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Author(s):	CLAs:	Pete Smith (UK), Daniel Martino (Uruguay)	
	LAs:	Zucong Cai China), Daniel Gwary (Nigeria), Henry Janzen (Canada), Pushpam Kumar (India), Bruce McCarl (USA), Stephen Ogle (USA), Frank O'Mara (Ireland), Charles Rice (USA), Bob Scholes (South Africa), Oleg Sirotenko (Russia)	
	CAs:	Mark Howden (Australia), Tim McAllister (Canada), Genxing Pan (China), Vladimir Romanenkov (Russia), Uwe Schneider (Germany), Sir-intornthep Towprayoon (Thailand), Martin Wattenbach (Germany)	
	REs:	Kristin Rypdal (Norway), Mukiri wa Githendu (Kenya)	
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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, 2006). Agriculture emits to the atmosphere significant quantities of GHGs, mainly carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Agriculture accounts for about 14% of anthropogenic non-CO_2 emissions. Of global anthropogenic emissions it accounts for 84% of N_2O (2825 Mt CO_2-eq. in 2000; US-EPA, 2006a) and 47% of CH_4 (2778 Mt CO_2-eq. in 2000; US-EPA, 2006a). Agriculture also emits CO_2, estimated to be 40 Mt CO_2-eq. in 2000; US-EPA, 2006b), less than 1% of global anthropogenic CO_2 emissions.

Many agricultural practices can, under some conditions, mitigate GHG emissions relative to the emissions that take place from agriculture in the absence of the mitigation practice. The practices reduce net emissions, often affecting more than one GHG by more than one mechanism. The most prominent mitigation options in agriculture are improved cropland and grazing land management (including improved agronomy and nutrient, tillage and residue management) and restoration of degraded lands and cultivated organic soils. Lower, but still significant mitigation potential is provided by water and rice management, set-aside, land use change and agro-forestry, livestock management and manure management. Agricultural GHG fluxes are complex and heterogeneous, but the active management of agricultural systems offers possibilities for mitigation. Many of these mitigation opportunities use current technologies and can be implemented immediately.

The global technical mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030, considering all gases, is estimated to be ~5500-6000 Mt CO_2-eq. yr^{-1}, with economic potentials of 1900-2100, 2400-2500, and 3100-3300 Mt CO_2-eq. yr^{-1} at carbon prices of 0-20, 0-50 and 0-100 US$ t CO_2-eq.$^{-1}$

Table 8.1 *Estimates of the global agricultural GHG mitigation potential (Mt CO_2-eq. yr^{-1}) by 2030 at a range of prices of CO_2-equivalents for the four SRES scenarios*[1]

	Price range (USD t CO_2-eq. $^{-1}$)			
Scenario	**0-20**	**0-50**	**0-100**	**0->>100 (technical potential)**
B1	1925	2384	3149	5480
A1b	1982	2439	3254	5670
B2	2047	2495	3330	5844
A2	2119	2549	3330	5957

[1] As described in Smith *et al.* (2006a), the data on regional costs and potentials did not uniformly give price quantity schedules, and were based on individual strategy evaluations rather than 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 re-

gional and global technical potentials. We assume in this analysis that the price relationships and technical potential apply globally, but further development of these relationships at national and regional scales may be needed. The Lee *et al.* (2005) results for afforestation were applied to agro-forestry (showing an increasing rate of gain as prices increase). The Lee *et al.* (2005) bio-fuel results were used in this analysis (showing an increasing rate of gain as prices increase) as were the tillage-induced soil carbon results (showing a large gain at low prices, then a plateau and a reduction as bio-fuels and afforestation become more important). All of the other categories used either the non-CO_2 or agricultural fossil fuel emission patterns, which essentially show 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).

Of these total mitigation potentials, about 90% derives from reduced soil emissions of CO_2, about 8% from mitigation of CH_4 and about 2% from mitigation of soil N_2O emissions. The upper and lower limits about the estimates are largely determined by uncertainty in the per-area estimate for each mitigation measure. For soil CO_2 emission reduction, this uncertainty arises from the model used to derive the mitigation potentials.

Across the range of prices, the role of alternative strategies changes. At low prices, the dominant strategies are those consistent with existing production such as change in tillage practice, fertilizer application, diet formulation and manure management, while higher prices elicit land use changes that displace existing production, such as bio-fuels, and allow the use of more costly animal feed-based mitigation options. 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 be no 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.

In addition to GHG emission reduction, agricultural land can provide feed stock for bio-energy production. GHG emissions could be reduced by substitution of fossil fuels for energy production by agricultural feed stocks (e.g. crop residues, dung, dedicated energy crops). Although the mitigation potential is counted in the user sectors, the economic mitigation potential of biomass energy from agriculture is estimated to be 640 Mt CO_2-eq. yr^{-1} at 0-20 USD t CO_2-eq.$^{-1}$, 2240 Mt CO_2-eq. yr^{-1} at 0-50 USD t CO_2-eq., and 16000 Mt CO_2-eq. yr^{-1} at 0-100 USD t CO_2-eq.$^{-1}$. At 0-20 USD t CO_2-eq.$^{-1}$, bio-energy could mitigate about 30% as much GHG as all other agricultural measures combined, at 0-50 USD t CO_2-eq^{-1}, the figure is 90-100% of all other measures, and at 0-100 USD t CO_2-eq.$^{-1}$, agriculturally derived bio-energy could mitigate nearly 5 times the GHG of all other agricultural measures combined. An additional mitigation of 770 Mt CO_2-eq. yr^{-1} could be delivered by 2030 by improved energy efficiency in agriculture, though like bio-energy, the mitigation potential is counted in the user sectors.

Many agricultural mitigation measures show synergy with Sustainable Development policies, and many explicitly influence social, economic and environmental aspects of sustainable development. Some mitigation options, however, 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 in the short, medium and long terms. Most mitigation measures are robust to future climate change (e.g. nutrient management), but others are vulnerable (e.g. irrigation in regions becoming more arid). It will be possible in some cases to adapt mitigation options to ameliorate the impacts of climate change on the efficacy of mitigation measures.

In many regions, non-climate policies, including macro-economic, agricultural and environmental policies, have a larger impact on agricultural mitigation options than climate policies. Despite significant technical potential for GHG mitigation in agriculture, there is some evidence that little progress has been made so far, and little is expected by 2010. There are barriers to implementation which may not be overcome without policy/economic incentives. 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. Soil C may become more vulnerable to loss under climate change or other pressures, though increases in production may offset some or all of this C loss.

Many agricultural mitigation options have both co-benefits (in terms of improved efficiency, reduced cost, environmental co-benefits) and trade-offs (e.g. increasing other forms of pollution). Balancing the co-benefits with trade-offs is necessary for successful implementation. Most agricultural GHG mitigation options can be implemented immediately, without further technological development, but a few options are still in 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.

8.1 Introduction

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

After describing the development of GHG emissions from the agricultural sector (8.2) this chapter addresses in detail agricultural practices that may mitigate GHGs (Section 8.4.1), with many practices affecting more that one GHG by more than one mechanism. These practices include:
- Cropland management
- Grazing land management/pasture improvement
- Management of agricultural organic soils
- Restoration of degraded lands
- Livestock management
- Manure/bio-solid management
- Bio-energy production.

It is theoretically possible to increase the storage of carbon in long lived agricultural products (e.g. strawboards, wool, leather, bio-plastics) but with an increase in C held in these products from 37 to 83 Mt C per year over the past 40 years, and assuming a first order decay rate of 10 to 20 % per year, this is estimated to be a global net annual removal of 3 to 7 Mt CO_2 from the atmosphere, which is negligible compared to other mitigation measures; the option is not considered further here.

Smith *et al.* (2006a) recently estimated a global potential mitigation of 770 Mt CO_2-eq. yr^{-1} by 2030 from improved energy efficiency in agriculture (e.g. through reduced fossil fuel use) but this is usually counted in the relevant user sector rather than in agriculture, so is not considered further here. Any saving from improved energy efficiency appears in the relevant sections elsewhere in this volume according to where the fossil fuel savings are made, e.g. from transport fuels in Chapter 6, through improved building design in Chapter 6 etc.

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

Population pressure, technological change, public policies, and economic growth and the cost/price squeeze have been the main drivers of change that have occurred during the last four decades in the agriculture sector[1]. 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 there are notable regional exceptions. This growth, however, has been at the expense of increased pressure on the environment, and depletion of natural resources (Tilman *et al.*, 2001; Rees, 2003), while it has not been successful in solving the problems of food security and child malnutrition suffered in poor countries (Conway and Toenniessen, 1999).

Agricultural land occupied 5020 Mha in 2002 (FAOSTAT, 2006). 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).

Table 8.2 *Agricultural land use in the last four decades (Source: FAOSTAT, 2006)*

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

The amount of cropland worldwide has increased by 8% since the 1960s, to its current level of ca. 1400 Mha (Table 8.2). This increase was the net result of a 5% decrease in developed countries, and

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[1] Smith *et al.* (2006b) have recently reviewed emission trends, policies and barriers affecting agricultural GHG mitigation. This section, and sections 8.3, 8.6 and 8.8, are largely based on that review.

a 22% increase in cropland area in developing countries. This trend will continue into the future (Huang *et al.*, 2002; Trewavas, 2002; Fedoroff and Cohen, 1999; Green *et al.*, 2005), and Rosegrant *et al.* (2001a) 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 8.3), despite a consistent decline in per-capita agricultural land (Figure 8.1). The share of animal products in the diet has increased consistently in the developing countries, whilst remaining constant in developed countries.

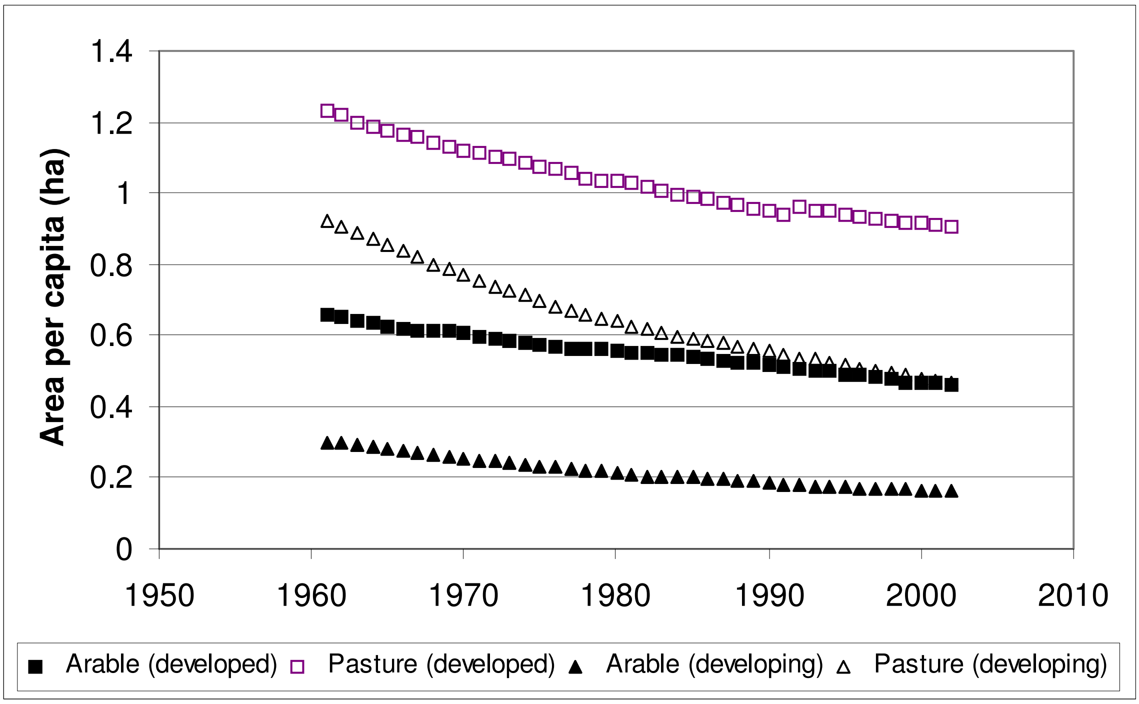

Figure 8.1 *Evolution of per capita area of arable land and pasture, in developed and developing countries. (Source FAOSTAT, 2006)*

Table 8.3 *Evolution of per capita food supply in developed and developing countries. (Source: FAOSTAT, 2006)*

						Change 2000's/1960's	
	1961-70	1971-80	1981-90	1991-00	2001-02	%	cal d^{-1} or g d^{-1}
1. Developed countries							
Energy, all sources (cal/day)	3,049	3,181	3,269	3,223	3,309	+9	261
% from animal sources	27	28	28	27	26	-2	--
Protein, all sources (g/day)	92	97	101	99	100	+9	8
% from animal sources	50	55	57	56	56	+12	--
2. Developing countries							
Energy, all sources (cal/day)	2,032	2,183	2,443	2,600	2,657	+31	625
% from animal sources	8	8	9	12	13	+77	--
Protein, all sources (g/day)	9	11	13	18	21	+123	48
% from animal sources	18	20	22	28	30	+67	--

Economic growth and changing lifestyles in some developing countries, most notably in China, are causing a growing demand for meat and dairy products. Meat demand in developing countries rose from 11 to 24 kg capita^{-1} yr^{-1} during the period 1967-1997, achieving an annual growth rate of more than 5% by the end of that period. Rosegrant *et al.* (2001a) forecast 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 a growth in demand for all meats, with the greatest increase for poultry (83 % increase by 2020; Roy *et al.*, 2002).

The annual emission of GHGs from agriculture is expected to increase in coming decades due to escalating demands for food and shifts in diet, 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 the agriculture sector, with the implications for GHG emissions or removals, are summarized as follows:

- Growth in land productivity is expected to continue, although at a declining rate, due to decreasing returns from further technological progress, and greater use of marginal land with lower productivity. Use of these marginal lands increases the risk of soil erosion and degradation. The consequences of soil erosion on CO_2 emissions are highly uncertain (Lal, 2004a; Van Oost *et al.*, 2004).
- 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 frequently combined with periodical tillage, thus making the assessment of the GHG balance highly uncertain.
- 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; Schlesinger, 1999). Also, irrigation and N fertilization may cause increased GHG emissions (Mosier, 2001).
- Growing demand for meat may induce further changes in land use (e.g. from forestland to grassland), and increased demand for animal feeds (e.g. cereals). Larger herds of beef cattle will cause increased emissions of CH_4 and N_2O, although use of intensive systems (with lower emissions per unit product) is expected to increase faster than growth in grazing-based systems, which may attenuate the expected rise in GHG emissions.
- Intensive production of beef, poultry and pork is increasingly more common, leading to increases in manure with consequent increases in GHG emissions. This is particularly true in the developing regions of South and East Asia, and Latin America, as well as in North America.
- Changes in policies (e.g. subsidies), and regional patterns of production and demand are causing an increase in international trade of agricultural products. This is expected to increase CO_2 emissions, due to greater use of energy for transportation.

There is an emerging trend for the greater use of agricultural products (e.g., bio-plastics bio-fuels and biomass for energy) as substitutes for fossil fuel-based products. This has the potential to reduce GHG emissions in the future.

8.3 Emission trends (global and regional)

With an estimated global emission of non-CO_2 GHGs of 5969 Mt CO_2-eq. yr^{-1} in 2005 (US-EPA, 2006a, Table 8.3), agriculture is estimated to account for about 14% of total global anthropogenic emissions of non-CO_2 GHGs (Bouwman, 2001), and 47% and 84% of total anthropogenic CH_4 and

N_2O emissions in 2000, respectively (US-EPA, 2006a). N_2O emissions from soils and CH_4 from enteric fermentation constitute the largest sources, with 44% and 31% of total non-CO_2 emissions in 2005, respectively (US-EPA, 2006a). Rice production (11%), manure management (7%) and biomass burning (7%) account for the rest. Emissions of CO_2 from agricultural soils are not normally estimated separately, but are included in the land use change and forestry sector (e.g. in national GHG inventories) so there are few comparable estimates of emissions of this gas in agriculture. However, US-EPA (2006b) recently estimated that agriculture emitted 40 Mt CO_2-eq. of CO_2 into the atmosphere in 2000, less than 1% of global anthropogenic CO_2 emissions.

