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Review

Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture

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Abstract

A recent assessment of agricultural greenhouse gas (GHG) emissions has demonstrated significant potential for mitigation, but suggests that the full mitigation will not be realized due to significant barriers to implementation. In this paper, we explore the constraints and barriers to implementation important for GHG mitigation in agriculture. We also examine how climate and non-climate policy in different regions of the world has affected agricultural GHG emissions in the recent past, and how it may affect emissions and mitigation implementation in the future. We examine the links between mitigation and adaptation and drives for sustainable development and the potential for agricultural GHG mitigation in the future.

We describe how some countries have initiated climate and non-climate policies believed to have direct effects or synergistic effects on mitigating GHG emissions from agriculture. 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 agriculture.

Previous studies have shown that as less than 30% of the total biophysical potential for agricultural GHG mitigation might be achieved by 2030, due to price- and non-price-related barriers to implementation. The challenge for successful agricultural GHG mitigation will be to remove these barriers by implementing creative policies. Identifying policies that provide benefits for climate, as well as for aspects of

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economic, social and environmental sustainability, will be critical for ensuring that effective GHG mitigation options are widely implemented in the future.

Keywords: Greenhouse gas; Agriculture; Mitigation; Cropland management; Grazing land; Rice; Livestock; Carbon sequestration; Policy

Contents

1. Introduction

Smith et al. (in press) recently examined the potential of a range of agricultural greenhouse gas (GHG) mitigation measures including land cover (use) change, agro-forestry, crop management, tillage/residue management, nutrient management, rice management, water management, manure/biosolid management, grazing land management/pasture improvement, management of organic soils, land restoration, bio-energy crops, enhanced energy efficiency, livestock management (improved feeding practices, specific agents and dietary additives, longer term structural and management changes, and breeding), increased C storage in products, and reduced biomass burning.

Smith et al. (in press) showed that there is significant potential for greenhouse gas (GHG) mitigation in agriculture, with a technical potential of ~5500–6000 Mt CO_2-eq. year^{-1} for all gases. The potential estimated to be achievable at different prices is much lower at 1900–2100, 2400–2500, and 3100–3300 Mt CO_2-eq. year^{-1} at carbon prices of 0–20, 0–50 and 0–100 US$ t CO_2-eq.$^{-1}$. Other studies have also suggested that the realistically achievable potential is much lower than biophysical potential, due to non-price-determined limitations to implementation including institutional, educational, social and political constraints (Cannell, 2003; European Climate Change Programme, 2003; Freibauer et al., 2004; Smith, 2004a). In addition, agriculturally derived biomass for use as a bio-energy feedstock might deliver net GHG benefits of 640 Mt CO_2-eq. year^{-1} at 0–20 USD t CO_2-eq.$^{-1}$, 2240 Mt CO_2-eq. year^{-1} at 0–50 USD t CO_2-eq.$^{-1}$, and 16,000 Mt CO_2-eq. year^{-1} at 0–100 USD t CO_2-eq.$^{-1}$ (Smith et al., in press).

According to an analysis by Smith et al. (in press), exceptionally high prices for CO_2-equivalents (e.g. 5000 US$ t CO_2-eq.$^{-1}$) would allow the full implementation of agricultural mitigation measures, whilst lower prices of 0–20, 0–50 and 0–100 US$ t CO_2-eq.$^{-1}$ would deliver 35%, 43% and 56%, respectively, of total mitigation potential by 2030.

In this paper, we explore the important constraints and barriers to implementation of GHG mitigation in agriculture and examine how climate and non-climate policy in different regions of the world has influenced agricultural GHG emissions in the recent past, and how it may affect emissions and mitigation implementation in the future. We examine links between mitigation and adaptation and drivers of sustainable development.

2. Barriers to implementing agricultural GHG mitigation options

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

- *Permanence*. 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 15–33 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 bioenergy 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., in press) 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 smallholders. For example, a 50 kt contract needs 25 kha under soil carbon management (uptake roughly 2 t CO_2 ha^{-1} $year^{-1}$). 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, in press).
- *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 bioenergy 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).

