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Chapter 8 Greenhouse Gas Mitigation in Agriculture

CONTENTS

EXECUTIVE SUMMARY

Agricultural lands (i.e. lands used for agricultural production, consisting of cropland, managed grassland and permanent crops including agro-forestry and dedicated bio-energy crops) occupy about 37% of the earth's land surface (FAOSTAT, 2005). Agriculture emits to the atmosphere significant quantities of GHGs, mainly as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Agriculture accounts for 49% of global anthropogenic emissions (FAO, 2003), 66% of global anthropogenic N_2O emissions (Robertson, 2004) and 15% of anthropogenic CO_2 emissions.

Many agricultural practices can, under some conditions, mitigate GHG emissions, often affecting more than one GHG by more than one mechanism. These practices include: land cover (use) change, agroforestry, crop management, tillage/residue management, nutrient management, rice management, water management, manure/biosolid management, grazing land management/pasture improvement, management of organic soils, land restoration, bioenergy crops, enhanced energy efficiency, livestock management (improved feeding practices, specific agents and dietary additives, longer term structural and management changes, and breeding), increased C storage in products, and reduced biomass burning.

The global biophysical agricultural mitigation potential is estimated to be ~7300 (-1100 to 16900) Mt CO_2-eq. yr^{-1} for all gases with a realistically achievable potential of 700-1500 (-200 to 3400) Mt CO_2-eq. yr^{-1}. Of this total, about 93% is from reduced soil emissions of CO_2, and about 7% is from mitigation of other GHGs. The upper and lower limits about the estimates are largely determined uncertainty in the mean estimate for soil C storage of the mixed effects model. There is a high degree of uncertainty associated with estimates of agricultural mitigation potential. The estimates for realistically achievable potentials are about 700-1400 (-150 to 2900) Mt CO_2-eq. yr^{-1} for soil C sequestration alone.

In addition to GHG emission reduction, agricultural land can provide feed stock for bioenergy production. Given projected land area under biofuels in 2025 from the IMAGE 2.0 models implementation of the IPCC SRES scenarios, mean yields of 4 and 12 odt ha^{-1} y^{-1} would produce 230-700 and 560-1700 od Mt of biomass y^{-1}, respectively. This biomass would deliver fossil fuel CO_2 savings of ~360 - ~2730 Mt CO_2 yr^{-1}, but increased GHG emissions of 270-660 Mt CO_2-eq. y^{-1} from biomass burning mean that the net GHG benefits would be ~100-2070 Mt CO_2-eq. yr^{-1}. This biomass would generate ~2-22 EJ yr^{-1} of energy depending upon yield, and the proportion of the energy used for combined heat and power (CHP) or for generating electricity alone, considerably less than the *technical potential* estimated for 2050 in the TAR: ~400 EJ yr^{-1} assuming 15 odt ha^{-1} and 20 GJ odt^{-1} (IPCC, 2001).

There is also a relationship between the amount paid for GHGs mitigation and the quantity of mitigation achieved. Price-based constraints on implementation diminish as the price per tCO_2-eq. increases. Assuming no other constraints on implementation, at low prices (~17 US\$ tCO_2-eq.$^{-1}$), less than 30% of the global biophysical potential will be realised (~2000 Mt CO_2-eq. yr^{-1}), whereas at prices of ~33 and 50 US\$ tCO_2-eq.$^{-1}$, 55 and 80% respectively (~4100 and ~6000 Mt CO_2-eq. yr^{-1}) of global biophysical potential could be realised. Exceptionally high prices (e.g. 5000 US\$ t CO_2-eq.$^{-1}$) would lead to full implementation, reaching the total biophysical potential of ~7400 Mt CO_2-eq. $^{-1}$. If both price- and non-price-related constraints to implementation of mitigation measures are considered, global agricultural mitigation potentials are estimated to range from 200 Mt CO_2-eq. yr^{-1} (for low price and 10% implementation possible by 2025) to 7300 Mt CO_2-eq. yr^{-1} (for very high price and implementation of entire biophysical potential by 2025). The interaction between price of CO_2-equivalents, the level of implementation possible by 2025 and mitigation potential is shown in table SP1.

[Table SP2 here - same as Table 8.4.3b]

Many agricultural mitigation activities also show synergy with the goals of sustainability, and many explicitly influence the constituents of sustainable development, including social, economic and environmental indicators. Other mitigation options have more uncertain impact on sustainable development. There are interactions between mitigation and adaptation in the agricultural sector. Mitigation and adaptation may occur simultaneously, but differ in their spatial and geographic characteristics. The main climate change benefits of mitigation actions taken now will emerge only over decades but where the drivers achieve other policy objectives, there may also be short-term benefits. Conversely, actions to enhance adaptation to climate change impacts even in the short term will have consequences both in the short as well as medium and long terms.

In many regions, non-climate policies, including macro-economic, agricultural and environmental policies, have greatest impact on agricultural mitigation options. Some evidence suggests that, despite significant biophysical potential for GHG mitigation in agriculture, very little progress has been made and little is expected by 2010. There are barriers to implementation which may not be overcome without policy/economic incentives.

Many agricultural mitigation options have both co-benefits (in terms of improved efficiency, reduced cost, environmental co-benefits) and trade-offs. Balancing the co-benefits with trade-offs is necessary for successful implementation. Many agricultural GHG mitigation options could be implemented immediately, without further technological development, but a few options are still undergoing technological development. Technological development has been shown to be a key driver in ensuring the efficacy of agricultural mitigation measures. The long-term outlook for GHG mitigation in agriculture suggests that there is significant potential, but many uncertainties, both price-and non-price-related, will determine the level of implementation. The estimates of potential for the next 20 years are considerably lower than those in the IPCC SAR and TAR.

The effectiveness of GHG mitigation in agriculture may depend on coming global changes. For example, population growth and changing diets may increase demands for food, resulting in higher emissions of CH_4 and N_2O. And soil C may become more vulnerable to loss under climate changes or other pressures.

8.1 Introduction

8.1.1 Agricultural GHG emissions, mitigation mechanisms and practices

Agricultural lands (i.e. lands used for agricultural production, consisting of cropland, managed grassland and permanent crops including agro-forestry and dedicated bio-energy crops) occupy about 37% of the earth's land surface (FAOSTAT, 2005). Agriculture emits significant quantities of GHGs to the atmosphere. The main GHG emissions from agriculture are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Agricultural emissions account for 49% anthropogenic methane emissions (FAO, 2003), 66% of global anthropogenic N_2O emissions (Robertson, 2004) and 15% of anthropogenic CO_2 emissions, which in some regions is the largest land-based CO_2 flux to the atmosphere (e.g. Janssens *et al.*, 2003). Agricultural GHG fluxes are complex and heterogeneous, but the active management of agricultural systems also offers possibilities for mitigation. Many agricultural mitigation opportunities use current technologies and are available for immediate implementation.

Mechanisms by which agricultural carbon dioxide emissions can be reduced include a) reducing losses from agricultural soils through decomposition of soil organic matter and root respiration, b) reducing emissions from biomass burning, c) reducing emissions from agricultural use of lime, and d) increasing the pool of carbon in long-lived agricultural products, e) increasing the non-soil pools of carbon, in agroforestry, f) offsetting fossil fuel carbon by providing feed-stocks for bioenergy, and g) improved energy efficiency in agriculture. Mechanisms by which agricultural nitrous oxide emissions can be reduced include reducing emissions from a) agricultural soils, b) manures and c) biomass burning. Mechanisms by which agricultural methane emissions can be reduced include reducing emissions from: a) enteric fermentation by ruminants, b) manures, c) cultivated wetland rice soils and d) biomass burning. These mechanisms are described further in Section 8.4.1.

There are a number of agricultural practices that may mitigate GHGs via one or more of the above mechanisms, with many practices affecting more that one GHG by more than one mechanism. These practices include:

- *land cover (use) change* - cropland to grassland (set-asides), wetlands
- *agroforestry* - tree crops, including shelter-belts, windbreaks, woodlots, cattle shelters
- *crop management* - increased productivity, rotations, catch crops, less fallow, more legumes, de-intensification, integrated pest management (IPM), crop cultivars
- *tillage/residue management* - reduced or no-till, less residue removal or burning
- *nutrient management* - fertilizer placement, timing, precision farming, fertilizer free zone, reduced fertilizer rates, slow-release forms, nitrification inhibitors,
- *rice management* - water management, nutrient management, cultivars
- *water management* - irrigation, drainage
- *manure/biosolid management* - storage, trapping, slurry cooling, controlled decomposition, anaerobic digestion, more efficient use of manure as nutrient source

- *grazing land management/pasture improvement* - grazing intensity, fertilization, fire management, species introduction, increased productivity
- *management of organic soils*
- *land restoration*
- *bioenergy crops* - (solid, liquid, biogas), residues
- *enhanced energy efficiency* - irrigation, drying, heating, more efficient power sources
- *livestock management - improved feeding practices*: replace forage with concentrates, extra fat in the diet, increased digestibility, optimize protein intake, mechanical treatment,
- *livestock management - specific agents and dietary additives*: ionospheres, propionate precursors, probiotics, bovine somatotrophin (BST) and growth implants, halogenated compounds, antibiotics, methane vaccine
- *livestock management - longer term structural and management changes and animal breeding*: improved livestock through breeding, improved fertility, lifetime management, methane capture from housing
- *increase C storage in agricultural products* - strawboards, wool, leather, bio-plastics
- *reduced emissions from biomass burning* - reduce burning or reduce emissions.

These practices, and how they influence GHG emissions from agriculture are addressed in detail in Section 8.4.2.

8.1.2 Agricultural GHG mitigation in the IPCC Second and Third Assessment Reports

Mitigation potential was not assessed separately for agriculture in the IPCC Third Assessment Report (TAR). Estimates in the IPCC Second Assessment Report (SAR) suggest that 400-800 Mt C y^{-1} (equivalent to about 1400-2900 $MtCO_2$-eq. y^{-1}) could be sequestered in global agricultural soils with a finite capacity saturating after 50-100 years. In addition, the SAR concluded that 300-1300 Mt C (equivalent to about 1100-4800 $MtCO_2$-eq. y^{-1}) from fossil fuels could be offset by using 10-15% of agricultural land to grow biofuels with crop residues potentially contributing 100-200 Mt C (equivalent to about 400-700 Mt CO_2-eq. per year) to fossil fuel offsets if recovered and burned. It was noted that this might increase N_2O emissions but this was not quantified. The SAR concluded that CH_4 emissions from agriculture could be reduced by 15-56%, mainly through improved nutrition of ruminants and better management of paddy rice. It was also estimated that improvements in agricultural management could reduce N_2O emissions by 9-26%. The SAR noted that GHG mitigation techniques will not be adopted by land managers unless they improve profitability, but that some measures are adopted for reasons other than for climate mitigation. Options that both reduce GHG emissions and increase productivity are more likely to be adopted than those which only reduce emissions.

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 the important changes that have occurred during the last four decades in the agriculture sector. Production of food and fibre has more than kept pace with the sharp increase in demand in a more populated world, so that the global average daily availability of calories per capita has increased (Gilland, 2002), though with regional exceptions. However, this growth has been at the expense of high pressures on the environment and depletion of natural resources (Tilman *et al.*, 2001; Rees, 2003), while it has not been successful in solving the problems of food security and child malnutrition suffered by large numbers of people from poor countries (Conway and Toenniessen 1999).

Agricultural land occupied 5020 Mha in 2002 (FAOSTAT, 2005). Most of this area was under pasture (3485 Mha, or 69%) and cropland occupied 1404 Mha (28%). During the last four decades, agricultural land has gained almost 500 Mha from other land uses. Every year during this period, an average 6 Mha of forestland and 7 Mha of other land were converted to agriculture, and this change occurred largely in the developing world (Table 8.2.1).

[Table 8.2.1 here]

The amount of cropland worldwide has increased by 8% since the 1960s, to its current level of ca. 1400 Mha (Table 8.2.1). This increase was the net result of a 5% decrease in developed countries, and a 22% increase in cropland area in developing countries. This trend will continue into the future (Huang *et al.*, 2002; Trewavas, 2002; Fedoroff & Cohen, 1999; Green *et al.*, 2005), and Rosegrant *et al.* (2001) predict that an additional 500 Mha would be converted to agriculture during the period 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 8.2.2), despite a consistent decline in per capita agricultural land (Figure 8.2.1). The share of animal products in the diet has consistently increased in the group of developing countries, whilst remaining constant in developed countries.

[Figure 8.2.1 here]
[Table 8.2.2 here]

Economic growth and changing lifestyles in some developing countries, most notably in China, are causing a growing demand for meat. Meat demand in developing countries rose from 11 to 24 kg/cap/year 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 yet further increases in global meat demand - 57% by 2020, mostly in developing regions such as South and Southeast Asia, and Sub-Saharan Africa. They project demand growth for all meats, with poultry having the highest (83 % by 2020; Roy *et al.*, 2002).

The annual emission of greenhouse gases from agriculture is expected to increase in coming decades because of escalating demands for food and shifts in diets. But improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or of protein) produced. The main trends in agriculture sector with implications on greenhouse gas emissions or removals are summarized as follows:

- Growth in land productivity is expected to continue, although at a declining rate, due to saturation of technological progress, and incorporation of marginal land. Use of these marginal lands will increase risks of land erosion and degradation. The consequences of soil erosion on CO_2 emissions are highly uncertain.
- Conservation tillage and zero-tillage are increasingly being adopted, thus reducing the use of energy and increasing carbon storage in soils. According to FAO (2001), the worldwide area under zero-tillage in 1999 was estimated to be ca. 50 Mha, which represented 3.5% of total arable land. However such practices are not always continuously employed.
- Further improvements in productivity will require increasing use of irrigation and fertilizer, with the consequence of increased energy demand (for moving water and manufacturing fertilizer). Also, irrigation and N fertilization may cause increased GHG emissions.

- Growing demand for meat may induce further changes in land use (e.g., from forestland to grassland), and increased demand for feeds (e.g., cereals, meals). 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) would grow more than grazing-based systems, and this would attenuate the expected rise in GHG emissions.
- Industrial production of beef, poultry and pork is increasingly more common, with the consequence of increased amounts of manure, and therefore, with higher GHG emissions. This is particularly true in the developing regions of Southeast Asia, and Latin America.
- Changes in policies (e.g., subsidies), and regional patterns of production/demandis are causing a large increase in international trade of agricultural products. This would cause an increase in CO_2 emissions due to an increased use of energy for transportation.

There is an emerging trend to increase the use of agricultural products (e.g., plastics, biofuels and biomass for energy) as substitutes for fossil-fuel based products and this may cause significant reductions of GHG emissions in the future.

8.3 Emission trends (global and regional)

Agriculture is estimated to account for about 30% of total global anthropogenic emissions of GHG's (Bouwman, 2001) although large seasonal and annual variation makes precise assessment difficult. Emissions of CO_2, mainly from land use change, especially deforestation, are estimated to account for 15% of anthropogenic CO_2 emissions (FAO, 2003). Methane of agricultural origin is estimated to make up 49% of total anthropogenic CH_4 emissions (FAO, 2003). This is composed mainly of methane from livestock (enteric fermentation in ruminants, manure), rice production and biomass burning. Agricultural N_2O emissions are 66% of total anthropogenic N_2O emissions (FAO, 2001, 2003).