Table 8.4 *GHG emissions by main sources in the agriculture sector in the different world regions in 2005. Adapted from US-EPA (2006a)*

Region		**N_2O soils**	**CH_4 enteric**	**CH_4 rice**	**CH_4, N_2O manure**	**CH_4, N_2O burning**	**Total**
Developing countries of South Asia	**Mt CO_2-eq.yr^{-1}**	**536**	**275**	**129**	**40**	**24**	**1,005**
	% of region's total	53	27	13	4	4	100
	% of source's world total	20	15	20	9	3	17
Developing countries of East Asia	**Mt CO_2-eq.yr^{-1}**	**600**	**294**	**432**	**127**	**53**	**1,505**
	% of region's total	40	20	29	8	4	100
	% of source's world total	23	16	68	29	14	25
Latin America & The Carribbean	**Mt CO_2-eq.yr^{-1}**	**359**	**446**	**25**	**25**	**141**	**996**
	% of region's total	36	45	3	3	14	100
	% of source's world total	14	24	4	6	37	17
Sub-Saharan Africa	**Mt CO_2-eq.yr^{-1}**	**350**	**244**	**21**	**16**	**143**	**775**
	% of region's total	45	32	3	2	18	100
	% of source's world total	13	13	3	4	37	13
Middle East & North Africa	**Mt CO_2-eq.yr^{-1}**	**101**	**41**	**10**	**3**	**2**	**157**
	% of region's total	64	26	6	3	2	100
	% of source's world total	4	2	2	1	0	3
Subtotal (developing regions)	**Mt CO_2-eq.yr^{-1}**	**1,946**	**1,300**	**617**	**211**	**363**	**4,438**
	% of region's total	44	29	14	5	8	100
	% of source's world total	74	70	97	48	92	74
Former Soviet Union	**Mt CO_2-eq.yr^{-1}**	**78**	**96**	**3**	**40**	**4**	**222**
	% of region's total	35	44	1	18	1	100
	% of source's world total	3	5	0	9	1	4
Central & Eastern Europe	**Mt CO_2-eq.yr^{-1}**	**83**	**52**	**0**	**28**	**3**	**166**
	% of region's total	50	31	0	17	2	100
	% of source's world total	3	3	0	6	1	3
Western Europe	**Mt CO_2-eq.yr^{-1}**	**203**	**135**	**2**	**82**	**1**	**424**
	% of region's total	48	32	1	19	0	100
	% of source's world total	8	7	0	19	0	7
OECD Pacific	**Mt CO_2-eq.yr^{-1}**	**33**	**93**	**7**	**7**	**17**	**156**
	% of region's total	21	60	5	4	10	100
	% of source's world total	1	5	1	2	4	3
OECD North America	**Mt CO_2-eq.yr^{-1}**	**303**	**178**	**8**	**68**	**7**	**564**
	% of region's total	54	32	1	12	1	100
	% of source's world total	11	10	1	16	2	9
Subtotal (developed regions)	Mt CO_2-eq.yr-1	**700**	**554**	**20**	**225**	**32**	**1,531**
	% of region's total	46	36	1	15	2	100
	% of source's world total	26	30	3	52	8	26
Total	**Mt CO_2-eq.yr^{-1}**	**2,646**	**1,854**	**637**	**436**	**395**	**5,969**
	% of region's total	44	31	11	7	7	100
	% of source's world total	100	100	100	100	100	100

Both the magnitude of the emissions and the relative importance of the different sources vary widely among world regions (Table 8.4). In 2005, the group of five regions mostly consisting of non-Annex

I countries were responsible for 74% of total agricultural emissions. The developing countries of East Asia emitted a total of 1505 Mt CO_2-eq., or 25% of world's total in that year. Latin America and The Caribbean, the developing countries of South Asia, and Sub-Saharan Africa were also important contributors to total agricultural emissions.
In seven out of ten regions, N_2O from soils was the main source of GHGs in the agricultural sector in 2005, mainly associated with the use of N fertilizers and manure application to soils. In the other three regions - Latin America and The Caribbean, the Former Soviet Union, and OECD Pacific, on the other hand, CH_4 from enteric fermentation was the dominant source (US-EPA, 2006a). This is due to the large livestock population in these three regions which, in 2004, had a combined stock of cattle and sheep equivalent to 36% and 24% of world totals, respectively (FAO, 2003).

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

The balance between CO_2 emissions and removals in agricultural land is uncertain. A study by US-EPA (2006b) showed that some countries and regions have net emissions, while others have net removals of CO_2. With the exception of the Former Soviet Union, which had an annual emission of 26 Mt $CO_2.yr^{-1}$ in 2000, all the other countries showed emissions or removals of very low magnitude. The global estimate of CO_2 emissions from agricultural soils in 2000 is 40 Mt CO_2-eq. (US-EPA, 2006a), less than 1% of global anthropogenic CO_2 emissions.

8.3.1 Trends since 1990

Globally, agricultural emissions have increased by 14% from 1990 to 2005 (Table 8.4), with an average annual emission of 49 Mt CO_2-eq.yr^{-1} (US-EPA, 2006a). N_2O from soils, N_2O from manure management, and CH_4 from enteric fermentation were the agricultural sources showing the greatest increase in emissions, at 21, 18 and 12%, respectively, while N_2O and CH_4 emissions from biomass burning decreased by 8 and 6%, respectively. N_2O emissions increased by 31 Mt CO_2-eq.yr^{-1}, almost twice the rate of increase seen for CH_4 emissions (US-EPA, 2006a).

***Table 8.5** GHG emission trends by main sources in the agriculture sector in the different world regions during the period 1990-2020. Adapted from US-EPA (2006a)*

Region		**N_2O soils**	**CH_4 enteric**	**CH_4 rice**	**CH_4, N_2O manure**	**CH_4, N_2O burning**	**Total**
Developing countries of South Asia	**Mt CO_2-eq.yr^{-1} in 1990**	**396**	**228**	**113**	**34**	**23**	**795**
	% change in 2005	35	21	14	18	4	26
	% change in 2020	62	48	41	44	4	52
Developing countries of East Asia	**Mt CO_2-eq.yr^{-1} in 1990**	**459**	**158**	**409**	**88**	**59**	**1,173**
	% change in 2005	31	87	6	44	-10	28
	% change in 2020	54	153	18	86	-10	54
Latin America & The Carribbean	**Mt CO_2-eq.yr^{-1} in 1990**	**258**	**384**	**19**	**20**	**160**	**840**
	% change in 2005	39	16	34	25	-12	18
	% change in 2020	114	43	57	55	-12	55
Sub-Saharan Africa	**Mt CO_2-eq.yr^{-1} in 1990**	**252**	**183**	**12**	**12**	**145**	**603**
	% change in 2005	39	34	81	33	-1	28
	% change in 2020	102	77	172	83	-1	70
Middle East & North Africa	**Mt CO_2-eq.yr^{-1} in 1990**	**76**	**34**	**7**	**3**	**2**	**121**
	% change in 2005	33	20	53	0	0	30
	% change in 2020	98	49	97	33	0	81
Subtotal (developing regions)	**Mt CO_2-eq.yr^{-1} in 1990**	**1,441**	**987**	**560**	**157**	**389**	**3,533**
	% change in 2005	35	32	11	54	-10	26
	% change in 2020	78	68	30	72	-7	58
Former Soviet Union	**Mt CO_2-eq.yr^{-1} in 1990**	**121**	**160**	**4**	**50**	**10**	**346**
	% change in 2005	-36	-40	-18	-20	-60	-36
	% change in 2020	-17	-28	-19	-8	-60	-22
Central & Eastern Europe	**Mt CO_2-eq.yr^{-1} in 1990**	**103**	**76**	**1**	**28**	**3**	**210**
	% change in 2005	-19	-32	-25	0	0	-21
	% change in 2020	11	-26	-15	7	0	-3
Western Europe	**Mt CO_2-eq.yr^{-1} in 1990**	**218**	**153**	**2**	**93**	**1**	**469**
	% change in 2005	-7	-12	1	-12	0	-10
	% change in 2020	-11	-17	1	-14	0	-14
OECD Pacific	**Mt CO_2-eq.yr^{-1} in 1990**	**25**	**92**	**8**	**4**	**10**	**140**
	% change in 2005	28	0	-8	75	70	11
	% change in 2020	54	4	-4	75	70	19
OECD North America	**Mt CO_2-eq.yr^{-1} in 1990**	**282**	**181**	**8**	**57**	**7**	**534**
	% change in 2005	7	-2	7	19	0	6
	% change in 2020	19	5	-2	37	0	16
Subtotal (developed regions)	**Mt CO_2-eq.yr^{-1} in 1990**	**749**	**662**	**23**	**229**	**31**	**1,699**
	% change in 2005	-7	-16	-13	-2	3	-10
	% change in 2020	5	-12	-16	5	3	-2
Total	**Mt CO_2-eq.yr^{-1} in 1990**	**2,190**	**1,649**	**583**	**389**	**430**	**5,230**
	% change in 2005	21	12	10	12	-8	14
	% change in 2020	53	36	27	31	-8	38

While the Former Soviet Union and the countries of Western and Central and Eastern Europe showed a sharp decrease in emissions during the period 1990-2005, the rest of the world showed a steady increase. The reasons for this are discussed in more detail in Sections 8.2 and 8.3.3.

The five regions composed of Non-Annex I countries showed a 26% increase, whereas the other five regions, with mostly Annex I countries, showed a 10% decrease, in their combined emissions. This was mostly due to non-climate macroeconomic policies in the Former Soviet Union and Eastern European countries (Section 8.7.2) and, to a lesser extent, to climate policies in the European Union (Section 8.7.1).

8.3.2 Future Trends

Agricultural N_2O emissions are forecast to increase by 35-60% up to 2030 due to increased nitrogen fertiliser use and increased animal manure production (FAO, 2003). Similarly, Mosier and Kroeze (2000) and US-EPA (2006a, Table 8.3.1), estimated that N_2O emissions will increase by about 50% by 2020 (relative to 1990). If demands for food increase and diets shift as projected, then annual emissions of GHGs from agriculture may escalate further, but improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or protein) produced.

If CH_4 emissions grow in direct proportion to increases in livestock numbers, then global livestock-related methane production is expected to increase by 60% up to 2030 (FAO, 2003). However, changes in feeding practices and manure management could ameliorate this increase. US-EPA (2006a) forecast that methane emissions from enteric fermentation and manure management will increase by 21% and 15%, respectively, between 2005 and 2020 (Table 8.5).

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 *et al.*, 1997). However, as shown in Table 8.5, US-EPA (2006a) project a further 16% increase in CH_4 emissions from rice crops between 2005 and 2020.

Emissions of CO_2, mainly from land use change, especially deforestation, are forecast to be stable or declining up to 2030 (FAO, 2003). This, combined with the increasing adoption of conservation tillage practices and increasing crop productivity, could result in decreasing CO_2 emissions from soils.

US-EPA (2006a) forecast an acceleration in global GHG emissions from agriculture for the period 2005-2020, compared to the period 1990-2005 (Table 8.4). In the developing regions the growth is expected to continue at a similar pace (25% increase up to 2020; a 58% increase relative to 1990), whereas in the more developed regions the decreasing trend would be reversed, and emissions would grow by 8% up to 2020. According to US-EPA (2006a), the two most significant sources, N_2O from soils and CH_4 from enteric fermentation, would also increase most rapidly toward 2020, by 26% and 21%, respectively. N_2O emissions, expected to average 49 Mt CO_2-eq.yr^{-1}, would continue to grow faster than CH_4 emissions, projected to average 35 Mt CO_2-eq.yr^{-1}.

8.3.3 Regional Trends

The group of regions with the largest share of global agricultural GHG emissions, those with developing countries, are also the regions with the largest expected rates of increase in emissions (Table 8.5, Figure 8.2).

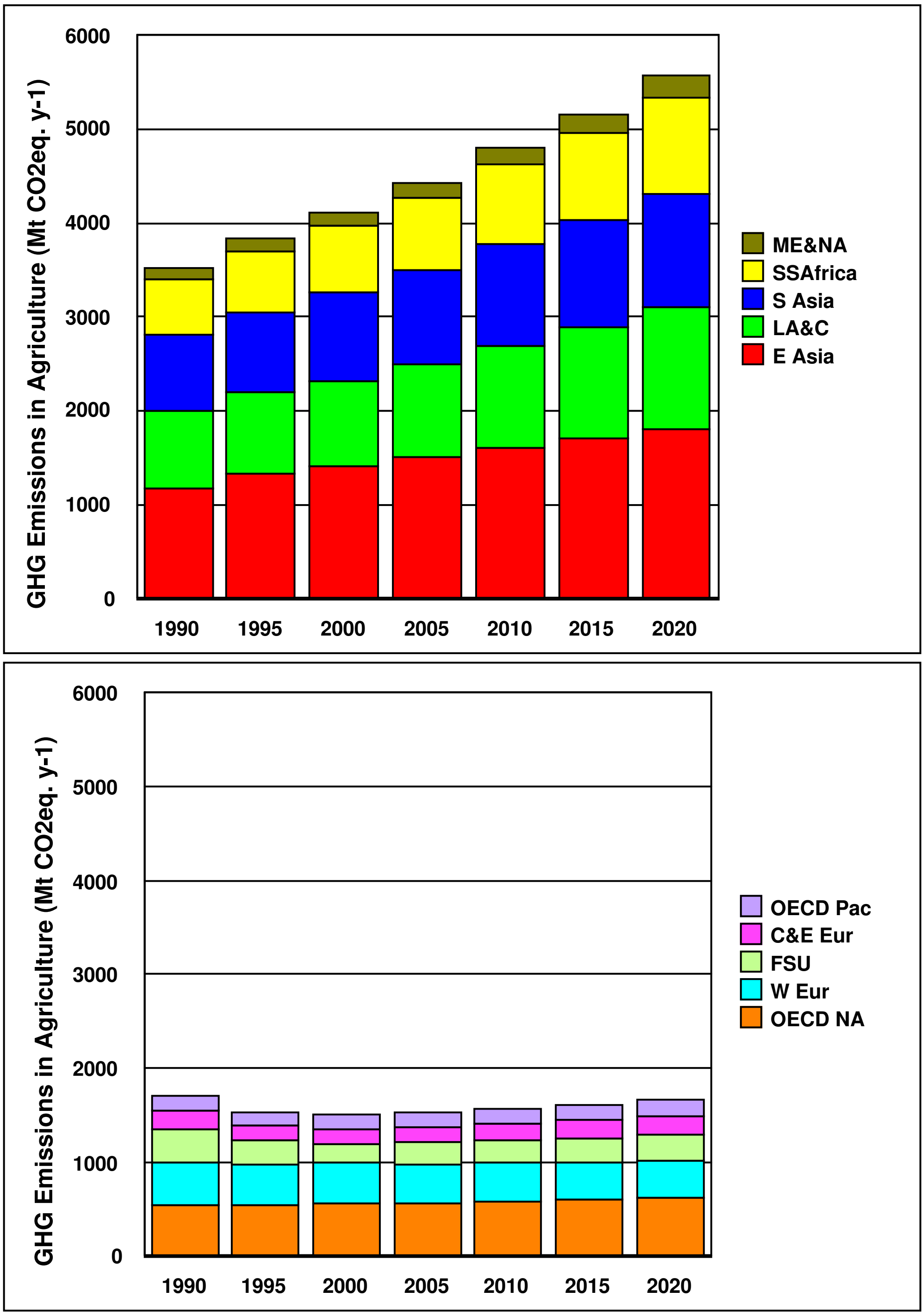

Figure 8.2 *Evolution of GHG emissions in agricultural sector of the ten world regions during the period 1990-2020. ME&NA = Middle East and North Africa; SS Africa = Sub-Saharan Africa; S Asia = Developing countries of South Asia; LA&C = Latin America and The Caribbean; E Asia = Developing countries of East Asia; OECD Pac = OECD countries of the Pacific Region; C&E Eur = Central and Eastern Europe; FSU = Former Soviet Union; W Eur = Western Europe; OECD NA = OECD countries of North America. Adapted from US-EPA (2006a).*

The Middle East and North Africa and Sub-Saharan Africa will experience the highest growth, with a combined 72% increase in emissions during the period 1990 to 2020 (US-EPA, 2006a). Sub-Saharan Africa is the one world region where per-capita food production is either in decline, or more-or-less constant at a level that is less than adequate (Scholes and Biggs, 2004). This trend can be linked to issues of low and declining soil fertility (Sanchez, 2002), and to inadequate fertiliser inputs. Although slow, the rising wealth of urban populations is likely to increase demand for live-stock products. This would result in the intensification of agriculture and its expansion to still largely unexploited areas, particularly in South-central Africa (including Angola, Zambia, DRC, Mozambique and Tanzania), with a consequent increase in GHG emissions.

East Asia is projected to show large increases in GHG emissions from animal sources. According to FAO statistics (FAOSTAT, 2006), 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. Accordingly, US-EPA (2006a) forecast a 153% and 86% increases in emissions from enteric fermentation and manure management, respectively, from 1990 to 2020. In South Asia, the main driver of increasing emissions is the use of N fertilisers and manure to keep up with the increasing demand for food resulting from rapid population growth.

In Latin America and the Caribbean, agricultural products, either primary or processed are the main source of exports. Significant changes in land use and management have occurred, with forest conversion to cropland and grassland being the most significant. These land use changes have resulted in increased GHG emissions from soils (CO_2 and N_2O). The cattle population has increased linearly from 176 to 379 Mhead between 1961 and 2004, a 115% increase. This was partly offset by a 36% decrease in the sheep population, from 125 to 80 Mhead. All other livestock categories have increased in the order of 30 to 600% since 1961. Cropland areas, including rice and soybean, and the use of N fertilisers have also shown dramatic increases (FAOSTAT, 2006). Another major trend in the region is the increased adoption of no-till agriculture, particularly in the Mercosur area (Brazil, Argentina, Paraguay and Uruguay). This technology, which was developed in the 1970's, is used on ~30 Mha of crops every year in the region. It is uncertain how much of this area is under permanent no-till, but it is likely that the net CO_2 removals due to this change in cropland management would at least offset the annual increase in all GHG emissions in the agriculture sector, estimated at nearly 20 Mt CO_2-eq. yr^{-1}.

In the Former Soviet Union and Eastern European countries, agricultural production is, at present, about 60-80% of that in 1990, but is expected to grow by 15-40% above 2001 levels by 2010, driven by the increasing wealth of these countries. A 10-14% increase of arable land is forecast for the whole of Russia due to agricultural expansion. The widespread application of intensive management technologies could result in a 2 to 2.5-fold rise in grain and fodder yields, with a consequent reduction of arable land, but may increase N fertiliser use. Decreases in fertiliser N use since 1990 has led to a significant reduction in N_2O emissions but, under favourable economic conditions the amount of N fertilizer applied will again increase. US-EPA (2006a) projected a 33% increase in N_2O emissions from soils in these two regions between 2005 and 2020, equivalent to an average rate of 3.5 Mt CO_2-eq.yr^{-1}.

OECD North America and OECD Pacific are the only developed regions showing a consistent increase in GHG emissions (16% and 19%, respectively between 1990 and 2020; Table 8.4) in the agricultural sector. In both cases, the trend is largely driven by N_2O emissions from soils. In Oceania, nitrogen fertiliser use has increased exponentially over the past 45 years with a fivefold increase since 1990 in NZ, and two and a half-fold increase in Australia. In North America, on the other hand, N fertiliser use has remained stable, and the main driver for increasing emissions is manure management associated with cattle, poultry and swine production, and manure application to soils. In both regions, conservation policies have resulted in reduced CO_2 emissions from land conversion. Land clearing in Australia has declined by 60% since 1990 with vegetation management policies restricting further clearing, while in North America, some marginal croplands are been returned to trees or grassland.

