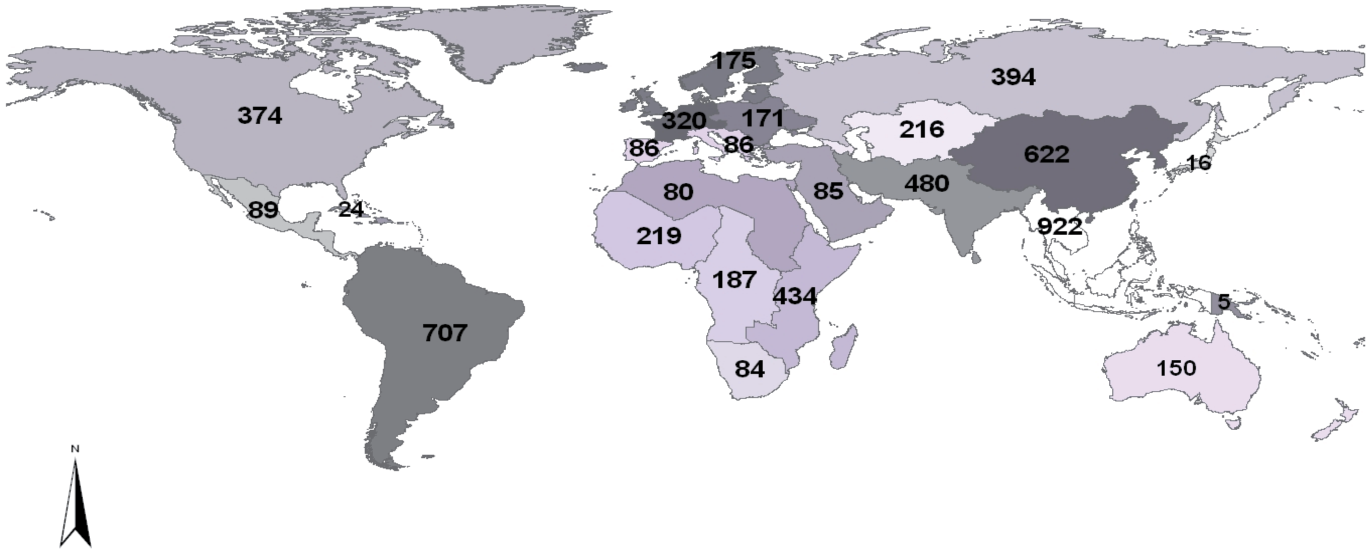

Figure 8.5: *Total technical mitigation potentials (all practices, all GHGs: MtCO2-eq/yr) for each region by 2030, showing mean estimates.*
Note: based on the B2 scenario though the pattern is similar for all SRES scenarios.
Source: Drawn from data in Smith et al., 2007a.

8.4.3.2 *Economic potential for GHG mitigation in agriculture*

US-EPA (2006b) provided estimates of the agricultural mitigation potential (global and regional) at various assumed carbon prices, for N_2O and CH_4, but not for soil carbon sequestration. Manne & Richels (2004) estimated the economic mitigation potential (at 27 US$/$tCO_2$-eq) for soil carbon sequestration only.

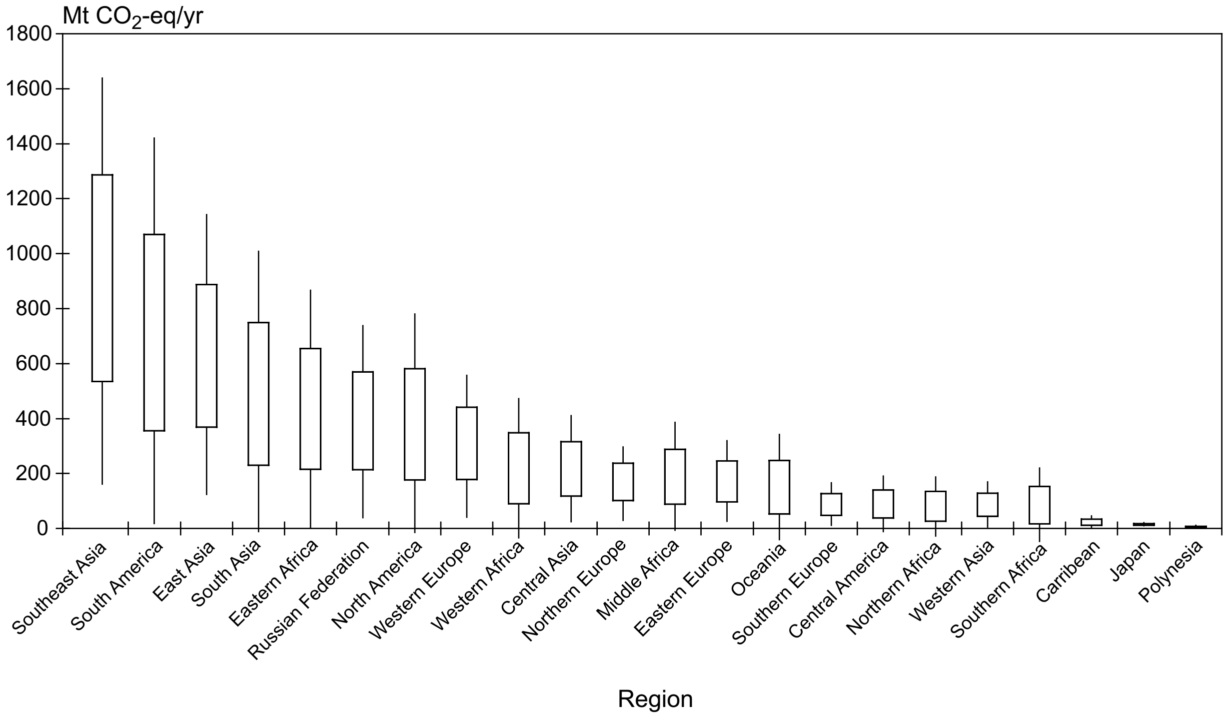

Figure 8.6: *Total technical mitigation potentials (all practices, all GHGs) for each region by 2030*
Note: Boxes show one standard deviation above and below the mean estimate for per-area mitigation potential, and the bars show the 95% confidence interval about the mean. Based on the B2 scenario, although the pattern is similar for all SRES scenarios.
Source: Drawn from data in Smith et al., 2007a.

Table 8.6: *Global agricultural mitigation potential in 2030 from top-down models*

Carbon price	Mitigation ($MtCO_2$-eq/yr)			Number of scenarios
US\$/tCO_2-eq	CH_4	N_2O	CH_4+N_2O	
0-20	0-1116	89-402	267-1518	6
20-50	348-1750	116-1169	643-1866	6
50-100	388	217	604	1
>100	733	475	1208	1

Note: From Chapter 3, Sections 3.3.5 and 3.6.2.
Source: Data assembled from USCCSP, 2006; Rose et al., 2007; Fawcett and Sands, 2006; Smith and Wigley, 2006; Fujino et al., 2006; and Kemfert et al., 2006.

In the IPCC Third Assessment Report (TAR; IPCC, 2001b), estimates of agricultural mitigation potential by 2020 were 350-750 MtC/yr (~1300-2750 $MtCO_2$/yr). The range was mainly caused by large uncertainties about CH_4, N_2O, and soil-related CO_2 emissions. Most reductions will cost between 0 and 100 US\$/tC-eq (~0-27 US\$/tCO_2-eq) with limited opportunities for negative net direct cost options. The analysis of agriculture included only conservation tillage, soil carbon sequestration, nitrogen fertilizer management, enteric methane reduction and rice paddy irrigation and fertilizers. The estimate for global mitigation potential was not broken down by region or practice.

Smith *et al.* (2007a) estimated the GHG mitigation potential in agriculture for all GHGs, for four IPCC SRES scenarios, at a range of carbon prices, globally and for all world regions. Using methods similar to McCarl and Schneider (2001), Smith *et al.* (2007a) used marginal abatement cost (MAC) curves given in US-EPA (2006b) for either region-specific MACs where available for a given practice and region, or global MACs where these were unavailable from US-EPA (2006b).

Recent bottom-up estimates of agricultural mitigation potential of CH_4 and N_2O from US-EPA (2006b) and DeAngelo *et al.* (2006) have allowed inclusion of agricultural abatement into top-down global modelling of long-term climate stabilization scenario pathways. In the top-down framework, a dynamic cost-effective portfolio of abatement strategies is identified. The portfolio includes the least-cost combination of mitigation strategies from across all sectors of the economy, including agriculture. Initial implementations of agricultural abatement into top-down models have employed a variety of alternative approaches resulting in different decision modelling of agricultural abatement (Rose *et al.*, 2007). Currently, only non-CO_2 GHG crop (soil and paddy rice) and livestock (enteric and manure) abatement options are considered by top-down models. In addition, some models also consider emissions from burning of agricultural residues and waste, and fossil fuel combustion CO_2 emissions. Top-down estimates of global CH_4 and N_2O mitigation potential, expressed in CO_2 equivalents, are given in Table 8.6 and Figure 8.7.

Comparing mitigation estimates from top-down and bottom-up modelling is not straightforward. Bottom-up mitigation responses are typically constrained to input management (e.g., fertilizer quantity, livestock feed type) and cost estimates are partial equilibrium in that input and output market prices are fixed as can be key input quantities such as acreage or production. Top-down mitigation responses include more generic input management responses and changes in output (e.g., shifts from cropland to forest) as well as changes in market prices (e.g., decreases in land prices with increasing production costs due to a carbon tax). Global estimates of economic mitigation potential from different studies at different assumed carbon prices are presented in Figure 8.8.