8.3.1 Trends since 1990

Emissions of N_2O and CH_4 are influenced by long-term trends in N fertilizer use and livestock numbers (Table 8.3.1). Overall, cattle numbers increased slightly from 1990 to 2004 but this was offset by a marked decrease in sheep numbers due to falling wool prices. In contrast, there have been significant increases in pig and especially chicken numbers between 1990 and 2004. N fertiliser usage did not change much from 1990 to 1995 overall but with marked variability between nations. For example, from 1990 to 2000, fertilizer use fell from 5.44 million to 0.91 million tonne in the Russian Federation, and from 1.78 million to 0.22 million tonne in the Ukraine. As well, Japan decreased its use by 35% over 15 years, but other nations increased their use substantially (e.g. NZ up 500% since 1990).

The net effect of these and other changes is that estimated global emissions of N_2O declined slightly in the early 1990's, but have been more or less stable since then (Figure 8.3.1). Methane emissions have shown a gradual but persistent decline since 1990, falling by about 10% (??) from 1990 to 2002 (Fig. 8.3.1) .

[Figure 8.3.1 here]
[Table 8.3.1 here]

8.3.2 Future Trends

Emissions of CO_2, mainly from land use change, especially deforestation, are forecast to be stable or declining up to 2030 (FAO, 2003). If methane emissions grow in direct proportion to increases in livestock numbers, then forecasts are that global livestock-related methane production will increase by 60% up to 2030 (FAO, 2003). However, changes in feeding practices and manure management could ameliorate this. The area of rice grown globally is forecast to increase by 4.5% to 2030 (FAO, 2003), and thus emissions of methane from rice production are not expected to increase substantially. There may even be reductions if there is less rice grown under continuous flooding (causing anaerobic soil conditions) due to water scarcity, or if new rice cultivars that emit less methane are developed and adopted (Wang, Neue & Samonte, 1997). Agricultural N_2O emissions are forecast to increase by 35-60% up to 2030 due to increased nitrogen fertilizer use and increased animal manure production (FAO, 2003). Mosier and Kroze (2000), similarly, estimate that N_2O emissions will increase by about 50% by 2020 (relative to 1990). In short, if demands for food increase and diets shift as projected, then annual emission of greenhouse gases from agriculture may escalate further. But improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or of protein) produced.

8.3.3 Regional Trends

The data in Table 8.3.1 on livestock numbers and N fertilizer usage suggest that reductions in agricultural emissions are occurring in some regions (Europe in particular) but that there is substantial growth in other regions (e.g. Asia, South America). This trend of relatively stable or even declining emissions in developed countries but increased emissions in developing countries is likely to continue, based on FAO (2003) projections. This is due to the increasing intensity of agricultural production systems in these countries.

Africa: Sub-Saharan Africa is the one world region where per-capita food production is either in decline, or more-or-less constant at a level that is less than adequate. This trend varies regionally within Sub-Saharan Africa: south of about 18 °S it is not generally apparent, whereas it is very strong north of this line. It is particularly the *protein* nutrition which is deficient and steeply declining (Scholes and Biggs 2004). This trend can be linked to issues of low and declining soil fertility (Sanchez 2002), and to inadequate fertiliser inputs due to high farm-gate fertiliser prices. South-central Africa (including Angola, Zambia, DRC, Mozambique and Tanzania) is one of the few remaining places on Earth where there is significant unexploited agricultural potential. Southern Africa is also the major region that was identified in one comprehensive study (Fischer *et al.* 2002) as projected to experience, on balance, more negative than positive impacts of climate change on crop production. The apparent reason is that the majority of climate models suggest a combination of warming and drying for the region. The same study notes that for this region the scope for improved yields per hectare as a result of application of proven agronomic techniques was substantially greater than the loss of yield anticipated due to climate change, and that the scope for expanding the area under agriculture was also more than sufficient to offset climate change impacts. The West African, Sahelo-Sudanian and North African regions do not offer as much scope for the 'horizontal' spread of agriculture, since the landscape is largely already densely populated where it is habitable. The key trend there is urbanisation, and the proliferation of peri-urban agriculture. Landscape restoration projects (increasing soil carbon content and replacement of lost tree cover are among the major mitigation opportunities. One key issue in Western and Southern Africa is the availability of fresh water, already declining on a per capita basis due to the depletion of ground water reserves and the growth of demand. Since agriculture is the major water user in Africa, irrigated agriculture will be under increasing to increase water use efficiency.

Since population growth is still high in most of sub-Saharan Africa, and the economic growth rate is low most of the affected countries, the expansion of low-input, low-output agriculture (such as swidden agriculture and extensive livestock pastoralism), is the likely response to growing food demand in the region. From a food security, biodiversity conservation and climate change mitigation point of view, this may not be the optimum outcome (MA, 2005). Therefore, opportunities exist from both an adaptation and mitigation perspective to intervene through establishing an agricultural development path with a better balance between extensification and intensification, which would maximise landscape-scale carbon storage, and minimise emissions of CH_4 and N_2O, while simultaneously addressing the Millennium Development Goal of reducing poverty and hunger. Agricultural intensification is also indicated in relation to the mitigation of emissions from livestock in Africa. The (slowly) rising wealth of urban populations is likely to increase demand for livestock products, which can only be met to a limited degree by expanding pastoralism onto new lands, especially if traditional techniques are used. Feed supplementation and changes in herd management could simultaneously increase off-take of meat while reducing greenhouse gas emissions, if attention is given to waste management issues and appropriate sourcing of the improved feeds.

East Asia: Many East Asian countries are developing very quickly economically. With urbanization and limits to the cultivable land resource, cropland areas are not expected to substantially increase and may even decrease. With increasing population pressure, the intensity of land use is expected to increase. With the adoption of modern agricultural technologies, total fertilizer consumption is expected to remain constant or increase slightly. All trends indicate that total direct GHG emissions from crop production are expected to remain similar or even decrease. For example, the rice harvested area is generally decreasing in China and shifting from south China where CH_4 emission per land area is generally larger, to north China where CH_4 emissions are smaller. Thus, total CH_4 emissions from rice fields in China are expected to decrease. The consumption of nitrogen fertilizers in China has not increased substantially since 2000. On the other hand, with economic development, the total demands of livestock products, such as meats and milks are increasing continuously. According to FAO statistics (FAOSTAT, 2005), the total production of meat and milk in Asian developing countries increased in 2004 by more than 12 times and 4 times respectively, compared to 1961 levels. Since the per-capita consumption of meat and milk is still much lower in these countries than in developed countries, the increasing trends are expected to continue for a relatively long time. Therefore, the GHG emissions directly and indirectly from livestock are expected to increase, although the emission rate per animal is expected to decrease by the development of intensive livestock and improved management of animal manures. Rapid economic development in East Asia is also altering the types of energy consumed in the countryside. Replacement of crop residues, brush and wood as domestic cooking/heating in the countryside by fossil fuels, provides an opportunity to incorporate more crop residues into the soil, which will stimulate C sequestration in soil, and through lower exploitation of forest and other vegetation, will also decrease the risk of soil erosion, thereby enhancing the C stock of terrestrial systems. On the other hand, the risk of burning crop residues in the field increases, thus increasing GHG emissions. The net change in GHG emissions from these future developments will depend on the effectiveness of policies and technologies to utilize these organic residues.

Oceania: Australia and New Zealand (NZ) are unusual amongst OECD nations in that agricultural emissions are substantial components of the national emissions budgets: 49% for NZ and 18% for Australia. In both cases agricultural emissions have increased about 16% since 1990 driven by several trends primarily related to increased intensity of practices as well as changes in the mix of livestock types driven by price changes. Even though legumes are widely used to fix nitrogen, nitrogenous fertiliser use has increased exponentially over the past 45 years with fivefold increases since 1990 in NZ and two and a half-fold increases in Australia. There have also been increases in intensive livestock such as dairy cattle, feedlot cattle, piggeries and poultry as well as increases in soil disturbance from larger areas being cropped. Collectively, these are calculated as increasing agricultural nitrous oxide emissions by about 30% in both nations since 1990. Decreases in wool price since 1990 have reduced sheep numbers substantially (20% in NZ and 42% in Australia) but the consequent reductions in methane emissions have largely been offset by increases in emissions from larger numbers of beef cattle and intensive livestock. However, increased per head productivity across all livestock types has resulted in lower emissions per unit product (Howden and Reyenga 1999). Reduced burning of crop residues (sugar cane, cereals) has reduced emissions from this source but they are very small components of the national totals. Widespread adoption of crop management practices such as zero tillage has the potential to store some carbon in surface soils but the potentially transient nature of these and the difficulty in monitoring the changes preclude effective estimation. Land clearing in Australia has declined by 60% since 1990 with vegetation management policies restricting further clearing. In both nations, afforestation and forest management is resulting in net emission sinks with these being very significant in NZ (30% of the national emissions) and smaller in Australia (3%).

Former USSR: Future trends in greenhouse gas emissions will be governed mainly by economic development of an agrarian-industrial sector. Growth in income is the primary factor for increasing food production. At present, agricultural production in Russia is about 60% of that in 1990, but is expected to increase by 15-40% above 2001 by 20100. Recently, agricultural management methods have improved against the background of decreased resource supply but a constant supply of labour. Reorganization of agricultural enterprises has resulted in a great increase in the number of subsidiary farms; their fraction of the gross agricultural product being about 50% of the total. Private production is less efficient and has decreased as a fraction of total production in recent years. Emissions associated with activities on these small farms are unlikely to increase. Methane emission in the private livestock sector will be governed by the efficiency of the organic fertilizers applied as well as the price policy for fodder. Farming has de-intensified. The expected variations in crop yield, even with the subsequent possible fall in soil fertility following the ploughing of new land, suggest that the current volume of grain and fodder production can be maintained over the next 40-70 years for Russia, against a background of climate-induced reduction in crop yield in Moldova, Kazakhstan and Ukraine, but climate-induced stimulation of crop yields in Belarus and the Baltic states. In Moldova, Kazakhstan and Ukraine the land area under extensive management may grow. A 10-14% increase of arable lands is forecast for the whole of Russia due to agricultural extensification but the increase will not be uniform. In all regions, except those in the south of Russia, agricultural area will not reach 1990 levels, and will remain practically unchanged in the Non-chernozem and Northern areas. The fallow in the Non-chernozem region will be succeeded by forest. <u>In this case</u> CO_2 emissions will be governed by degradation, including the loss of organic matter from arable soils and the partial ploughing of abandoned lands. In this case the increase in arable land area will be less pronounced than that of agricultural production. The widespread application of intensive management technologies could result in a 2-2.5 fold rise in the grain and fodder yield with a consequent reduction of arable lands but may increase N fertilizer use. Decreases in fertilizer N use since 1990 has led to a significant reduction in N_2O emissions. Under favourable economic conditions the amount of N fertilizer applied will again increase.

North America: Agricultural productivity in North and Central America has been relatively stable over the last decade. Cattle numbers, for example, are virtually unchanged, while numbers of poultry and pigs have increased, and numbers of sheep have decreased (Table 8.3.1). The intensity of crop production, similarly, has been stable, is indicated by only minor increases in fertilizer N use. Prospective changes in coming decades include the continued development of improved production practices through adoption of advanced technology (e.g., new varieties, more efficient fertilizer techniques, improved manure management systems, more efficient feeding practices). Some marginal croplands may be returned to trees or grassland. Any changes, however, depend largely on economic factors such as commodity prices and policy incentives.

Latin America and the Caribbean: the region has experienced dramatic changes during the last few decades. Economic growth (81% increase in total gross domestic product since 1970) has kept pace with population growth (52% since 1980), although wealth distribution has been very unequal, and poverty remains a major unresolved issue in the region. Virtually all the increase in population has occurred in urban areas, and the proportion of workers in agriculture sector has dropped from 34.5 to 18.6% of total workers during the period since 1980. The region has a growing positive trade balance, with exports equivalent to 20% ot total gross domestic product. Agriculture products, either primary or processed are the main source of exports. The total value of agriculture production has increased at a rate of 2.5% per year since 1980. Only three countries (Brazil, Mexico and Argentina) concentrate about three fourths of the total value.
Significant changes in land use and management have also occurred, with forest conversion to cropland and grassland being the most significant. Forest land area decreased by 13% since 1970 (from 878 to 730 Mha, according to FAOSTAT), whereas cropland and grassland area increased by 47 and 19%, respectively (from 116 to 232 Mha, and from 543 to 645 Mha, respectively) during the same period. Much of the land converted has suffered moderate to severe soil degradation. These land use changes have resulted in greenhouse gas emissions from soils (CO_2 and N_2O), particularly in the case of forest land converted to cropland, which occurred at a more or less constant rate during the period. Livestock activity is the main source of greenhouse gas emissions in Latin America & The Caribbean region, and has shown an increasing trend over the last few decades. Cattle population increased linearly from 176 to 379 million heads between 1961 and 2004, a 115% increase. This was partly offset by a 36% decrease in sheep population, from 125 to 80 million heads. Poultry population increased, at an increasing rate, by 611%, from 0.4 to 2,6 billion heads during the same period. All other livestock categories showed increases in the order of 30 to 60%. Methane emissions from enteric fermentation, which account for nearly 50% of total GHG emissions in agriculture in the region, roughly doubled, from 0.2 to 0.4 Pg CO_2 eq, from 1961 to 2003. Direct nitrous oxide emissions from deposition of manure on the soil by grazing animals also doubled, from 78 to 143 Tg CO_2 eq. Consumption of nitrogenous fertilizers, an important source of GHG emissions, increased by 1,079%, from 0.4 to 5.0 Gt N/year, between 1961 and 2003. On the other hand, the area of leguminous crops (soybean and pulses) increased from 6.1 Mha in 1961 to 33.6 Mha in 2001 (FAOSTAT). Since productivity of these crops also increased dramatically, total production, and therefore, the amount of biologically fixed nitrogen incorporated into soils, increased by 1,846% during that period. All other crops increased their production by 155%. Total direct nitrous oxide emissions from soils due to use of N fertilizers and manure, and incorporation of crop residues into soil increased from 21 to 91 Tg CO_2 eq between 1961 and 2003. 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, which was developed in the 1970's, is used on ca. 30 Mha of crops every year in the region. It is uncertain how much of this area is under permanent no till, but it can be safely assumed that the net CO2 removals due to this change in cropland management would at least offset the annual increase in all GHG emissions in the agriculture sector.

8.4 Description and assessment of mitigation technologies and practices, options and potentials (technical, economic, market and social), costs and sustainability

8.4.1 Mitigation technologies and practices - per area estimates of potential

Greenhouse gas mitigation practices in agriculture include methods to reduce emissions of carbon dioxide, nitrous oxide and methane (or increase the storage of C in soils). Many practices, described in more detail below, affect more than one gas. Section 8.4.1.1 describes the mechanisms of mitigation for each gas and Section 8.4.1.2 describes the individual mitigation practices.