Western Europe is the only region where, according to US-EPA (2006a), GHG emissions from agriculture are projected to decrease until 2020 (Table 8.3). This is associated with the adoption of a number of climate-specific and other environmental policies in the European Union, as well as economic constraints on agriculture, as discussed in Sections 8.7.1 and 8.7.2 below.

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

8.4.1 Mitigation technologies and practices

Opportunities for mitigating GHGs in agriculture fall into three broad categories[2], based on the underlying mechanism:

a. Reducing emissions: Agriculture releases to the atmosphere significant amounts of CO_2, CH_4, or N_2O (Cole *et al.*, 1997; IPCC, 2001, Paustian *et al.*, 2004). The fluxes of these gases can be reduced by managing more efficiently the flows of carbon and nitrogen in agricultural ecosystems. For example, practices that deliver added N more efficiently to crops often suppress the emission of N_2O (Bouwman, 2001), and managing livestock to make most efficient use of feeds often suppresses the amount of CH_4 produced (Clemens and Ahlgrimm, 2001). The approaches that best reduce emissions depend on local conditions, and therefore vary from region to region.

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

c. Avoiding (or displacing) emissions: Crops and residues from agricultural lands can be used as a source of fuel, either directly or after conversion to fuels such as ethanol or diesel (Schneider and McCarl, 2003; Cannell, 2003). These bio-energy feed-stocks still release CO_2 upon combustion, but now the C is of recent atmospheric origin (via photosynthesis), rather than from fossil C. The net benefit of these bio-energy sources to the atmosphere is equal to the fossil-derived

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[2] Smith *et al.* (2006a) have recently reviewed mechanisms for agricultural GHG mitigation. This section draws largely from that study.

emissions displaced, less any emissions from producing, transporting, and processing. Emissions of GHGs, notably CO_2, can also be avoided by agricultural management practices that forestall the cultivation of new lands now under forest, grassland, or other non-agricultural vegetation (Foley *et al.*, 2005).

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

The impacts of various mitigation options considered are summarised in Table 8.6. The most important options are discussed in Sections 8.4.1.1 to 8.4.1.7.

Table 8.6 *A list of proposed measures for mitigating greenhouse gas emissions from agricultural ecosystems, their apparent effects on reducing emissions of individual gases (mitigative effect), and an estimate of scientific confidence that the proposed practice can reduce overall net emissions.*

		Mitigative effects[1]			**Net mitigation[2] (confidence)**	
Measure	**Examples**	**CO_2**	**CH_4**	**N_2O**	**Agree-ment**	**Evi-dence**
Cropland management	Agronomy	+		+/-	***	**
	Nutrient management	+		+	***	**
	Tillage/residue management	+		+/-	**	**
	Water management (irrigation, drainage)	+/-		+	*	*
	Rice management		+	+/-	**	**
	Agro-forestry	+		+/-	***	*
	Set-aside, land-use change	+	+	+	***	***
Grazing land management/ pasture improvement	Grazing intensity	+/-		+/-	*	*
	Increased productivity (e.g. fertilization)	+		+/-	**	*
	Nutrient management	+		+/-	**	**
	Fire management	+		+/-	*	*
	Species introduction (including legumes)	+		+/-	*	**
Management of organic soils	Avoid drainage of wetlands	+	-	+/-	**	**
Restoration of degraded lands	Erosion control, organic amendments, nutrient amendments	+		+/-	***	**
Livestock management	improved feeding practices		+		***	***
	specific agents and dietary additives		+		**	***
	longer term structural and management changes and animal breeding		+		**	*
Manure/biosolid management	Improved storage and handling		+	+/-	***	**
	anaerobic digestion		+	+/-	***	*
	more efficient use as nutrient source	+		+	***	**
Bio-energy	energy crops, solid, liquid, biogas, residues	+		+/-	***	**

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

[2] A qualitative estimate of the confidence in describing the proposed practice as a measure for reducing *net* emissions of greenhouse gases, expressed as CO_2 equivalence. 'Agreement' refers to the relative degree of agreement or consensus in the literature (the more asterisks, the higher the agreement); 'Evidence' refers to the relative amount of data in support of the proposed effect (the more asterisks, the greater the amount of evidence). (based on 'Uncertainty guidance' by Swart, Rogner, and Duong)

8.4.1.1 Cropland management

Croplands, because they are often intensively managed, offer many opportunities to impose practices that reduce net emissions of GHGs (Table 8.6). Mitigation practices in cropland management include the following partly-overlapping categories:

a. Agronomy:

Improved agronomic practices that increase yields and generate higher inputs of residue C can lead to increased soil C storage (Follett, 2001). Examples of such practices include: using improved crop varieties; extending crop rotations, notably those with perennial crops which allocate more C below-ground; and avoiding or reducing use of bare (unplanted) fallow (West and Post, 2002; Smith, 2004a,b; Lal, 2003, 2004a; Freibauer *et al.*, 2004). Adding more nutrients, when deficient, can also promote soil C gains (Alvarez, 2005), but the benefits from N fertilizer can be offset by higher emissions of N_2O from soils and CO_2 from fertilizer manufacture (Schlesinger, 1999; Robertson *et al.*, 2004; Gregorich *et al.*, 2005).

Emissions can also be reduced by adopting less intensive cropping systems, which reduce reliance on pesticides and other inputs (and therefore the GHG cost of their production: Paustian *et al.*, 2004). An important example is the use of rotations with legume crops (West and Post, 2002; Izaurralde *et al.*, 2001), which reduce reliance on inputs of N, though legume-derived N can also be a source of N_2O (Rochette and Janzen, 2005)

A third group of agronomic practices are those that provide temporary vegetative cover between agricultural crops. These 'catch' or 'cover' crops add C to soils (Barthès *et al.*, 2004; Freibauer *et al.*, 2004) and may also extract plant-available N unused by the preceding crop, thereby reducing N_2O emissions.

b. Nutrient management:

Nitrogen applied in fertilizers and manures is not always used efficiently by crops (Galloway *et al.*, 2003; Cassman *et al.*, 2003). Improving this efficiency can reduce emissions of N_2O, generated by soil microbes largely from surplus N, and it can indirectly reduce emissions of CO_2 from N fertilizer manufacture (Schlesinger, 1999). Practices that improve N use efficiency include: adjusting application rates based on precise estimation of crop needs (e.g. precision farming); using slow-release fertilizer forms or nitrification inhibitors (which slow the microbial processes leading to N_2O formation); avoiding time delays between N application and plant N uptake (improved timing); placing the N more precisely into the soil to make it more accessible to crops roots; avoiding excess N applications, or eliminating N applications where possible (Robertson, 2004; Dalal *et al.*, 2003; Paustian *et al.*, 2004; Cole *et al.*, 1997; Monteny *et al.*, 2006).

c. Tillage/residue management:

Advances in weed control methods and farm machinery now allow many crops to be grown with minimal tillage (reduced tillage) or without tillage (no-till). These practices are now increasingly used throughout the world (e.g. Cerri *et al.* 2004). Since soil disturbance tends to stimulate soil C losses through enhanced decomposition and erosion, reduced- or no-till agriculture often results in soil C gain, though not always (West and Post 2002; Ogle *et al.* 2005; Gregorich *et al.* 2005; Alvarez 2005). Adopting reduced- or no-till may also affect emissions of N_2O, but the net effects are inconsistent and not well-quantified globally (Smith and Conen 2004; Helgason *et al.* 2005; Li *et al.* 2005; Cassman *et al.* 2003). The effect of reduced tillage on N_2O emissions may depend on soil and climatic conditions: in some areas reduced tillage promotes N_2O emissions; elsewhere it may reduce emissions or have no measurable influence (Marland *et al.* 2001).

Systems that retain crop residues also tend to increase soil C because these residues are the precursors for soil organic matter, the main store of carbon in the soil. Avoiding the burning of residues, for instance mechanising the harvesting of sugarcane, which eliminates the need for pre-harvest burning (Cerri *et al.* 2004), also avoids emissions of aerosols and GHGs generated from fire.

d. Water management:

About 18% of the world's croplands now receive supplementary water through irrigation (Millennium Ecosystem Assessment, 2005). Expanding this area, or using more effective irrigation measures can enhance C storage in soils through enhanced yields and residue returns (Follett 2001; Lal 2004a). But some of these gains may be offset by CO_2 from energy used to deliver the water (Schlesinger 1999; Mosier *et al.* 2005) or from N_2O emissions from higher moisture and fertilizer N inputs (Liebig *et al.* 2005), though the latter effect has not been widely measured.

Drainage of agricultural lands in humid regions can promote productivity (and hence soil C) and perhaps also suppress N_2O emissions by improving aeration (Monteny *et al.* 2006). Any nitrogen lost through drainage, however, may be susceptible to loss as N_2O (Reay *et al.* 2003).

e. Rice management:

Cultivated wetland rice soils emit significant quantities of methane (Yan *et al.*, 2003). Emissions during the growing season can be reduced by many practices (Yagi *et al.*, 1997; Wassmann *et al.*, 2000; Aulakh *et al.*, 2001). For example, draining the wetland rice once or several times during the growing season effectively reduces CH_4 emissions (Smith and Conen 2004; Yan *et al.*, 2003), although this benefit may be partly offset by higher N_2O emissions, and the practice may be constrained by water supply. Rice cultivars with low exudation rates could offer an important methane mitigation option (Aulakh *et al.*, 2001). In the off-rice season, methane emissions can be reduced by improved water management, especially by keeping the soil as dry as possible and avoiding water-logging (Cai *et al.*, 2000, 2003; Kang *et al.*, 2002; Xu *et al.*, 2003).

Methane emissions can also be reduced by adjusting the timing of organic residue additions (e.g., incorporating organic materials in the dry period rather than in flooded periods; Xu *et al.*, 2000; Cai and Xu, 2004), by composting the residues before incorporation, or by producing biogas for use as fuel for energy production (Wang and Shangguan, 1996; Wassmann *et al.*, 2000).

f. Agro-forestry:

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

g. Land cover (use) change:

One of the most effective methods of reducing emissions is to allow or encourage the reversion of cropland to another land cover, typically one similar to the native vegetation. The conversion can occur over the entire land area ('set-asides'), or in localized spots, such as grassed waterways, field margins, or shelterbelts (Follett, 2001; Freibauer *et al.*, 2004; Lal, 2004b; Falloon *et al.*, 2004; Ogle *et al.*, 2003). Such land cover change often increases storage of C; for example, converting arable cropland to grassland typically results in the accrual of soil C because of lower soil disturbance and reduced C removal in harvested products. Compared to cultivated lands, grasslands may also have reduced N_2O emissions from lower N inputs, and higher rates of CH_4 oxidation, though recovery of oxidation may be slow (Paustian *et al.*, 2004).

Similarly, converting drained croplands back to wetlands can result in rapid accumulation of soil carbon (removal of atmospheric CO_2), although this conversion may stimulate CH_4 emissions, because water-logging creates anaerobic conditions (Paustian *et al.*, 2004). Planting trees can also reduce emissions, but these practices are considered under agro-forestry (Section 8.4.2f) afforestation (Chapter 9), or reforestation (Chapter 9).

Because land cover (or use) conversion comes at the expense of lost agricultural productivity, it is usually an option only on surplus agricultural land or on croplands of marginal productivity.

8.4.1.2 Grazing land management and pasture improvement

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

a. Grazing intensity:

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

b. Increased productivity (including fertilization):

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

c. Nutrient management:

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

d. Fire management:

Biomass burning (not to be confused with bio-energy, where biomass is combusted off-site for energy) contributes to climate change in several ways. Firstly, it releases GHGs, notably CH_4 and, and to a lesser extent, N_2O (the CO_2 released is of recent origin, is re-absorbed by vegetation and is usually not counted). Secondly, it generates hydrocarbon and reactive nitrogen emissions, which react to form tropospheric ozone. Smoke contains a range of aerosols which can have either warming or cooling effects on the atmosphere though the *net* effect is thought to be positive radiant forcing (Andreae *et al.*, 2005; Jones *et al.*, 2003; Venkataraman *et al.*, 2005; Andreae, 2001; Andreae and Merlet, 2001; Anderson *et al.*, 2003; Menon *et al.*, 2002). Thirdly, fire blackens the land surface, reducing its albedo for several weeks, causing a warming (Beringer *et al.* 2003). Fourthly, burning can affect the proportions of woody versus grass cover, notably in savannas, which occupy about an eighth of the global land surface. Reducing the frequency or intensity of fires typically leads to increased tree and shrub cover, resulting in higher landscape C density in soil and biomass (Scholes and van der Merwe, 1996). This woody-plant encroachment mechanism is higher initially, but saturates over 20-50 years, whereas avoided CH_4 and N_2O emissions are ongoing as long as the fires are suppressed.

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

e. Species introduction:

Introducing grass species with higher productivity, or C allocation to deeper roots, has been shown to increase soil C. For example, establishment of deep-rooted grasses in savannas has been reported to yield very high rates of C accrual (Fisher *et al.*, 1994), although the applicability of these results has not been widely confirmed (Conant *et al.*, 2001; Davidson *et al.*, 1995). Introducing legumes into grazing lands can promote soil C storage (Soussana *et al.*, 2004), through enhanced productivity from the associated N inputs, and perhaps also reduce N_2O emissions, if the biological N_2 fixation displaces the need for fertilizer N.

Lands used for grazing also emit GHGs from livestock, notably CH_4 from ruminants and from their manures. Practices for reducing these emissions are considered under 'Livestock management' (8.4.1.5).

8.4.1.3 Management of organic soils

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

8.4.1.4 Restoration of degraded lands

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

8.4.1.5 Livestock management

Livestock, predominantly ruminants such as cattle and sheep, are important sources of CH_4, accounting for about 18% of global anthropogenic emissions of this gas (US-EPA, 2006a). The methane is produced primarily by enteric fermentation and voided by eructation (Crutzen, 1995; Murray *et al.*, 1976; Kennedy and Milligan, 1978). Practices for reducing CH_4 emissions from this source fall into three general categories: improved feeding practices, use of specific agents or dietary additives, and longer-term management changes and animal breeding.

a. Improved feeding practices:

Methane emissions can be reduced by feeding more concentrates, normally replacing forages (Blaxter and Claperton, 1965; Johnson and Johnson, 1995; Lovett *et al.*, 2003; Beauchemin and McGinn, 2005). Although concentrates may increase daily methane emissions, emissions per kg-feed intake and per kg-product are almost invariably reduced. The net benefit, however, depends on reduced animal numbers or younger age at slaughter for beef animals, and on how the practice affects emissions when producing and transporting the concentrates (Phetteplace *et al.*, 2001; Lovett *et al.*, 2006).

Other practices that can reduce CH_4 emissions include: adding oils to the diet (e.g. Machmuller *et al.*, 2000; Jordan *et al.*, 2004); improving pasture quality, especially in less developed regions, because it improves animal productivity, and reduces the proportion of energy lost as CH_4

(Leng, 1991; McCrabb *et al.*, 1998; Alcock and Hegarty, 2005); and optimising protein intake to reduce N excretion and N_2O emissions (Clark *et al.*, 2005).

b. Specific agents and dietary additives:

A wide range of specific agents, mostly aimed at suppressing methanogenesis, have been proposed as dietary additives to reduce CH_4 emissions:

- Ionophores are antibiotics that can reduce methane emissions (Benz and Johnson, 1982; Van Nevel and Demeyer, 1996; McGinn *et al.*, 2004), but their effect may be transitory (Rumpler *et al.*, 1986;) and they have been banned in the EU.
- Halogenated compounds inhibit methanogenic bacteria (Wolin *et al.*, 1964; Van Nevel and Demeyer, 1995) but their effects, too, are often transitory and they can have side effects such as reduced intake.
- Probiotics, such as yeast culture, have shown only small, insignificant effects (McGinn *et al.*, 2004) but selecting strains specifically for methane reducing ability could improve results (Newbold and Rode, 2005).
- Propionate precursors such as fumarate or malate reduce methane formation by acting as alternative hydrogen acceptors (Newbold *et al.*, 2002), but they elicit response only at high doses and are therefore expensive (Newbold *et al.*, 2005).
- Vaccines against methanogenic bacteria are being developed but are not yet commercially available (Wright *et al.*, 2004).
- Bovine somatotropin (BSt) and hormonal growth implants do not specifically suppress CH_4 formation, but by improving animal performance (Bauman, 1992; Schmidely, 1993), they can reduce emissions per-kg of animal product (Johnson *et al.*, 1991; McCrabb, 2001).

c. Longer-term management changes and animal breeding:

- Increasing productivity through breeding and better management practices spreads the energy cost of maintenance across a greater feed intake, often reducing methane output per kg of animal product (Boadi *et al.*, 2004) With improved efficiency, meat-producing animals reach slaughter weight at a younger age, with reduced lifetime emissions (Lovett and O'Mara, 2002). The whole-system effects of such practices are not entirely clear, however; for example, selecting for higher yield might reduce fertility, requiring more replacement animals (Lovett *et al.*, 2006).

8.4.1.6 Manure management

Animal manures can release significant amounts of N_2O and CH_4 during storage, but the magnitude of these emissions varies. Methane emissions from manure stored in lagoons or tanks can be reduced by cooling or covering the sources, or by capturing the CH_4 emitted (Clemens and Ahlgrimm, 2001; Monteny *et al.* 2001, 2006; Paustian *et al.*, 2004). The manures can also be digested anaerobically to maximize retrieval of CH_4 as an energy source (Clemens and Ahlgrimm, 2001; Clemens *et al.*, 2006). Storing and handling the manures in solid rather than liquid form can suppress CH_4 emissions, but may increase N_2O formation (Paustian *et al.*, 2004). Preliminary evidence suggests that covering manure heaps can reduce N_2O emissions (Chadwick, 2005). For most animals worldwide there is limited opportunity for manure management, treatment, or storage; excretion happens in the field and handling for fuel or fertility amendment occurs when it is dry and methane emissions are negligible (Gonzalez-Avalos and Ruiz-Suarez, 2001). To some extent, emissions from manure might be curtailed by altering feeding practices (Külling *et al.*, 2003), or by composting the manure

(Pattey *et al.*, 2005) but these mechanisms and the system-wide influence have not been widely explored.