The top-down 2030 carbon prices, as well as the agricultural mitigation response, reflect the confluence of multiple forces, including differences in implementation of agricultural emissions and mitigation, as well as the stabilization target used, the magnitude of baseline emissions, baseline energy technology options, the eligible set of mitigation options, and the solution algorithm. As a result, the opportunity cost of agricultural mitigation in 2030 is very different across scenarios (i.e., model/baseline/mitigation option combinations). As illustrated by the connecting lines in Figure 8.7, agricultural abatement

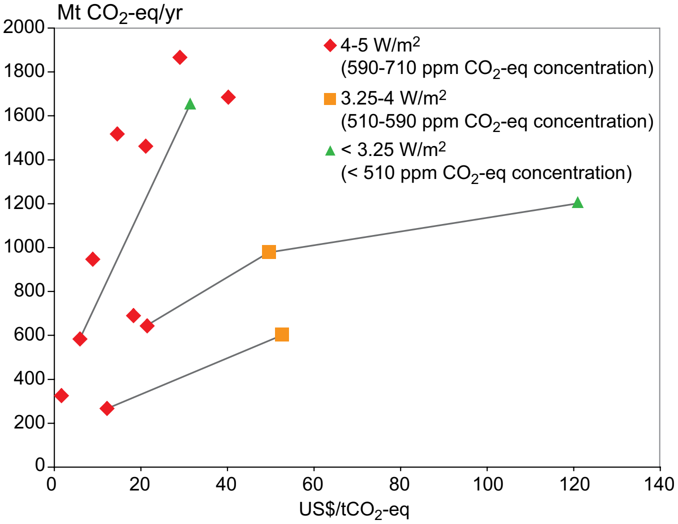

Figure 8.7: *Global agricultural mitigation potential in 2030 from top-down models by carbon price and stabilisation target*
Note: Dashed lines connect results from scenarios where tighter stabilization targets were modelled with the same model and identical baseline characterization and mitigation technologies. From Chapter 3, Sections 3.3.5 and 3.6.2.
Source: Data assembled from USCCSP, 2006; Rose et al., 2007; Fawcett and Sands, 2006; Smith and Wigley, 2006; Fujino et al., 2006; Kemfert et al., 2006.

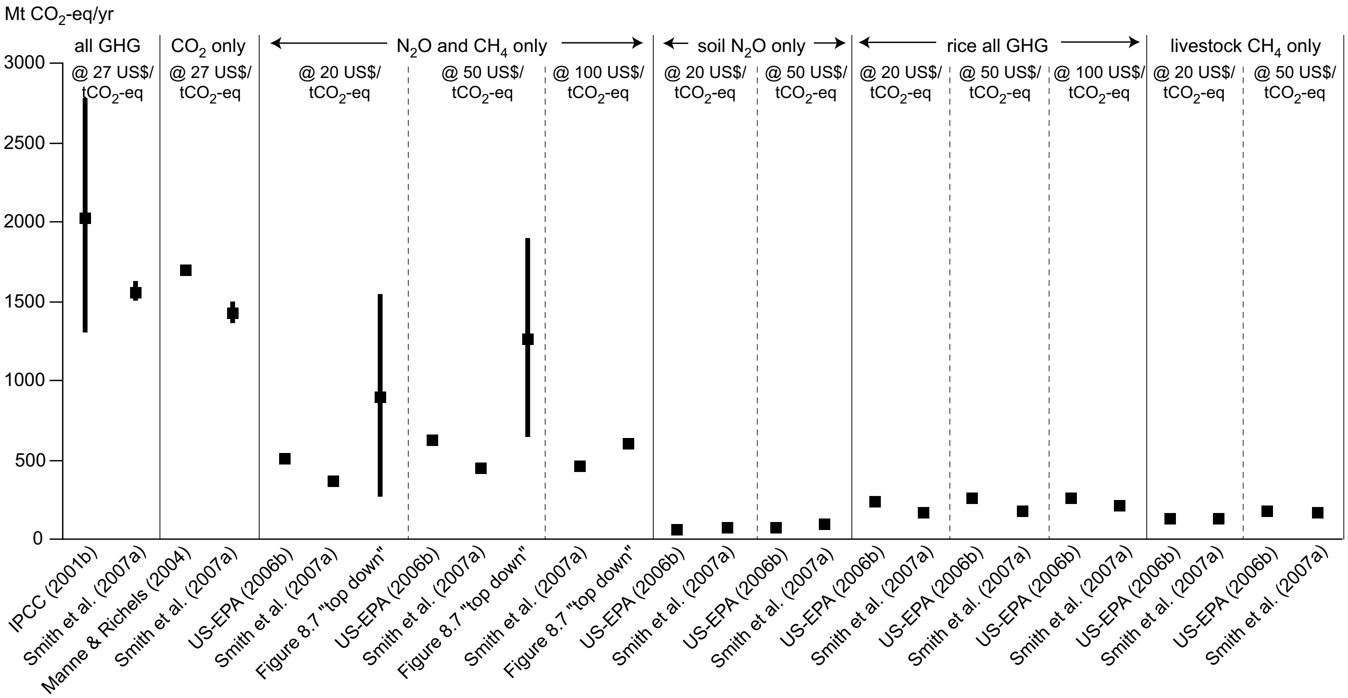

Figure 8.8: *Global economic potentials for agricultural mitigation arising from various practices shown for comparable carbon prices at 2030.*
Notes: US-EPA (2006b) figures are for 2020 rather than 2030. Values for top-down models are taken from ranges given in Figure 8.7.

is projected to increase with the tightness of the stabilization target. On-going model development in top-down land-use modelling is expected to yield more refined characterizations of agricultural alternatives and mitigation potential in the future.

Smith *et al.* (2007a) estimated global economic mitigation potentials for 2030 of 1500-1600, 2500-2700, and 4000-4300 MtCO$_2$-eq/yr at carbon prices of up to 20, 50 and 100 US$/tCO$_2$-eq., respectively shown for OECD versus EIT versus non-OECD/EIT (Table 8.7). The change in global mitigation potential with increasing carbon price for each practice is shown in Figure 8.9.

Table 8.7: *Estimates of the global agricultural economic GHG mitigation potential (MtCO$_2$-eq/yr) by 2030 under different assumed prices of CO$_2$-equivalents*

		Price of CO$_2$-eq (US$/tCO$_2$-eq)		
SRES Scenario		**Up to 20**	**Up to 50**	**Up to 100**
B1	OECD	310 (60-450)	510 (290-740)	810 (440-1180)
	EIT	150 (30-220)	250 (140-370)	410 (220-590)
	Non-OECD/EIT	1080 (210-1560)	1780 (1000-2580)	2830 (1540-4120)
A1b	OECD	320 (60-460)	520 (290-760)	840 (450-1230)
	EIT	160 (30-230)	260 (150-380)	410 (220-610)
	Non-OECD/EIT	1110 (210-1610)	1820 (1020-2660)	2930 (1570-4290)
B2	OECD	330 (60-470)	540 (300-780)	870 (460-1280)
	EIT	160 (30-240)	270 (150-390)	440 (230-640)
	Non-OECD/EIT	1140 (210-1660)	1880 (1040-2740)	3050 (1610-4480)
A2	OECD	330 (60-480)	540 (300-790)	870 (460-1280)
	EIT	165 (30-240)	270 (150-400)	440 (230-640)
	Non-OECD/EIT	1150 (210-1670)	1890 (1050-2760)	3050 (1620-4480)

Note: Figures in brackets show one standard deviation about the mean estimate.

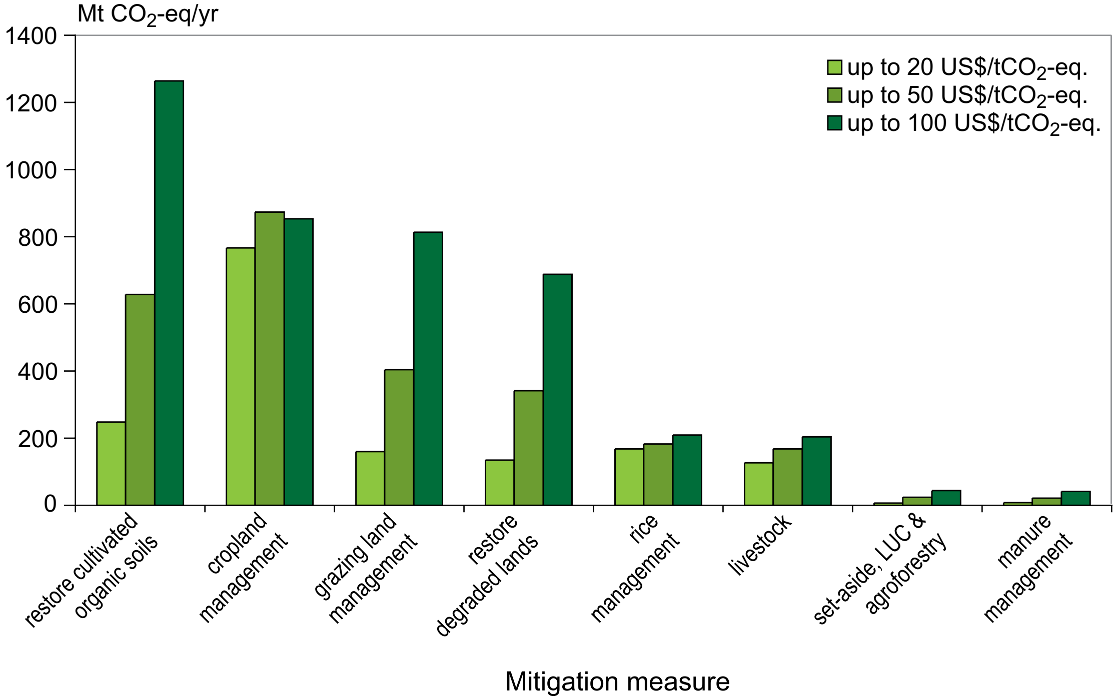

Figure 8.9: *Economic potential for GHG agricultural mitigation by 2030 at a range of prices of CO_2-eq*
Note: Based on B2 scenario, although the pattern is similar for all SRES scenarios.
Source: Drawn from data in Smith et al., 2007a.