8.4.1.1 Mechanisms for agricultural mitigation

8.4.1.1.1 Reducing carbon dioxide losses from agricultural soils

Carbon dioxide is lost from agricultural soils by the decomposition of soil organic matter. Changes in organic carbon content are a function of the balance between inputs to soil of carbon fixed by photosynthesis and losses of soil carbon via decomposition. Soil erosion can also result in the loss (or gain) of carbon locally, but the net effect of erosion on carbon losses as CO_2 for large areas on a national scale is unclear. For soils, both the quantity and quality of organic matter inputs and the rate of decomposition of soil organic carbon will be determined by the interaction of climate, soil, and land use/management (including land-use history). In native ecosystems, climate and soil conditions are the primary determinants of the carbon balance, because they control both production and decomposition rates. In agricultural systems, land use and management act to modify both the input of organic matter via residue production, crop selection, fertiliser application, harvest procedures, residue management and the rate of decomposition (by modifying microclimate and soil conditions through crop selection, soil tillage, mulching, fertiliser application, irrigation and liming). Management practices that increase soil disturbance cause short-term effluxes of CO_2 to the atmosphere, whilst practices that increase the rate of decomposition of organic matter lead to longer-term losses of soil organic carbon in the form of carbon dioxide. Carbon is also lost from ecosystems in harvested products; the carbon in these short-lived products is assumed to be quickly lost to the atmosphere as CO_2.

8.4.1.1.2 Reducing carbon dioxide losses from biomass burning

Biomass burning in the agricultural sector consists of two major terms: the burning of crop residues, and the burning of extensive rangelands. Biomass burning can contribute to climate change in several ways. Firstly, it is a net source of some radiatively active gases. It is generally not considered a net source of CO_2, since the liberated CO_2 is taken up again in the subsequent crop or vegetation regrowth, but it is a significant net source of CH_4, and a minor source of N_2O. Recent research indicates that the net effect of the large quantity of mixed aerosols it produces (black soot, white ashy material, mineral dust, cloud condensation nuclei) is a positive radiant forcing (Andreae *et al.*, 2005; Jones *et al.*, 2003; Venkataraman *et al.*, 2005; Andreae, 2001; Andreae & Merlet, 2001; Anderson *et al.*, 2003; Menon *et al.*, 2002). Several gases prominent in the smoke contribute to tropospheric ozone production, which has a warming effect on the atmosphere. Secondly, the land surface is temporarily blackened, which reduces its albedo for a period of several weeks, causing a warming. Thirdly, in rangelands where both woody plants and grasses can grow (i.e., primarily the savannas, which occupy about an eighth of the global land surface), the proportions of woody versus grass cover are controlled by the fire regime. A change in the fire regime (usually in the direction of reducing both the frequency and intensity of fires) typically leads to a large increase in tree and shrub cover over a period of 20-50 years. The increased cover by woody plants increases the landscape carbon density in both the soil and woody biomass substantially (Scholes and van der Merwe 1996). Through a combination of these processes, the potential for changing the pattern of emissions resulting from biomass burning in agriculture, and thus effecting mitigation, is high, and can be inexpensive. In most cases, and where reasonable precautions are taken, the ancillary environmental and social impacts of reduced agricultural biomass burning are either positive, or only weakly negative. There is some evidence, however, that without human ignition, the fire prone ecosystems would burn through other agencies and that the area burned is ultimately under climatic control (van Wilgen et al 2004).

8.4.1.1.3 Reducing emissions from agricultural use of lime

Limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are commonly applied to agricultural fields to raise the pH of acidified soils (often occurring after long periods of fertilization). Each compound releases CO_2, and together account for x?% of agricultural CO_2 emissions globally. A carbon mitigation option is to reduce the use of these compounds in agriculture, perhaps indirectly by measures that avoid soil acidification (e.g., using less acid-forming fertilizers).

8.4.1.1.4 Increasing the pool of carbon in long-lived agricultural products

Some agricultural products (e.g., hides, wool) may store carbon removed from the atmosphere for long periods of time, as do some pools of harvested wood. Further, the use of crop residues for manufacturing long-lived products (i.e., strawboards) may extend the residence time of carbon, which would otherwise decompose quickly, or could be partially stored as soil organic carbon if added to agricultural soils.

World production of hides and skins has increased from 6.3 Mt in the 1960’s to 10.8 Mt in the 2000’s. Similarly, vegetable fibre output has risen from 17.0 to 25.5 Mt in the same period. Wool and hair, on the other hand, decreased from 2.8 to 2.2 Mt (FAO Statistics). The production of strawboards is still of little significance globally. Overall, the trend for long-lived agricultural products is a sustained increase in output.

The carbon held within these products each year has increased from 37 to 83 Mt C per year over the last 40 years. As these products are manufactured and put into use, part of their carbon returns to the atmosphere, mostly as carbon dioxide. Assuming a first order decay rate of 10 to 20 % per year, it can be estimated that there is an annual increase in the carbon stocks in agricultural products equivalent to a global net annual removal of 3 to 7 Mt CO_2 from the atmosphere. These figures do not include net emissions of greenhouse gases that may have resulted from increased animal production to produce these products. Based on this analysis, C stored in agricultural products is negligible as a C sink since it amounts to only about 0.02% of annual CO_2 emissions from fossil fuel.

8.4.1.1.5 Increasing the non-soil pools of carbon in agroforestry

Agroforestry is the production of livestock or food crops on land that also grows trees, either for timber, firewood of for products of the trees. It includes shelter belts and riparian zones/buffer strips that include 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 the soil carbon sequestration (Guo & Gifford, 2002).

8.4.1.1.6 Offsetting fossil fuel carbon by providing feed-stocks for bioenergy

Agriculture can contribute to GHG offsets by producing feedstocks for energy production. The energy produced offsets carbon emissions from fossil fuels in that the carbon is derived from the photosynthetic fixation of atmospheric carbon dioxide which is then released back to the atmosphere when combusted. Biomass feedstocks therefore recycle carbon with much lower net carbon emissions. Thus the net emissions only involve the GHG emissions encountered in raising and transporting the crops. In particular the use of biomass feedstocks for electricity generation can offset as much as 90% of the carbon that would be released by coal-fired electrical generation, while the use of feedstocks for ethanol production offsets a smaller percentage (10-30%) due to the energy involved in transforming the biomass into liquid energy products. The biomass feedstocks for energy generation involve: (a) conventional commodities like corn, sorghum and sugar cane for ethanol (b) cropping residues, specialized energy crops such as short-rotation tree crops or fast growing grasses, logging and forest product milling residues for power plant generation or conversion to cellulosic ethanol and (c) plant oils and by products of animal rendering as feedstocks for biodiesel. The key implication for agriculture is the impact that allocating land and water resources to energy farming may have on food and fibre production.

In addition to production of feedstocks for bioenergy, another important agricultural energy source and potential offset involve rural household use of biomass energy for the domestic energy. The biomass-burning emissions from this source are often of a similar magnitude to those from the burning of residues or rangelands. Domestic biomass burning emissions are partly complementary to those from residue burning and from forest clearing, since much of the fuel is from those activities. In general, fuels burned in confined hearths tend to produce more methane than the same fuels burned in the field.

When crop residues are used to generate bioenergy, their withdrawal from croplands reduce the amount of C stored in organic matter, thereby offsetting some of the net gains in atmosphere CO_2 mitigation.

8.4.1.1.7 Improved energy efficiency in agriculture

Agriculture consumes energy directly through machinery operations including transportation, irrigation, grain drying, livestock feeding, and other livestock related operations. In addition, substantial energy is used in agricultural buildings and to produce inputs such as fertilizers and pesticides. Greenhouse gas emission reductions through improved energy efficiency in agricultural operations can be achieved in different ways. First, energy can be saved through technical progress, i.e. increased crop and livestock yields for a given energy input level or decreased energy input requirements for a given crop and livestock product level. These options include increased energy efficiency of agricultural machinery, agricultural buildings, and manufacturing processes for fertilizers, pesticides, and livestock feed. The impact of technical progress depends on the rate of technical progress and the costs of implementing it. Second, energy can be saved in agricultural operations by making different choices among existing technologies. This set of options includes higher utilization of emission-saving crops, crop varieties, and animal breeds and the increased use of agricultural inputs and machinery with below-average energy requirements. Different choices in the agricultural production sector require incentives and thus are not free of costs. Third, energy can be saved through different consumption patterns. Particularly, decreases in the share of meat and highly processed food consumption relative to the consumption of vegetable and less-processed food would decrease the average energy input in agriculture per person.

For all of the above-mentioned opportunities, different mitigation potentials arise depending on the definition of energy efficiency, on the allocation of emissions across sectors, and on technical and political developments. Alternative definitions relate to a) energy use per hectare, b) energy use per unit of agricultural product, and c) energy use per capita. The allocation of emissions matters especially for products which involve activities across sectors. For example, emissions (and emission reductions) from fertilizer manufacture could be allocated to either the agricultural or the chemical production sector. Finally, technical and political developments are crucial because they affect choices made by agricultural producers and agricultural consumers. A recent energy tax policy analysis of the US agricultural sector (Schneider and McCarl, 2005) shows that for relatively high tax levels the energy use per hectare of traditional cropland increases because it allows farmers to produce the same amount of food on less land. Less land for food in turn allows more land to be used for planting bioenergy (see Section 8.4.1.1.6). Overall, the combination of a relatively energy intensive food sector and a large energy crop production sector may reduce fossil energy consumption more than a large land area devoted to extensive agriculture with relatively little area left to plant energy crops.

8.4.1.1.8 Reducing nitrous oxide losses from agricultural soils

Biogenic emissions of N_2O from soils result primarily from microbial nitrification and denitrification processes. Nitrification is the aerobic oxidation of ammonium to nitrate (with N_2O as by-product); denitrification is the anaerobic reduction of nitrate through nitrite, nitric oxide (NO) and N_2O to N_2. Major environmental regulators of these processes are temperature, pH, soil moisture (i.e. oxygen availability) and carbon availability. In most agricultural soils, biogenic formation of N_2O is enhanced by an increase in available mineral nitrogen, which in turn increases nitrification and denitrification rates. Hence, in general, adding fertiliser N or manures and wastes containing inorganic N will stimulate N_2O emission, as modified by soil conditions at the time of application. N_2O losses due to denitrification under anaerobic conditions are usually considered more important than nitrification-N_2O losses under aerobic conditions. Therefore no-tillage will perhaps decrease CO_2 losses, but, due to poorer aeration, might enhance N_2O losses due to denitrification (McKenzie *et al.*, 1998; Smith *et al.* 2001; Smith and Conen 2004), though the effect is not always consistent (Helgason *et al.* 2005; Lemke *et al.* 1999). Whilst N_2O emissions have been estimated in both process-based and inventory studies using various models, the outstanding problem is the uncertainty of these estimates. The uncertainty is high because N_2O in soils is produced biologically and emissions usually occur in “hot spots” around particles of residues and fertiliser, despite the spreading of fertilisers and manure and is also highly variable in time (EEA, 2003). Furthermore, the effects of topography and other factors on soil moisture, aeration, and nitrogen dynamics introduces large differences in emission rates across landscapes, even within small plots of land. Hence, a key difficulty with inventories is that the information needed on these factors is not available at the correct spatial and temporal scale, and even if it was, it would be a highly non-transparent inventory due to complexity. Other emissions of N_2O occur from drained and/or cultivated organic soils used for agriculture.

The differences in N_2O emission among various management practices may often be smaller than the resolution of measurement or modelling techniques for estimating emissions. Hence, the effectiveness of proposed management options may sometimes be difficult to quantify.

8.4.1.1.9 Reducing nitrous oxide emissions by improved manure management

Nitrous oxide emissions from manure management include direct emissions N_2O, as well as indirect emissions of N_2O derived from volatilized NH_3 or leached NO_x. Animal manure is collected as solid manure and urine, as liquid manure (slurry) or as deep litter, or it is deposited outside in dry-lots or on pastures. These manure categories represent very different potentials for GHG emissions. However, even within each category the variations in manure composition and storage conditions can lead to highly variable emissions in practice. This variability is a major source of error in the quantification of the GHG balance for a system. Improved manure management can reduce these emissions.

8.4.1.1.10 Reducing nitrous oxide losses from biomass burning

Biomass burning in the agricultural sector is only a minor source of N_2O and mitigation potential is therefore limited. The N_2O emissions scale with the N content of the material burned, which is typically very low, since high-N residues are used as forage.

8.4.1.1.11 Reducing methane emissions from enteric fermentation in ruminants

Biomass burning in the agricultural sector is only a minor source of N_2O and mitigation potential is therefore limited. The N_2O emissions scale with the N content of the material burned, which is typically very low, since high-N residues are used as forage.

Emissions of methane by ruminants are primarily from the anaerobic degradation of organic matter by the process known as biomethanogenesis (Crutzen, 1995). This occurs predominantly in the rumen but some methane is also formed in the hind-gut by a similar fermentation process (Murray *et al.*, 1976; Kennedy and Miligan, 1978) and this is mostly absorbed across the intestinal wall into the blood, and transported to the lungs where it is excreted (Murray *et al.*, 1976).

The organic matter of plants eaten by the animal is hydrolysed to amino acids and sugars and then fermented to pyruvate via the Embden-Meyerhof-Parnas pathway (Wolin and Miller, 1988) by enzymes from ruminal bacteria, protozoa and fungi. Further fermentation results in the end products, volatile fatty acids (VFA), hydrogen and CO_2. Hydrogen, is the central metabolite in ruminal fermentation (Hegarty and Gerdes, 1999), and if it accumulated, would inhibit fermentation. However, it is immediately used by other bacteria primarily for the reduction of CO_2 to methane.

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

Both methane and CO_2 are subsequently voided through erudication. This fermentation process enables continued microbial protein synthesis, whilst the VFA end products are absorbed across the rumen wall and oxidised within the liver. Microbial protein biomass, together with VFA absorption, provide the major sources of both amino acids and energy to the host animal (Allison, 1984; McDonald *et al.*, 1995; Merchen *et al.*, 1997).

The balance of volatile fatty acids produced affects the amount of hydrogen and thus of methane formed. The relationship between methane emissions and the ratio of the various VFAs has been well documented (Hungate, 1966), and it is the management of the ruminal hydrogen pathways which will enable the control or manipulation of ruminant methane emissions (Joblin, 1999).

Ruminants are the major methane producers, accounting for 95 % of total enteric methane emissions. Global enteric emissions are estimated to be 60-80 Tg per year contributing around 18% of global methane emissions. The direct contribution of enteric methane to the total greenhouse effect has been estimated to be 2-3% (refs).

he various mitigation options to reduce methane emissions by ruminants can be classified as (i) nutritional intervention, (ii) use of specific agents or dietary additives, and (iii) longer-term structural or management changes and animal breeding. Nutritional intervention includes strategies such as increased use of concentrates (normally replacing forages), addition of oils to the diet, improving diet digestibility by manipulating forage species, composition or management, and optimising protein intake. Concentrate feeds can have significant effect: methane emission is typically 6-8% of gross energy intake on forage diets, but can be as low as 2-3% on high concentrate diets (Johnson and Johnson, 1995; Lovett *et al.* 2003; Beauchemin and McGinn, 2005). Added concentrates generally increase total feed intake and may increase daily methane emissions, but emissions per kg feed intake and per kg product are almost invariably reduced. However, the net benefit of this strategy is contingent on reduced animal numbers (i.e. some ceiling on output) or reduced age at slaughter in beef animals. As well, the net effect depends on consequences for emissions on and off the farm (e.g., production of imported feed or fertilizer) as well as on indirect emissions related to N losses (Phetteplace *et al.* 2001;Lovett *et al.* ,in press). Another mitigation option in this category is feeding of oils which can reduce methane emissions (e.g. Machmuller *et al.*, 2000; Jordan *et al.*, 2004), but delivery is a problem with grazing ruminants. Improving pasture quality is often cited as a means of reducing emissions (Leng, 1991; McCrabb et al, 1998), especially in less developed regions, because it improves animal productivity, and reduces the proportion of energy lost as methane. However, Alcock and Hegarty (2005) recently modelled the effect of pasture improvement in Australian sheep farms, and noted only a 25% reduction in methane output per kg live-weight. Optimising protein intake can reduce excretion of excess dietary nitrogen by ruminants, and thus reduce nitrous oxide emissions (Clark *et al.*, 2005).