3. Potential co-benefits and adverse impacts of agricultural GHG 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. Agro-ecosystems are inherently complex, however, 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; Diaz-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; 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). As well, 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, 2005). 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 items (Elbakidze and McCarl, in press).

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 1 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.

4. Trends in agriculture affecting GHG emissions

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. 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

Table 1
Summary of possible co-benefits and trade-offs of mitigation options in agriculture

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

‘+’, a positive effect (benefit); ‘−’, a negative effect (trade-off). The co-benefits and trade-offs may vary among regions. Economic costs and benefits are also often key driving variables.

[a] Foley et al. (2005) and Lal (2001, 2004a).

[b] Mosier (2002), Freibauer et al. (2004), Paustian et al. (2004) and Cerri et al. (2004).

[c] Lal (2004b), de Oliveira et al. (2005) and Rockström (2003).

[d] Lal (2001), Janzen (2005), Cassman et al. (2003), Cerri et al. (2004) and Wander and Nissen (2004).

[e] Mosier (2001, 2002) and Paustian et al. (2004).

[f] Foley et al. (2005), de Oliveira et al. (2005), Freibauer et al. (2004), Falloon et al. (2004), Huston and Marland (2003) and Totten et al. (2003).

[g] Lal et al. (2003) and West and Marland (2003).

[h] Balmford et al. (2005), Trewavas (2002), Green et al. (2005) and West and Marland (2003).

[i] Freibauer et al. (2004).

Table 2
Agricultural land use in the last four decades (source: FAOSTAT, 2006)

	Area (Mha)					Change (2000s − 1960s)	
	1961–1970	1971–1980	1981–1990	1991–2000	2001–2002	%	Mha
World							
Agricultural land	4562	4684	4832	4985	5023	+10	461
Arable land	1297	1331	1376	1393	1405	+8	107
Permanent crops	82	92	104	123	130	+59	49
Permanent pasture	3182	3261	3353	3469	3488	+10	306
Developed countries							
Agricultural land	1879	1883	1877	1866	1838	−2	−41
Arable land	648	649	652	633	613	−5	−35
Permanent crops	23	24	24	24	24	+4	1
Permanent pasture	1209	1210	1201	1209	1202	−1	−7
Developing countries							
Agricultural land	2682	2801	2955	3119	3184	+19	502
Arable land	650	682	724	760	792	+22	142
Permanent crops	59	68	80	99	106	+81	48
Permanent pasture	1973	2051	2152	2260	2286	+16	313

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 2).

The amount of cropland worldwide has increased by 8% since the 1960s, to its current level of ca. 1400 Mha (Table 2). This increase was the net result of a 5% decrease in developed countries, and a 22% increase in cropland area in developing countries. This trend will continue into the future (Huang et al., 2002; Trewavas, 2002; Fedoroff and Cohen, 1999; Green et al., 2005), and Rosegrant et al. (2001) predict that an additional 500 Mha would be converted to agriculture during the period 1997–2020, mostly in Latin America and Sub-Saharan Africa.

Technological progress has made it possible to achieve remarkable improvements in land productivity, increasing per-capita food availability (Table 3), despite a consistent decline in per-capita agricultural land (Fig. 1). The share of animal products in the diet has increased consistently in developing countries, whilst remaining constant in developed countries.

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} year^{-1} during the period 1967–1997, achieving an annual growth rate of more than 5% by the end of that period. Rosegrant et al. (2001) forecast 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

Table 3
Evolution of per-capita food supply in developed and developing countries (source: FAOSTAT, 2006)

	1961–1970	1971–1980	1981–1990	1991–2000	2001–2002	Change (2000s − 1960s)	
						%	Cal day^{-1} or g day^{-1}
Developed countries							
Energy, all sources (cal day^{-1})	3049	3181	3269	3223	3309	+9	261
% from animal sources	27	28	28	27	26	−2	–
Protein, all sources (g day^{-1})	92	97	101	99	100	+9	8
% from animal sources	50	55	57	56	56	+12	–
Developing countries							
Energy, all sources (cal day^{-1})	2032	2183	2443	2600	2657	+31	625
% from animal sources	8	8	9	12	13	+77	–
Protein, all sources (g day^{-1})	9	11	13	18	21	+123	48
% from animal sources	18	20	22	28	30	+67	–