8.4.4 Bioenergy feed stocks from agriculture

Bioenergy to replace fossil fuels can be generated from agricultural feedstocks, including by-products of agricultural production, and dedicated energy crops.

8.4.4.1 Residues from agriculture

The energy production and GHG mitigation potentials depend on yield/product ratios, and the total agricultural land area as well as type of production system. Less intensive management systems require re-use of residues for maintaining soil fertility. Intensively managed systems allow for higher utilization rates of residues, but also usually deploy crops with higher crop-to-residue ratios.

Estimates of energy production potential from agricultural residues vary between 15 and 70 EJ/yr. The latter figure is based on the regional production of food (in 2003) multiplied by harvesting or processing factors, and assumed recoverability factors. These figures do not subtract the potential competing uses of agricultural residues which, as indicated by (Junginger et al., 2001), can reduce significantly the net availability of agricultural residues for energy or materials. In addition, the expected future availability of residues from agriculture varies widely among studies. Dried dung can also be used as an energy feedstock. The total estimated contribution could be 5 to 55 EJ/yr worldwide, with the range defined by current global use at the low end, and technical potential at the high end. Utilization in the longer term is uncertain because dung is considered to be a "poor man's fuel".

Organic wastes and residues together could supply 20-125 EJ/yr by 2050, with organic wastes making a significant contribution.

8.4.4.2 Dedicated energy crops

The energy production and GHG mitigation potentials of dedicated energy crops depends on availability of land, which must also meet demands for food as well as for nature protection, sustainable management of soils and water reserves, and other sustainability criteria. Because future biomass resource availability for energy and materials depends on these and other factors, an accurate estimate is difficult to obtain. Berndes *et al.* (2003) in reviewing 17 studies of future biomass availability found no complete integrated assessment and scenario studies. Various studies have arrived at differing figures for the potential contribution of biomass to future global energy supplies, ranging from below 100 EJ/yr to above 400 EJ/yr in 2050. Smeets *et al.* (2007) indicate that ultimate technical potential for energy cropping on current agricultural land, with projected technological progress in agriculture and livestock, could deliver over 800 EJ/yr without jeopardizing the world's food supply. In Hoogwijk *et al.* (2005) and Hoogwijk (2004), the IMAGE 2.2 model was used to analyse biomass production potentials for different SRES scenarios. Biomass production on abandoned agricultural land is calculated at 129 EJ (A2) up to 411 EJ (A1) for 2050 and possibly increasing after that timeframe. 273 EJ (for A1) – 156 EJ (for A2) may be available below US$ 2/GJ production costs. A recent study (Sims *et al.*, 2006) which used lower per-area yield assumptions and bioenergy crop areas projected by the IMAGE 2.2 model suggested more modest potentials (22 EJ/yr) by 2025.

Based on assessment of other studies, Hoogwijk *et al.* (2003), indicated that marginal and degraded lands (including a land surface of 1.7 Gha worldwide) could, be it with lower productivities and higher production costs, contribute another 60-150 EJ. Differences among studies are largely attributable to uncertainty in land availability, energy crop yields, and assumptions on changes in agricultural efficiency. Those with the largest projected potential assume that not only degraded/surplus land are used, but also land currently used for food production (including pasture land, as did Smeets *et al.*, 2007).

Converting the potential biomass production into a mitigation potential is not straightforward. First, the mitigation potential is determined by the lowest supply and demand potentials, so without the full picture (see Chapter 11) no estimate can be made. Second, any potential from bioenergy use will be counted towards the potential of the sectors where bioenergy is used (mainly energy supply and transport). Third, the proportion of the agricultural biomass supply compared to that from the waste or forestry sector cannot be specified due to lack of information on cost curves.

Top-down integrated assessment models can give an estimate of the cost competitiveness of bioenergy mitigation options relative to one another and to other mitigation options in achieving specific climate goals. By taking into account the various bioenergy supplies and demands, these models can give estimates of the combined contribution of the agriculture, waste, and forestry sectors to bioenergy mitigation potential. For achieving long-term climate stabilization targets, the competitive cost-effective mitigation potential of biomass energy (primarily from agriculture) in 2030 is estimated to be 70 to 1260 MtCO$_2$-eq/yr (0-13 EJ/yr) at up to 20 US$/t CO$_2$-eq, and 560-2320 MtCO$_2$-eq/yr (0-21 EJ/yr) at up to 50 US$/tCO$_2$-eq (Rose et al., 2007, USCCSP, 2006). There are no estimates for the additional potential from top down models at carbon prices up to 100 US$/tCO$_2$-eq, but the estimate for prices above 100 US$/tCO$_2$-eq is 2720 MtCO$_2$-eq/yr (20-45 EJ/yr). This is of the same order of magnitude as the estimate from a synthesis of supply and demand presented in Chapter 11, Section 11.3.1.4. The mitigation potentials estimated by top-down models represent mitigation of 5-80%, and 20-90% of all other agricultural mitigation measures combined, at carbon prices of up to 20, and up to 50 US$/tCO$_2$-eq, respectively.

8.4.5 Potential implications of mitigation options for sustainable development

There are various potential impacts of agricultural GHG mitigation on sustainable development. The impacts of mitigation activities in agriculture, on the constituents and determinants of sustainable development are set out in Table 8.8. Broadly, three constituents of sustainable development have been envisioned as the critical minimum: social, economic, and environmental factors. Table 8.8 presents the degree and direction of the likely impact of the mitigation options. The exact magnitude of the effect, however, depends on the scale and intensity of the mitigation measures, and the sectors and policy arena in which they are undertaken.

Agriculture contributes 4% of global GDP (World Bank, 2003) and provides employment to 1.3 billion people (Dean, 2000). It is a critical sector of the world economy, but uses more water than any other sector. In low-income countries, agriculture uses 87% of total extracted water, while this figure is 74% in middle-income countries and 30% in high-income countries (World Bank, 2003). There are currently 276 Mha of irrigated croplands (FAOSTAT, 2006), a five-fold increase since the beginning of the 20th century. With irrigation increasing, water management is a serious issue. Through proper institutions and effective functioning of markets, water management can be implemented with favourable outcomes for both environmental and economic goals. There is a greater need for policy coherence and innovative responses creating a situation where users are asked to pay the full economic costs of the water. This has special relevance for developing countries. Removal of subsidies in the electricity and water sectors might lead to effective water use in agriculture, through adaptation of appropriate irrigation technology, such as drip irrigation in place of tube well irrigation.

Agriculture contributes nearly half of the CH$_4$ and N$_2$O emissions (Bhatia *et al.*, 2004) and rice, nutrient, water and tillage management can help to mitigate these GHGs. By careful drainage and effective institutional support, irrigation costs for farmers can also be reduced, thereby improving economic aspects of sustainable development (Rao, 1994). An appropriate mix of rice cultivation with livestock, known as integrated annual crop-animal systems and traditionally found in West Africa, India and Indonesia and Vietnam, can enhance net income, improve cultivated agro-ecosystems, and enhance human well-being (Millennium Ecosystem Assessment, 2005). Such combinations of livestock and cropping, especially for rice, can improve income generation, even in semi-arid and arid areas of the world.

Groundwater quality may be enhanced and the loss of biodiversity can be influenced by the choice of fertilizer used and use of more targeted pesticides. Further, greater demand for farmyard manure would create income for the animal husbandry sector where usually the poor are engaged. Various country

Table 8.8: *Potential sustainable development consequences of mitigation options*

Activity category	Sustainable development			Notes
	Social	Economic	Environmental	
Croplands – agronomy	?	+	+	1
Croplands – nutrient management	?	+	+	2
Croplands – tillage/residues	?	?	+	3
Croplands – water management	+	+	+	4
Croplands – rice management	+	+	+	5
Croplands – set-aside & LUC	?	-	+	6
Croplands – agro-forestry	+	?	+	7
Grasslands – grazing, nutrients, fire	+	+	+	8
Organic soils – restoration	?	?	+	9
Degraded soils – restoration	+	+	+	10
Biosolid applications	+	-	+/-	11
Bioenergy	+	?	+/-	12
Livestock – feeding	-/?	+	?	13
Livestock – additives	-/?	n/d	n/d	14
Livestock – breeding	-/?	n/d	n/d	14
Manure management	?	n/d	n/d	15

Notes:
+ denotes beneficial impact on component of SD
- denotes negative impact
? denotes uncertain impact
n/d denotes no data
1 Improved yields would mean better economic returns and less land required for new cropland. Societal impact uncertain - impact could be positive but could negatively affect traditional practices.
2 Improved yields would mean better economic returns and less land required for new cropland. Societal impact uncertain - impact could be positive but could negatively affect traditional practices.
3 Improves soil fertility may not increase yield so societal and economic impacts uncertain.
4 All efficiency improvements are positive for sustainability goals and should yield economic benefits even if costs of irrigation are borne by the farmer.
5 Improved yields would mean better economic returns and less land required for new cropland. Societal impacts likely to benign or positive as no large-scale change to traditional practices.
6 Improve soil fertility but less land available for production; potential negative impact on economic returns.
7 Likely environmental benefits, less travel required for fuelwood; positive societal benefits; economic impact uncertain.
8 Improved production would mean better economic returns and less land required for grazing; lower degradation. Societal effects likely to be positive.
9 Organic soil restoration has a host of biodiversity/environmental co-benefits but opportunity cost of crop production lost from this land; economic impact depends upon whether farmers receive payment for the GHG emission reduction.
10 Restoration of degraded lands will provide higher yields and economic returns, less new cropland and provide societal benefits via production stability.
11 Likely environmental benefits though some negative impacts possible (e.g., water pollution) but, depending on the bio-solid system implemented, could increase costs.
12 Bio-energy crops could yield environmental co-benefits or could lead to loss of bio-diversity (depending on the land use they replace). Economic impact uncertain. Social benefits could arise from diversified income stream.
13 Negative/uncertain societal impacts as these practices may not be acceptable due to prevailing cultural practices especially in developing countries. Could improve production and economic returns.
14 Negative/uncertain societal impacts as these practices may not be acceptable due to prevailing cultural practices especially in developing countries. No data (n/d) on economic or environmental impacts.
15 Uncertain societal impacts. No data (n/d) on economic or environmental impacts.

strategy papers on The Millennium Development Goal (MDG) clearly recommend encouragement to animal husbandry (e.g., World Bank, 2005). This is intended to enhance livelihoods and create greater employment. Better nutrient management can also improve environmental sustainability.