Several specific agents or dietary additives that could reduce methane emissions have been used or proposed. Most of these affect methanogenic bacteria in the rumen. Ionophores are antibiotics which cause a shift from gram-positive to gram-negative bacteria (Russell and Strobel, 1989; Stewart and Robertson, 1989; Wallace, 1994), but the reduction in methane may be transitory (Johnson and Johnson, 1995) and these compounds have been recently banned for use as feed additivies in the EU. Halogenated compounds inhibit methanogenic bacteria (Wolin *et al.*, 1964; van Nevel et Demeyer, 1995) but often the effects are transitory and there are side effects such as reduced intake. Results with probiotics such as yeast culture are variable. McGinn *et al.* (2004) reported that some yeast products may be able to decrease GE lost as CH_4 but it was only by 3% and non-significant. However, selection of strains specifically for methane reducing ability could in future give better results (Newbold and Rode, 2005). Propionate precursors such as fumarate or malate act as alternative hydrogen acceptors and reduce methane formation (Newbold *et al.*, 2002). However, large quantities have to be fed to obtain a notable response, making this is a very expensive option. Work to develop a vaccine against methanogenic bacteria has been undertaken in Australia, but no product is commercially available yet (Wright *et al.* 2004). Finally, in his category, are products such as bovine somoatotrophin (BSt) and hormonal growth implants. They improve animal performance through effects on animal metabolism rather than in the rumen, but can reduce methane emissions per kg of animal product.

Longer-term structural or management change includes improved livestock through breeding programmes. Higher producing animals spread the energy cost of maintenance across a greater feed intake, and will have better food conversion efficiencies, and lower methane output per kg of animal product. However, whole system effects are not entirely clear, as selection for higher yield might reduce fertility, perhaps requiring higher number of replacement animals. In meat producing animals, if the efficiency of production systems can be improved, they will reach slaughter weight at a younger age, with reduced lifetime emissions. Methane capture from ruminant housing is not considered a viable option as concentrations are too low for economical capture.

8.4.1.1.12 Reducing methane emissions by improved manure management

Manures lead to direct emissions of CH_4. Animal manure is collected as solid manure and urine, as liquid manure (slurry) or as deep litter, or it is deposited outside in dry-lots or on pastures. These manure categories represent very different potentials for GHG emissions. However, even within each category the variations in manure composition and storage conditions can lead to highly variable emissions in practice. This variability is a major source of error in the quantification of the GHG balance for a system. Improved manure management can reduce these emissions.

8.4.1.1.13 Reducing methane emissions from cultivated wetland rice soils

Methane is formed under anaerobic conditions at the end of the reduction chain when all other electron acceptors such as, for example nitrate and sulphate, have been used. Methane emissions from freely drained cropland soils are, therefore, negligible. In fact, aerobic cropland soils tend to oxidise methane, but less so than uncultivated soils (Goulding *et al.*, 1995; Willison *et al.*, 1995) with the oxidising capacity for forest, grassland and cropland soils showing the trend forests>grasslands>crops = 10 > 6 > 3 kg CH_4 ha^{-1} yr^{-1} respectively (Boeckx & Van Cleemput, 2001). However, cultivated wetland rice soils emit significant quantities of methane, estimated to be 25.1 Tg CH_4 annually in the region of East, Southeast and South Asia. The global emission from rice fields was estimated to be 28.2 Tg CH_4 (Yan *et al.*, 2003). Mitigation options in wetland rice include water management, organic amendment, fertilization, rice cultivar selection, crop rotation etc. Among these water management and organic amendment are the most important. Shortening the duration of continuous flooding during rice growing period (Yan *et al.*, 2003) and keeping soil as dry as possible during the non-rice growing period (Cai *et al.*, 2000; Xu *et al.*, 2003) significantly decrease CH_4 emissions from cultivated wetland rice soils. In rice-based agricultural systems with a flooded rice crop and upland crop rotation or with a fallow period, the stimulation effect on CH_4 emission can be mitigated significantly either by incorporating organic materials into soil in the dry period rather than in flooded period (Cai and Xu, 2004) or prior to composting, or by producing biogas for use as fuel for energy production (Wang and Shangguan, 1996).

8.4.1.1.14 Reducing methane losses from biomass burning

Biomass burning in the agricultural sector is a significant net source of CH_4. Mitigation involves reducing wildfires through fire suppression, replacement of manual harvesting of sugarcane (which is usually accompanied by pre-harvest residue burning) by fully mechanised harvesting and the use of alternative sources of energy for domestic cooking/heating in developing countries, in place of agricultural residues.

8.4.1.2 Agricultural management practices for mitigation

Many practices affect more than one GHG and the best available data have been used to estimate the impact on all GHGs of each practice. Mitigation options are listed in Section 8.1.1. When assessing the impact of agriculture on changes in greenhouse gas emissions, it is important to consider the impacts on all greenhouse gases together (Robertson *et al.*, 2000; Smith *et al.*, 2001; Gregorich *et al.*, 2005). For the non-livestock based options, ranges for per area mitigation potentials for each practice are given for each GHG (in t CO_2-equivalents ha^{-1} $year^{-1}$) for each of four climate regions in Table 8.4.1.2a. For soil carbon, estimates of soil C storage, CO_2 mitigation potential and the low and high values for the 95% confidence interval were derived using mixed effect modelling on a large dataset of long term agricultural soil carbon experiments from a variety of countries, though temperate studies were more prevalent in the database (Ogle *et al.*, 2005). Estimates were made using this method for all land-based mitigation options except for the estimates for bioenergy crops and agroforestry which are derived from data presented in Smith *et al.* (1997 & 2000) and the organic soil estimates which are for emissions under drained conditions from IPCC guidelines. Soil methane and nitrous oxide emission reduction potentials were derived from fewer experiments as detailed in the footnotes of table 8.4.1.2a.

[Table 8.4.1.2a here]

For the livestock-based options, the mitigation potentials (dairy, other cattle, combined dairy/other and sheep) are given for reducing methane emissions through improved feeding practices (Table 8.4.1.2b), specific agents and dietary additives (Table 8.4.1.2c), and longer term structural and management changes/breeding (Table 8.4.1.2d).

As seen from the tables, some of the mitigation measures operate predominantly on one GHG (e.g. dietary management of ruminants to reduce CH_4 emissions) whilst others have impacts on more than one (e.g. rice management). For some management practices, there are GHG benefits for more than one gas (e.g. set-aside/headland management) whilst for others there may be a trade off between gases (e.g. tillage practice). Table 8.4.1.2a also shows that the effectiveness of specific some mitigation practices differs between climate regions, and there is much variation even within a climate region. A practice that is highly effective in reducing emissions at one site, may be less effective, or even counter-productive elsewhere. This means that there may not be a universally-applicable list of mitigation practices, but that any proposed practices will need to be tuned to individual agricultural systems present in specific climatic, edaphic, and social settings.

The effectiveness of mitigation strategies also changes with time. Some practices, like those which induce soil C gains, have diminishing effectiveness after several decades; others, such as methods that reduce energy use, may mitigate 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.

8.4.2 Regional estimates of the biophysical mitigation potential and the estimated socioeconomic mitigation potential of each agricultural management practice

The per-area/per-animal values for mitigation potential for each climate region given in table 8.4.1.2 were scaled up to regions and to the world by multiplying by the area under each climate in each region. The regions, climate zones within each region, areas of crop, crop mix and grassland in each climate zone in each region, area of cultivated organic soils within each climate zone in each region, the area of degraded land in each climate zone in each region, and the total area of rice cultivation for each region, were derived from the FAO Global Agro-Ecological Zones (AEZ; FAO/IIASA, 2000), FAO Digital Soils Map of the World (FAO/UNESCO, 2002) and FAO statistical (FAOSTAT, 2005) databases as follows:

- *Areas of each region*: Area of each region in the FAO AEZ database.
- *Areas of climate zones within each region*: GIS overlay of FAO AEZ regions with climate regions defined as follows. "Warm" for use with the mitigation factors in Table 8.4.1.2 is defined by "tropical" and "subtropical" categories of the thermal climate data set, and "cool" is defined by the "temperate" categories of the thermal climate data set. Boreal climates were excluded as little agriculture takes place in these zones. "Dry" climates are defined by areas with "severe moisture constraints or moisture constraints" in the climate constraints data set with all other areas defined as "moist". The GIS overlay gives the areas in region in the cool-dry, cool-moist, warm-dry and warm-moist climate categories used in Table 8.4.1.2.
- *Areas of crop, crop mix and grassland in each climate zone within each region*: GIS overlay of the above regional and climate data with the "crops", "mixture including crops" and "grassland" areas from the "dominant land cover" data set of FAO AEZ.
- *Areas of cultivated organic soils in each climate zone within each region*: GIS overlay of areas under "crops" and "mixture including crops" of the "dominant land cover" data set of FAO AEZ and the FAO Soils database, with organic soils defined by soil carbon contents greater than 30 kg/m^{-2} to 100cm depth.

- *Area of degraded land in each climate zone within each region*: GIS overlay of areas under "crops" and "mixture including crops" from the "dominant land cover" data set of FAO AEZ with the "severe fertility constraints" and "unsuitable for agriculture" categories of the "soil fertility constraints" data set of the FAO AEZ database.
- *Areas of rice cultivation within each region*: The harvested rice area in 2004 for each region was taken from the FAOSTAT database.
- *Changes in areas of biofuel crops, cropland and grassland within each region by 2025*: The projected cropland, grassland and biofuel crop area in each region by 2025 as projected by the IMAGE 2 model (CIESIN, 1995).

All data were converted to real-area projections and the areas in m^2 were converted to ha. For emissions from livestock, total cattle and sheep numbers in the various regions were obtained from FAOSTAT (2005). The cattle numbers for each region were broken down into numbers of dairy cattle and other cattle (because of the different reduction potentials of both types) using numbers of dairy cows according to USDA (http://www.fas.usda.gov/dlp/circular/2005/05-07Dairy/toc.htm).

Figure 8.4.2a shows the low, mean and high estimates of the global biophysical mitigation potential of each agricultural management practice. Figure 8.4.2b shows the global mitigation potentials, comparing the total biophysical potential with the realistically achievable potentials under assumptions of 10 and 20% implementation over the next 20 years. Implementation levels of 10 and 20% are the maximum percentage of full biophysical potential assumed to be possible over the next 20 years, irrespective of the price of CO_2-equivalents (Cannell, 2003; ECCP, 2003; Freibauer *et al.*, 2004; Smith 2004a) which are considered in Section 8.4.3. Non-price determined limitations to implementation include such factors as institutional, educational, social and political constraints (Smith, 2004b; Smith *et al.*, 2005). Limits to implementation of mitigation options resulting from the price paid for CO_2-equivalents are dealt with in Section 8.4.3.

[Figure 8.4.2a here]
[Figure 8.4.2b here]

For each region, the biophysical potential is defined by the sum of the potential due to a) improvements in cropland management (mean of cropland management, tillage practice, nutrient and manure management and water management) for the whole cropland area in 2025, b) improved grazing land management for the whole grassland area in 2025, c) bioenergy cropping, d) improved rice management of the whole rice area, e) restoration of native ecosystems on currently cultivated organic soils, f) restoration of all degraded lands, g) improved energy efficiency, h) improved livestock management (mean of mitigation due to feeds/inocula/breeding & systems) and i) increased storage of C in agricultural products. Figure 8.4.2c shows the low, mean and high regional estimates of the biophysical mitigation potential for all practices and GHGs considered together. It is important to note that the most appropriate agricultural mitigation response will vary at the regional level and different portfolios of strategies will be developed in different regions, and in countries within a region.

[Figure 8.4.2c here]

The global biophysical agricultural mitigation potential is estimated to be ~7300 (-1100 to 16900) Mt CO_2-eq. y^{-1} for all gases with a realistically achievable potential of 700-1500 (-200 to 3400) Mt CO_2-eq. y^{-1}. Of this total, about 93% is attributable to reduced soil emissions of CO_2, and about 7% is due to mitigation of other GHGs. The upper and lower limits about the estimates are largely determined by the confidence intervals surrounding the mean estimate for soil C storage of the mixed effects model. There is a high degree of uncertainty associated with estimates of agricultural mitigation potential.

These estimates, based on the best data currently available, are somewhat lower than previous estimates. In the IPCC SAR, it was estimated that about 1400-2900 Mt CO_2-eq. y^{-1} could be sequestered in global agricultural soils. The estimates presented here suggest realistically achievable potentials (assuming 10-20% implementation over the next 20 years) of about 700-1400 (-150 to 2900) Mt CO_2-eq. y^{-1} for soil C sequestration, and 700-1500 (-200 to 3400) Mt CO_2-eq. y^{-1} for all GHGs.

The global soil carbon sequestration potential estimated by Lal (2003) was 3300 ± 1100 Mt CO_2 y^{-1}. The estimate of total soil biophysical potential presented here is about twice this value at 6900 Mt CO_2 y^{-1}, but the realistically achievable potential is estimated to be only 20-45% the estimates of Lal (2003). Caldeira *et al.* (2004) also suggested feasible abatement rates for agriculture (all gases: enteric fermentation, rice cultivation, biomass burning, animal waste treatment, and agricultural soils over a 0-20 year time horizon) that were much higher than the estimates presented here, at 1230 Mt C-eq. y^{-1} (4510 Mt CO2-eq. y^{-1}). Values in the IPCC SR-LULUCF (2000) were 400 Mt C-eq. y^{-1} for 2010 from C stock change in croplands, grazing lands, agroforestry, rice paddies and urban lands, which is equivalent to 1467 Mt CO_2-eq. y^{-1}, putting the SR-LULUCF report estimates at the high end of the range estimated here. Manne & Richels (2004) suggest values similar to the SR-LULCF for soil carbon sink enhancement at 464 Mt C (1700 Mt CO_2) in 2010 assuming a marginal cost of US$ 100 t C $^{-1}$.

The estimates from this global synthesis also compare well with regional, bottom-up estimates of GHG mitigation potential. In Europe, Smith *et al.* (2000) estimated the carbon sequestration potential of European agricultural soils (excluding Russia) to be 205 Mt CO_2 y^{-1}. The estimate of the realistically achievable potential (assuming 20% implementation) for Europe is 181 Mt CO_2 y^{-1}. The similarity between the two figures is striking.