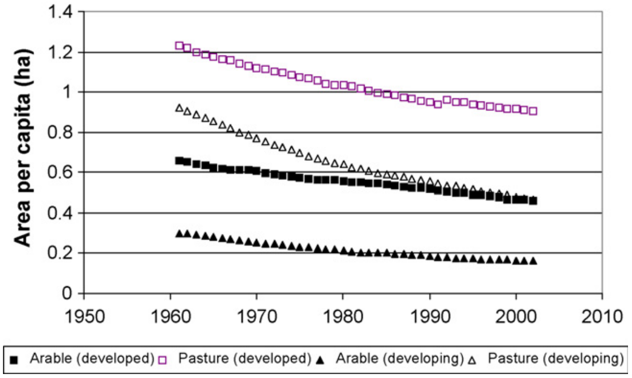

Fig. 1. Evolution of per capita area of arable land and pasture, in developed and developing countries (source: FAOSTAT, 2006).

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 saturation of 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.
- Industrial 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.

4.1. Global emission trends

With an estimated global emission of non-CO_2 GHGs of 5969 Mt CO_2-eq. year^{-1} in 2005 (US-EPA, 2006a, Table 4), agriculture is estimated to account for about 14% of total global anthropogenic emissions of GHGs (Bouwman, 2001), and 47% and 84% of total anthropogenic CH_4 and N_2O emissions, 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, mainly from land use change, especially deforestation, are estimated to account for 15% of anthropogenic CO_2 emissions (FAO, 2003), although a reliable assessment is made difficult by large spatial and temporal variability and the simultaneous occurrence of emissions and removals of this gas in different areas.

Both the magnitude of the emissions and the relative importance of the different sources vary widely among world regions (Table 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 10 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

Table 4
GHG emissions by main sources in the agriculture sector in the different world regions in 2005

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. year^{-1}	536	275	129	40	24	1005
% 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. year^{-1}	600	294	432	127	53	1505
% of region's total	40	20	29	8	4	100
% of source's world total	23	16	68	29	14	25
Latin America and The Carribbean						
Mt CO_2-eq. year^{-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. year^{-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 and North Africa						
Mt CO_2-eq. year^{-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. year^{-1}	1946	1300	617	211	363	4438
% 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. year^{-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 and Eastern Europe						
Mt CO_2-eq. year^{-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. year^{-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. year^{-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. year^{-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. year^{-1}	700	554	20	225	32	1531
% 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. year^{-1}	2646	1854	637	436	395	5969
% of region's total	44	31	11	7	7	100
% of source's world total	100	100	100	100	100	100

Adapted from US-EPA (2006a).

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 year^{-1} in 2000, all the other countries showed emissions or removals of very low magnitude.

Globally, agricultural emissions have increased by 14% from 1990 to 2005 (Table 5), with an average annual emission of 49 Mt CO_2-eq. year^{-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. year^{-1}, almost twice the rate of increase seen for CH_4 emissions (US-EPA, 2006a).

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 in detail in Section 5.

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 and, to a lesser extent, to climate policies in the European Union (see Section 5).

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 4), 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 emission 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. US-EPA (2006a) forecast that methane emissions from enteric fermentation and manure management would increase by 21% and 15%, respectively, between 2005 and 2020 (Table 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 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 5). 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. year^{-1}, would continue to grow faster than CH_4 emissions, projected to average 35 Mt CO_2-eq. year^{-1}.

4.2. Regional emission 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 5, Fig. 2).

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 1990–2020 (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 livestock 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.

Table 5
GHG emission trends by main sources in the agriculture sector in the different world regions during the period 1990–2020

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. year^{-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. year^{-1} in 1990	459	158	409	88	59	1173
% change in 2005	31	87	6	44	−10	28
% change in 2020	54	153	18	86	−10	54
Latin America and The Carribbean						
Mt CO_2-eq. year^{-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. year^{-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 and North Africa						
Mt CO_2-eq. year^{-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. year^{-1} in 1990	1441	987	560	157	389	3533
% 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. year^{-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 and Eastern Europe						
Mt CO_2-eq. year^{-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. year^{-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. year^{-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. year^{-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. year^{-1} in 1990	749	662	23	229	31	1699
% change in 2005	−7	−16	−13	−2	3	−10
% change in 2020	5	−12	−16	5	3	−2
Total						
Mt CO_2-eq. year^{-1} in 1990	2190	1649	583	389	430	5230
% change in 2005	21	12	10	12	−8	14
% change in 2020	53	36	27	31	−8	38

Adapted from US-EPA (2006a).