Manures also release GHGs, notably N_2O, after application to cropland or deposition on grazing lands, but the practices for reducing these emissions are considered under 'cropland management' and 'grazing land management' (8.4.1.1 and 8.4.1.2).

8.4.1.7 Bioenergy

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

The interactions of an expanding bio-energy sector with other land uses, and impacts on agro-ecosystem services such as food production, biodiversity, soil and nature conservation, and carbon sequestration has not yet been adequately studied, but bottom up approaches (Smeets *et al.*, 2006) and integrated assessment modelling (Hoogwijk *et al.*, 2005; Hoogwijk, 2004) offer opportunities to improve understanding. Latin America, Sub-Saharan Africa and Eastern Europe are promising regions for bio-energy, with additional long-term contributions from Oceania and East and NE Asia. The technical potential for biomass production may be developed at low production costs in the range of 2 USD GJ^{-1} (Hoogwijk, 2004, Rogner *et al.*, 2000).

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

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

Many mitigation practices (Section 8.4.1) affect more than one GHG[3]. When assessing the impact of agriculture on changes in GHG emissions, it is important to consider the impacts on all GHGs 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 for each GHG (in t CO_2-eq. ha^{-1} yr^{-1}) as described in Smith *et al.* (2006a) are summarised in Table 8.7.

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[3] Smith *et al.* (2006a) have recently collated per-area estimates of agricultural GHG mitigation options. This section draws largely from that study.

***Table 8.7** Per-area annual mitigation potentials for each climate region for non-livestock mitigation options (adapted from Smith et al., 2006)*[1]

			CO_2 (t CO_2 ha^{-1} y^{-1})			CH_4 (t CO_2-eq. ha^{-1} y^{-1})			N_2O (t CO_2-eq. ha^{-1} y^{-1})			All GHG (t CO_2-eq. ha^{-1} y^{-1})		
Climate zone	**Activity**	**Practice**	**Emission reduction (estimate)**	**Low**	**High**	**Emission reduction (estimate)**	**Low**	**High**	**Emission reduction (estimate)**	**Low**	**High**	**Emission reduction (estimate)**	**Low**	**High**
Cool-dry	Croplands	agronomy	0.29	0.07	0.51	0.00	0.00	0.00	0.10	0.00	0.20	0.39	0.07	0.71
	Croplands	nutrient management	0.26	-0.22	0.73	0.00	0.00	0.00	0.07	0.01	0.32	0.33	-0.21	1.05
	Croplands	tillage and residue management	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
	Croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	rice management	0.70	-3.56	4.95	9.81	4.21	35.02	0.02	-0.77	1.18	10.53	-0.12	41.15
	Croplands	set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	2.30	0.00	4.60	3.93	-0.07	7.90
	Croplands	agro-forestry	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
	Grasslands	grazing, fertilizaltion, fire	0.11	-0.55	0.77	0.02	0.01	0.02	0.00	0.00	0.00	0.13	-0.54	0.79
	Organic soils	restoration	36.67	3.67	69.67	-3.32	-0.05	-15.30	0.16	0.05	0.28	33.51	3.67	54.65
	Degraded lands	restoration	3.45	-0.37	7.26	0.08	0.04	0.14	0.00	0.00	0.00	3.53	-0.33	7.40
	Manure / biosol	application	1.54	-3.19	6.27	0.00	0.00	0.00	0.00	-0.17	1.30	1.54	-3.36	7.57
	Bioenergy	soils only	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
Cool-moist	Croplands	agronomy	0.88	0.51	1.25	0.00	0.00	0.00	0.10	0.00	0.20	0.98	0.51	1.45
	Croplands	nutrient management	0.55	0.01	1.10	0.00	0.00	0.00	0.07	0.01	0.32	0.62	0.02	1.42
	Croplands	tillage and residue management	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	Croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	rice management	-0.62	-6.57	0.00	9.81	4.21	35.02	0.02	-0.77	1.18	9.21	-3.13	36.20
	Croplands	set-aside and LUC	3.04	1.17	4.91	0.02	0.00	0.00	2.30	0.00	4.60	5.36	1.17	9.51
	Croplands	agro-forestry	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	Grasslands	grazing, fertilizaltion, fire	0.81	0.11	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.11	1.50
	Organic soils	restoration	36.67	3.67	69.67	-3.32	-0.05	-15.30	0.16	0.05	0.28	33.51	3.67	54.65
	Degraded lands	restoration	3.45	-0.37	7.26	1.00	0.69	1.25	0.00	0.00	0.00	4.45	0.32	8.51
	Manure / biosol	application	2.79	-0.62	6.20	0.00	0.00	0.00	0.00	-0.17	1.30	2.79	-0.79	7.50
	Bioenergy	soils only	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
Warm-dry	Croplands	agronomy	0.29	0.07	0.51	0.00	0.00	0.00	0.10	0.00	0.20	0.39	0.07	0.71
	Croplands	nutrient management	0.26	-0.22	0.73	0.00	0.00	0.00	0.07	0.01	0.32	0.33	-0.21	1.05
	Croplands	tillage and residue management	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	Croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	rice management	0.70	-3.56	4.95	9.81	4.21	35.02	0.02	-0.77	1.18	10.53	-0.12	41.15
	Croplands	set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	2.30	0.00	4.60	3.93	-0.07	7.90
	Croplands	agro-forestry	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	Grasslands	grazing, fertilizaltion, fire	0.11	-0.55	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.11	-0.55	0.77
	Organic soils	restoration	73.33	7.33	139.33	-3.32	-0.05	-15.30	0.16	0.05	0.28	70.18	7.33	124.31
	Degraded lands	restoration	3.45	-0.37	7.26	0.00	0.00	0.00	0.00	0.00	0.00	3.45	-0.37	7.26
	Manure / biosol	application	1.54	-3.19	6.27	0.00	0.00	0.00	0.00	-0.17	1.30	1.54	-3.36	7.57
	Bioenergy	soils only	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
Warm-moist	Croplands	agronomy	0.88	0.51	1.25	0.00	0.00	0.00	0.10	0.00	0.20	0.98	0.51	1.45
	Croplands	nutrient management	0.55	0.01	1.10	0.00	0.00	0.00	0.07	0.01	0.32	0.62	0.02	1.42
	Croplands	tillage and residue management	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89
	Croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	rice management	-0.62	-6.57	0.00	9.81	4.21	35.02	0.02	-0.77	1.18	9.21	-3.13	36.20
	Croplands	set-aside and LUC	3.04	1.17	4.91	0.02	0.00	0.00	2.30	0.00	4.60	5.36	1.17	9.51
	Croplands	agro-forestry	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89
	Grasslands	grazing, fertilizaltion, fire	0.81	0.11	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.11	1.50
	Organic soils	restoration	73.33	7.33	139.33	-3.32	-0.05	-15.30	0.16	0.05	0.28	70.18	7.33	124.31
	Degraded lands	restoration	3.45	-0.37	7.26	0.00	0.00	0.00	0.00	0.00	0.00	3.45	-0.37	7.26
	Manure / biosol	application	2.79	-0.62	6.20	0.00	0.00	0.00	0.00	-0.17	1.30	2.79	-0.79	7.50
	Bioenergy	soils only	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89

[1] 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; Smith *et al.*, 2006b). Estimates were made using this method for all land-based mitigation options except estimates for soils under bio-energy crops and agro-forestry which were assumed to derive their mitigation potential mainly from cessation of soil disturbance; the figures for soils under bio-energy crops and agro-forestry were therefore assumed to be the same as for no-till within the same climatic region, and for organic soil estimates, which were derived using estimated emissions under drained conditions from IPCC guidelines (IPCC, 1997, 2003). Soil methane and nitrous oxide emission reduction potentials were derived as follows; a) for organic soils, the mean of low and high nutrient status organic soil N_2O emission factors were used the IPCC GPG LULUCF (IPCC, 2003) where low and high values correspond to best estimates for low and high nutrient status organic soils and for CH_4, low, high and median values from CH_4 emissions were taken from Le Mer and Roger (2001), b) N_2O figures for nutrient management were derived from US-EPA (2006b; assuming a reduction in N to 80% current N application), c) N_2O figures for tillage and residue management were derived from US-EPA (2006b; figures for no till were used), d) Rice figures were derived from US-EPA (2006b) using the mean of water management figures (since conversion of all rice to upland rice was considered unlikely by US-EPA (2006b) and water management is a more effective measure that N management). Since midseason drainage already occurs on 80% of paddy rice, mitigation was assumed to occur only on the remaining 20% of rice land.

For the livestock-based options, mitigation potentials (dairy cows, beef cattle, sheep, dairy buffalo and other buffalo) for reducing enteric methane emissions through improved feeding practices, specific agents and dietary additives, and longer term structural and management changes/animal breeding are shown in Table 8.8. These estimates were derived using a model similar to that described in US-EPA (2006b) by Smith *et al.* (2006a).

Table 8.8 *Summary of technical reduction potential (proportion of an animal's enteric methane production) for enteric methane emissions due to (i) improved feeding practices, (ii) specific agents and dietary additives and (iii) longer term structural/management change and animal breeding (adapted from Smith et al., 2006a)*[1]

	Improved feeding practices[2]					Specific agents and dietary additives[3]					Longer term structural/management change and animal breeding[4]				
AEZ regions	Dairy cows	Beef cattle	Sheep	Dairy buffalo	Non-dairy buffalo	Dairy cows	Beef cattle	Sheep	Dairy buffalo	Non-dairy buffalo	Dairy cows	Beef cattle	Sheep	Dairy buffalo	Non-dairy buffalo
N Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
S. Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
W. Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
E. Europe	0.11	0.06	0.03			0.04	0.01	0.002			0.03	0.07	0.003		
Russian Federation	0.10	0.05	0.03			0.03	0.04	0.002			0.03	0.06	0.003		
Japan	0.17	0.11	0.04			0.08	0.09	0.004			0.03	0.03	0.003		
South Asia	0.04	0.02	0.02	0.04	0.02	0.01	0.01	0.0005	0.01	0.002	0.01	0.01	0.001	0.01	0.02
East Asia	0.10	0.05	0.03	0.10	0.05	0.03	0.05	0.002	0.03	0.012	0.03	0.06	0.003	0.03	0.07
West Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Southeast Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Central Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Oceania	0.22	0.14	0.06			0.08	0.08	0.004			0.05	0.03	0.004		
N America	0.16	0.11	0.04			0.11	0.09	0.004			0.03	0.03	0.003		
S. America	0.06	0.03	0.02			0.03	0.02	0.001			0.02	0.03	0.002		
Central America	0.03	0.02	0.02			0.02	0.01	0.001			0.01	0.02	0.002		
East Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
West Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
North Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
South Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
Middle Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		

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

[2] Includes replacing roughage with concentrate (Blaxter & Claperton, 1965; Moe & Tyrrell, 1979; Johnson & Johnson, 1995; Yan *et al.*, 2000; Mills *et al.*, 2003; Beauchemin & McGinn, 2005; Lovett *et al.*, 2006), improving forages / inclusion of legumes (Leng, 1991; McCrabb *et al.*, 1998; McCaughey *et al.*, 1999; Woodward *et al.*, 2001; Waghorn *et*

al., 2002; Pinares-Patino *et al.*, 2003; Alcock & Hegarty, 2005) and feeding extra dietary oil (Machmüller *et al.*, 2000; Dohme *et al.*, 2001; Machmüller *et al.*, 2003, Lovett *et al.*, 2003; McGinn *et al.*, 2004; Beauchemin & McGinn, 2005; Jordan *et al.*, 2006; Jordan *et al.*, in press).

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

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

As can be 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). Some practices benefit more than one gas (e.g. set-aside/headland management) whilst others involve a trade-off between gases (e.g. restoration of organic soils). Table 8.6 also shows that the effectiveness of some mitigation practices differs between climate regions, and can also differ 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 be no 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 elicit soil C gain, have diminishing effectiveness after several decades; others, such as methods that reduce energy use, may reduce emissions indefinitely. For example, Six *et al.* (2004) found a strong time dependency of emissions from no-till agriculture, in part because of changing influence of tillage on N_2O emissions.

8.4.3 Global and regional estimates of agricultural GHG mitigation potential

A recent analysis of global GHG mitigation potential in agriculture is the first and only analysis to date to present a global assessment of the agricultural GHG mitigation potential broken down by world regions, with all GHGs considered together, for each option and for a range of potential CO_2-eq. prices (Smith *et al.*, 2006a). This section summarises the findings of that analysis and compares to other global and regional mitigation estimates where available.

The per-area/per-animal values for mitigation potential for each climate region used in Smith *et al.* (2006a) are summarised in tables 8.4.2a and b. These were used to scale-up to regions and to the world by multiplying by the appropriate area under each climate in each region. The study of Smith *et al.* (2006a) used areas 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, 2006) databases and projected changes in area for the four IPCC SRES scenarios from the IMAGE 2.2 model (Strengers *et al.*, 2004) and change in rice area for each region, as projected by the IMPACT model (Rosegrant *et al.*, 2001b). For emissions from livestock, total cattle, sheep and buffalo numbers in the various regions were obtained from FAOSTAT (2006). The cattle numbers for each region were broken down into numbers of dairy cattle and other cattle (because of the different reduction potentials of each type) using FAOSTAT (2006). The technical emission reduction potentials of the various practices were determined as described in Section 8.4.2. Full details are given in Smith *et al.* (2006a). The total area of cropland and grassland for each region in 2030 for each SRES scenario is shown in Table 8.9 and the estimated marginal costs of implementing each mitigation practice assumed by Smith *et al.* (2006a) are shown in Table 8.1.

Table 8.9 *The total crop area and grassland area for each region for each SRES scenario as used in the mitigation analysis (Smith et al., 2006a)*

	B1	**B1**	**A1b**	**A1b**	**B2**	**B2**	**A2**	**A2**
Region	**Crop area (Mha)**	**Grass area (Mha)**	**Crop area (Mha)**	**Grass area (Mha)**	**Crop area (Mha)**	**Grass area (Mha)**	**Crop area (Mha)**	**Grass area (Mha)**
North America	222.3	159.0	234.4	146.6	222.7	170.7	251.0	188.5
Eastern Europe	96.9	23.5	99.8	24.1	97.1	22.3	103.3	24.5
Northern Europe	37.3	7.4	40.6	6.7	31.1	7.0	34.7	7.6
Southern Europe	70.0	10.2	76.1	9.2	58.4	9.6	65.1	10.5
Western Europe	99.2	1.2	107.8	1.1	82.7	1.1	92.2	1.2
Russian Federation	205.6	72.8	222.3	74.2	196.9	71.6	209.3	75.8
Carribean	8.1	1.1	8.1	1.1	8.1	1.2	8.6	1.3
Central America	42.5	39.9	42.2	41.3	42.5	45.9	44.9	49.9
South America	300.4	241.1	311.5	253.2	307.6	300.9	360.8	374.8
Oceania	50.6	182.5	55.1	177.0	53.4	180.8	61.2	186.8
Polynesia	1.4	3.4	1.5	3.3	1.5	3.4	1.7	3.5
Eastern Africa	137.0	227.4	130.0	227.8	160.2	247.6	157.4	248.5
Middle Africa	47.0	129.7	44.6	130.0	54.9	141.3	53.9	141.8
Northern Africa	10.7	101.9	10.2	102.8	12.5	97.4	13.1	95.4
Southern Africa	51.2	86.4	53.1	90.7	52.4	107.8	61.5	134.2
Western Africa	33.8	268.3	33.3	275.1	41.3	269.4	39.5	272.0
Western Asia	36.6	40.2	35.9	40.7	41.5	41.5	47.4	44.9
Southeast Asia	173.5	63.0	192.3	72.6	196.0	75.8	178.2	55.0
South Asia	293.1	88.4	323.6	91.9	374.2	91.6	301.8	87.9
East Asia	217.5	279.8	218.5	286.1	244.2	300.6	245.0	319.0
Central Asia	72.1	183.0	70.6	185.3	81.6	188.9	93.2	204.3
Japan	6.5	2.5	6.4	2.1	5.9	3.3	6.0	3.3
Global total	**2213.4**	**2212.6**	**2317.7**	**2242.8**	**2366.5**	**2379.7**	**2429.8**	**2530.7**

Table 8.10 *Estimated costs (USD per t CO_2-eq.) of each mitigation option*

Climate zone	Activity	Practice	\$ ha^{-1} y^{-1}	\$ t CO_2-eq.$^{-1}$ y^{-1}
Cool-dry	Croplands	agronomy	20	51
	Croplands	nutrient management	5	15
	Croplands	tillage and residue manag	5	30
	Croplands	water management	-	2500
	Croplands	rice management	10	1
	Croplands	set-aside and LUC	10	3
	Croplands	agro-forestry	20	119
	Grasslands	grazing, fertilizaltion, fire	-	5
	Organic soils	restoration	340	10
	Degraded lands	restoration	50	14
	Manure / biosolids	soil application	-	10
	Bioenergy	soils only	-	15
	Livestock	feeding	-	60
	Livestock	additives	-	5
	Livestock	breeding	-	50
	Manure management	storage, biogas	0	200
Cool-moist	Croplands	agronomy	20	20
	Croplands	nutrient management	5	8
	Croplands	tillage and residue manag	5	9
	Croplands	water management	-	2500
	Croplands	rice management	10	1
	Croplands	set-aside and LUC	10	2
	Croplands	agro-forestry	20	38
	Grasslands	grazing, fertilizaltion, fire	-	5
	Organic soils	restoration	340	10
	Degraded lands	restoration	50	11
	Manure / biosolids	soil application	-	10
	Bioenergy	soils only	-	15
	Livestock	feeding	-	60
	Livestock	additives	-	5
	Livestock	breeding	-	50
	Manure management	storage, biogas	0	200
Warm-dry	Croplands	agronomy	20	51
	Croplands	nutrient management	5	15
	Croplands	tillage and residue manag	5	14
	Croplands	water management	-	2500
	Croplands	rice management	10	1
	Croplands	set-aside and LUC	10	3
	Croplands	agro-forestry	20	58
	Grasslands	grazing, fertilizaltion, fire	-	5
	Organic soils	restoration	340	5
	Degraded lands	restoration	50	15
	Manure / biosolids	soil application	-	10
	Bioenergy	soils only	-	15
	Livestock	feeding	-	60
	Livestock	additives	-	5
	Livestock	breeding	-	50
	Manure management	storage, biogas	0	200
Warm-moist	Croplands	agronomy	20	20
	Croplands	nutrient management	5	8
	Croplands	tillage and residue manag	5	7
	Croplands	water management	-	2500
	Croplands	rice management	10	1
	Croplands	set-aside and LUC	10	2
	Croplands	agro-forestry	20	28
	Grasslands	grazing, fertilizaltion, fire	-	5
	Organic soils	restoration	340	5
	Degraded lands	restoration	50	15
	Manure / biosolids	soil application	-	10
	Bioenergy	soils only	-	15
	Livestock	feeding	-	60
	Livestock	additives	-	5
	Livestock	breeding	-	50
	Manure management	storage, biogas	0	200

Footnotes: Nutrient management excludes precision farming, slow release fertilizers & nitrification inhibitors. Livestock additives excludes propionate precursors & halogenated compounds. Organic soil restoration includes the cost of restoration (est. 40 USD ha^{-1}) plus an opportunity cost associated with the crop that could be grown on the land of 300 USD ha^{-1} (based on costs of 120 USD t dry grain^{-1} and mean US wheat yields during the 1990s of 2.5 t dry grain ha^{-1}; FAO, 2006); cost t CO_2-eq.$^{-1}$ is not very sensitive to these costs as the per-area mitigation is large (Table 8.8).