In addition to GHG emission reduction, agricultural land can provide feed stock for bioenergy production. Low and high estimates for the fossil fuel offset from bioenergy crops can be calculated using biofuel crop areas in each region in 2025 for each IPCC SRES scenario projected by the IMAGE 2 model (CIESIN, 1995), based on the following assumptions: low and high yields of 4 and 12 oven dry t ha^{-1} for bioenergy crops and agricultural residues (Andersen *et al.*, 2005), fossil fuel savings (compared to oil) of 1.61 t of oil CO_2-eq. saved per oven dry tonne (odt) biomass (from figures in Cannell, 2003) and energy output of 7.4 GJ odt $biomass^{-1}$ for electricity generation, and 12.95 GJ odt $biomass^{-1}$ for combined heat and power (CHP) production (Cannell, 2003. The B1 scenario has the smallest biofuel crop area in 2025 (~60 Mha) whilst the B2 scenario has the largest biofuel crop area (~140 Mha). Using these figures, mean yields of 4 and 12 odt ha^{-1} y^{-1} would produce 230-700 and 560-1700 od Mt of biomass y^{-1}, respectively. This biomass would deliver fossil fuel CO_2 savings of ~360 - ~2730 Mt CO_2 y^{-1}, but increased GHG emissions of 270-660 Mt CO_2-eq. y^{-1} from biomass burning (based on IPCC defaults for methane and nitrous oxide equivalent to 1.73 and 2.97 t CO_2-eq. ha^{-1} y^{-1}, respectively; Smith *et al.*, 2001) mean that the net GHG benefits would be ~100-2070 Mt CO_2-eq. y^{-1} (shown for each region in Figure 8.4.2d). This biomass would generate ~2-22 EJ y^{-1} of energy depending upon yield and the proportion of the energy used for CHP or for generating electricity alone, considerably less than the *technical potential* estimated to be possible by 2050 in the TAR: ~400 EJ y^{-1} assuming 15 odt ha^{-1} and 20 GJ odt^{-1} (IPCC, 2001).

These figures are somewhat lower than the estimates for biomass energy mitigation in the SAR (1100-4800 Mt CO_2-eq. y^{-1}) but are based on projected biofuel crop areas rather than an assumption of 10-15% of agricultural land used in the SAR, and also account for non-CO_2 GHGs which were not accounted for in the SAR. The net GHG benefits of bioenergy crops are of a similar order of magnitude to all other agricultural mitigation options combined.

[Figure 8.4.2d here]

8.4.3 Effects of the price of CO_2-equivalents on the implementation of mitigation technologies and practices

Costs associated with agricultural mitigation practices are shown in table 8.4.3a.

[Table 8.4.3a here]

While mitigation potential can be assessed technically and with economics in mind, there is a relationship between the amount paid for GHGs and the quantity produced. Results in McCarl and Schneider (2001), Lee *et al.* (2005) and Antle *et al.* (200?) indicate that total GHG mitigation increases as the GHG price becomes higher. Across the range of prices, the role of alternative strategies changes. At low prices, the dominant strategies are those consistent with existing production like tillage changes, fertilizer manipulations and manure management while higher prices elicit land use changes that displace existing production, such as biofuels and afforestation. The portfolio of mitigation strategies also varies over time because of (a) the limited ecological capacity of the sequestration related strategies (i.e. their approach to a carbon equilibrium under a set of practices over time) and (b) the limited market penetration potential of capital intensive strategies like biofuels (which are constrained by the rate of turnover in energy processing plants, prospects and costs of retrofits and energy product growth) and afforestation (where capital for replanting and land payments must be sufficient to carry land owners until trees become mature). Finally, it is important to note that while the most prevalent cost-mitigation quantity schedules are for single strategies (i.e. the amount of sequestration obtained as prices increase; as in Antle *et al.*, 200?), it is not valid to sum these to gain a total mitigation potential, due to resource competition among strategies. For example McCarl and Schneider (2006) show that at higher prices, adding individual strategies can yield a total mitigation estimate that is as much as 5 times too large.

As part of the analysis done here, a schedule of mitigation quantities at alternative CO_2 equivalent prices was developed. This schedule uses a relationship where greater quantities of offsets are generated across the sector as higher prices are paid for offsets, as in McCarl and Schneider (2001), Lee *et al.* (2005) and Antle *et al.* (200?). The data on regional costs and potentials did not uniformly give price quantity schedules and also were based on individual strategy evaluations, not joint evaluations. Consequently this analysis relies on the form of the price quantity schedules available for North America arising from the study by Lee et al (2005). In particular, the Lee *et al.* (2005) percentage approach to technical maximum was applied to the total regional and global biophysical potentials outlined in Section 8.4.3. The Lee *et al.* (2005) results for afforestation were applied to agroforestry (showing an increasing rate of gain as prices increase). The Lee *et al.* (2005) biofuel results were used in this analysis for biofuels (showing an increasing rate of gain as prices increase) and the tillage induced soil carbon results from Lee *et al.* (2005) were used for tillage in this analysis (showing a large gain at low prices, then a plateau and a reduction as biofuels and afforestation become more important). All of the other categories used either the non-CO_2 or agricultural fossil fuel emission patterns which are essentially linear increasing trends with price. Water management is only used at very high CO_2-equivalent prices. Further discussion and illustration of these trends can be found in Lee *et al.* (2005) or McCarl and Schneider (2001). The effect of price of CO_2-eq.

(US$ t CO_2-eq.$^{-1}$) on the global mitigation potential of each group of activities is seen in figure 8.4.3a.

[Figure 8.4.3a here]

Assuming no other constraints on implementation, Figure 8.4.3b shows that at low prices (~17 US$ t CO_2-eq.$^{-1}$) for CO_2 equivalents, less than 30% of the global biophysical potential will be realised (~2000 Mt CO_2-eq. yr^{-1}), whereas at prices of ~33 and 50 US$ t CO_2-eq.$^{-1}$, 55 and 80% respectively (~4100 and ~6000 Mt CO_2-eq. yr^{-1}) of total global biophysical potential could be realised. Exceptionally high prices (e.g. 5000 US$ t CO_2-eq.$^{-1}$) would lead to full implementation to ultimately reach the total biophysical potential of ~7400 Mt CO_2-eq. $^{-1}$. If other, non-price related constraints also occur (i.e. assuming 10-20% implementation of full biophysical potential over the next 20 years), mitigation potentials are reduced accordingly (also shown in Figure 8.4.3b).

[Figure 8.4.3b here]

If both price-related, and non-price-related, constraints to implementation of mitigation measures are considered, global agricultural mitigation potentials (using mean per-area mitigation estimates) are estimated to range from 200 Mt CO_2-eq. yr^{-1} (for low price and 10% implementation possible by 2025) to 7300 Mt CO_2-eq. yr-1 (for very high price and implementation of entire biophysical potential by 2025). The interaction between price of CO_2-equaivalents, the level of implementation possible by 2025 and mitigation potential is shown in table 8.4.3b.

[Table 8.4.3b here]

8.4.4 Potential implications for sustainable development of mitigation options

As discussed in chapter 2 some GHG mitigation strategies also show synergy with the goals of sustainability. For example (a) reducing rice methane by adopting improved water management reduces water use; (b) reducing tillage prevents erosion; or (c) reducing rice fertilization reduces nitrous oxide emissions and minimizes nitrogen runoff (Pathak and Nedwell, 2001). Gains can be achieved in soil health, and water quality that in the long run improve agricultural productivity and water quality and productivity. Such productivity gains generally increase income, depending on whether the increase in productivity is small enough that it does not lead to reductions in commodity prices.

The long-term economic sustainability of practices that have limited duration is questionable. For example, some sequestration-related practices only exhibit carbon gains until the ecosystem reaches a new equilibrium at which time the carbon gains cease. Consequently the GHG component of the income increment from practice adoption may cease after a number of years but the practice itself must be sustained to avoid release of stored C.

Various activities in the agricultural sector (e.g. land use practices, tillage management, nutrient management and soil management) have explicit impact on the constituents of sustainable development. The widely agreed constituents of Sustainable Development – economic, social and environmental dimensions - have been considered while analyzing mitigation options in agriculture. In the table 8.4.4, the activities under mitigation options fall into two categories. In the first category, there is clear evidence of impacts of those activities having synergy and co-benefits among the indicators of sustainable development. They clearly enhance and strengthen the economic, social and environmental criteria of Sustainable Development. Rice management through water and other nutrient management, grazing land management, land restoration, greater use of bio-energy, efficient energy use in all agricultural activities, and greater storage of carbon in agricultural products, directly enhance productivity or reduce cost of operations. They also help in enriching social harmony and gender equality. Agro- forestry for example, helps females, otherwise devoted to fuel-wood and fodder collection, to participate in local decision-making, especially in developing countries (Agarwal, 1987). The availability of fodder and fuel wood allows children, who would otherwise spend time collecting these resources, to go to school (literacy). The efficient use of inputs, whether it is water, organic matter or other chemical fertilizer has favorable impacts on cultivated ecosystems and their capability to yield various ecological services (MA, 2005). Agroforestry also provides greater biomass (fuel-wood, fodder) and becomes the basis of co-benefits by helping the livestock sector. Effective drainage and irrigation saves land from environmental catastrophe like soil salinity and water logging. The examples of mitigation activities mentioned above illustrate the synergy among the economic, social and environmental criteria of sustainable development.

In the second category of mitigation activities, the impact on sustainable development is more uncertain. In the table 8.4.4, impact of tillage/residue management and precision farming on economic indicators cannot be inferred with adequate certainty unless the change in prices of agricultural products and that of inputs (labour, fertilizers etc.) are known with accuracy. Similar uncertainty is prevalent in the case of impacts of pasture improvement/grazing land and biosolid management. In some cases, there are trade-offs among different constituents of sustainable development. For example, under land cover change, conversion from cropland to grassland might yield a growth in biomass and ground-water recharge leading to social gain, but reduced cropland will have adverse effect on food supply. The trade off is clear but the resultant impact on sustainable development would be determined by the relative strength of the economic *versus* social and environmental impact. In a more general sense, the impact of mitigation option on sustainable development should be analyzed in the context of the criteria where impact and effectiveness of the response itself is designed, executed and monitored. Many of the trade-offs between the economic and environmental dimensions of sustainable development would vanish if the ecological services and benefits were incorporated into the analysis. Many of the mitigation option listed in the Table 8.4.4 have the potential to yield useful environmental co-benefits. In the long run they would enhance the productive ability of economy and environmental paving the path of sustainable development.

8.5 Interactions of mitigation options with adaptation and vulnerability

As discussed in Chapters 3, 11 and 12, mitigation and adaptation may occur simultaneously, but differ in their spatial and geographic characteristics. The main climate change benefits of mitigation actions taken in the short term will emerge over decades but where the drivers serve to achieve other policy objectives, there may also be short-term benefits. Conversely, actions to enhance adaptation to climate change impacts even in the short term will have consequences both in the short as well as medium and long terms (Kram, 2003). The geographic characteristics are also completely different. Mitigating greenhouse gas emissions has global benefits regardless of where the actions themselves are taken.

The co-benefits will mostly be local. Conversely, impacts of climate change on ecosystems and human systems will vary in severity from place to place. They will also vary with respect to the ability of the ecosystem or human community's ability to cope (i.e. its adaptive capacity) with such adverse impacts. Some (but by no means all) the adverse impacts of climate change may be reduced by taking advance action (i.e. adaptations), but these will always be at a location-specific level (Huq & Grubb, 2004). Because of these differences, both synergies and tradeoffs arise from mitigation and adaptation.

Huq and Grubb (2004) note a number of examples where synergies and trade-offs may occur. For example, 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). 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) or negative consequences for mitigation (e.g. increasing use of nitrogen fertiliser to overcome falling yield leading to increased nitrous oxide emissions). In many cases actions will be taken for reasons which have nothing to do with either mitigation or adaptation (i.e. are unrelated to climate considerations) but may have considerable consequences for either (or both) mitigation as well as adaptation (e.g. deforestation for agriculture or other purposes results in both carbon loss as well as loss of ecosystems and resilience of local populations).

Mitigation and adaptation actions and policies within nations relate to inherently different sectors (although there is some overlap). Mitigation actions, for example, usually relate to energy, industry and transport sectors in most countries. The most vulnerable sectors (and hence the ones where adaptation actions will need to be taken) are usually the agriculture, land use, forestry, water and coastal zone management sectors (Huq & Grubb, 2004).

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 realised GHG mitigation occurs due to barriers to implementation (Fig. 8.6; Smith 2004b).

[Figure 8.6 here]

Globally and for Europe, Cannell (2003) showed that the realistically achievable potential for carbon sequestration and bioenergy-derived fossil fuel offsets were less than 20% of the technical potential. Similar figures were derived by Freibauer *et al.* (2004) and the ECCP (2001) for agricultural carbon sequestration in Europe. Smith *et al.* (2005) have shown recently that carbon sequestration in Europe, and for four case-study countries in Europe, is likely to be negligible by the first Commitment Period of the Kyoto Protocol (2008-2012), despite significant biological/technical potential (e.g. Smith *et al.*, 2000; Freibauer *et al.*, 2004; Smith, 2004a). In Europe, there is little evidence that climate policy is affecting GHG emissions from agriculture (see Smith *et al.*, 2005), with most emission reduction occurring through non-climate policy (Freibauer *et al.*, 2004). Non-climate policies affecting GHG emissions are discussed in Section 8.7. Some countries have agricultural policies designed to reduce GHG emissions (e.g. Belgium), but most do not (Smith *et al.*, 2005). In Europe, the ECCP (2001) recommended the reduction of livestock methane emissions as being the most cost effective GHG mitigation options for European agriculture.

In North America, whilst the US is not a participant in the Kyoto Protocol, it hosts multinational companies which have reduced GHG intensity as a by-product of their world wide current Kyoto exposure, or through their activities to explore options for future climate agreements. Some of this activity has involved agricultural sector activities including pig manure management, afforestation, and farm tillage. In the US, some states are imposing or considering imposing policies, for example

nine north-eastern states are close to imposing a cap, and Oregon has a program that involves power plant licensing and tree establishment. The US also runs the Clear Skies Initiative which is a voluntary program to reduce GHG intensity per dollar of GDP by 18% by 2010. A substantial signup has occurred on the voluntary registry. However, the program is projected to allow emissions to increase by 12% even though the intensity has been reduced as GDP is growing. There also is a long term diminishing trend in emissions per capita largely caused by energy conservation and the program does not deviate much from a continuation of that trend. In Canada, the agriculture sector contributes about 10% to national emissions, so mitigation (removals and emission reductions) is considered to be an important contribution to achieving Kyoto targets (and at the same time reduce risk to air, water and soil quality). Examples include: the AAFC Mitigation program which encourages voluntary adoption of GHG Mitigation practices on farms; National research programs aimed at reducing the energy intensity of crop production systems, enhancing biological sinks, and enhanced bio-energy capacity (i.e. methane capture); and the domestic offset trading system designed to encourage soil C sequestration and emission reductions.
In Oceana, vegetation management policies in Australia have assisted in progressively restricting the 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 in both Australia and New Zealand as well as improved forest management. There is a range of research being supported into safe, cost-effective greenhouse gas abatement technologies for livestock including methanogen vaccination (Wright *et al.* 2004), dietary manipulation and other methods of reducing enteric methane emissions, as well as manure management, nitrification inhibitors and fertiliser management.

In Latin America and the Caribbean climate change mitigation has still not been considered as an issue for mainstream policy implementation. Most countries in the region have devoted efforts to capacity building for complying with obligations under the UNFCCC, and a few of them have prepared National Strategy Studies for the CDM. Carbon sequestration in agricultural soils would be the climate change mitigation option with the highest potential in the region, and its exclusion from the CDM has hindered a wider adoption of land use management practices (e.g., zero tillage) leading to net CO_2 removals from the atmosphere. The region has been particularly active in the development of CDM projects for reducing emissions from manure management and by displacement of fossil fuel by biomass energy. However, in spite of a relatively large number of projects based on these activities, their mitigation potential is of low significance. In fact, as of October 2005, 69 projects in the region had reached the validation stage, and their combined expected emissions reductions is only 4.8 Mt CO_2eq/year (UNFCCC, 2005).