Controlling overgrazing through pasture improvement has a favourable impact on livestock productivity (greater income from the same number of livestock) and slows or halts desertification (environmental aspect). It also provides social security to the poorest people during extreme events such as drought (especially in Sub-Saharan Africa). One effective strategy to control overgrazing is the prohibition of free grazing, as was done in China (Rao, 1994) but approaches in other regions need to take into account cultural and institutional contexts. Dryland and desert areas have the highest number of poor people (Millennium Ecosystem Assessment, 2005) and measures to halt overgrazing, coupled with improved livelihood options (e.g., fisheries in Syria , Israel and other central Asian countries), can help reduce poverty and achieve sustainability goals.

Land cover and tillage management could encourage favourable impacts on environmental goals. A mix of horticulture with optimal crop rotations would promote carbon sequestration and could also improve agro-ecosystem function.

Societal well-being would also be enhanced by providing water and enhanced productivity. While the environmental benefits of tillage/residue management are clear, other impacts are less certain. Land restoration will have positive environmental impacts, but conversion of floodplains and wetlands to agriculture could hamper ecological function (reduced water recharge, bioremediation, nutrient cycling, etc.) and therefore, could have an adverse impact on sustainable development goals (Kumar, 2001).

The other mitigation measures listed in Table 8.8 are context- and location-specific in their influence on sustainable development constituents. Appropriate adoption of mitigation measures is likely in many cases to help achieve environmental goals, but farmers may incur additional costs, reducing their returns and income. This trade-off would be most visible in the short term, but in the long term, synergy amongst the constituents of sustainable development would emerge through improved natural capital. Trade-offs between economic and environmental aspects of sustainable development might become less important if the environmental gains were better acknowledged, quantified, and incorporated in the decision-making framework.

Large-scale production of modern bioenergy crops, partly for export, could generate income and employment for rural regions of world. Nevertheless, these benefits will not necessarily flow to the rural populations that need them most. The net impacts for a region as a whole, including possible changes and improvements in agricultural production methods should be considered when developing biomass and bioenergy production capacity. Although experience around the globe (e.g., Brazil, India biofuels) shows that major socioeconomic benefits can be achieved, new bioenergy production schemes could benefit from the involvement of the regional stakeholders, particularly the farmers. Experience with such schemes needs to be built around the globe.

8.5 Interactions of mitigation options with adaptation and vulnerability

As discussed in Chapters 3, 11 and 12, mitigation, climate change impacts, and adaptation will occur simultaneously and interactively. Mitigation-driven actions in agriculture could have (a) positive adaptation consequences (e.g., carbon sequestration projects with positive drought preparedness aspects) or (b) negative adaptation consequences (e.g., if heavy dependence on biomass energy increases the sensitivity of energy supply to climatic extremes; see Chapter 12, Subsection 12.1.4). Adaptation-driven actions also may have both (a) positive consequences for mitigation (e.g., residue return to fields to improve water holding capacity will also sequester carbon); and (b) negative consequences for mitigation (e.g., increasing use of nitrogen fertilizer to overcome falling yield leading to increased nitrous oxide emissions). In many cases, actions taken for reasons unrelated to either mitigation or adaptation (see Sections 8.6 and 8.7) may have considerable consequences for either or both(e.g., deforestation for agriculture or other purposes results in carbon loss as well as loss of ecosystems and resilience of local populations). Adaptation to climate change in the agricultural sector is detailed in (IPCC, 2007; Chapter 5).

For mitigation, variables such as growth rates for bioenergy feedstocks, the size of livestock herds, and rates of carbon sequestration in agricultural lands are affected by climate change (Paustian *et al.*, 2004). The extent depends on the sign and magnitude of changes in temperature, soil moisture, and atmospheric CO_2 concentration, which vary regionally (Christensen *et al*., 2007). All of these factors will alter the mitigation potential; some positively and some negatively. For example: (a) lower growth rates in bioenergy feedstocks will lead to larger emissions from hauling and increased cost; (b) lower livestock growth rates would possibly increase herd size and consequent emissions from manure and enteric fermentation; and (c) increased microbial decomposition under higher temperatures will lower soil carbon sequestration potential. Interactions also occur with adaptation. Butt *et al.* (2006) and Reilly *et al.* (2001) found that modified crop mix, land use, and irrigation are all potential adaptations to warmer climates. All would alter the mitigation potential. Some of the key vulnerabilities of agricultural mitigation strategies to climate change, and the implications of adaptation on GHG emissions from agriculture are summarized in Table 8.9.

8.6 Effectiveness of, and experience with, climate policies; potentials, barriers and opportunities/implementation issues

8.6.1 Impact of climate policies

Many recent studies have shown that actual levels of GHG mitigation are far below the technical potential for these measures. The gap between technical potential and realized GHG mitigation occurs due to costs and other barriers to implementation (Smith, 2004b).

Globally and for Europe, Cannell (2003) suggested that, for carbon sequestration and bioenergy-derived fossil fuel offsets, the realistically achievable potential (potential estimated to take account of all barriers) was ~20% of the technical potential. Similar figures were derived by Freibauer *et al.* (2004) and the European Climate Change Programme (2001) for agricultural carbon sequestration in Europe. Smith *et al.* (2005a) showed recently that carbon sequestration in Europe is likely to be negligible by the first Commitment Period of the Kyoto Protocol (2008-2012), despite the significant technical potential (e.g.,

Table 8.9: *Some of the key vulnerabilities of agricultural mitigation strategies to climate change and the implications of adaptation on GHG emissions from agriculture*

Agricultural mitigation strategies	Vulnerability of the mitigation option to climate change	Implication for GHG emissions of adaptation actions
Cropland management – agronomy	Vulnerable to decreased rainfall, and in cases near the limit of their climate niche, to higher temperatures.	NO_2 emissions would increase if fertilizer use increased, or if more legumes were planted in response to climate-induced production declines.
Cropland management – nutrient management	Only weakly sensitive to climate change, except in cases where the entire cropping enterprise becomes unviable.	No significant adaptation to effects of climate change possible beyond tailoring of practices to ambient conditions. Therefore, additional GHGs not expected.
Cropland management – tillage/residue management	Sensitive to climate change. Higher temperatures could lower soil carbon sequestration potential. Warmer, wetter climates can increase risk of crop pests and diseases associated with reduced till practices.	Adaptation not anticipated to have a significant GHG effect.
Cropland management – water management	Irrigation is susceptible to climate changes that reduce the availability of water for irrigation or increases crop water demand.	Possible increase in energy-related GHG emissions if greater pumping distances or volumes are required. Adoption of more water-use efficient practices will generally lower GHG emissions.
Cropland management – rice management	Vulnerable to climate-change-induced changes in water availability. Low CH_4 emitting cultivars may be susceptible to changes in temperature beyond their tolerance limits.	Adaptation strategies are limited and not expected to have large GHG consequences.
Cropland management – set-aside and land-use change	Set-asides may be needed to offset loss of productivity on other lands.	Adaptation is either to try to keep production high on non-set-aside land, which could increase GHG emissions, or return some set-asides to production. Increases in GHGs are in both cases fairly small, and less than the case of not having set-asides in the first place. They could be further mitigated by applying low GHG emitting practices in all cases.
Cropland management – agro-forestry	Large changes in climate could make certain forms of agro-forestry unviable in particular situations.	Adaptation of practices and species used to less favourable climates could lead to some loss of CO_2 uptake potential.
Grazing land management/pasture improvement	Fire management can be impacted negatively or positively by climate change depending on ecosystem and sign of climate change. Extreme drying or warming could make marginal grazing lands unviable. Wetter conditions will promote conversion of grazing lands to crops.	Increased fire protection activities can increase GHGs emissions by a small amount, thus reducing the net benefit obtained from reducing fire extent and frequency.
Management of agricultural organic soils	The mitigation measure is sensitive to increases in temperature or decreases in moisture, both of which would decrease the carbon sequestration potential.	Some trade-offs between CO_2 uptake and CH_4 emissions can be expected if the soils become wetter as a result of the adaptation management.
Restoration of degraded lands	The sustainability of restored lands could be vulnerable to increased temperature and/or decreased soil moisture.	Energy used to replant, or fertilizer used to increase establishment, success could lead to small additional GHG emissions
Livestock - improved feeding practices, specific agents and dietary additives, longer term structural and management changes and animal breeding	Weakly vulnerable to climate change except if it leads to the loss of viability of livestock enterprises in marginal areas or increased cost (or decreased availability) of feed inputs.	No general adaptation strategies. Specific strategies may have minor impacts on GHG emissions, for example, transport of feed supplements from distant locations could lead to increased net GHG emissions.
Manure/biosolid management	Controlled waste digestion generally positively affected by moderately rising temperatures. Where GHGs are not trapped, higher temperatures could hamper management.	If used as a nutrient source on pasture can increase CO_2 uptake and carbon storage.
Bioenergy – energy crops, solid, liquid, biogas, residues	Particular bioenergy crops potentially sensitive to climate change, either positively or negatively. Areas devoted to bioenergy could be under increasing competition with the needs for food agriculture or biodiversity conservation under changing climate.	Generally, results in net CO_2 uptake on land (apart from the fossil-fuel substitution). N_2O emissions would increase if N turnover rates were greater than under previous land uses. Possible positive and negative impacts on net GHG emissions at various stages of the energy chain (cultivation, harvesting, transport, conversion) must be managed.