In agriculture, there is a relationship between the amount paid for GHGs (i.e. the price of CO_2-eq.) and the level of mitigation realised. Results in McCarl and Schneider (2001), Lee *et al.* (2005) and Antle *et al.* (2001) 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 such as change in tillage practice, fertilizer application, diet formulation and manure management, while higher prices elicit land use changes that displace existing production, such as bio-fuels (and afforestation; Chapter 9), and allow the use of more costly animal feed-based mitigation options. 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 new carbon equilibrium over time) and (b) the limited market penetration potential of capital intensive strategies like bio-fuels (which are constrained by the rate of turnover in energy processing plants, prospects and costs of retrofits, and energy product growth; Lee *et al.*, 2005). A schedule of mitigation quantities at alternative CO_2-eq. prices was developed and used by Smith *et al.* (2006a), where greater quantities of offsets are generated across the sector as higher prices are paid for offsets, as originally developed in McCarl and Schneider (2001), Lee *et al.* (2005) and Antle *et al.* (2001).

The global technical mitigation potential from agriculture by 2030, considering all gases, was estimated to be ~5500-6000 Mt CO_2-eq. yr^{-1}, with cumulative economic potentials of 1900-2100, 2400-2500, and 3100-3300 Mt CO_2-eq. yr^{-1} at carbon prices of 0-20, 0-50 and 0-100 US$ t CO_2-eq.$^{-1}$ (Smith *et al.*, 2006a; see Table 8.1).

Table 8.1 *Estimates of the global agricultural GHG mitigation potential (Mt CO_2-eq. yr^{-1}) by 2030 at a range of prices of CO_2-equivalents for the four SRES scenarios*[1]

	Price range (USD t CO_2-eq. $^{-1}$)			
Scenario	**0-20**	**0-50**	**0-100**	**0->>100 (technical potential)**
B1	1925	2384	3149	5480
A1b	1982	2439	3254	5670
B2	2047	2495	3330	5844
A2	2119	2549	3330	5957

[1] As described in Smith *et al.* (2006a), the data on regional costs and potentials did not uniformly give price quantity schedules, and were based on individual strategy evaluations rather than 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 technical potentials. We assume in this analysis that the price relationships and technical potential apply globally, but further development of these relationships at national and regional scales may be needed. The Lee *et al.* (2005) results for afforestation were applied to agro-forestry (showing an increasing rate of gain as prices increase). The Lee *et al.* (2005) bio-fuel results were used in this analysis (showing an increasing rate of gain as prices increase) as were the tillage-induced soil carbon results (showing a large gain at low prices, then a plateau and a reduction as bio-fuels and afforestation become more important). All of the other categories used either the non-CO_2 or agricultural fossil fuel emission patterns, which essentially show 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).

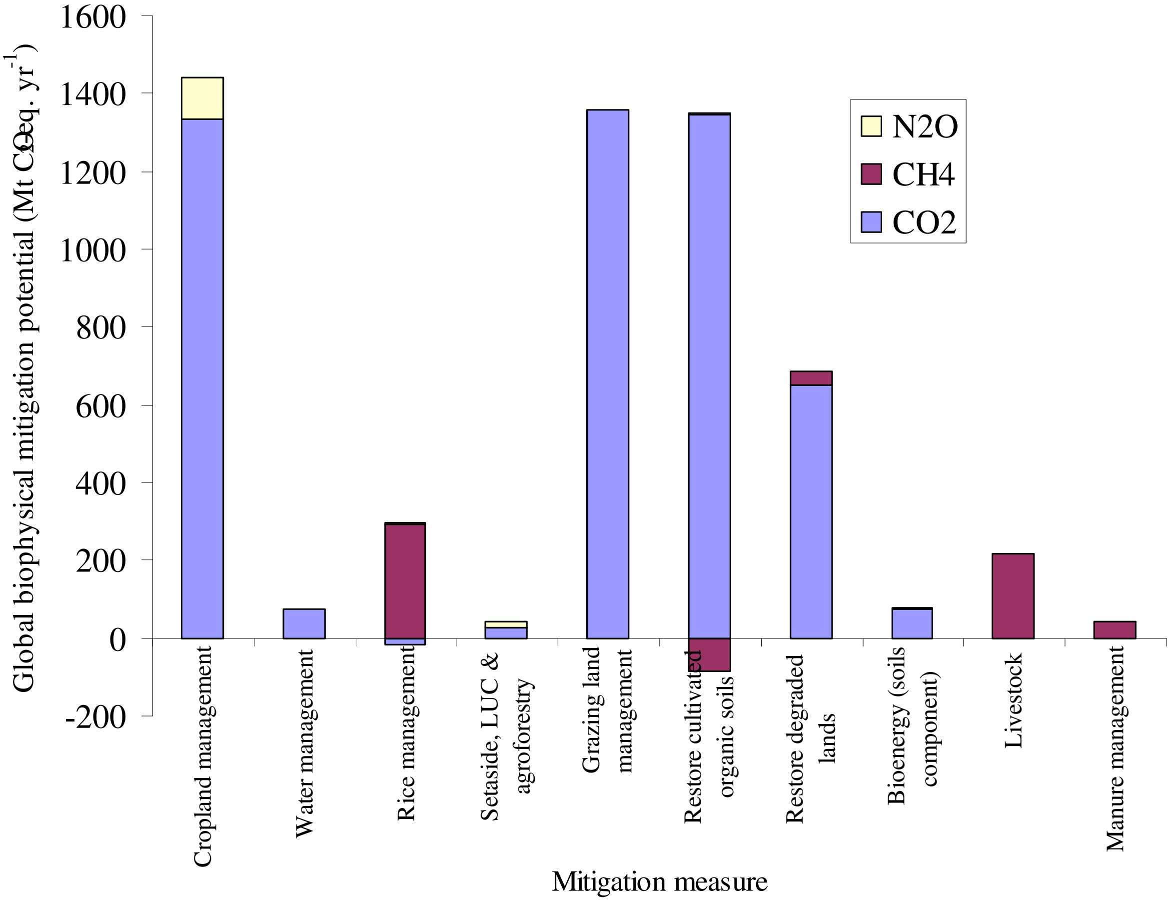

***Figure 8.3** Global technical mitigation potential (Mt CO_2-eq. yr^{-1}) by 2030 of each agricultural management practice showing the impacts of each practice on each GHG stacked to give the total for all GHGs combined (B1 scenario shown though the pattern is similar for all SRES scenarios)*

Of these total mitigation potentials, about 90% is from reduced soil emissions of CO_2, about 8% from mitigation of methane and about 2% from mitigation of soil N_2O emissions (Figure 8.3). For each region, the technical 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 2030, b) improved grazing land management for the whole grassland area in 2030, c) reduction of soil GHG emissions under bioenergy cropping, d) improved rice management of the whole rice area in 2030, e) restoration of native ecosystems on currently cultivated organic soils, f) restoration of all degraded lands, g) improved livestock management (mean of mitigation due to feeds / inocula / breeding and systems) and h) improved manure management. Figure 8.4 shows the total mitigation potential per region using the mean per-area estimates of potential for all practices and GHGs considered together.

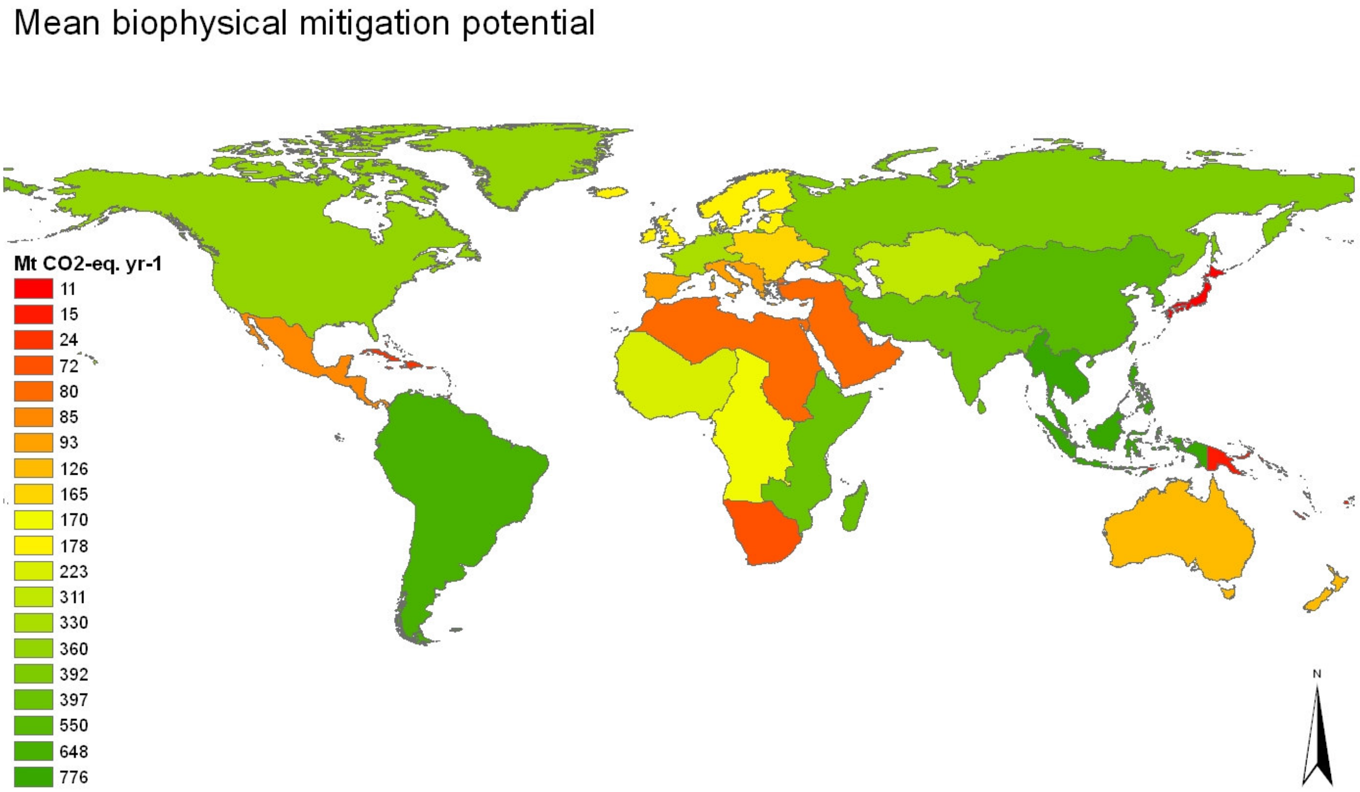

Figure 8.4 *Total technical mitigation potentials (all practices, all GHGs: Mt CO_2-eq. yr^{-1}) for each region by 2030, showing mean estimates (B1 scenario shown though the pattern is similar for all SRES scenarios)*

The low, mean and high regional estimates of the technical mitigation potential are shown in Figure 8.5. The low and high estimates about the mean (e.g. low and high estimates are ~30 and ~11400 Mt CO_2-eq. yr^{-1}, respectively about the mean estimate of 5500 Mt CO_2-eq. yr^{-1}) are largely determined by uncertainty in the per-area estimate for the mitigation measure. For soil CO_2 emission reduction, this arises from the mixed linear effects model used to derive the mitigation potentials, accounting for ~90% of the total potential. 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.

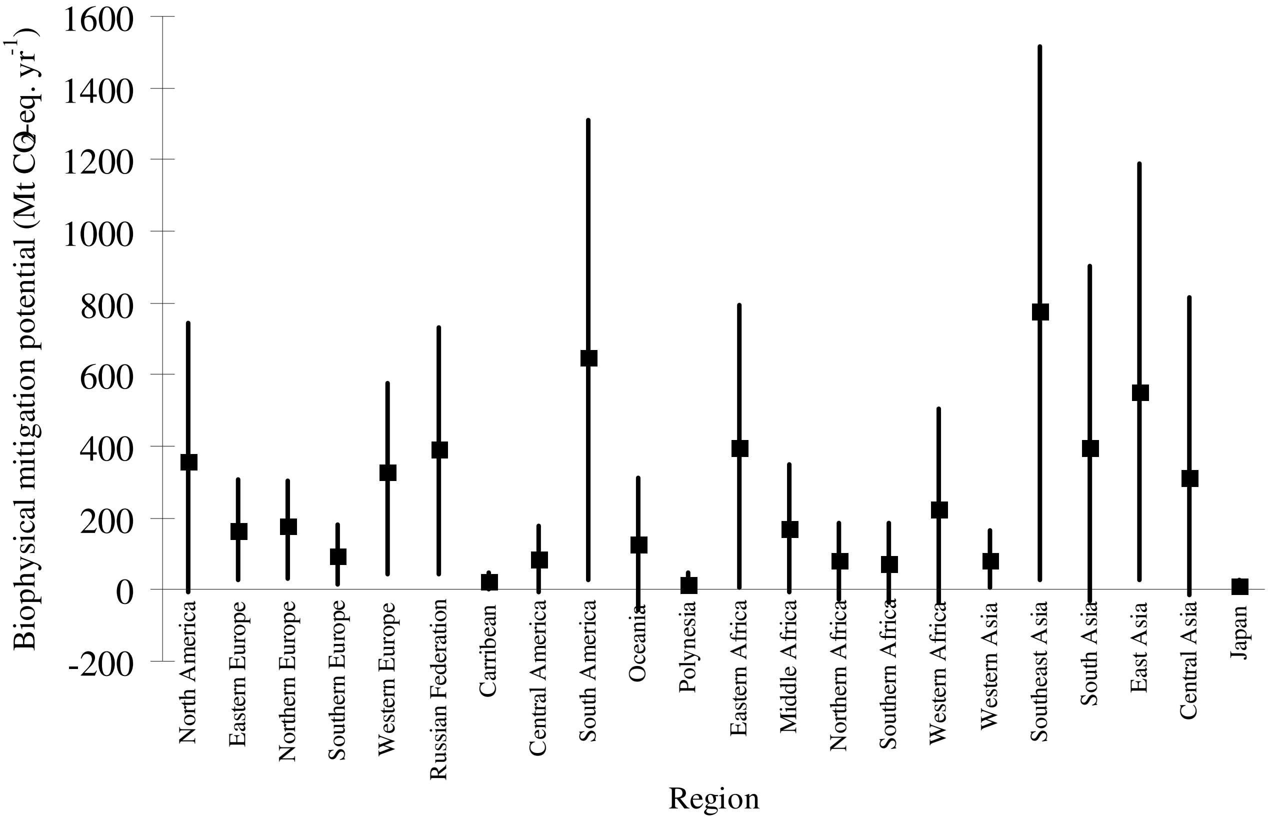

Figure 8.5 *Total technical mitigation potentials (all practices, all GHGs: Mt CO_2-eq. yr^{-1}) for each region by 2030, showing the best estimate using the mean per-area mitigation potential (square) and the range of estimates derived using the low and high per-area mitigation potentials (line; B1 scenario shown though the pattern is similar for all SRES scenarios).*

Estimates in the IPCC Second Assessment Report (SAR; IPCC, 1996) suggested that 400-800 Mt C yr^{-1} (equivalent to about 1400-2900 $MtCO_2$-eq. yr^{-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. yr^{-1}) from fossil fuels could be offset by using 10-15% of agricultural land to grow energy crops, with crop residues potentially contributing 100-200 Mt C (equivalent to about 400-700 Mt CO_2-eq. yr^{-1}) to fossil fuel offsets if recovered and burned. It was noted that burning residues for bio-energy might increase N_2O emissions but this effect 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.

In the IPCC Third Assessment Report (TAR; IPCC, 2001), estimates of agricultural mitigation potential by 2020 were 350-750 Mt C yr^{-1} (~1300-2750 Mt CO_2 yr^{-1}). It was noted that the range was mainly caused by large uncertainties about CH_4, N_2O, and soil-related emissions of CO_2 and that most reductions will cost between USD 0-100 tC-eq.$^{-1}$ (~USD 0-27 t CO_2-eq.$^{-1}$) with limited opportunities for negative net direct cost options. The analysis of agriculture in the TAR included only conservation tillage, soil C sequestration, nitrogen fertilizer management, enteric methane reduction and rice paddy irrigation and fertilisers. The estimate for global mitigation potential was not broken down by region or practice.

The estimates made by Smith *et al.* (2006a) are the only to date to be derived using a common analytical framework, for all regions, all GHGs, at a range of potential carbon costs. A comparison of previous estimates of agricultural mitigation potential with and comparable figures from Smith *et al.* (2006a) is given in Table 8.11. Given the differences in areas considered and the different assumptions made in previous studies, the similarity between the estimates of Smith *et al.* (2006a) and other studies is striking.