No African country has emission reduction targets under the Kyoto Protocol, so the impacts of climate policy on agricultural emissions in Africa are small. We are unaware of any approved CDM projects in Africa related to the reduction of agricultural GHG emissions *per se*, although several projects are under investigation in relation to the restoration of agriculturally-degraded lands, the carbon sequestration potential of agroforestry, and the reduction in sugarcane burning.

8.6.2 Barriers and opportunities/implementation issues

A number of barriers and implementation issues arise. In the international dialogue over sequestration, commonly mentioned issues involve the following.

Permanence: A number of agricultural activities, particularly those related to C sequestration,, only remove carbon from the atmosphere until the capacity is reached which can occur as early as 15-20 years after adoption(West and Post 2002). The real value of such strategies is that they can buy time for other more capital-intensive developments in places like the energy industry to be deployed (Sands and McCarl, 2005).

Additionality: A number of the practices that can be expanded are already being employed to some extent largely due to energy, environmental or water conservation concerns. However there is substantial additional potential that could be tapped by incentives provided that incentive schemes allow payments to expansions of partially implemented practices.

Uncertainty: Agricultural production exhibits substantial variability and so will offset quantities. However in a multi-year, multi-location setting, much of this variability is reduced with the measures of variance reducing by more than an order of magnitude. Thus multi-region, multi-year contracts may need to be designed (McCarl and Kim, 2005).

Leakage: Adoption of certain agricultural mitigation practices reduces production within implementing countries which may be offset by production increases in other countries that are not as involved with GHG mitigation efforts. Leakage discounts may need to be employed (Murray *et al.*, 2004).

Beyond the widely discussed items above a number of other implementation issues arise.

Transaction costs: Farmers will not adopt otherwise unprofitable agricultural mitigation practices in the absence of policies or incentives. Under an incentive-based system such as a carbon market, the amount of money that farmers receive is not the market price but rather the market price less any costs involved in getting the commodity into the market. This may involve substantial transaction costs especially for small-holders. For example, in the case of soil carbon with annual production of roughly 2 t CO_2 ha^{-1}, if one is trying to assemble a 50,000 tonne contract for trading to a large power plant, then 25,000 ha are needed which, particularly in developing countries, would involve many thousands of farmers. In turn, the process of passing the money and obligations back and forth would likely involve substantial transaction costs, greatly reducing the pass-through of the GHG offset price. For example the broker costs of crop insurance which involves many farmers assembled and sold to one insurance agent amount to 25% of the market price. Smith *et al.* (2005) have shown that, despite significant potential, soil carbon sequestration in Europe by 2010 will be negligible due to lack of policies and incentives for farmers/land managers to store carbon in soils.

Measurement and monitoring costs: Mooney *et al.* (2004) argue that such costs are likely to be small; under 2% of the value of a contract.

Property rights: Both property rights and the lack of a clear single party land ownership in certain areas may inhibit the ability to implement management changes.

Other constraints: Other possible constraints include the availability of capital, the rate of capital stock turnover, the penetration of biofuels into the marketplace, risk attitudes, need for new knowledge, availability of extension-service-supported technology dissemination, and consistency with traditional practices.

Significant barriers for agricultural GHG mitigation arise through pressure for agricultural land, demand for agricultural products and competing demands for water. Other barriers include the costs of implementation (e.g. soil tests before fertilization in China) and ease of compliance (e.g. straw burning in China is quicker than residue removal so farmers favour straw burning).

8.7 Integrated and non-climate policies affecting emissions of greenhouse gases

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 8.4.4), macroeconomic policy such as CAP/CAP reform, international free trade agreements, trading blocks, trade barriers, region-specific programmes and energy policy and price adjustment, and other environmental policies such as various environmental/agro-environmental schemes.

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 to conservation zones for wildlife. This may increase soil C sequestration by if restored to wetland, could increase CH_4 emissions. In support of UN Sustainable Development guidelines, China has introduced a Land Reclaimation Regulation (1988) in which land degraded by construction, mining, and collapse should be restored for use in agricultural. This Regulation will have increases carbon storage in these degraded soils.

In Europe (including the former USSR) and North America none of the UN conventions have had significant impacts on agricultural GHG emissions.

8.7.2 Macroeconomic policy

In North America, there is momentum toward energy conservation and energy security. Incentives will help reduce some forms of energy use and increase the use of renewables. This may fail to deliver significant GHG benefits since some of the energy security provisions may cause reliance on emission-increasing energy sources. In addition, energy price adjustments have played a role in encouraging agricultural mitigation with a greater incidence of reduced tillage resulting from rising energy prices. However, alternative fuels may increase in production, and some may increase GHG emissions. In Canada, the removal of the Grain Transportation Subsidy (Crow Rate in Prairie Canada) resulted in an increase in grain transportation costs which shifted production from annual to perennial crops and livestock; benefits include carbon sequestration and reduced inputs of synthetic N fertilizer.

In Europe, reform of the Common Agricultural Policy (CAP) has resulted in single farms payments, which move subsidies away from production targets, and encourage schemes such as farm woodland and biodiversity areas. In addition, less nitrogen fertilizer is likely to be used under this system, with N_2O emissions potentially decreasing. Some political changes in Europe in recent years may have reduced agricultural GHG emissions, such as the reunification of Germany which resulted in the closure of many intensive pig units, with consequently reduced GHG emissions, but others, such as enlargement of the European Union (EU) may encourage more intensive agriculture in the new EU countries, thereby potentially increasing GHG emissions.

In the countries of the former Soviet Union, numerous economic changes have occurred since the early 1990s. There has been a mass abandonment or croplands (1.5 Mha) with the resulting grasslands sequestering carbon in soil, and regenerating forests (12-15% of abandoned lands; Romanovskaya, 2005) sequestering carbon in soils and woody biomass. The use of agricultural machinery has declined in Russia (1.6 M tractors in 1990 compared to 0.6 M tractors in 2003) as has the fossil fuel use per ha of cropland (20-60% less in 2001 compared to 1991; Romanenkov *et al.*, 2004). This has decreased CO_2 emissions from fossil fuel but increased CO_2 releases from straw burning. Machinery use is predicted to increase over the coming decade. Fertilizer consumption in Russia has dropped from 99 kg ha^{-1} in 1986-1990 to 18 kg ha^{-1} in 2001-2004 and in Belarus has dropped from 259 kg ha^{-1} in 1990 to 149 kg ha^{-1} in 2004, with organic fertilizers showing an 8 fold decrease over a similar period in Russia and halving in Belarus. As a result, 1999 N_2O emissions from agriculture were only 19.5% of the 1990 level (16 Gg N_2O; Third national communication of the Russian Federation for the United Nations Framework Convention on Climate Change, 2002). Soil C may have declined due to lower residue and manure inputs but this is unquantified. Fertilizer use is predicted to increase in the coming decade (Lapa, 2005). CO_2 emissions from liming in Russia dropped by to 8% of 1990 levels (13.8 Mt of CO_2 in 1990 to 1.1 Mt of CO_2 in 1999; Third national communication of the Russian Federation to the United Nations Framework Convention on Climate Change. M., 2002). Increase in lime application from 1.7 Mha in 2002-2005 to 2.5-20 Mha in 2006-2010 is planned, subject to economic growth (Concept of Federal purpose-oriented program "Soil conservation and fertility restoration of agricultural lands and agrolandscapes as national resource of Russia in 2006-1010"). Lime application in Belarus currently is 1.6-2 Mt on 0.43 Mha annually and is not predicted to rise in the near future. In terms of CH_4 emissions from livestock in Russia, emissions in 1990 were less than 48% of the 1990 level. The observed decline in CH_4 emissions is associated with a decrease in livestock and poultry number in Russia (Third national communication of the Russian Federation submitted to the United Nations Framework Convention on Climate Change. M., 2002). The use of bare fallowing in Russia has declined (88% of the area in bare fallow in 1999 compared to 1990; Agriculture of Russia, 2004). This will have decreased soil CO_2 emissions though the rate is unquantified. Changes in rotational structure have also potentially caused increases in soil C. A 3-10% rise of perennial grasses in crop rotations in different regions of the non-chernozem zone during 1990-2000 has occurred through the maintenance of annual and perennial grass (at 28% in crop rotations in 1997-2003) in the fodder sector, with simultaneous decreases of silage corn and fodder root crops areas (Agriculture of Russia, 2004).

In Asia, some Chinese croplands are currently in set aside due to prevailing economic conditions in agriculture. This reduces N_2O emission directly, and may increase carbon storage in soil.

Australia and New Zealand continue to provide little direct subsidy to agriculture, resulting in highly efficient industries that have a focus on minimising unnecessary inputs and reducing waste. Consequently, the potential for high levels of loss such as nitrous oxide emissions tend to be 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. National competition policies cover various aspects of agriculture including water markets. There is a general expectation that establishment of comprehensive water markets will over time result in reductions in the size of industries such as rice and irrigated dairy with consequent reductions in the emissions from these sectors.

In Latin America, the burden of a high external debt triggered the adoption, in the 1970's, of policies designed for increasing the trade balance mainly through a promotion of exports of agricultural commodities (Tejo, 2004). This resulted in the changes in land use and management described in Section 8.3.3 above, which are still causing increases in annual greenhouse gas emissions. On the other hand, some policies tending to promote the use of biofuels that were implemented in the region have helped to reduce emissions. The most significant example is the PROALCOOL Program, implemented in Brazil as a response to the 1973 oil crisis and to large fluctuations in sugar prices. This program promoted the use of ethanol from sugar cane in substitution of gasoline, and was based on economic incentives to producers and a subsidy to consumers financed by a tax on gasoline. As a result of this policy, 96% of all cars sold in the country in 1985 were powered by pure ethanol, and by 1990, consumption of ethanol had equaled that of gasoline (Moreira and Goldemberg, 1997). After 1990, incentives were progressively removed, and ethanol consumption dropped to a level determined by the legal blend of 20 to 25% ethanol in all the gasoline consumed in the country. More recently, Brazil and Argentina implemented policies to make compulsory the blend of up to 5% biodiesel in all diesel fuels consumed in these countries, also in response to increasing oil prices.

The cultivated area in southern Africa has increased 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.

8.7.3 Other environmental policies

In North America, a number of US federal programs encourage agricultural mitigation options. The Environmental Quality Incentives Program (EQIP), provides cost-sharing and incentive payments for conservation practices on working farm lands. The Natural Resources Conservation Service (NRCS) delivered guidance to its state offices to reward and recognize actions that provide greenhouse gas benefits within the EQIP ranking systems. By including this ranking criterion, NRCS can provide cost-share assistance to livestock producers to install greenhouse gas mitigating technologies, including construction of methane digesters. Producers who improve the quality of their nutrient management systems by achieving a higher level of nitrogen use efficiency can also be rewarded. Some forest activities such as forest site preparation and riparian forest buffers can occur under this program. Limited funding may be a barrier to full implementation. The Conservation Reserve Program (CRP) encourages farmers to convert highly erodible cropland or other environmentally sensitive acreage to native grasses, wildlife plantings, trees, filter strips, or riparian buffers. The Farm Service Agency (FSA) has issued a new rule that codifies existing policy, which allows the private sale of carbon credits for lands enrolled in the CRP. In addition, the rule will add trading of environmental credits as a permissive use on CRP acreage. FSA has modified the Environmental Benefits Index used t o score and rank offers to enrol land in the CRP to give more points for installing vegetative covers that sequester more carbon. The agency announced it will target 500,000 acres of continuous signup enrolment toward hardwood tree planting. Some of the CRP areas have moved into forest lands. The Conservation Security Program (CSP) is a voluntary program that provides financial and technical assistance to promote conservation on working cropland, pasture, and range land, as well as forested land that is an incidental part of an agriculture operation. NRCS is providing enhancement payments under the CSP to promote energy conservation and the production and use of renewable fuels and electricity. Limited funding may be a barrier to full implementation. In addition, the USDA announced in September 2004, $22.8 million to support renewable energy initiatives in 26 States. The grants support 167 projects including financing for anaerobic digesters and small and large wind power ventures. Limited funding may be a barrier to full implementation. The US President, in February 2002, directed USDA to develop new accounting rules and guidelines for crediting carbon sequestration. USDA has released a draft for public comment of comprehensive new accounting rules and guidelines for forest and agriculture greenhouse gas emissions and carbon sequestration, known as the 1605b Voluntary Greenhouse Gas Registry. In Canada, a set-aside program has encouraged a shift from annual to perennial crop production on poor quality soils, thereby enhancing carbon sequestration and reducing synthetic N fertilizer inputs (i.e. Greencover in Canada and various provincial initiatives). Furthermore, the Agriculture Policy

Framework (APF) in Canada includes programs to reduce agriculture risks to the environment, including GHG emissions; implemented mainly through environmental farm planning and adoption of beneficial management practices (BMP). However, The APF is still at the implementation stage so full impact assessment has not been done and the development of fully integrated BMPs requires more research. In Canada, Nutrient Management programs, introduced to improve water quality, may indirectly reduce N_2O emissions.

In Europe, the set aside program has to some extent encouraged C sequestering practices, but this has now been replaced by the single farm payment under the new CAP, which may deliver greater benefits in terms of GHG mitigation (see Section 8.7.2). The EU and a number of member states have soil action plans to promote soil quality/health/sustainability, all of which encourage soil C sequestering practices. The encouragement of composting in some EU member states (e.g. Belgium; Sleutel *et al.* 2005) may increase soil C stocks, but such policies are limited (Smith *et al.*, 2005). The EU Water Framework Directive (WFD) promotes careful use of N fertilizer which may reduce N_2O emissions, but buffer strips to remove nitrate from soils before they reach water courses may increase N_2O emissions. The impact of the WFD on agricultural GHG emissions remains unclear. Other policies, such as the banning of burning of field residues in the 1980s (for air quality purposes) mean that there is more surplus straw, which could increase soil C stocks (Smith *et al.*, 1997; 2000). The banning of dumping at sea of sewage sludge in Europe in 1998 meant that more sewage sludge reached agricultural land. This may have increased soil C stocks slightly (Smith *et al.*, 2000), but may have increased soil N_2O emissions (Smith *et al.*, 2001).

In the former Soviet Union various environmental programmes have helped to reduce agricultural GHG emissions. The Land Codes of the Russian Federation, Belarus and the Ukraine have provided opportunity for land conservation within land-retirement programmes, for promoting soil quality restoration, and economic incentives for soil protection potentially encouraging soil C sequestering practices. Other Federal purpose-oriented initiatives such as 'Land reform development in Russian Federation', 'Fertility 2006-2010'(Russia) and Ukrainian law 'Land protection' provide complex action plans to promote soil conservation/increase commercial yields/fertility/ sustainability and also encourage soil C sequestering practices. Laws in the Ukraine and Belarus such as 'State control of land-use and land protection' provide agrochemical land classification to encourage C sequestering practices and in the Ukraine, promote conversion of degraded lands to set-aside. Water quality initiatives such as the Water Codes of the Russian Federation, Ukraine and Belarus encourage reforestation and grassland riparian zone establishment which potentially encourage soil sequestering practices (Russia). The banning of fertilizer application in many areas may also reduce N_2O emissions (Russia, Belarus, Ukraine). Other land conservation regulations encourage sequestration in forests for erosion prevention. In 2002-2005 forest protection belts were planted in Russia on 30 Mha with conservation afforestation on an area of 67 Mha. These areas are planned to increase up to 527 and 232 Mha, respectively, in 2006-2010 under the programme “Soil conservation and fertility restoration of agricultural lands and agrolandscapes as national resource of Russia in 2006-1010”. According to existing estimates, in 2000 erosion processes contributed more than 12% to the total anthropogenic emissions of CO_2 (Kondratiev *et al.*, 2003). There are also regional programs such as the Revival of the Volga, which encourages the utilization of farm animal wastes, the reduction of CH_4 emissions, and the increase of commercial yields/fertility which encourages C sequestration.