Smith *et al.*, 2000; Freibauer *et al.*, 2004; Smith, 2004a). The estimates of global economic mitigation potential in 2030 at different costs reported in Smith *et al.* (2007a) were 28, 45 and 73% of technical potential at up to 20, 50 and 100 US$/$tCO_2$-eq, respectively.

In Europe, there is little evidence that climate policy is affecting GHG emissions from agriculture (see Smith *et al.*, 2005a), with most emission reduction occurring through non-climate policy (see Section 8.7; Freibauer *et al.*, 2004). Some countries have agricultural policies designed to reduce GHG emissions (e.g., Belgium), but most do not (Smith *et al.*, 2005a). The European Climate Change Programme (2001) recommended improvement of fertilizer application, set-aside, and reduction of livestock methane emissions (mainly through biogas production) as being the most cost-effective GHG mitigation options for European agriculture.

In North America, the US Global Climate Change Initiative aims to reduce GHG intensity by 18% by 2012. Agricultural sector activities include manure management, reduced tillage, grass plantings, and afforestation of agricultural land. In Canada, agriculture contributes about 10% to national emissions, so mitigation (removals and emission reductions) is considered to be an important contribution to reducing emissions (and at the same time to reduce risk to air, water and soil quality). Various programmes (e.g., AAFC GHG Mitigation programme) encourage voluntary adoption of mitigation practices on farms.

In Oceania, vegetation management policies in Australia have assisted in progressively restricting emissions from land-use change (mainly land clearing for agriculture) to about 60% of 1990 levels. Complementary policies that aim to foster establishment of both commercial and non-commercial forestry and agro-forestry are resulting in significant afforestation of agricultural land in both Australia and New Zealand. Research is being supported to develop cost-effective GHG abatement technologies for livestock (including dietary manipulation and other methods of reducing enteric methane emissions, as well as manure management), agricultural soils (including nutrient and soil management strategies), savannas, and planted forests. The Greenhouse Challenge Plus programme and other partnership initiatives between the Government and industry are facilitating the integration of GHG abatement measures into agricultural management systems.

In Latin America and the Caribbean, climate change mitigation is still not considered in mainstream policy. Most countries have devoted efforts to capacity building for complying with obligations under the UNFCCC, and a few have prepared National Strategy Studies for Kyoto Protocol's Clean Development Mechanism (CDM). Carbon sequestration in agricultural soils has the highest mitigation potential in the region, and its exclusion from the CDM has hindered wider adoption of pertinent practices (e.g., zero tillage).

In Asia, China has policies that reduce GHG emissions, but these were implemented for reasons other than climate policy. These are discussed further in Section 8.7. Currently, there are no policies specifically aimed at reducing GHG emissions. Japan has a number of policies such as Biomass Nippon Strategy, which promotes the utilization of biomass as an alternative energy source, and Environment-Conserving Agriculture, which promotes energy-efficient agricultural machinery, reduction in use of fertilizer, and appropriate management of livestock waste, etc.

In Africa, the impacts of climate policy on agricultural emissions are small. There are no approved CDM projects in Africa related to the reduction of agricultural GHG emissions *per se.* Several projects are under investigation in relation to the restoration of agriculturally-degraded lands, carbon sequestration potential of agro-forestry, and reduction in sugarcane burning. Many countries in Africa have prepared National Strategy Studies for the CDM in complying with obligations under UNFCCC. The main obstacles to implementation of CDM projects in Africa, however, are lack of financial resources, qualified personnel, and the complexity of the CDM.

Agricultural GHG offsets can be encouraged by market-based trading schemes. Offset trading, or trading of credits, allows farmers to obtain credits for reducing their GHG emission reductions. The primary agricultural project types include CH_4 capture and destruction, and soil carbon sequestration. Although not included in current projects, measures to reduce N_2O emissions could be included in the future. The vast majority of agricultural projects have focused on CH_4 reduction from livestock wastes in North America (Canada, Mexico and the United States), South America (Brazil), China, and Eastern Europe. Most of these projects have resulted in the production of Certified Emission Reductions (CERs) from the CDM. Credits are bought and sold through the use of offset aggregators, brokers, and traders. Although the CDM does not currently support soil carbon sequestration projects, emerging markets in Canada and the United States are supporting offset trading from soil carbon sequestration. In Canada, farm groups such as the Saskatchewan Soil Conservation Association (SSCA) encourage farmers to adopt no-till practices in return for carbon offset credits. In the USA, the Pacific Northwest Direct Seed Association offers soil carbon credits generated from no-till management to an energy company The Chicago Climate Exchange (CCX) (www.chicagoclimatex.com/) allows GHG offsets from no-tillage and conversion of cropland to grasslands to be traded by voluntary action through a market trading mechanism. These approaches to agriculturally derived GHG offset will likely expand geographically and in scope. Policy instruments are detailed in Chapter 13 (Section 13.2).

8.6.2 Barriers and opportunities/implementation issues

The commonly mentioned barriers to adoption of carbon sequestration activities on agricultural lands include the following:

Maximum Storage: Carbon sequestration in soils or terrestrial biomass has a maximum capacity for the ecosystem, which may be reached after 15 to 60 years, depending on management practice, management history, and the system (West and Post, 2002). However, sequestration is a rapidly and cheaply deployable mitigation option, until more capital-intensive developments, and longer-lasting actions become available (Caldeira *et al.*, 2004; Sands and McCarl, 2005).

Reversibility: A subsequent change in management can reverse the gains in carbon sequestration over a similar period of time. Not all agricultural mitigation options are reversible; reduction in N_2O and CH_4 emissions, avoided emissions as a result of agricultural energy efficiency gains or substitution of fossil fuels by bio-energy are non-reversible.

Baseline: The GHG net emission reductions need to be assessed relative to a baseline. Selection of an appropriate baseline to measure management-induced soil carbon changes is still an obstacle in some mitigation projects. The extent of practices already in place in project regions will need to be determined for the baseline.

Uncertainty: This has two components: mechanism uncertainty and measurement uncertainty. Uncertainty about the complex biological and ecological processes involved in GHG emissions and carbon storage in agricultural systems makes investors more wary of these options than of more clear-cut industrial mitigation activities. This barrier can be reduced by investment in research. Secondly, agricultural systems exhibit substantial variability between seasons and locations, creating high variability in offset quantities at the farm level. This variability can be reduced by increasing the geographical extent and duration of the accounting unit (e.g., multi-region, multi-year contracts; Kim and McCarl, 2005).

Displacement of Emissions: Adopting certain agricultural mitigation practices may reduce production within implementing regions, which, in turn, may be offset by increased production outside the project region unconstrained by GHG mitigation objectives, reducing the net emission reductions. 'Wall-to-wall' accounting can detect this, and crediting correction factors may need to be employed (Murray *et al.*, 2004; US-EPA, 2005).

Transaction costs: Under an incentive-based system such as a carbon market, the amount of money farmers receive is not the market price, but the market price less brokerage cost. This may be substantial, and is an increasing fraction as the amount of carbon involved diminishes, creating a serious entry barrier for smallholders. For example, a 50 kt contract needs 25 kha under soil carbon management (uptake ~ 2 tCO_2 ha/yr). In developing countries, this could involve many thousands of farmers.

Measurement and monitoring costs: Mooney *et al.* (2004) argue that such costs are likely to be small (under 2% of the contract), but other studies disagree (Smith, 2004c). In general, measurement costs per carbon-credit sold decrease as the quantity of carbon sequestered and area sampled increase. Methodological advances in measuring soil carbon may reduce costs and increase the sensitivity of change detection. However, improved methods to account for changes in soil bulk density remain a hindrance to quantification of changes in soil carbon stocks (Izaurralde and Rice, 2006). Development of remote sensing, new spectral techniques to measure soil carbon, and modelling offer opportunities to reduce costs but will require evaluation (Izaurralde and Rice, 2006, Brown *et al.*, 2006; Ogle and Paustian, 2005; Gehl and Rice, 2007).

Property rights: Property rights, landholdings, and the lack of a clear single-party land ownership in certain areas may inhibit implementation of management changes.

Other barriers: Other possible barriers to implementation include the availability of capital, the rate of capital stock turnover, the rate of technological development, risk attitudes, need for research and outreach, consistency with traditional practices, pressure for competing uses of agricultural land and water, demand for agricultural products, high costs for certain enabling technologies (e.g., soil tests before fertilization), and ease of compliance (e.g., straw burning is quicker than residue removal and can also control some weeds and diseases, so farmers favour straw burning).

8.7 Integrated and non-climate policies affecting emissions of GHGs

Many policies other than climate policies affect GHG emissions from agriculture. These include other UN conventions such as Biodiversity, Desertification and actions on Sustainable Development (see Section 8.4.5), macroeconomic policy such as EU Common Agricultural Policy (CAP)/CAP reform, international free trade agreements, trading blocks, trade barriers, region-specific programmes, energy policy and price adjustment, and other environmental policies including various environmental/agro-environmental schemes. These are described further below.