Table 8.11 *Comparison of the estimates of agricultural GHG mitigation potential (Mt CO_2-eq. yr^{-1}) by 2030 with previous global and regional estimates, for combinations of practices, gases considered and different marginal costs assumed.*

Study	Region	Practice / gas cons	Price of CO_2	Previous mitigation potential estimate (Mt CO_2-eq. yr^{-1})	Equivalent mitigation potential estimate from Smith *et al.* (2006a; Mt CO_2-eq. yr^{-1})	Notes
IPCC SAR (1996)	Globe – soil sequestration	CO_2 only	Technical potential	1400-2900	1700-2900	1
Lal (2003 ; 2004a)	Globe – soil sequestration	CO_2 only	Technical potential	3300 ± 1100	2800-2900	1
IPCC LULUCF (2000)	Globe – soil sequestration	CO_2 only	Technical potential	1470	1700-1900	2
Manne & Richels (2004)	Globe – soil sequestration	CO_2 only	USD 27 t CO_2-eq.$^{-1}$	1700	1700-1900	3
IPCC TAR (2001)	Globe – all measures	CO_2, CH_4 & N_2O	USD 27 t CO_2-eq.$^{-1}$	1300-2750	1900-2100	4
Caldeira *et al.* (2004)	Globe – all measures	CO_2, CH_4 & N_2O	Technical potential	4510	3100-6000	5
Lal & Bruce (1999)	Globe – croplands only	CO_2 only	Technical potential	1580-2090	1980-2140	6
Conant *et al.* (2001)	Globe – permanent pastures only	CO_2 only	Technical potential	6860	1360-1560	7
Squires *et al.* (1999)	Globe - desertification control only	CO_2 only	Technical potential	3670	~650	8
Lal (2001b)	Globe - desertification control only	CO_2 only	Technical potential	730-1470	~650	8
US-EPA (2006b)	Globe – soil N_2O only	N_2O only	USD 100 t CO_2-eq.$^{-1}$	200	130	9
US-EPA (2006b)	Globe – rice CH_4 only	CH_4 only	USD 100 t CO_2-eq.$^{-1}$	230	230	9
US-EPA (2006b)	Globe – livestock CH_4 only	CH_4 only	USD 100 t CO_2-eq.$^{-1}$	200-300	210	9
US-EPA (2006b)	US – livestock CH_4 only	CH_4 only	USD 20 t CO_2-eq.$^{-1}$	40	32	9
US-EPA (2006b)	China – livestock CH_4 only	CH_4 only	USD 50 t CO_2-eq.$^{-1}$	45	42	9
US-EPA (2006b)	India – livestock CH_4 only	CH_4 only	USD 10 t CO_2-eq.$^{-1}$	17	12	9
US-EPA (2006b)	Brazil – livestock CH_4 only	CH_4 only	USD 30 t CO_2-eq.$^{-1}$	23	46 (for all South America)	9
Smith *et al.* (2000)	Europe (excluding Russia)	CO_2 only	Limited by suitability	205	120, 160, 240	10
Lal *et al.* (2003)	US – croplands only	CO_2 only	Technical potential	165-360	140	11
Lal *et al.* (2003)	US – grasslands only	CO_2 only	Technical potential	48-257	60	11
Lal *et al.* (2003)	US – land conversion only	CO_2 only	Technical potential	77-282	-	11
Lal *et al.* (2003)	US – land restoration only	CO_2 only	Technical potential	92-220	30	11
Sperow *et al.* (2003)	US – croplands only	CO_2 only	Technical potential	220-257	140	11
Boehm *et al.* (2004)	Canada – all agriculture	CO_2 only	Technical potential	16.5-29.9	-	12
Boehm *et al.* (2004)	Canada – all agriculture	CO_2, CH_4 & N_2O	Technical potential	4 – 15.6	-	12
Lal (2004c)	China	CO_2 only	Technical potential	436-829	425	13
Lal (2004e)	Central Asia	CO_2 only	Technical potential	~60±30	-	12
Lal (2004f)	India	CO_2 only	Technical potential	~160±18	330 (for all South Asia)	14
Lal (2005)	Brazil	CO_2 only	Technical potential	400	570 (for all South America)	15

[1] Economic potentials estimated here at 0-20 USD t CO_2-eq.$^{-1}$ of ~1700-1900 Mt CO_2-eq. yr^{-1} rising to 2100-2300 and 2800-2900 Mt CO_2-eq. yr^{-1} at 0-50 and 0-100 USD t CO_2-eq.$^{-1}$, respectively.

[2] IPCC LULUCF (2000) estimate is based on C stock change in croplands, grazing lands, agro-forestry, rice paddies and urban lands. Compared to estimates here at 0-20 USD t CO_2-eq.$^{-1}$.

[3] Manne & Richels (2004) estimates for 2010 assuming a marginal cost of USD 100 $t\ C^{-1}$ (equivalent to USD 27 $t\ CO_2\text{-eq.}^{-1}$); figures from this study are from closest comparable price range of 0-20 USD $t\ CO_2\text{-eq.}^{-1}$.

[4] IPCC TAR (2001) estimates for 2020 assuming a marginal cost of USD 100 $t\ C^{-1}$ (equivalent to USD 27 $t\ CO_2\text{-eq.}^{-1}$); figures from this study are from closest comparable price range of 0-20 USD $t\ CO_2\text{-eq.}^{-1}$.

[5] Caldeira *et al.* (2004) estimates are for all gases for practices: enteric fermentation, rice cultivation, biomass burning, animal waste treatment, and agricultural soils over a 0-20 year time horizon; estimates here are between the *estimates* at 0-100 USD $t\ CO_2\text{-eq.}^{-1}$ and total technical potential (up to 6000 Mt CO_2-eq. yr^{-1}).

[6] Estimate for croplands only; comparable figure is for the technical potential of cropland management, plus restoration of degraded croplands.

[7] The Conant *et al.* (2001) estimate for permanent pasture only is much larger than many estimates for all agricultural mitigation measures combined; as such, it may be unrealistically high.

[8] Comparable estimates for this study are for restoration of degraded lands.

[9] All US-EPA (2006b) estimates are for 2020. Global estimates are for prices of 100 USD $t\ CO_2\text{-eq.}^{-1}$. US-EPA (2006b) estimate for Brazil should be equivalent to ~60% the estimate from this study for South America.

[10] Comparable figures for this study are quoted for prices of 0-20, 0-50, 0-100 USD $t\ CO_2\text{-eq.}^{-1}$, respectively. Other studies from individual European countries not included as there is no comparable area in the present study.

[11] From this study, biophyiscal potentials used for all North America (US plus Canada) from cropland management, grassland management and restoration of degraded lands.

[12] No comparable area in present study. [13] Estimate in this study for East Asia. [14] Estimate in this study for South Asia; covers a larger area than just India. [15] Lal (2005) estimates that 180 Mt CO_2 yr^{-1} could be sequestered in the soils of Brazil, plus a further 220 Mt CO_2 yr^{-1} mitigated by erosion prevention; estimate from this study from South America; covers a larger area than just Brazil.

In addition to GHG emission reduction, agricultural land can provide feed stocks for bio-energy production, as discussed is Section 8.4.4.

8.4.4 Bio-energy feed stocks from agriculture

Bio-energy to replace fossil fuels can be generated from agricultural feed stocks, including a) by-products of agricultural production, and b) dedicated energy crops.

8.4.4.1 Residues from agriculture

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

Estimates of energy production potential from agricultural residues vary between 15 and 70 EJ yr^{-1}. The latter figure is based on the regional *production* of food (in 2003) multiplied by harvesting or processing factors, and the assumed recoverability factors. These figures do not subtract the potential alternative use for agricultural residues. As indicated by (Junginger *et al.*, 2001), competing applications can reduce the net availability of agricultural residues for energy or materials significantly. In addition, the expectations about future availability of residues from agriculture vary widely among the studies. Dried dung can also be used as an energy feedstock. The total estimated contribution could be 5-55 EJ yr^{-1} worldwide, with the range defined by current global use at the low end, to technical potential at the high end. Utilisation in the longer term is uncertain because dung is considered a "poor man's fuel".

Organic wastes and residues together could supply 20-125 EJ yr^{-1} by 2050, with organic wastes potentially having an important role. The potential fossil fuel offset for 2050 from agricultural organic wastes and residues when used for energy production, assuming that it replaces gas, that its energy content is 20 GJ dry t^{-1} biomass (IPCC, 2001) and that 1 dry t biomass used to generate electricity prevents 0.28 t C from gas from being emitted to the atmosphere (Cannell, 2003), is 1000-6000 Mt CO_2-eq. yr^{-1}. If we assume linear uptake, a rough estimate of the potential by 2030 is 600-4000 Mt CO_2-eq. yr^{-1}.

8.4.4.2 Dedicated energy crops

The energy production and GHG mitigation potentials of dedicated energy crops depends on land availability, considering that food demand has to be met, combined with nature protection, sustainable management of soils and water reserves, and other sustainability criteria. Because future biomass resource availability for energy and materials depend on these and other factors, an accurate estimate is difficult to obtain. Berndes *et al.* (2003) reviewed 17 studies of future biomass availability and showed that no complete integrated assessment and scenario studies were available.

Energy cropping on current agricultural land could, with projected technological progress, could deliver over 800 EJ yr^{-1}, without jeopardising the world's food supply. Various studies have arrived at differing figures for the potential contribution of biomass to future global energy supplies ranging from below 100 EJ yr^{-1} to above 400 EJ yr^{-1} in 2050. A recent study (Sims *et al.*, 2006), using lower per-area yield assumptions and bio-energy crop areas projected by the IMAGE 2.2 model, suggests more modest potentials by 2025. The differences among studies are largely attributable to uncertainty in land availability and yield levels. The potential fossil fuel offset from dedicated energy crops by 2050, if assumed to supply 100 to 400 EJ yr^{-1} by replacing gas, and assuming 20 GJ dry t^{-1} biomass (IPCC, 2001) and that 1 dry t biomass used to generate electricity prevents 0.28 tC from gas from being emitted to the atmosphere (Cannell, 2003), is 5000-20000 Mt CO_2-eq. yr^{-1}. If we assume linear uptake, a rough estimate of the potential by 2030 is 3000-12000 Mt CO_2-eq. yr^{-1}.

Total GHG mitigation potential from agricultural bio-energy by 2030, including dedicated energy crops and agricultural wastes and residues is 4000-16000 Mt CO_2-eq. yr^{-1}. The economic analysis presented in Section 8.4.3, using figures for bio-energy uptake from Lee *et al.* (2005), suggests that 4, 14 and 100% of the technical potential would be implemented at 0-20, 0-50, 0-100 USD t CO_2-eq., respectively. Assuming that 16000 Mt CO_2-eq. yr^{-1} represents the total technical potential, economic mitigation potential of biomass energy from agriculture at 0-20, 0-50, 0-100 USD t CO_2-eq. is estimated to be 640, 2240 and 16000 Mt CO_2-eq. yr^{-1} accounting for 30, 90-100 and 500% of all other agricultural GHG mitigation measures combined, respectively. The bio-energy mitigation potential is compared to other agricultural GHG mitigation options at a range of prices of CO_2-eq. in Figure 8.6.

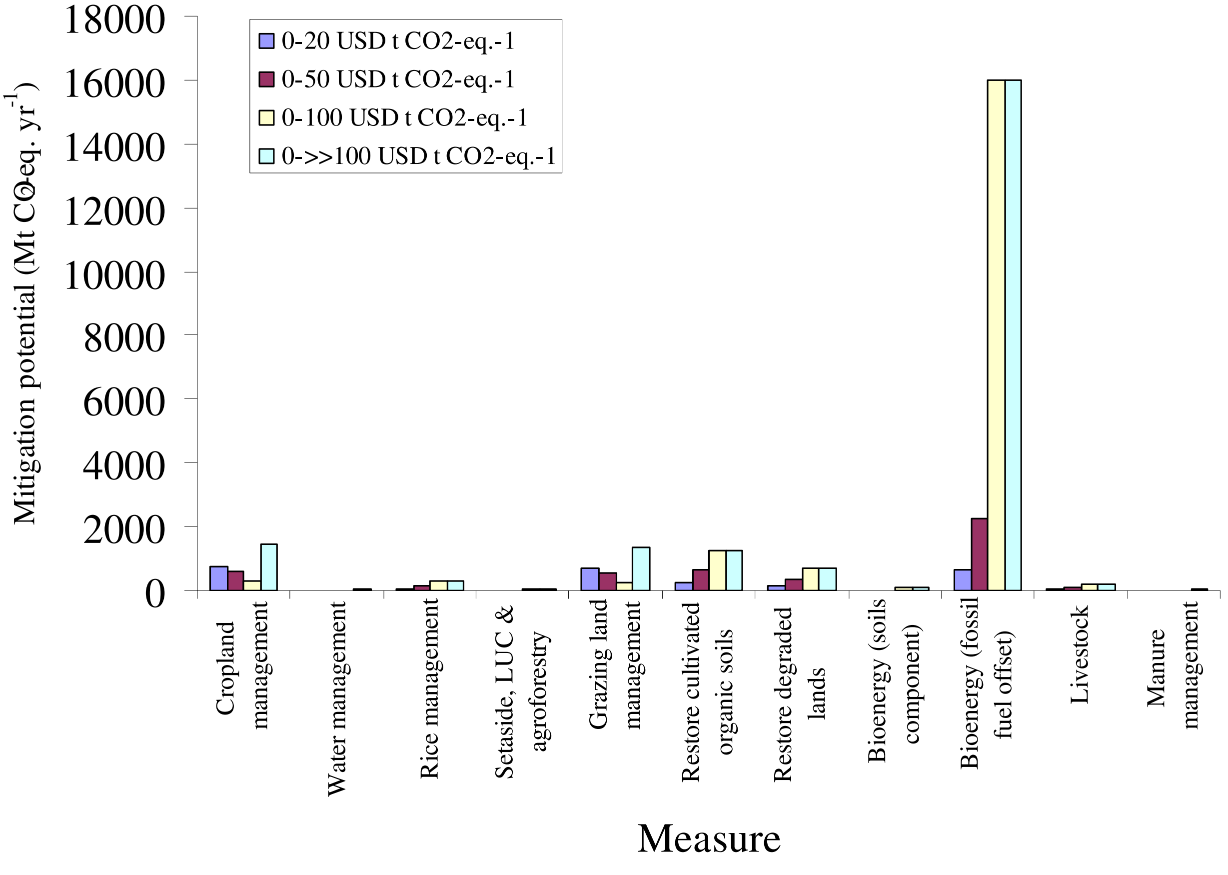

Figure 8.6 *Potential for GHG agricultural mitigation (including bio-energy) at a range of prices of CO_2-eq. (B1 scenario shown though the pattern is similar for all SRES scenarios)*

8.4.5 Potential implications of mitigation options for sustainable development

There are various potential impacts of agricultural GHG mitigation on sustainable development. Table 8.12 evaluates the impact of different mitigation activities in the agriculture sector on the constituents and determinants of sustainable development i.e. the social, economic and environmental factors. Table 8.12 suggests the direction of the likely impact, but the exact magnitude will depend upon the scale and intensity of the mitigation measures and where they are undertaken.

Table 8.12 *Potential sustainable development consequences of mitigation options*

Activity category	Sustainable development			
	Social	**Economic**	**Environmental**	**Notes**
1. land cover (use) change	Positive as it enhances the ecological services by increasing the biomass and watershed functions	Farmers will loss their income from cropland	Positive	1
2. agroforestry	Uncertain	Uncertain	Positive	
3. crop management	Uncertain	Uncertain	Positive	2
4. tillage/residue management	Uncertain	Uncertain	Positive	3
5. nutrient management	Uncertain	Overall efficient use of nutrients will yield cost reduction and productivity improvement	positive	4
6. rice management	Positive	Positive	Might result in less pollution	5
7. water management	Positive	Positive (even if the farmers are supposed to pay for water!)	Positive	6
8. manure/biosolid management	Positive	Could be adverse due to higher cost structure under new scheme of biosolid management	Positive	7
9. grazing land management / pasture improvement	Positive	Positive	Positive	8
10. management of organic soils	Uncertain	Uncertain		
11. land restoration	Positive	Likely to be positive	Positive	9
12. bioenergy	Positive	Uncertain	Positive	10
13. enhanced energy efficiency	Positive	Positive	Uncertain	
14. livestock management – improved feeding practices	Uncertain to negative as these practices may not be acceptable due to prevailing cultural practices especially in developing and underdeveloped society	Positive	Uncertain	
15. livestock management – additives, inocula, vaccine	Same as above	n/d	n/d	n/d
16. livestock management –breeding, improved systems	Same as above	n/d	n/d	n/d
17. increase C storage in agricultural products	Positive	Positive	Positive	
18. manure management	n/d	n/d	n/d	n/d

[1] Economic benefits might decline but other benefits will increase.
[2] Technology-based production increase fertilizer efficiency, which leads to decreased demands on arable land.
[3] Improves fertility of the land.
[4] Overall reduction in fertiliser use.
[5] Favourable.
[6] All efficiency improvements are positive for sustainability goals.
[7] Green industrial development becomes feasible and hence positive.
[8] Positive.
[9] Favourable.
[10] Positive.

Agriculture contributes 24% of global GDP (World Bank, 2003) and provides employment to 1.3 billion people (Dean, 2000). It is a critical sector of the world economy, but uses more water than any other sector. In low-income countries, agriculture uses 87% of total extracted water, while this figure is 74% in middle-income countries and 30% in high-income countries (World Bank, 2003).

There are currently 276 Mha of irrigated croplands (FAOSTAT, 2006) which is five times higher than at the beginning of the twentieth century. With cropland irrigation increasing, water management is a serious issue. Through proper institutions, and effective functioning of markets, water management can be implemented with favourable outcomes for both environmental and economic goals.