In Asia, China has a number of environmental policies that will reduce GHG emissions for agriculture, including soil sustainability programmes in which N fertilizer is added to soils only after soil N testing (which will reduce N_2O emissions), regional agricultural development programmes to enhance soil C storage, water quality programmes that control non-point source pollution and may reduce N_2O emissions from aquatic systems, and air quality legislation that bans straw burning, thus reducing CO_2 (and CH_4 and N_2O) emissions. Other initiatives include energy saving and GHG mitigation in “Township Enterprises”, funded by Chinese Ministry of Agriculture in 2000, and the Demonstration Programme “Ecological Municipality”, which aims to reduce waste disposal, chemical fertilizer and pesticides application, and bans straw burning.

In Oceania, growing expectations from the predominantly urban population in relation to the maintenance of ecosystem function and conservation of agricultural landscapes, river systems and other ecosystems has resulted in a large range of policy developments in both Australia and New Zealand. In both nations, the rapid increase in nitrogenous fertiliser use over the past decade (250% and 500% increases respectively) and increases in intensive livestock production have raised concerns about water quality and the health of riverine and offshore ecosystems such as the Great Barrier Reef. Policy responses are being developed that include monitoring, regulatory, research and extension components. These are likely to eventually reduce nitrous oxide emissions. Concerns over the sustainability of farming and broadscale conservation have resulted in policies such as the Natural Heritage Trust in Australia. This and other complementary policies foster action such as re-establishment of native vegetation; reduction of degrading processes such as soil erosion, salinisation or acidification; and enhancing the rate of adoption of sustainable farming practices. In most cases, these are likely to reduce greenhouse gas emissions although this is not necessarily the prime focus of the policy. In Australia, the Mandatory Renewable Energy Target has the potential to increase the use of renewable bioenergy from energy crops (e.g. sweet sorghum), forest industry waste streams and sugar cane waste, reducing use of fossil fuels.

In Latin America and the Caribbean there is an increasing adoption of environmental policies driven by globalization, consolidation of democratic regimes and awareness of negative impacts of human activities, among other factors. Over the last two decades, 14 countries have introduced environmental regulations in their constitutional laws, and virtually all countries have implemented all kinds of measures to protect the environment. However, the major objective continues to be the inflow of capitals and the increase of exports, usually at the expense of sustainability, and environmental policies have so far been mostly ineffective (UNEP, 1999). Perhaps one case of a successful environmental policy with an implication on climate change mitigation was the promotion of no-till agriculture in the Mercosur area (Brazil, Argentina, Uruguay and Paraguay), where currently nearly 20% of the cropped area uses this technology. However, this change in land management was only partly driven by public policies (e.g., for soil conservation), and was strongly based on economics and land owners' concerns for the preservation of their land resources.

In Africa, policies associated with the combating of desertification (including such activities as reducing the livestock densities, switching to stall-fed rather than range-fed animals, and the restoration of degraded lands) typically also have climate change mitigation benefits, and may often also benefit the conservation of biodiversity. However, the carbon sequestration rates in the marginal lands most severely affected by desertification are low, even if the areas involved are large. This makes it difficult to convert the climate change ecosystem service into sustainable and substantial project funding through mechanisms such as carbon trading. The reduction of the area of rangelands burned has been an objective of both colonial and post-colonial administrations, with little obvious success. Current renewed efforts in South Africa (South Africa, 1998) have been driven by the desire to reduce loss of human life and property rather than climate change considerations, although the latter are a potential benefit.

8.8 Co-benefits and trade-offs of mitigation options

Many of the measures aimed at reducing greenhouse gas emissions have other potential benefits; indeed, they are often adopted for reasons other than mitigating greenhouse gases. For example, practices that store more carbon in soil may also prevent soil erosion and enhance moisture conservation, thereby increasing yields (Lal, 2002; Dumanski, 2004). Furthermore, building soil carbon reserves is, in itself, a desirable objective because of the links between soil organic matter (which contains carbon) and productivity. Consequently, increasing soil carbon reserves benefits both the atmosphere and the soil. Similarly, measures to reduce N_2O emissions can have other advantages. Often, high N_2O emissions indicate inefficiencies in the use of fertilizer or manure nitrogen; eliminating these efficiencies can therefore also reduce other 'leaks' of nitrogen into the environment (e.g., nitrate leaching, ammonia volatilization) and reduce the cost of nitrogen inputs. Moreover, practices that increase nitrogen use efficiency can also reduce CO_2 emissions, since the manufacture of nitrogen fertilizers is energy-intensive. Methane emissions from livestock represent an inefficient use of feed energy. Consequently, practices that suppress these emissions often increase the performance of animals, per unit of feed intake.

These examples illustrate how practices that reduce emissions often can be recommended for other reasons. But probably very few practices yield purely 'win-win' scenarios; most also have some potential drawbacks that merit attention. For example, while no-till methods can increase soil carbon, they may increase reliance on herbicides and lead to higher leaching of pesticides because of more porous soil structure. Further, any practice that increases soil carbon will reduce atmospheric CO_2, but the carbon held in storage is susceptible to later release into the atmosphere if the practice is suspended or conditions change (Knorr *et al.*, 2005; Fang *et al.*, 2005). Consequently, carbon-storing measures increase the risk of future (perhaps sudden) CO_2 release. Another potentially-adverse consequence of some mitigation measures is the transfer of emissions from one site to another. For example, if cropland is converted to 'set-aside' vegetation in one region, the loss of food and fibre production there might be replaced by newly-cultivated cropland elsewhere, perhaps with a large emission from land-use change. Agroecosystems are inherently complex, with numerous biophysical and social interactions. The main co-benefits and trade-offs presented by each group of mitigation practices are as follows.

8.8.1 Land cover (use) change (including riparian zones, buffer strips and field margins)

Co-benefits: Riparian zones/buffer strips can yield improved field biodiversity and other wildlife benefits. Further, reduction in fertilizer applications can lead to reduced nitrate leaching ammonia emissions. There are also water-quality benefits associated with buffer strips, which may also reduce erosion. De-intensification could yield animal welfare benefits and improved soil structure (Smith *et al.*, 2001), with other potential benefits due to reduced fertiliser, pesticide and herbicide production (hence less CO_2 produced during manufacture). Wetland restoration may provide major amenity, landscape, flood control and biodiversity benefits.
Trade-offs: The use of riparian zones/buffer strips can reduce land availability. More pests and weeds on strips surrounding production areas could lead to higher pesticide and herbicide inputs. If such land were brought back into production, the stored carbon would rapidly be lost. There are potential negative effects on the fertilizer industry if N demand is reduced.

8.8.2 Agroforestry

Co-benefits: Some forms of agro-forestry may improve biodiversity and leisure and amenity value of the land (Smith *et al.*, 2001).
Trade-offs: Some forms of agro-forestry could yield less agricultural product per unit area, leading to greater land pressure.

Co-benefits: Improved crop management should improve food security. If nitrogen fertilizer use is reduced then leaching and ammonia emissions (air pollution) would also be reduced, as well as N_2O emissions. For integrated pest management and organic production, the reduced pesticide/herbicide use might reduce CO_2 manufacture costs but fuel C use may increase through increases in mechanical weeding.
Trade-offs: Use of liming to increase crop yields may enhance CO_2 emission. Minimizing idle land to increase productivity may influence biodiversity habitat;, for example, reducing availability of stubble fields for over-wintering birds in some areas. There are potential negative effects on the fertilizer industry if N demand is reduced.

8.8.3 Tillage/residue management

Co-benefits: Effects are regionally specific. Reduced tillage can often improve soil structure, prevent erosion (thereby also avoiding silting of waterways), reduce fossil fuel use, increase soil water retention, increase binding of pollutants by soil, and favour biodiversity in soil (Smith *et al.*, 2001).
Trade-offs: Effects are regionally specific. Possible trade-offs include: increased soil bulk density, leading to reduced root penetration and infiltration; risk of increased pesticide usage; potential for rapid, or by-pass, and flow through continuous macropores leading to potentially increases in leaching of contaminants because drainage is not disrupted as in ploughed fields. For residue incorporation, there may be additional energy costs required for chopping and incorporating residues. Other potential problems under zero tillage include poorer germination through physical effects or via toxin production which may affect germination (Addiscott & Dexter, 1994; Harper & Lynch, 1981), crop pathogen accumulation (Jenkyn *et al.*, 1995; but see Prew *et al.*, 1995 who found no difference), immobilisation of nutrients, and the unpredictable release of N (Powlson *et al.*, 1985; Smith *et al.*, 2001).

8.8.4 Nutrient management

Co-benefits: Improved production resulting from improved nutrient management will improve food security. If nitrogen fertiliser use is reduced, then there will be less N leaching (water quality) and ammonia emissions (air pollution). For N inhibitors, since all products are tested and approved by independent organisations, the inhibitors should have no adverse impacts.
Trade-offs: If productivity is increased by greater additions of nitrogen fertiliser, ammonia emissions (air quality) and nitrate leaching (water quality) could increase. CO_2 carbon costs of chemical fertiliser production can be greater than the soil carbon sequestration benefits (Schlesinger, 1999). For N inhibitors there may be long term impacts on soil micro-organisms that are poorly understood (ECCP, 2001).

8.8.5 Rice management

Co-benefits: Upland rice cultivation, which is now developing, will make producing rice in areas with water shortage possible and mitigate CH_4 emissions. Ridged cultivation in year-round flooded rice fields, which are commonly distributed in mountainous and hilly areas in southwest China, and elsewhere in East Asia, reduces CH_4 emission (Cai *et al.*, 2003) and increases rice crop production by enhancing soil temperature and improving soil properties.
Trade-offs: A trade-off relationship between CH_4 and N_2O emissions commonly exists in wetland rice fields. A practice which mitigates CH_4 emission usually stimulates N_2O emissions from wetland rice fields. For instance, intermittent irrigation during the rice-growing period mitigates CH_4 emission, but usually stimulates N_2O emission. This water management will also lead to use of

more irrigation water. However, for rice fields with large CH_4 emission, the beefits of reducing CH_4 emissions usually more than offset increases in N_2O emission.

8.8.6 Water management

Co-benefits: More efficient use of water often improves productivity with positive effects on food security. Improved water management will lead to more water being available for other uses, with impacts in the water sector.
Trade-offs: The CO_2 carbon costs of pumping irrigation water can be greater than the soil carbon sequestration benefit (Schlesinger, 1999). Irrigation could put pressure on water availability in other sectors - there will be major implications for water resources if irrigation increases (ECCP, 2001).

8.8.7 Manure/biosolid management

Co-benefits: Additions of animal manure will improve the organic matter of the soil, contributing to better structure, reduced erosion, and run off (potentially reducing flooding in the long-term), and improving water quality (Smith *et al.*, 2001). It is also a source of N, which can replace chemical N fertiliser. Environmental benefits of compost application on the field include the avoided use of chemical fertilisers and pesticides, improved tilth, and positive effects on trace minerals (ECCP, 2001). There are also benefits of reduced pathogens in stored/composted materials. If manure is composted, N_2O and methane emissions can be reduced.
Trade-offs: There can be significant transport fuel costs associated with moving manure and sludge over large distances (Smith & Smith, 2000), the C costs of which are about 30% of sequestered carbon if average distance moved is 100km. Consequently, there could be increased demand for fuel, increased particulate losses from combustion of fuel, and increased ammonia and other gaseous emissions from transport (ECCP, 2001). There is a risk of increased pollution incidents if the manure is not managed properly. There are also biosecurity concerns of taking manure onto arable farms if they also have livestock. There may be an increased risk of soil salinisation due to high salt levels in manure from piggeries. Increased spreading of biosolids on crop fields could lead to increased N leaching as manure may remain on the soil during wet periods (e.g. MAFF, 1994). Biosolids such as sewage sludge potentially have negative environmental effects, such as the build-up of heavy metals and organic pollutants (prevented by applying sewage sludge below the safe limits; Smith *et al.*, 2001). In addition, there is the possible release of methane during composting, and ammonia emissions can be high.

8.8.8 Grazing land management/pasture improvement

Co-benefits: The use of deep rooting species could lead to improved continuity of soil pores to greater depth, yielding enhanced deep infiltration. Enhanced production will lead to improved food security and may reduce soil degradation and compaction.
Trade-offs: Pasture improvement by increased N fertilizer additions could increase N leaching.

8.8.9 Management of organic soils

Co-benefits: Restoration of organic soils can improve biodiversity, maintain habitat, prevent flooding, and enhance leisure/amenity value.
Trade-offs: There are technical challenges to rewetting dried peat. As well, wetland restoration can reduce agricultural productivity, since organic soils are often very productive.

8.8.10 Land restoration

Co-benefits: Restoring degraded lands can improve food security and, in arid climates, reduce the risk of desertification.
Trade-offs: Restoration of degraded lands may be resource-intensive, competing for nutritive amendments and other inputs that might otherwise be used in already-productive farmlands.

8.8.11 Bioenergy crops

Co-benefits: Establishing bioenergy crops may improve biodiversity and leisure and amenity value of the land (depending on crop; Smith *et al.*, 2001).
Trade-offs: If applied on existing wetland/grassland sites already high in carbon the hydrology may be negatively affected, thereby also reducing C in soils. Although nutrient demand is low compared to arable crops, compared to set aside conditions, there is an increased nutrient demand, with corresponding CO_2 and N_2O emissions. Increased production of bioenergy crops might negatively affect the oil industry. Use of croplands to produce energy may raise ethical questions, particularly in the event of food shortages. The planting of bioenergy monocultures into previously uncropped lands, for instance in marginal drylands, would lead to a net loss of biodiversity.

8.8.12 Enhanced energy efficiency

Co-benefits: Adoption of more energy-efficient practices can reduce air pollution from reduced fossil fuel use, and improve profit margins.
Trade-offs: If produced using GM technology, energy conservation techniques may be unacceptable in some areas.

8.8.13 Livestock management - improved feeding practices

Co-benefits: Greater use of concentrates and oil additives may benefit some feed manufacturing industries and the oil-producing industry.
Trade-offs: There may be negative environmental impact from intensification and changing land use from forage production to concentrates (C loss from soils, biodiversity, etc). Trade-offs for oil additions to diet may include: reduction in tropical forests in regions where oil crops are grown; increases in price of edible oils.

8.8.14 Livestock management - additives, inocula, vaccine

Co-benefits: Potential benefits include: expanded vaccine manufacture industry, and better control of animals in extensive livestock operations, thereby allowing for better husbandry.
Trade-offs: In some regions there is consumer resistance to these products, and to some other livestock options such as feed additives, hormone, antibiotic treatments etc.