8.7.1 Other UN conventions

In Asia, China has introduced laws to convert croplands to forest and grassland in Vulnerable Ecological Zones under the UN Convention on Desertification. This will increase carbon storage and reduce N_2O emissions. Under the UN Convention on Biodiversity, China has initiated a programme that restores croplands close to lakes, the sea, or other natural lands as conservation zones for wildlife. This may increase soil carbon sequestration but, if restored to wetland, could increase CH_4 emissions. In support of UN Sustainable Development guidelines, China has introduced a Land Reclamation Regulation (1988) in which land degraded by, for example, construction or mining is restored for use in agriculture, thereby increasing soil carbon storage. In Europe (including Eastern Europe, the Caucasus and Central Asia) and North America, the UN conventions have had few significant impacts on agricultural GHG emissions. In Europe, the UN Convention on Long Range Trans-boundary Air Pollutants also leads to regulations to control air pollutants (e.g., by regulating N emissions) that could have substantial impacts on emission reductions in the agricultural sector.

8.7.2 Macroeconomic and sectoral policy

Some macro-economic changes, such as the burden of a high external debt in Latin America, triggered the adoption in the 1970s of policies designed for improving the trade balance, mainly by promoting agricultural exports (Tejo, 2004). This resulted in the changes in land use and management (see Section 8.3.3), which are still causing increases in annual GHG emissions today. In other regions, such as the countries of Eastern Europe, the Caucasus and Central Asia and many Central and East European countries, political changes since 1990 have meant agricultural de-intensification with less inputs, and land abandonment, leading to a decrease in agricultural GHG emissions. In Africa, the cultivated area in Southern Africa has increased by 30% since 1960, while agricultural production has doubled (Scholes and Biggs, 2004). The macroeconomic development framework for Africa (NEPAD, 2005) emphasises agriculture-led development. It is, therefore, anticipated that the cropped area will continue to increase, especially in Central, East, and Southern Africa, perhaps at an accelerating rate. In Western Europe, North America, Asia (China) and Oceania, macroeconomic policy has tended to reduce GHG emissions. The declining emission trend in Western Europe is likely a consequence of successive reforms of the Common Agricultural Policy (CAP) since 1992. The 2003 EU CAP reform is expected to lead to further reductions, mainly through reduction of animal numbers (Binfield *et al.*, 2006). The reduced GHG emissions could be offset by activity elsewhere. Various macro-economic policies that potentially affect agricultural GHG emissions in each major world region are presented in Table 8.10.

WTO negotiations, to the extent they move toward free trade, would permit countries to better adjust to climate change and the dislocations in production caused by mitigation activities, by adjusting their import/export mix. International trade agreements such as WTO may also have impacts on the amount and geographical distribution of GHG emissions. If agricultural subsidies are reduced and markets become more open, a shift in production from developed to developing countries would be expected, with the consequent displacement of GHG emissions to the latter. Since agricultural practices and GHG emissions per unit product differ between countries, such displacement may also cause changes in total emissions from agriculture. In addition, the increase in international flow of agricultural products which may result from trade liberalization could cause higher GHG emissions from the use of transport fuels.

8.7.3 Other environmental policies

In most world regions, environmental policies have been put in place to improve fertility, to reduce erosion and soil loss, and to improve agricultural efficiency. The majority of these environmental policies also reduce GHG emissions. Various environmental policies not implemented specifically to address GHG emissions but potentially affect agricultural GHG emissions in each major world region are presented in Table 8.11.

In all regions, policies to improve other aspects of the environment have been more effective in reducing GHG emissions from agriculture than policies aimed specifically at reducing agricultural GHG emissions (see Section 8.6.1). The importance of identifying these co-benefits when formulating climate and other environmental policy is addressed in Section 8.8.

8.8 Co-benefits and trade-offs of mitigation options

Many of the measures aimed at reducing GHG emissions have other impacts on the productivity and environmental integrity of agricultural ecosystems, mostly positive (Table 8.12). These measures are often adopted mainly for reasons other than GHG mitigation (see Section 8.7.3). Agro-ecosystems are inherently complex and very few practices yield purely win-win outcomes; most involve some trade-offs (DeFries *et al.*, 2004; Viner *et al.*, 2006) above certain levels or intensities of implementation. Specific examples of co-benefits and trade-offs among agricultural GHG mitigation measures include:

- Practices that maintain or increase crop productivity can improve global or regional food security (Lal, 2004a, b; Follett *et al.*, 2005). This co-benefit may become more important as global food demands increase in coming decades (Sanchez and Swaminathan, 2005; Rosegrant and Cline, 2003; FAO, 2003; Millennium Ecosystem Assessment, 2005). Building reserves of soil carbon often also increases the potential productivity of these soils. Furthermore, many of the measures that promote carbon sequestration also prevent degradation by avoiding erosion and improving soil structure. Consequently, many carbon conserving practices sustain or enhance future fertility, productivity and resilience of soil resources (Lal, 2004a; Cerri *et al.*, 2004; Freibauer *et al.*, 2004; Paustian *et al.*, 2004; Kurkalova

Table 8.10: *Summary of various macro-economic policies that potentially affect agricultural GHG emissions, listing policies for each major world region and the potential impact on the emissions of each GHG*

Region	Macro-economic policies potentially affecting agricultural GHG emissions	Impact on CO_2 emissions	Impact on N_2O emissions	Impact on CH_4 emissions
North America	• Energy conservation and energy security policies – promote bio-energy – increase fossil fuel offsets and possibly SOC (USA)	+		
	• Energy price adjustments - encourage agricultural mitigation - more reduced tillage – increase SOC (USA)	+	?	
	• Removal of the Grain Transportation Subsidy shifted production from annual to perennial crops and livestock (Canada)	+	+	+
Latin America	• Policies since 1970s to promote agricultural products exports (Tejo, 2004) resulting in land management change –increasing GHG emissions (Latin America)	-	-	-
	• Promotion of biofuels (e.g., PROALCOOL (Brazil)	+		
	• Brazil and Argentina implemented policies to make compulsory 5% biodiesel in all diesel fuels consumed (Brazil & Argentina)	+		
Europe, the Caucasus and Central Asia	• Common Agricultural Policy (CAP) 2003 - Single Farm Payment decoupled from production - replaces most of the previous area-based payments. Income support conditional to statutory environmental management requirements (e.g., legislation on nitrates) and the obligation to maintain land under permanent pasture (cross-compliance).	+	+	
	• Political changes in Eastern Europe - closure of many intensive pig units - reduced GHG emissions (EU and wider Europe)	+	+	+
	• Macro-economic changes in the countries of Eastern Europe, the Caucasus and Central Asia:			
	a) Abandonment of croplands since 1990 (1.5 Mha); grasslands and regenerating forests sequestering carbon in soils and woody biomass (all countries of Eastern Europe, the Caucasus and Central Asia:)	+ +	+	
	b) Use of agricultural machinery declined and fossil fuel use per ha of cropland (Romanenkov *et al.,* 2004) - decreased CO_2 (fossil fuel) increased CO_2 (straw burning – all countries of Eastern Europe, the Caucasus and Central Asia)		+	
	c) Fertilizer consumption has dropped; 1999 N_2O emissions from agriculture 19.5% of 1990 level (Russia & Belarus).	+		
	d) CO_2 emissions from liming have dropped to 8% of 1990 levels (Russia)			+
	e) Livestock CH_4 emissions in 1999 were less than 48% of the 1990 level (Russia)	+		
	f) The use of bare fallowing has declined (88% of the area in bare fallow in 1999 compared to 1990; Agriculture of Russia, 2004) (Russia)	+		
	g) Changes in rotational structure (more perennial grasses) (Russia)			
Africa	• The cultivated area in Southern Africa has increased 30% since 1960, while agricultural production has doubled - agriculture-led development (Scholes and Biggs 2004; NEPAD 2005).Cropped area will continue to increase, especially in Central, East and Southern Africa, perhaps at an accelerating rate.	-	-	-
Asia	• In some areas, croplands are currently in set-aside for economic reasons (China)	+	+	
Oceania	• Australia and New Zealand continue to provide little direct subsidy to agriculture - highly efficient industries that minimize unnecessary inputs and reduce waste - potential for high losses (such as N_2O) is reduced. Continuing tightening of terms of trade for farm enterprises, as well as ongoing relaxation of requirements for agricultural imports, is likely to maintain this focus (Australia and New Zealand)		+ +	+
	• The establishment of comprehensive water markets are expected, over time, to result in reductions in the size of industries such as rice and irrigated dairy with consequent reductions in the emissions from these sectors (Australia)			

Note: + denotes a positive effect (benefit); - denotes a negative effect

Table 8.11: *A non-exhaustive summary of environmental policies that were not implemented specifically to address GHG emissions, but that can affect agricultural GHG emissions. Examples of policies are listed for major world region and the potential impact on the emissions of each GHG is indicated.*