Agriculture contributes more than half of emissions of CH_4 and N_2O (Bhatia *et al.*, 2004) and rice, nutrient, water and tillage management can help to mitigate these GHGs. By careful drainage and effective institutional support, irrigation costs for farmers can also be reduced, thereby improving economic aspects of sustainable development (Rao, 1994). An appropriate mix of rice cultivation with livestock, known as integrated annual crop-animal systems and traditionally found in West Africa, India and Indonesia and Vietnam, can enhance net income, improve cultivated agro-ecosystems, and enhance human well-being (Millennium Ecosystem Assessment, 2005). Such combinations of livestock and cropping, especially for rice, can improve income generation, even in semi-arid and arid areas of the world.

Ground water quality may be enhanced and the loss of biodiversity slowed by greater use of farmyard manure and use of more targeted pesticides. The impact on social and economic aspects of this mitigation measure remains uncertain. Better nutrient management can improve environmental sustainability.

Controlling overgrazing through pasture improvement has a favourable impact on livestock productivity (greater income from the same number of livestock) and slows / halts desertification (environmental aspect). It also provides social security to the poorest people during extreme events such as drought and other crisis (especially in Sub-Saharan Africa). One effective strategy to control overgrazing is the prohibition of free grazing, as was done in China (Rao, 1994).

Land cover and tillage management could encourage favourable impacts on environmental goals. A mix of horticulture with optimal crop rotations would promote carbon sequestration and could also improve agro-ecosystem function. Societal well-being would also be enhanced through provisioning of water and enhanced productivity. Whilst the environmental benefits of tillage/ residue management are clear, other impacts are less certain. Land restoration will have positive environmental impacts, but conversion of floodplains and wetlands to agriculture could hamper ecological function (reduced water recharge, bioremediation, nutrient cycling etc.) and therefore, could have an adverse impact on sustainable development goals (Kumar, 2001).

The other mitigation measures listed in Table 8.12, are context and location specific in there influence of sustainable development constituents. Appropriate adoption of mitigation measures is likely to help achieve environmental goals, but farmers may incur additional costs, reducing their returns and their income. This trade-off would be most visible in the short term, but in the long term, synergy amongst the constituents of sustainable development would emerge through improved natural capital. Trade-offs between economic and environmental aspects of sustainable development might become less important if the environmental gains were better acknowledged, quantified and incorporated in the decision making framework.

Large scale production of modern bio-energy crops, partly for export, could generate income and employment for rural regions of world. Nevertheless, these benefits will not necessarily flow to the rural populations that need them most. The net impacts for a region as a whole, including possible changes and improvements in agricultural production methods should be considered when developing biomass and bio-energy production capacity. Although various experiences around the globe (Africa-WB, Brazil, India biofuels) show that major socio-economic benefits can be achieved, new bio-energy production schemes should ensure the involvement of the regional stakeholders, in particular the farmers. Experience with such schemes needs to be built around the globe.

8.5 Interactions of mitigation options with adaptation and vulnerability

As discussed in Chapters 3, 11 and 12, mitigation, climate change impacts and adaptation will occur simultaneously and interactions will occur. 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 (b) 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 (see sections 8.6 and 8.7) 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).

In terms of mitigation, the accumulation rates for sequestered carbon, the growth rates for bio-energy feed stocks, the size of livestock herds and rates of sequestration are variables affected by climate change (IPCC, 2007). Depending upon the climatic impact, there are likely to be shifts in, among other things, plant and tree growth, microbial decomposition of soil carbon, and livestock growth (Paustian *et al.*, 2004; IPCC, 2007). All of these factors will alter mitigation potential; some positively and some negatively. For example (a) lower growth rates in bio-energy feed stocks will lead to larger emissions from hauling and increased cost; (b) lower livestock growth rates would possibly increase herd size and consequent emissions from manure and enteric fermentation; and (c) increased microbial decomposition under higher temperatures will lower soil carbon sequestration potential. Interactions also occur with adaptation. Butt *et al.* (2006) and Reilly *et al.* (2001) found that crop mix, land use and irrigation are all potential adaptations to warmer climates. All would alter mitigation potential. Table 8.13 summarises some of the key vulnerabilities of agricultural mitigation strategies to climate change, and the implications of adaptation on GHG emissions from agriculture.

***Table 8.13** Summary of some of the key vulnerabilities of agricultural mitigation strategies to climate change and the implications of adaptation on GHG emissions from agriculture*

Mitigation strategies / technologies in agriculture	**Vulnerability of the mitigation option to climate change [or impact of climate change on mitigation potential]**	**Implication for GHG emissions due to adaptation, both positive and negative (if emissions increase, strategies for minimizing emissions)**
Cropland management – agronomy	Vulnerable to decreased rainfall, and in cases near the limit of their climate niche, to higher temperatures	Can increase NO_2 emissions if fertilizer use increases or if more legumes are planted in response to climate induced production declines
Cropland management – nutrient management	Only weakly sensitive to climate change, except in cases where the entire cropping enterprise becomes unviable	No significant adaptation to effects of climate change possible beyond tailoring of practices to ambient conditions. Therefore additional GHGs not expected.
Cropland management – tillage/residue management	Slightly sensitive to climate change. Warmer, wetter climates can increase risk of crop pests and diseases associated with reduced till practices.	Adaptation not anticipated to have a significant GHG effect
Cropland management – water management	Irrigation is susceptible to climate changes that reduce the availability of water for irrigation	Possible increase in energy-related GHG emissions if greater pumping distances required
Cropland management – rice management	Vulnerable to climate-change-induced changes in water availability. Low CH_4 emitting cultivars may be susceptible to changes in temperature beyond their tolerance limits	Adaptation strategies are limited and not expected to have large GHG consequences
Cropland management – set-aside and land-use change	Set-asides may become needed to offset loss of productivity on other lands	Adaptation is either to try to keep production high on non-set-aside land, which could increase GHG emissions, or to apply low GHG emitting practices on the former set-asides now returned to production. Increases in GHGs are in both cases fairly small, and less than the case of not having set-asides in the first place.
Cropland management –agro-forestry	Large changes in climate could make certain forms of agro-forestry unviable in particular situations	Adaptation to less favourable climates could lead to some loss of CO_2 uptake potential
Grazing land management / pasture improvement	Fire management can be impacted negatively or positively by climate change depending on ecosystem and sign of climate change. Extreme drying or warming could make marginal grazing lands unviable. Wetter conditions will promote conversion of grazing lands to crops	Increased fire protection activities can increase GHGs emissions by a small amount, thus reducing the net benefit
Management of agricultural organic soils	The mitigation measure is sensitive to large increases in temperature or decreases in moisture	Some tradeoffs with CH_4 emissions can be expected if the soils become wetter as a result of the adaptation management
Restoration of degraded lands	The sustainability of restored lands could be vulnerable to increased temperature and/or decreased precipitation.	Efforts to replant or increase establishment success could lead to small additional GHG emissions
Livestock - improved feeding practices	Not especially vulnerable to climate change except if it leads to increased cost (or decreased availability) of feed inputs	Transport of feed supplements from distant locations could lead to increased net GHG emissions
Livestock - specific agents and dietary additives	Not known to be vulnerable to climate change	
Live stock - longer term structural and management changes and animal breeding	Weakly sensitive to climate change	No general adaptation strategies. Specific strategies may have minor impacts on GHG emissions.
Manure / biosolid management	Controlled waste digestion generally positively affected by moderately rising temperatures. Where GHGs are not trapped, higher temperatures could hamper management	If used as a nutrient source on pasture can increase CO_2 uptake and carbon storage
Bio-energy – energy crops, solid, liquid, biogas, residues	Particular bio-energy crops potentially sensitive to climate change, either positively or negatively. Large areas devoted to bio-energy could decrease adaptation options in food agriculture and biodiversity	Generally results in net CO_2 uptake on land (apart from the fossil-fuel substitution). If fertilizers are used in the cultivation of bio-energy crops, emissions of N_2O could increase. Possible positive and negative impacts on net GHG emissions at various stage of the energy chain (cultivation, harvesting, transport, conversion) must be managed

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 and cost considerations (Smith 2004b).

Globally and for Europe, Cannell (2003) suggested that the realistically achievable potential for carbon sequestration and bio-energy-derived fossil fuel offsets were ~20% of the technical potential. Similar figures were derived by Freibauer *et al.* (2004) and the European Climate Change Programme (2001) for agricultural carbon sequestration in Europe. Smith *et al.* (2005a) 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 technical potential (e.g. Smith *et al.*, 2000; Freibauer *et al.*, 2004; Smith, 2004a). The estimates of global economic mitigation potential at different costs reported in Smith *et al.* (2006a) were 35, 43 and 56% of technical potential at 0-20, 0-50 and 0-100 USD t CO_2-eq.$^{-1}$.

In Europe, there is little evidence that climate policy is affecting GHG emissions from agriculture (see Smith *et al.*, 2005a), with most emission reduction occurring through non-climate policy (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.*, 2005a). In Europe, the European Climate Change Programme (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 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, reduced tillage, grass plantings and afforestation of agricultural land. In the US, some states are imposing, or are considering imposing, policies. 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 is also a long term diminishing trend in per-capita emissions, largely caused by energy conservation, and the programme does not deviate much from a continuation of that trend. In Canada, agriculture 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 a domestic offset trading system designed to encourage soil C sequestration and emission reductions.

In Oceania, 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 noncommercial forestry and agro-forestry are resulting in significant afforestation of agricultural land in both Australia and New Zealand. Research is being supported to encourage safe, cost-effective GHG 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 in mainstream policy. 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 is the 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).

In Asia, China has policies that reduce GHG emissions, but these were implemented for reasons other than climate policy. These are discussed further in Section 8.7. India currently has no policies that reduce GHG emissions.

No African country has emission reduction targets under the Kyoto Protocol, so the impacts of climate policy on agricultural emissions in Africa are small. There are no 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 agro-forestry, and reduction in sugarcane burning.

Agricultural GHG offsets can be encouraged by market-based trading schemes. Offset trading, or trading of credits, allows farmers to obtain credits for reducing their GHG emission reductions. The primary agricultural project types include CH_4 capture and destruction, and soil C sequestration. Although not currently included in current projects, measures to reduce N_2O emissions could be included in the future. The vast majority of agricultural projects have been focused on reducing CH_4 from livestock wastes in North America (Canada, Mexico and the United States), South America (Brazil), China, and Eastern Europe. Of those projects that do exist, the majority have resulted in the production of Certified Emission Reductions (CERs) from Kyoto's Clean Design Mechanism (CDM) and other types of certificate. CERs are then bought and sold through the use of offset aggregators, brokers and traders. Although the CDM does not currently support soil C sequestration projects, emerging markets in Canada and the United States are considering supporting offset trading from this project type. Credits created from CH_4 capture in the US will provide an active role in the developing Regional Greenhouse Gas Initiative (RGGI) on the East Coast and will certainly be included should any national market-based trading scheme be implemented. For soil carbon offsets, Canada's Pilot Emission Removals, Reductions and Learning's (PERRL) initiatives programme, under the direction of the Saskatchewan Soil Conservation Association (SSCA) encourages farmers to adopt no-till practices in return for carbon offset credits. In addition Chicago Climate Exchange (CCX) (http://www.chicagoclimatex.com/) allows GHG offsets from no-tillage and conversion of cropland to grasslands to by traded by a voluntary market trading mechanism. These approaches to agriculturally derived GHG offset will likely expand geographically and in scope.

8.6.2 Barriers and opportunities/implementation issues

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

Permanence: In agro-ecosystems, there both removals and emissions occur during a given time period, but mitigation focuses on decreasing net emissions or maximising net removals. Carbon sequestration in soils or terrestrial biomass only remove carbon from the atmosphere until the maximum capacity for the ecosystem is reached, which may take 15 to 33 years, depending on management practice and system (West and Post, 2002). A subsequent change in management can reverse the gains in C sequestration over a similar period of time. Sequestration is a rapidly and cheaply deployable interim measure until more capital-intensive developments, and longer-lasting actions become available (Sands and McCarl, 2005). Not all agricultural mitigation options are impermanent: reduction in N_2O and CH_4 emissions are non-saturating, and avoided emissions as a result of agricultural energy efficiency gains or substitution of fossil fuels by bio-energy are permanent.

Additionality: The GHG net emission reductions need to be additional to what would have happened in the absence of a market. Many of the agricultural mitigation possibilities are already well known, and some are financially viable in their own right, so an obstacle may arise in identifying how much activity is additional to ongoing activities.

Uncertainty: This has two components: mechanism uncertainty and measurement uncertainty. Uncertainty about the complex biological and ecological processes involved in trace gas emissions and carbon storage in agricultural systems makes investors more wary of these options than the more clear-cut industrial mitigation activities. This barrier can be reduced by investment in research. Secondly, agricultural systems exhibit substantial variability between seasons, and between locations. These translate to high variability in offset quantities at the farm level, which can be reduced by increasing the geographical extent and duration of the accounting unit. Thus multi-region, multi-year contracts are needed (McCarl *et al.*, 2006) to overcome this barrier.

Leakage: Adoption of certain agricultural mitigation practices may reduce production within implementing regions. In the face of sustained high demand for the products, the production can shift to regions unconstrained by GHG mitigation objectives, resulting in no net reduction of emissions. ‘Wall-to-wall’ accounting is a mechanism to detect leakage and cancel it out within an accounting region; between regions, leakage correction factors may need to be employed (Murray *et al.*, 2004).

Beyond the above widely-discussed items, 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 the market price less any costs involved in getting the commodity to the market, here termed a brokerage cost. This may be substantial, and is an increasing fraction of the market price as the amount of carbon involved decreases, creating a serious entry barrier for small-holders. For example, a 50 kt contract needs 25 kha under soil carbon management (uptake roughly 2 t CO_2 ha^{-1} yr^{-1}). In developing countries in particular, this could involve many thousands of farmers. The process of passing the money and obligations back and forth involves substantial transaction costs, which increases with the number of participants. The brokerage 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.* (2005a) have projected that, despite significant potential, soil C sequestration in Europe by 2010 will be negligible due to, among other factors, high transaction costs.

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), but other studies disagree (Smith, 2004c). In general, measurement costs per C-credit sold decrease as the quantity of C sequestered and area sampled increase in size. Methodological advances in measuring percentage soil C at the field and regional scales may reduce costs and increase the sensitivity of change detection (Izaurralde and Rice, 2006), but calculations of the C stock change also require measurement of changes in soil bulk density, for which cheap or remote methods are not yet readily available, but some are in development (Izaurralde and Rice, 2006, Gehl and Rice, 2007).

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

Other constraints: Other possible constraints or barriers to implementation include the availability of capital, the rate of capital stock turnover, the rate of penetration of bio-energy stocks into the marketplace, risk attitudes, need for new knowledge, availability of extension-service-supported technology dissemination, consistency with traditional practices, pressure for competing uses of agricultural land and water, demand for agricultural products, high costs for certain enabling technologies (e.g. soil tests before fertilization 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 GHGs

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

8.7.1 Other UN conventions

In Asia, China has introduced laws to convert croplands to forest and grassland in Vulnerable Ecological Zones under the UN Convention on Desertification. This will increase carbon storage and reduce N_2O emissions. Under the UN Convention on Biodiversity, China has initiated a programme that restores croplands close to lakes, the sea or other natural lands to conservation zones for wildlife. This may increase soil C sequestration but if restored to wetland, could increase CH_4 emissions. In support of UN Sustainable Development guidelines, China has introduced a Land Reclamation Regulation (1988) in which land degraded by, for example, construction or mining is restored for use in agriculture and will increase carbon storage in these degraded soils. In Europe (including the former Soviet Union) and North America, none of the UN conventions have had significant impacts on agricultural GHG emissions.

8.7.2 Macroeconomic policy

Some macro-economic changes, for example, the burden of a high external debt in Latin America, triggered the adoption in the 1970's of policies designed for improving the trade balance, mainly through a promotion of exports of agricultural commodities (Tejo, 2004). This resulted in the changes in land use and management (as described in Section 8.3.3 above), which are still causing increases in annual GHG emissions today. In other regions, for example in the former Soviet Union and many East European countries, political changes occurring since 1990 have meant that agriculture has de-intensified with less inputs of organic and mineral fertilizer, and more land abandonment. This has led to a decrease in agricultural GHG emissions. In Africa, the cultivated area in southern Africa has increased by 30% since 1960, while agricultural production has doubled (Scholes and Biggs, 2004). The macroeconomic development framework for Africa (NEPAD 2005) emphasises agriculture-led development. It is therefore anticipated that the cropped area will continue to increase, especially in Central, East and Southern Africa, perhaps at an accelerating rate. In Western Europe, North America, Asia (China) and Oceania, macroeconomic policy has tended to reduce GHG emissions, though enlargement of the EU may intensify agriculture in the new member states and may increase GHG emissions. On the other hand, the Luxembourg Agreement on CAP reform in 2003 is predicted to lead to reductions in animal numbers in the EU (Binfield *et al.*, 2006) which will result in reduced enteric methane emissions. Table 8.14 provides a non-exhaustive summary of various macro-economic policies that potentially affect agricultural GHG emissions in each major world region.