8.8.15 Livestock management - breeding, improved systems

Co-benefits: Use of improved systems may have potential benefits for the animal feed concentrate manufacturing industry since higher yielding animals require more concentrates in their diet. For other industry, there are positive impacts through demand for the development and manufacture of methane capture technology.
Trade-offs: Higher genetic merit cows may have higher risk of health problems. Intensification associated with higher yielding animals may have negative environmental effects. For methane cap-

ture in housing, there are impacts on the construction industry since rebuilding/modification of housing stock is necessary.

8.8.16 Increased C storage in agricultural products

Co-benefits: Agricultural products may furnish building materials in the residential and commercial building sectors, thereby also potentially reducing deforestation and energy-intensive concrete production.
Trade-offs: If products are derived from agricultural residues, then there may be fewer residues available for soil improvement and bioenergy production.

8.8.17 Reduced emissions from biomass burning

Co-benefits: Fire management could improve biodiversity in fire prone areas. In some regions burning is used for fertility building and improving soil structure.
Trade-offs: Preventing burning may increase the risk of large, uncontrollable fires after a number of years where the fuel loading is high.

8.9 Technology research, development, deployment, diffusion and transfer

Technology to reduce greenhouse gas emissions in the agriculture sector has a very wide scope and description. For example, increases in crop yields and animal production will reduce emissions per unit of production. Such increases in crop and animal production will be implemented through many better management and husbandry techniques, breeding of improved animals or crops, etc. Thus, 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, biofuels, anaerobic slurry digestion and methane capture systems, etc., would all be considered technology improvement in the agriculture sector. These are outlined in some detail in Section 8.4. Technological improvement may have very significant effects. Based on technology change scenarios developed by Ewert *et al.* (2005), derived from extrapolation current trends in FAO data, Smith *et al.* (2005) showed that technology 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), suggests that technological improvement will be a key factor in GHG mitigation in the future.

The emission reduction potentials of mitigation options for agriculture are outlined in Table 8.4.1.2 on a per area or per animal basis. The costs per tonne of CO_2 avoided are outlined in Section 8.4.3. This is the appropriate way to outline costs and potential in agriculture. It is not possible in most cases to outline a mitigation potential in terms of amount of CO_2 avoided per unit of production, or to ascribe a cost per unit of production for the option. This is because most of the mitigation options involve changes to agricultural practice (e.g. feeding more concentrates and less forage, improving forage quality, minimum cultivation of tillage land) rather than production of a product or technology.

The overall biophysical potential of the various options to reduce emissions is outlined in Figure 8.4.2a, and this further outlined in terms of low or high implementation (10 and 20% of biophysical potential over the next 20 years) in Figure 8.4.2b. These are based on assumptions of a maximum implementation over 20 years of 10 to 12% of the maximum biophysical potential, due to constraints other than cost such as, logistical, institutional, educational etc. constraints.

In most instances, the cost on employing the 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 over time, but these are unlikely to be radical. 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 the impact of changing the composition of the concentrates fed to ruminants, and (ii) options where new technology is being developed, such as probiotics or yeasts for use in animal diets, which may have a reduction potential.

Many of the mitigation strategies outlined for the agriculture sector involve employment of existing technology (e.g. crop management, livestock feeding - replace roughage with concentrates). 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 a lot of research to allow viable systems to operate (e.g. biofuels). Finally, there are many novel strategies in the early stages of development, such as probiotics or yeasts for animal feedings. Thus, there is still a major role for R & D in this area.

Regional differences in the mitigation options are outlined on a climatic regions basis in Table 8.4.1. On a geopolitical basis, there are large differences, as outlined in Figures 8.4.2c, 8.4.2d and 8.4.2e. As well as climate, these differences can be due to the state of development of the agriculture industry, the resources available and legislation. For example, the scope to use specific agents and dietary additives in ruminants is much greater in developed regions than in the developing world because of cost, opportunity (i.e. it is much easier to administer products to animals in confinement systems than in free ranging or nomadic systems), availability of the technology, etc. Some technologies are not allowed in some regions: e.g ionophores are banned from use in animal feeding in the EU, while genetically modified crops are banned/restricted in some countries.

Some of the technologies will have co-benefits or trade-offs, as outlined in Section 8.8. The impact of the technologies on sustainable development is outlined in Section 8.4.4, and the interaction of mitigation options on adaptation and vulnerability is discussed in Section 8.5.

8.10 Long-term outlook/system transitions, decision making; inertia and its relation with long/short term choices, decision tools

There is a large potential for mitigating GHG emissions in the agricultural sector in future. Trends in GHG emissions in the agricultural sector are mainly dependent on the level and rate of socio-economic development, application of adequate technologies, climate and non-climate policies, and future climate change. As projected by the IMAGE 2.2 model, CO_2, CH_4, and N_2O emissions associated with land use sources vary greatly between scenarios (Strenger *et al.*, 2004), depending on globalisation or regionalisation and on the emphasis placed on material wealth relative to sustainability and equity. Globalisation and moves toward sustainable development and equity are projected to leave cropland area similar to current levels or decrease it slightly while forest area is projected to remain similar or increase slightly by 2100.

GHG emissions from the agricultural sector are characterized by large uncertainties and it is difficult to assess the effectiveness of GHG mitigation measures. This makes a consensus difficult to achieve and hinders policy making. For sustainable development and environment quality improvement, some countries have initiated several climate and non-climate policies as described in

8.6 and 8.7, most of which are believed to have direct effects or synergistic effects on mitigating GHG emissions from agricultural sector. Global sharing of innovated technologies for efficient use of land resources and agricultural chemicals, to eliminate poverty and malnutrition, will significantly mitigate GHG emissions from the agricultural sector.

Recycling agricultural byproducts, such as crop residues and animal manures, and production of energy crops will directly mitigate GHG emissions from fossil fuel offsets. It has been estimated that 10-15% of total arable lands could potentially be used to grow energy crops. However, there are still significant 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 agricultural wastes and energy crops. Government investment for the development of these technologies, and subsidies for using these forms of energy, is essential.

Climate and global change are expected to influence agricultural in different ways. It has been demonstrated that elevated atmospheric CO_2 concentration alone, on average, increases crop yield 10-15%. This feedback effect will increase crop production per land unit, hence reduceing the demand for arable lands, and also fixing more atmospheric CO_2. But other changes, such as change in the distribution of precipitation, elevation of atmospheric O_3 concentration, enhanced demand for N, and increases in temperature make this feedback effect uncertain. Increase in temperature may have positive effects on crop growth, especially in cold areas, but may also accelerate decomposition of soil organic matter (Smith *et al.*, 2005). The net effects of climate and global change on GHG emissions from agricultural sector remain uncertain and the topic of further research.

A number of agricultural mitigation options which have limited potential now, may show significant improvement in the long-term. Examples include better use of fertilizer through precision farming, reducing N application and N_2O emissions. Similarly, less N is required as technologies such as field diagnostics, fertilizer recommendation expert/decision support systems and fertilizer placement technologies are developed and become more widely used. Further development of nitrification inhibitors is also possible in the long term. New fertilizers and water management systems in paddy rice are also likely to develop significantly in the longer term.

The long term outlook for mitigation from livestock is good. Continuous improvements in animal breeds are likely, and these will improve the greenhouse gas emissions per kg of animal product. Enhanced production efficiency due to structural change or better application of existing technologies is 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, methane inhibitors, etc. However, increased world demand for animal products may mean that while emissions per kg of product decline, total emissions increase.

Mitigation of greenhouse gas emissions associated with various agricultural activities and soil carbon sequestration could be achieved through best management practices to a certain extent. Best management practices are not only essential for mitigating greenhouse gas emissions, but also for other facets of environmental protection such as air and water quality management. However, there are very large uncertainties due to sparse data and incomplete knowledge. Before the options for mitigating greenhouse gas emissions from agricultural sectors can be recommended as measures, their socio-economic aspects need to be fully evaluated.

<u>CO_2</u>

Generally, soil organic carbon (SOC) storage in cultivated agricultural lands is lower than that of natural soils because cultivation stimulates decomposition of native soil organic matter and more of the photosynthetically-fixed C is exported from the ecosystem. Organic carbon storage in arable soils could be increased to a certain extent through best management practices, such as returning crop residues to soils, minimizing tillage, preventing soil from erosion, etc (see Table 8.4.1). The potential of SOC sequestration seems to be larger in arable soils with less SOC than the soils with higher SOC. For example, soils in arid and semiarid regions and degraded soils in subtropical and tropical regions of the world provide significant potential for CO_2 mitigation because these soils are usually depleted in SOC and have poor productivity. The global potential of SOC sequestration and restoration of degraded/desertified soils is estimated to be 0.6 to 1.2 Pg C/yr for about 50 years with a cumulative sink capacity of 30 to 60 Pg (Lal, 2003). Increasing SOC storage, generally speaking, improves soil productivity, thus it is a "win-win" strategy. However, the capacity of soil carbon sequestration will be limited in the long-term because a new equilibrium will be reached after 10-50 years, depending on climatic region and the practice considered. Because of data limitations, the duration for soil carbon sequestration remains uncertain. The restoration of SOC storage would be constrained, for instance, by available irrigation water supplies in arid and semiarid regions. The increase in SOC in flooded rice fields would stimulate CH_4 emission.

Mitigation of CO_2 emissions can also be achieved by optimizing application of chemical compounds, minimizing tillage, raising water use efficiency, etc. because these options reduce energy consumption and fuel consumption (see also Table 8.4.1). Fertilizer utilization efficiencies are generally lower in developing countries, which consume the majority of fertilizers at present, than in developed countries. Whereas the soil C sequestration can continue for only a limited time, the CO_2-savings from reduced energy consumption can continue indefinitely.

<u>CH_4</u>

Rice production and livestock are major sources of atmospheric CH_4. There are many options that have been demonstrated to be effective for mitigating CH_4 emissions from flooded rice fields. Among them, water management, and the amount and time of organic incorporating into rice fields are crucial factors controlling CH_4 emissions from rice fields. According to IPCC guidelines (IPCC, 1997), single drainage and multiple drainage of rice fields can reduce CH_4 emission by 50% and 80% per year, respectively, for irrigated rice fields during the rice growing period. However, the mitigation effect of rice field drainage is partly offset by stimulation of N_2O emission. Implementation of this option will also be limited by water supplies. Soil moisture influences CH_4 emissions significantly in the season between two rice crops (in regions where there are separate rice crop seasons) and the fallow or upland crop season (Cai *et al.*, 2000; Kang *et al.*, 2002; Xu *et al.*, 2003). Therefore, keeping soil as dry as possible and avoiding water-logging in the fallow or upland crop season by drainage will reduce CH_4 emissions from irrigated rice fields significantly. In China, about 10% of total rice fields are flooded permanently. These have CH_4 emission rates several times larger than those that are drained in the period of fallow or upland crops. CH_4 emission could be reduced by about 70% by draining flooded water in the fallow season if irrigation and drainage systems could be significantly improved (Cai *et al.*, 2003).

In rice-based agricultural systems with a flooded rice crop and upland crop rotation or with a fallow period, the stimulation effect on CH_4 emission can be mitigated significantly by either incorporating organic materials into soil in the dry period rather than in flooded period (Xu *et al.*, 2000) or prior to composting, or by producing biogas for use as fuel for energy production (Wang and Shangguan, 1996).

There is potential for mitigating CH_4 emissions from livestock sector. The CH_4 emissions from enteric fermentation can be mitigated by many nutritional factors such as type of feed and feed intake, feed processing and preservation and nutrient composition of feeds (Lee *et al.*, 2000; Clemens and Ahlgrimm, 2001; see also Table 8.4.1). Further research is needed on mitigating CH_4 emissions from ruminants by using anti-methanogen vaccine (Wright *et al.*, 2004). The proportion of CH_4 emission per unit manure varies greatly with methods of manure storage, treatment, and usage (IPCC, 1997). Appropriate manure storage, treatment, and usage are essential not only for mitigating CH_4 emission but also for preventing environmental pollution caused by factors such as nitrate leaching and NH_3 volatilization. It may be difficult to reduce CH_4 emissions from manure in intensive animal production (Monteny *et al.*, 2001) where anaerobic digestion of the animal excreta may be the most efficient way to reduce greenhouse gas emissions within animal husbandry (Clemens and Ahlgrimm, 2001). 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 (if any) occurs when it is dry and methane emissions are negligible (Gonzalez-Avalos & Ruiz-Suarez, 2001).

N_2O

Fertilizer-derived N is the largest anthropogenic source of atmospheric N_2O. With increasing demand for food, due to world population increase, fertilizer consumption is expected to increase further in the future. The amount of nitrogen fertilizer used is projected to increase by about 15% for cereal production by 2015 (IFA/FAO, 2001) and fuhter increases are expected by 2050 (Galloway *et al.* 2004; MEA 2005). N_2O emissions (direct and indirect) from N fertilization would increase if fertilization practices are not improved. However, fertilization increase crop yields, particularly in the regions where nutrient supplies are not sufficient for sustainable production, thus increasing SOC storage, although the effect is usually minor (Glendining & Powlson, 1995). A wide range of N_2O emissions can be observed (Bouwman, 2001) indicating that there is a large potential for mitigating N_2O emission from fertilization. The emission factor of 1.25% is used as a default value of N fertilizer direct-emission in IPCC guidelines (IPCC, 1997). By optimizing application rate, timing and placement, and optimizing irrigation and drainage, both direct and indirect N_2O emission can be mitigated. If emission factor of N fertilizer could be reduced from 1.25% to 1% on world average, based on the amount of N fertilizer consumption of 81 Tg N in 2000 (FAOSTAT), direct N_2O emission could reduced by 0.2 Tg N per year. However, the N_2O mitigated by reducing emission factors would be cancelled by the increases in world N fertilizer consumption for agricultural production in future (Mosier & Kroeze, 2000).

From the view of environment protection, land application of organic wastes, including animal and human wastes and crop residues, is appropriate since it can reduce chemical fertilizer application, increase SOC, and prevent loss to water bodies or as air pollution through burning. However, there are very large uncertainties associated with the impact of organic waste management on N_2O emissions.

Peak N_2O emission rates are often observed after irrigation or rainfall events (Li *et al.*, 1992) or after draining floodwaters. The emission induced by a change in soil moisture contributes a substantial proportion of total N_2O, although the emission is usually short lived. Thus, avoiding unnecessary irrigation might not only reduce N_2O emissions, but also save water.

According to current projections, the global population may reach about 9 billion by 2050, an increase of about 50% over current levels (Lutz *et al.*, 2001; Cohen, 2003; United Nations). 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.* 2002; 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 can be found (Galloway 2004; Mosier 2002). Increased demands for food might conceivably also escalate CH_4 from enteric fermentation, if livestock numbers increase in response to demands for meat and other livestock products.

Possible changes to climate and atmosphere in coming decades may influence greenhouse gas 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 agrocecosystems through changes in plant growth rates, plant litter composition, drought tolerance, and nitrogen demands (e.g. Henry *et al.* 2005; van Groenigen *et al.* 2005; Jensen *et al.* 2004; Torbert *et al.* 2000; Norby *et al.* 2001) Increases in temperature could accelerate decomposition of soil organic matter, releasing stored soil C into the atmosphere (Knorr *et al.* 2005; Fang *et al.*, 2005). And changes in precipitation patterns could change the adaptability of crops or cropping systems selected to reduce greenhouse gas emissions. Many of these changes have high levels of uncertainty; but these few examples demonstrate that practices chosen to reduce greenhouse gas emissions now may not have the same effectiveness under conditions that may exist in coming decades.

8.11 References

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