Region	Other environmental policies potentially affecting agricultural GHG emissions	Impact on CO_2 emissions	Impact on N_2O emissions	Impact on CH_4 emissions
North America	• Environmental Quality Incentives Program (EQIP) – cost-sharing and incentive payments for conservation practices on working farms (USA) • Conservation Reserve Program (CRP) - environmentally sensitive land converted to native grasses, trees, etc. (USA) • Conservation Security Program (CSP) – assistance promoting conservation on cropland, pasture and range land (and farm woodland) (USA) • Green cover in Canada and provincial initiatives – encourages shift from annual to perennial crop production on poor quality soils (Canada) • Agriculture Policy Framework (APF) programmes to reduce agriculture risks to the environment, including GHG emissions (Canada) • Nutrient Management programmes – introduced to improve water quality, may indirectly reduce N_2O emissions (Canada)	+ + + + + +	+ + + + + +	 + +
Latin America	• Increasing adoption of environmental policies driven by globalization, consolidation of democratic regimes (Latin America & Caribbean) • 14 countries have introduced environmental regulations over the last 20 years – most have implemented measures to protect the environment • Promotion of no-till agriculture in the Mercosur area (Brazil, Argentina, Uruguay and Paraguay) • “Program Crop-Livestock Integration” promotes soil carbon, reduced erosion, reduced pathogens, fertility for pastures, no till cropping (Brazil)	+/- + + +	+/- ? ?	+/-
Europe, the Caucasus and Central Asia	• EU set aside programme - encouraged carbon sequestering practices, but now replaced by the single farm payment under the new CAP (EU) • EU/number of member states - soil action plans to promote soil quality/health/ sustainability, encourages soil carbon sequestration (EU) • Encouragement of composting in some EU member states (e.g., Belgium; Sleutel 2005), but policies are limited (Smith *et al*., 2005a) (EU) • EU Water Framework Directive (WFD) promotes careful use of N fertilizer. Impact of WFD on agricultural GHG emissions as yet unclear (EU) • The ban of burning of field residues in the 1980s (for air quality purposes) enhance soil carbon, reduce N_2O and CH_4 (Smith *et al*., 1997; 2000) (EU) • The dumping ban at sea of sewage sludge in Europe in 1998 - more sludge reached agricultural land (Smith *et al*., 2000; 2001) (EU) • "Vandmiljøplaner" (water environmental plans) for the agricultural sector with clear effect (decrease) of GHGs (Denmark) • Land Codes of the Russian Federation, Belarus and the Ukraine - land conservation for promoting soil quality restoration and protection • “Land Reform Development in Russian Federation” & “Fertility 2006-2010” - plans to promote soil conservation/fertility/sustainability (Russia) • Ukrainian law “Land protection” - action plans to promote soil conservation/increase commercial yields/fertility/sustainability (Ukraine) • Laws in Belarus such as “State Control of Land Use and Land Protection” encourages carbon sequestration (Belarus) • Laws in the Ukraine to promote conversion of degraded lands to set-aside (Ukraine) • Water quality initiatives, for example, Water Codes encourage reforestation and grassland riparian zones (Russia, Ukraine and Belarus) • The ban of fertilizer application in some areas - reduce N_2O emissions (Russia, Belarus, Ukraine) & regional programmes for example, Revival of the Volga	+ + + ? + + + + + + + + + +	 + + + ? +	 + +
Africa	• The reduction of the area of rangelands burned - objective of both colonial and post-colonial administrations; renewed efforts (South Africa, 1998)	+	+	+
Asia	• Soil sustainability programmes - N fertilizer added to soils only after soil N testing (China) • Regional agricultural development programmes - enhance soil carbon storage (China) • Water quality programmes that control non-point source pollution (China) • Air quality legislation - bans straw burning, thus reducing CO_2 (and CH_4 and N_2O) emissions (China) • “Township Enterprises” & “Ecological Municipality” - reduce waste disposal, chemical fertilizer and pesticides, and bans straw burning (China)	 + + +	+ + + +	 + +
Oceania	• Wide range of policies to maintain function/conservation of agricultural landscapes, river systems and other ecosystems (Australia and New Zealand) • Industry changes leading to rapid increase in N fertilizer use over the past decade (250% and 500% increases in Australia and New Zealand, respectively) • Increases in intensive livestock production; raised concerns about water quality and the health of riverine/offshore ecosystems (Australia and New Zealand) • Policy responses are being developed that include monitoring, regulatory, research and extension components (Australia and New Zealand)	+ + + +	- + + +	- +

Note: + denotes a positive effect (benefit); - denotes a negative effect

Table 8.12: *Summary of possible co-benefits and trade-offs of mitigation options in agriculture.*

Measure	Examples	Food security (productivity)	Water quality	Water conservation	Soil quality	Air quality	Bio-diversity, wildlife habitat	Energy conservation	Conservation of other biomes	Aesthetic/ amenity value
Cropland management	Agronomy	+	+/-	+/-	+	+/-	+/-	-	+	+/-
	Nutrient management	-/+	+		+	+		+		
	Tillage/residue management	+	+/-	+	+		+	+		
	Water management (irrigation, drainage)	+	+/-	+/-	+/-			-	+	
	Rice management	+	+	+/-		+/-			+	
	Agro-forestry	+/-	+/-	-			+	+		
	Set-aside, land-use change	-	+	+	+	+	+	+	-	+
Grazing land management/ pasture improvement	Grazing intensity	+/-			+		+			+
	Increased productivity (e.g., fertilization)	+	+/-							
	Nutrient management	+	+/-	+	+		+	-	+	+/-
	Fire management	+	+			+	+/-			+/-
	Species introduction (including legumes)	+			+			+		
Management of organic soils	Avoid drainage of/restore wetlands	-			+		+	+	-	+
Restoration of degraded lands	Erosion control, organic amendments, nutrient amendments	+	+		+		+		+	+
Livestock management	Improved feeding practices	+			+/-				+	
	Specific agents and dietary additives	+								
	Longer term structural and management changes and animal breeding	+								
Manure/biosolid management	Improved storage and handling	+	+/-		+	+/-				
	Anaerobic digestion					+		+		
	More efficient use as nutrient source	+	+		+	+		+		
Bioenergy	Energy crops, solid, liquid, biogas, residues	-					-	+	-	
	References (see footnotes)	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*

Note:+ denotes a positive effect (benefit); - denotes a negative effect (trade-off). The co-benefits and trade-offs vary among regions. Economic costs and benefits, often key driving variables, are considered in Section 8.4.3

Sources:

- *a* *Foley et al., 2005; Lal, 2001a, 2004a;*
- *b* *Mosier, 2002; Freibauer et al., 2004; Paustian et al., 2004; Cerri et al.., 2004*
- *c* *Lal, 2002, 2004b; Dias de Oliveira et al., 2005; Rockström, 2003.*
- *d* *Lal, 2001b, Janzen, 2005; Cassman et al., 2003; Cerri et al., 2004; Wander and Nissen, 2004*
- *e* *Mosier, 2001; 2002; Paustian et al.., 2004*
- *f* *Foley et al.., 2005; Dias de Oliveira et al., 2005; Freibauer et al., 2004; Falloon et al., 2004; Huston and Marland, 2003; Totten et al., 2003*
- *g* *Lal et al., 2003; West and Marland, 2003*
- *h* *Balmford et al., 2005; Trewavas, 2002; Green et al., 2005; West and Marland, 2003*
- *i* *Freibauer et al., 2004*

et al., 2004; Díaz-Zorita *et al.*, 2002). In some instances, where productivity is enhanced through increased inputs, there may be risks of soil depletion through mechanisms such as acidification or salinization (Barak *et al.*, 1997; Díez *et al.*, 2004; Connor, 2004).

- A key potential trade-off is between the production of bio-energy crops and food security. To the extent that bio-energy production uses crop residues, excess agricultural products or surplus land and water, there will be little resultant loss of food production. But above this point, proportional losses of food production will be strongly negative. Food insecurity is determined more by inequity of access to food (at all scales) than by absolute food production insufficiencies, so the impact of this trade-off depends among other things on the economic distributional effects of bio-energy production.
- Fresh water is a dwindling resource in many parts of the world (Rosegrant and Cline, 2003; Rockström, 2003). Agricultural practices for mitigation of GHGs can have both negative and positive effects on water conservation, and on water quality. Where measures promote water use efficiency (e.g., reduced tillage), they provide potential benefits. But in some cases, the practices could intensify water use, thereby reducing stream flow or groundwater reserves (Unkovich, 2003; Dias de Oliveira *et al.*, 2005). For instance, high-productivity, evergreen, deep-rooted bio-energy plantations generally have a higher water use than the land cover they replace (Berndes, 2002, Jackson *et al.*, 2005). Some practices may affect water quality through enhanced leaching of pesticides and nutrients (Freibauer *et al.*, 2004; Machado and Silva, 2001).
- If bio-energy plantations are appropriately located, designed, and managed, they may reduce nutrient leaching and soil erosion and generate additional environmental services such as soil carbon accumulation, improved soil fertility; removal of cadmium and other heavy metals from soils or wastes. They may also increase nutrient recirculation, aid in the treatment of nutrient-rich wastewater and sludge; and provide habitats for biodiversity in the agricultural landscape (Berndes and Börjesson, 2002; Berndes *et al.* 2004; Börjesson and Berndes, 2006).
- Changes to land use and agricultural management can affect biodiversity, both positively and negatively (e.g., Xiang *et al*., 2006; Feng *et al*., 2006). For example, intensification of agriculture and large-scale production of biomass energy crops will lead to loss of biodiversity where they occur in biodiversity-rich landscapes (European Environment Agency, 2006). But perennial crops often used for energy production can favour biodiversity, if they displace annual crops or degraded areas (Berndes and Börjesson, 2002).
- Agricultural mitigation practices may influence non-agricultural ecosystems. For example, practices that diminish productivity in existing cropland (e.g., set-aside lands) or divert products to alternate uses (e.g., bio-energy crops) may induce conversion of forests to cropland elsewhere. Conversely, increasing productivity on existing croplands may 'spare' some forest or grasslands (West and Marland, 2003; Balmford *et al.*, 2005; Mooney *et al.*, 2005). The net effect of such trade-offs on biodiversity and other ecosystem services has not yet been fully quantified (Huston and Marland, 2003; Green *et al.*, 2005).
- Agro-ecosystems have become increasingly dependent on input of reactive nitrogen, much of it added as manufactured fertilizers (Galloway *et al.*, 2003; Galloway, 2004). Practices that reduce N_2O emission often improve the efficiency of N use from these and other sources (e.g., manures), thereby also reducing GHG emissions from fertilizer manufacture and avoiding deleterious effects on water and air quality from N pollutants (Oenema *et al.*, 2005; Dalal *et al.*, 2003; Olesen *et al.*, 2006; Paustian *et al.*, 2004). Suppressing losses of N as N_2O might in some cases increase the risk of losing that N via leaching. Curtailing supplemental N use without a corresponding increase in N-use efficiency will restrict yields, thereby hampering food security.
- Implementation of agricultural GHG mitigation measures may allow expanded use of fossil fuels, and may have some negative effects through emissions of sulphur, mercury and other pollutants (Elbakidze and McCarl, 2007).