Table 8.14 *A non-exhaustive summary of various macro-economic policies that potentially affect agricultural GHG emissions. Examples of policies are listed for each major world region and the potential impact on the emissions of each GHG is indicated. '+' denotes a positive effect (benefit); '-' denotes a negative effect*

Region	Macro-economic policies potentially affecting agricultural GHG emissions	Impact on CO_2 emissions	Impact on N_2O emissions	Impact on CH_4 emissions
North America	• Energy conservation and energy security policies - promote bioenergy – increase fossil fuel offsets and possibly SOC (US) • Energy price adjustments - encourage agricultural mitigation - more reduced tillage – increase SOC (US) • Removal of the Grain Transportation Subsidy (Crow Rate in Prairie Canada – shifted production from annual to perennial crops and livestock (Canada)	+ + +	? +	
Latin America	• Policies since the 1970s to promote exports of agricultural products (Tejo, 2004) - land management change – still increasing annual GHG emissions (all Latin America) • Promotion of biofuels (e.g. PROALCOOL in Brazil) – peak in mid 1980s but incentives progressively removed after 1990, ethanol consumption dropped (Brazil) • Brazil and Argentina have implemented policies to make compulsory the blend of up to 5% biodiesel in all diesel fuels consumed in these countries (Brazil & Argentina)	- + +	-	-
Europe & FSU	• Common Agricultural Policy (CAP) reform - single farms payment move subsidies away from production targets - encourages farm woodland and biodiversity areas (EU) • Political changes in eastern Europe (e.g. reunification of Germany) - closure of many intensive pig units - reduced GHG emissions (EU and wider Europe) • Enlargement of the EU may encourage more intensive agriculture in the new member states - potentially increasing GHG emissions (EU) • Macro-economic changes in the FSU: a) mass abandonment or croplands since 1990 (1.5 Mha) with the resulting grasslands and regenerating forests sequestering C in soils and woody biomass (FSU) b) Use of agricultural machinery declined and fossil fuel use per ha of cropland (Romanenkov *et al.*, 2004) - decreased CO_2 (fossil fuel) increased CO_2 (straw burning - FSU) c) Fertilizer consumption has dropped; 1999 N_2O emissions from agriculture were 19.5% of 1990 level but less organic fertilisation (Russia & Belarus). d) CO_2 emissions from liming in Russia have dropped to 8% of 1990 levels (Russia) e) Livestock CH_4 emissions in 1999 were less than 48% of the 1990 level (Russia) f) The use of bare fallowing has declined (88% of the area in bare fallow in 1999 compared to 1990; Agriculture of Russia, 2004) (Russia) g) Changes in rotational structure (more prennial grasses) (Russia)	+ + - + + + + +	+ + - + +	+ - +
Africa	• The cultivated area in southern Africa has increased 30% since 1960, while agricultural production has doubled - agriculture-led development (Scholes and Biggs 2004; NEPAD 2005).Cropped area will continue to increase, especially in Central, East and Southern Africa, perhaps at an accelerating rate	-	-	-
Asia	• In some areas, croplands are currently in set aside for economic reasons (China)	+	+	
Oceania	• Australia and New Zealand continue to provide little direct subsidy to agriculture - highly efficient industries that minimise unnecessary inputs and reduce waste - potential for high losses (such as N2O) is reduced. Continuing tightening of terms of trade for farm enterprises, as		+	

	well as ongoing relaxation of requirements for agricultural imports, is likely to maintain this focus (Australia & NZ). • The 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 (Australia).		+	+

8.7.3 *Other environmental policies*

In most world regions, environmental policies have been put in place to improve fertility, reduce erosion and soil loss, improve agricultural efficiency and reduce losses from agriculture. The majority of these environmental policies also reduce GHG emissions (Table 8.15). Table 8.15 provides a non-exhaustive summary of various environmental policies that were not implemented specifically to address GHG emissions but that potentially affect agricultural GHG emissions in each major world region.

Table 8.15 *A non-exhaustive summary of various environmental policies that were not implemented specifically to address GHG emissions but that potentially affect agricultural GHG emissions. Examples of policies are listed for major world region and the potential impact on the emissions of each GHG is indicated. '+' denotes a positive effect (benefit); '-' denotes a negative effect*

Region	Other environmental policies potentially affecting agricultural GHG emissions	Impact on CO_2 emissions	Impact on N_2O emissions	Impact on CH_4 emissions
North America	• Environmental Quality Incentives Program (EQIP) – cost-sharing and incentive payments for conservation practices on working farms (USA) • The Natural Resources Conservation Service (NRCS) – rewards and recognizes actions that provide GHG benefits – improved N use efficiency rewarded (USA) • The Conservation Reserve Program (CRP) - environmentally sensitive land converted to native grasses, wildlife plantings, trees, filter strips, riparian zones (USA) • The Conservation Security Program (CSP) – (voluntary) assistance promoting conservation on cropland, pasture, and range land (and farm woodland) (USA) • USDA renewable energy initiatives in 26 States (USA) • USDA 1605b Voluntary Greenhouse Gas Registry – new accounting rules and guidelines for forest and agriculture GHG emissions and C sequestration (USA) • Greencover in Canada and provincial initiatives – encourages shift from annual to perennial crop production on poor quality soils (Canada) • Agriculture Policy Framework (APF) in Canada includes programs to reduce agriculture risks to the environment, including GHG emissions (Canada) • Nutrient Management programs – introduced to improve water quality, may indirectly reduce N2O emissions (Canada)	+ + + + + + + + +	+ + + + + + + +	 + +
Latin America	• Increasing adoption of environmental policies driven by globalization, consolidation of democratic regimes (all Latin America & Caribbean) • 14 countries have introduced environmental regulations over the last 2 decades – virtually all countries have implemented measures to protect the environment • Promotion of no-till agriculture in the Mercosur area (Brazil, Argentina, Uruguay and Paraguay)	 + +	 ? ?	

	• Ministry of Agriculture, Livestock and Food Supply in Brazil's "Program Crop-Livestock Integration" to promote soil organic matter, reduce erosion process, minimize pathogens, improve soil chemical fertility for pastures, and promote the use of no tillage cropping			

Table 8.15 (Continued)

Europe & FSU	• The EU set aside program - encouraged C sequestering practices, but now replaced by the single farm payment under the new CAP (EU) • The EU / number of member states - soil action plans to promote soil quality/health/ sustainability, all of which encourage soil C sequestering practices (EU) • The encouragement of composting in some EU member states (e.g. Belgium; Sleutel 2005), but such policies are limited (Smith et al., 2005) (EU) • The EU Water Framework Directive (WFD) promotes careful use of N fertilizer. The impact of the WFD on agricultural GHG emissions remains unclear (EU) • The ban of burning of field residues in the 1980s (for air quality purposes) mean that there is more surplus straw (Smith et al., 1997; 2000) (EU) • The ban of dumping at sea of sewage sludge in Europe in 1998 - more sewage sludge reached agricultural land (Smith et al., 2000; 2001) (EU) • The Land Codes of the Russian Federation, Belarus and the Ukraine - land conservation for promoting soil quality restoration and protection (FSU) • 'Land reform development in Russian Federation' & 'Fertility 2006-2010' - action plans to promote soil conservation / fertility / sustainability (Russia) • Ukrainian law 'Land protection' - action plans to promote soil conservation/increase commercial yields / fertility / sustainability (Ukraine) • Laws in Belarus such as 'State control of land-use and land protection' encourage C sequestering practices (Belarus) • Laws in the Ukraine to promote conversion of degraded lands to set-aside (Ukraine) • Water quality initiatives such as the Water Codes of the Russian Federation, Ukraine and Belarus encourage reforestation and grassland riparian zones (Russia) • The banning of fertilizer application in many areas may reduce N2O emissions (Russia, Belarus, Ukraine) • Numerous regional programmes, such as the Revival of the Volga	+ + + ? + + + + + + + + + +	 ? + ? + +	 +
Africa	• The reduction of the area of rangelands burned - objective of both colonial and post-colonial administrations - renewed efforts in South Africa (South Africa, 1998)	+	+	+
Asia	• Soil sustainability programmes - N fertilizer added to soils only after soil N testing (China) • Regional agricultural development programmes - enhance soil C storage (China) • Water quality programmes that control non-point source pollution (China) • Air quality legislation t - bans straw burning, thus reducing CO_2 (and CH_4 and N_2O) emissions (China) • "Township Enterprises" & "Ecological Municipality" - reduce waste disposal, chemical fertilizer and pesticides application, and bans straw burning (China)	 + + +	+ + + +	 + +
Oceania	• A wide range of policy developments to maintain ecosystem function / conservation of agricultural landscapes, river systems & other ecosystems (Australia & NZ) • Rapid increase in nitrogenous fertiliser use over the past decade (250% and 500% increases in Australia and NZ respectively) • Increases in intensive livestock production have raised concerns about water quality and the health of riverine and offshore ecosystems	+ + +	 - - + +	 -

	(Australia & NZ) • Policy responses are being developed that include monitoring, regulatory, research and extension components (Australia & NZ) • Natural Heritage Trust (and others) in Australia –re-establish native vegetation; reduce degrading processes (Australia) • The Mandatory Renewable Energy Target - potential to increase the use of energy crops and sugar cane waste, reducing use of fossil fuels (Australia)	+	+	+

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

8.8 Co-benefits and trade-offs of mitigation options

Many of the measures aimed at reducing GHG emissions have other potential benefits for the productivity and environmental integrity of agricultural ecosystems. Indeed, these measures are often adopted mainly for reasons other than GHG mitigation (see Section 8.7.3). Agro-ecosystems are inherently complex and very few practices yield purely 'win-win' outcomes; most involve some trade-offs (DeFries *et al.*, 2004). Specific examples of co-benefits and trade-offs among agricultural GHG mitigation measures include:

- Practices that maintain or increase productivity can improve global or regional food security (Lal, 2004a, b, c; Follett *et al.*, 2005.). This co-benefit may become more important as global food demands increase in coming decades (Sanchez and Swaminathan, 2005; Rosegrant and Cline, 2003; FAO, 2003; Millennium Ecosystem Assessment, 2005).
- Building reserves of soil C often also increases the potential productivity of these soils. Furthermore, many of the measures that promote C sequestration also prevent degradation by avoiding erosion and improving soil structure. Consequently, many C-conserving practices sustain or enhance the future fertility, productivity and resilience of soil resources (Lal, 2004a; Cerri *et al.*, 2004; Freibauer *et al.*, 2004; Paustian *et al.*, 2004; Kurkalova *et al.*, 2004; Díaz-Zorita *et al.*, 2002). In some instances, where productivity is increased through intensified inputs, there may be risks of soil depletion through mechanisms such as acidification or salinisation (Barak *et al.*, 1997; Díez *et al.*, 2004; Connor, 2004).
- Fresh water is a dwindling resource in many parts of the world (Rosegrant and Cline, 2003; Rockström, 2003). Practices for mitigation GHGs can have both negative and positive effects on conservation of water, and on its quality. Where the measures promote water-use efficiency (e.g., reduced tillage), they exert potential benefits. But in some case, the practices could intensify water use, thereby depleting reserves (Unkovich, 2003; Dias de Oliveira *et al.*, 2005). For example, large-scale bio-energy production could, in some regions, apply further stress to limited water supplies (Berndes, 2002). In addition, some practices may affect quality of water, through enhanced leaching of pesticides and nutrients (Freibauer *et al.*, 2004; Machado and Silva, 2001).
- Mitigation practices imposed on agricultural lands may influence other ecosystems elsewhere. For example, practices that diminish productivity in cropland (e.g. set-aside lands, bio-energy crops) may elsewhere induce conversion of forests by cultivation; conversely, increasing productivity on existing croplands may 'spare' some forest- or grasslands (West and Marland, 2003; Balmford *et al.*, 2005; Mooney *et al.*, 2005). Similarly, more intensive management of grazing land could release some grasslands for producing feed stocks for energy production. The net effect of such trade-offs on biodiversity and other ecosystem services has not yet been fully quantified (Huston and Marland, 2003; Green *et al.*, 2005).
- Agro-ecosystems have become increasingly dependent on input of reactive nitrogen, much of it added as fertilizers (Galloway *et al.*, 2003, 2004). Practices that reduce N_2O emission often improve the efficiency of N use, thereby also reducing energy use for fertilizer manufacture and avoiding deleterious effects on water and air quality from N pollutants (Oenema *et al.*, 2005;

Dalal *et al.*, 2003; Olesen *et al.*, 2006; Paustian *et al.*, 2004). In some cases, curtailing supplemental N use could restrict yields, thereby hampering food security.

- Changes to land use and agricultural management can affect biodiversity, both positively and negatively. For example, intensification of agriculture and large-scale production of biomass energy crops may, in some cases, lead to loss of biodiversity (European Environment Agency, 2006). But perennial crops often used for energy production can favour biodiversity, if they displace annual crops (Berndes and Börjesson, 2002).
- If bio-energy plantations are located, designed and managed in specific ways, they can generate additional environmental services such as reduction of nutrient leaching and soil erosion; soil carbon accumulation leading to improved soil fertility; removal of cadmium and other heavy metals from cropland soils; increased nutrient recirculation and improved treatment efficiency of nutrient-rich drainage water and pre-treated municipal wastewater and sludge; provision of habitats and contribution to enhanced biodiversity and game potential in the agricultural landscape (Berndes and Börjesson, 2002; Berndes *et al.* 2004; Börjesson and Berndes, 2006).
- Implementation of agricultural GHG mitigation measures may allow expanded use of fossil fuels, and may have some negative effects through emissions of sulphur, ozone, mercury and other pollutants (Elbakidze and McCarl, 2006).

The co-benefits and trade-offs of a practice may vary from place to place because of differences in climate, soil, or the way the practice is adopted. In producing bio-energy, for example, if the feedstock is crop residue, that may reduce soil quality by depleting soil organic matter; conversely, if the feedstock is a densely-rooted perennial crops, that may replenish organic matter and thereby improve soil quality (Paustian *et al.*, 2004).These few examples, and the general trends described in Table 8.16, demonstrate that GHG mitigation practices on farm lands exert complex, interactive effects on the environment, sometimes far from the site at which they are imposed. The merits of a given practice, therefore, cannot be judged solely on effectiveness of GHG mitigation.

Table 8.16 *Summary of possible co-benefits and trade-offs of mitigation options in agriculture. '+' denotes a positive effect (benefit); '-' denotes a negative effect (trade-off). The co-benefits and trade-offs may vary among regions. Economic costs and benefits, which are often key driving variables, are considered elsewhere (see Section 8.4.3)*

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

[a] Foley *et al.*, 2005; Lal, 2001a, 2004a;

[b] Mosier, 2002; Freibauer *et al.*, 2004; Paustian *et al.*, 2004 ; Cerri *et al.*, 2004

[c] Lal, 2004b; dias de Oliveira *et al.*, 2005; Rockström, 2003.

[d] Lal, 2001b, Janzen, 2005; Cassman *et al.*, 2003; Cerri *et al.*, 2004; Wander and Nissen, 2003

[e] Mosier, 2001; 2002; Paustian *et al.*, 2004

[f] Foley *et al.*, 2005; Dias de Oliveira *et al.*, 2005; Freibauer *et al.*, 2004; Falloon *et al.*, 2004; Huston and Marland, 2003 ; Totten *et al.*, 2003

[g] Lal *et al.*, 2003 ; West and Marland, 2003

[h] Balmford *et al.*, 2005; Trewavas, 2001; Green *et al.*, 2005; West and Marland, 2003

[i] Freibauer *et al.*, 2004.

8.9 Technology research, development, deployment, diffusion and transfer

There is much scope for technological developments to reduce GHG emissions in the agricultural sector. For example, increases in crop yields and animal production will reduce emissions per unit of production. Such increases in crop and animal production will be implemented through improved management and husbandry techniques. Better management, genetically modified crops, improved cultivars, fertilizer recommendation systems, precision agriculture, improved animal breeds, improved animal nutrition, dietary additives and growth promoters, improved animal fertility, bio-energy crops, anaerobic slurry digestion and methane capture systems, etc., all are, to some extent, dependent upon technological developments. 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.* (2005b) showed that technological improvements could potentially counteract the negative impacts of climate change on cropland and grassland soil carbon stocks in Europe. This, and other work (Rounsevell *et al.*, 2006), suggests that technological improvement will be a key factor in GHG mitigation in the future.

In most instances, the cost of employing mitigation strategies will not alter radically in the medium term. There will be some shifts in costs due to changes in prices of agricultural products and inputs 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 improved nutrient utilization and (ii) options where new technology is being developed, such as probiotics or yeasts for use in animal diets, or nitrification inhibitors.

Many of the mitigation strategies outlined for the agriculture sector employ 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 further research to allow viable systems to operate (e.g. bio-energy crops). 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 research and development in this area.

Differences between regions can arise due to the state of development of the agricultural industry, the resources available and legislation. For example, the scope to use specific agents and dietary additives in ruminants is much greater in developed than in the developing regions because of cost, opportunity (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. (US-EPA, 2006a). Futhermore, certain 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.

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 the longer term. 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.

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). Because of these increases and changing consumption patterns, some analyses estimate that the production of cereals will need to roughly double in coming decades (Tilman *et al.* 2001; Roy *et al.* 2002; Green *et al.* 2005). Achieving these increases in food production may require more use of N fertilizer, leading to possible increases in N_2O emissions, unless more efficient fertilization techniques can be found (Galloway 2003; 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. 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 (Strengers *et al.*, 2004), depending on globalisation or regionalisation and on the emphasis placed on material wealth relative to sustainability and equity.

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 a number of 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 innovative technologies for efficient use of land resources and agricultural chemicals, to eliminate poverty and malnutrition, will significantly mitigate GHG emissions from the agricultural sector.

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.

Recycling agricultural by-products, such as crop residues and animal manures, and production of energy crops will directly mitigate GHG emissions from fossil fuel offsets. 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.

The long term outlook for mitigation from livestock is good. Continuous improvements in animal breeds are likely, and these will improve the GHG emissions per kg of animal product. Enhanced production efficiency due to structural change or better application of existing technologies is 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 GHG 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 GHG emissions, but also for other facets of environmental protection such as air and water quality management. However, there are large uncertainties due to sparse data and incomplete knowledge. Options for mitigating GHG emissions from agriculture can be recommended, but socio-economic aspects also need to be fully evaluated.

Climate and global change are expected to influence agriculture 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 reducing 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.*, 2005b). The net effects of climate and global change on GHG emissions from agricultural sector remain uncertain and the topic of further research.

Possible changes to climate and atmosphere in coming decades may influence GHG emissions from agriculture, and the effectiveness of practices adopted to minimize them. For example, atmospheric CO_2 concentrations, likely to double within the next century may affect agro-ecosystems through changes in plant growth rates, plant litter composition, drought tolerance, and nitrogen demands (e.g. Henry *et al.*, 2005; Van Groenigen *et al.*, 2005; Jensen & Christensen, 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 GHG emissions. Many of these changes have high levels of uncertainty; but these few examples demonstrate that practices chosen to reduce GHG emissions now may not have the same effectiveness under conditions that may exist in coming decades.

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