The co-benefits and trade-offs of a practice may vary from place to place because of differences in climate, soil, or the way the practice is adopted. In producing bio-energy, for example, if the feedstock is crop residue, that may reduce soil quality by depleting soil organic matter. Conversely, if the feedstock is a densely rooted perennial crop that may replenish organic matter and thereby improve soil quality (Paustian *et al.*, 2004).These few examples, and the general trends described in Table 8.12, demonstrate that GHG mitigation practices on farm lands exert complex, interactive effects on the environment, sometimes far from the site at which they are imposed. The merits of a given practice, therefore, cannot be judged solely on effectiveness of GHG mitigation.

8.9 Technology research, development, deployment, diffusion and transfer

There is much scope for technological developments to reduce GHG emissions in the agricultural sector. For example, increases in crop yields and animal productivity will reduce emissions per unit of production. Such increases in crop and animal productivity will be implemented through improved management and husbandry techniques, such as better management, genetically modified crops, improved cultivars, fertilizer recommendation systems, precision agriculture, improved animal breeds, improved animal nutrition, dietary additives and growth promoters, improved animal fertility, bio-energy crops, anaerobic slurry digestion and methane capture systems. All of these depend to some extent on technological developments. Although technological improvement may have very significant effects, transfer of these technologies is a key requirement for these mitigations to be realized. For example, the efficiency of N use has improved over the last two decades in developed countries, but continues to decline in many developing countries due to barriers to technology transfer (International Fertilizer Industry Association, 2007). Based on technology change scenarios developed by Ewert *et al.* (2005), and derived from extrapolation of current trends in FAO data, Smith *et al.* (2005b) showed that technological improvements could potentially counteract the negative impacts of climate change on cropland and grassland soil carbon stocks in Europe. This and other work (Rounsevell *et al.*, 2006) suggest that technological improvement will be a key factor in GHG mitigation in the future.

In most instances, the cost of employing mitigation strategies will not alter radically in the medium term. There will be some shifts in costs due to changes in prices of agricultural products and inputs, but these are unlikely to be of significant magnitude. Likewise, the potential of most options for CO_2 reduction is unlikely to change greatly. There are some exceptions which fall into two categories: (i) options where the practice or technology is not new, but where the emission reduction potential has not been adequately quantified, such as improved nutrient utilization; and (ii) options where technologies are still being refined such as probiotics in animal diets, or nitrification inhibitors.

Many of the mitigation strategies outlined for agriculture employ existing technology (e.g., crop management, livestock management). With such strategies, the main issue is technology transfer, diffusion, and deployment. Other strategies involve new use of existing technologies. For example, oils have been used in animal diets for many years to increase dietary energy content, but their role as a methane suppressant is relatively new, and the parameters of the technology in terms of scope for methane reduction are only now being defined. Other strategies still require further research to allow viable systems to operate (e.g., bio-energy crops). Finally, many novel mitigation strategies are presently being refined, such as the use of probiotics, novel plant extracts, and the development of vaccines. Thus, there is still a major role for research and development in this area.

Differences between regions can arise due to the state of development of the agricultural industry, the resources available and legislation. For example, the scope to use specific agents and dietary additives in ruminants is much greater in developed than in the developing regions because of cost, opportunity (e.g., it is easier to administer products to animals in confined systems than in free ranging or nomadic systems), and availability of the technology (US-EPA, 2006a). Furthermore, certain technologies are not allowed in some regions, for example, ionophores are banned from use in animal feeding in the EU, and genetically modified crops are not approved for use in some countries.

8.10 Long-term outlook

Trends in GHG emissions in the agricultural sector depend mainly on the level and rate of socio-economic development, human population growth, and diet, application of adequate technologies, climate and non-climate policies, and future climate change. Consequently, mitigation potentials in the agricultural sector are uncertain, making a consensus difficult to achieve and hindering policy making. However, agriculture is a significant contributor to GHG emissions (Section 8.2). Mitigation is unlikely to occur without action, and higher emissions are projected in the future if current trends are left unconstrained. According to current projections, the global population will reach 9 billion by 2050, an increase of about 50% over current levels (Lutz *et al.*, 2001; Cohen, 2003). Because of these increases and changing consumption patterns, some analyses estimate that the production of cereals will need to roughly double in coming decades (Tilman *et al.*, 2001; Roy *et al.*, 2002; Green *et al.*, 2005). Achieving these increases in food production may require more use of N fertilizer, leading to possible increases in N_2O emissions, unless more efficient fertilization techniques and products can be found (Galloway, 2003; Mosier, 2002). Greater demands for food could also increase CH_4 emissions from enteric fermentation if livestock numbers increase in response to demands for meat and other livestock products. As projected by the IMAGE 2.2 model, CO_2, CH_4, and N_2O emissions associated with land use vary greatly between scenarios (Strengers *et al.*, 2004), depending on trends towards globalization or regionalization, and on the emphasis placed on material wealth relative to sustainability and equity.

Some countries are moving forward with climate and non-climate policies, particularly those linked with sustainable development and improving environmental quality as described in Sections 8.6 and 8.7. These policies will likely have direct or synergistic effects on GHG emissions and provide a way forward for mitigation in the agricultural sector. Moreover, global sharing of innovative technologies for efficient use of land resources and agricultural inputs, in an effort to eliminate poverty and malnutrition, will also enhance the likelihood of significant mitigation from the agricultural sector.

Mitigation of GHG emissions associated with various agricultural activities and soil carbon sequestration could be achieved through best management practices, many of which are currently available for implementation. Best management practices are not only essential for mitigating GHG emissions, but also for other facets of environmental protection such as air and water quality management. Uncertainties do exist, but they can be reduced through finer scale assessments of best management practices within countries, evaluating not only the GHG mitigation potential but also the influences of mitigation options on socio-economic conditions and other environmental impacts.

The long-term outlook for development of mitigation practices for livestock systems is encouraging. Continuous improvements in animal breeds are likely, and these will improve the GHG emissions per kg of animal product. Enhanced production efficiency due to structural change or better application of existing technologies is also generally associated with reduced emissions, and there is a trend towards increased efficiency in both developed and developing countries. New technologies may emerge to reduce emissions from livestock such as probiotics, a methane vaccine or methane inhibitors. However, increased world demand for animal products may mean that while emissions per kg of product decline, total emissions may increase.

Recycling of agricultural by-products, such as crop residues and animal manures, and production of energy crops provides opportunities for direct mitigation of GHG emissions from fossil fuel offsets. However, there are barriers in technologies and economics to using agricultural wastes, and in converting energy crops into commercial fuels. The development of innovative technologies is a critical factor in realizing the potential for biofuel production from agricultural wastes and energy crops. This mitigation option could be moved forward with government investment for the development of these technologies, and subsidies for using these forms of energy.

A number of agricultural mitigation options which have limited potential now will likely have increased potential in the long-term. Examples include better use of fertilizer through precision farming, wider use of slow and controlled release fertilizers and of nitrification inhibitors, and other practices that reduce N application (and thus N_2O emissions). Similarly, enhanced N-use efficiency is achievable as technologies such as field diagnostics, fertilizer recommendations from expert/decision support systems and fertilizer placement technologies are developed and more widely used. New fertilizers and water management systems in paddy rice are also likely in the longer term.

Possible changes to climate and atmosphere in coming decades may influence GHG emissions from agriculture, and the effectiveness of practices adopted to minimize them. For example, atmospheric CO_2 concentrations, likely to double within the next century, may affect agro-ecosystems through changes in plant growth rates, plant litter composition, drought tolerance, and nitrogen demands (e.g., Long *et al.*, 2006; Henry *et al.*, 2005; Van Groenigen *et al.*, 2005; Jensen and Christensen, 2004; Torbert *et al.*, 2000; Norby *et al.*, 2001). Similarly, atmospheric nitrogen deposition also affects crop production systems as well as changing temperature regimes, although the effect will depend on the magnitude of change and response of the crop, forage, or livestock species. For example, increasing temperatures are likely to have a positive effect on crop production in colder regions due to a longer growing season (Smith *et al.*, 2005b). In contrast, increasing temperatures could accelerate decomposition of soil organic matter, releasing stored soil carbon into the atmosphere (Knorr *et al.*, 2005; Fang *et al.*, 2005; Smith *et al.* 2005b). Furthermore, changes in precipitation patterns could change the adaptability of crops or cropping systems selected to reduce GHG emissions. Many of these effects have high levels of uncertainty; but demonstrate that practices chosen to reduce GHG emissions may not have the same effectiveness in coming decades. Consequently, programmes to reduce emissions in the agricultural sector will need to be designed with flexibility for adaptation in response to climate change.

Overall, the outlook for GHG mitigation in agriculture suggests significant potential. Current initiatives suggest that identifying synergies between climate change policies, sustainable development, and improvement of environmental quality will likely lead the way forward to realization of mitigation potential in this sector.

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