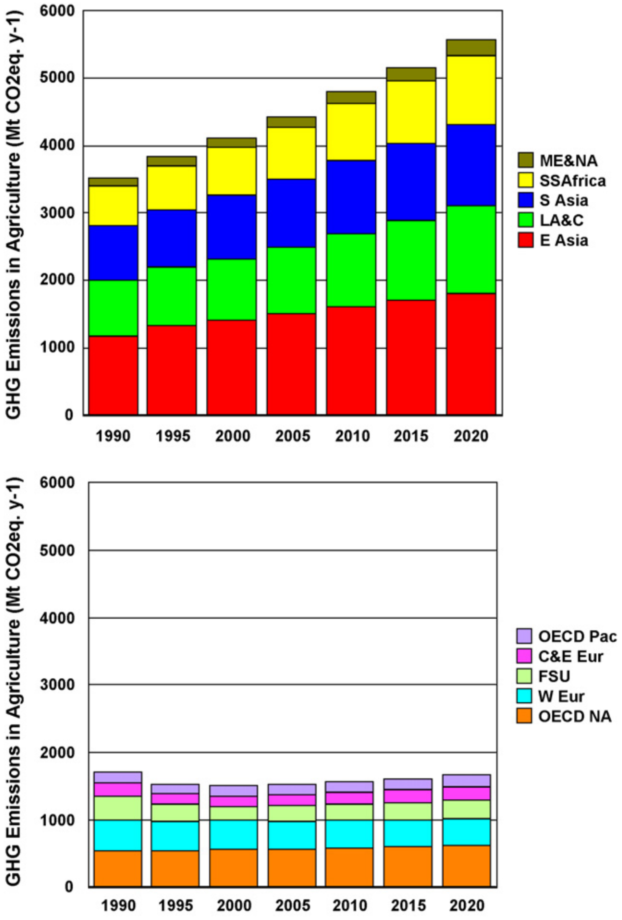

Fig. 2. Evolution of GHG emissions in agricultural sector of the 10 world regions during the period 1990–2020. ME&NA, Middle East and North Africa; SS Africa, Sub-Saharan Africa; S Asia, developing countries of South Asia; LA&C, Latin America and The Caribbeans; E Asia, developing countries of East Asia; 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).

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 30–600% since 1961. Cropland areas, including rice and soybean, and the use of N fertilisers have also shown dramatic increases. 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 1970s, 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 can safely be assumed 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. year^{-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 2–2.5-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. year^{-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 5) 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 five-fold 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 4). 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 Section 5.

5. Effectiveness of policy on agricultural GHG mitigation

5.1. 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 (Fig. 3; Smith, 2004b).

Globally and for Europe, Cannell (2003) showed that the realistically achievable potential for carbon sequestration and bio-energy-derived fossil fuel offsets were less than 20% of the technical potential. Similar figures were derived by Freibauer et al. (2004) and the European Climate Change Programme (2003) 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 biological/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. (in press) 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 5.2. 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.

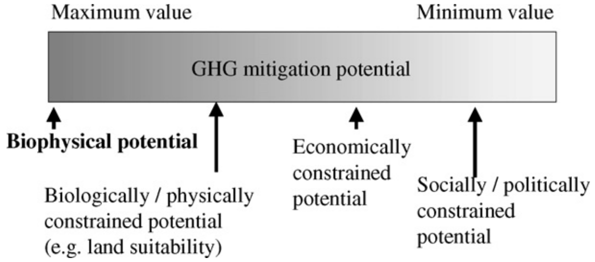

Fig. 3. Impact of different constraints on reducing the GHG mitigation potential from its theoretical biological maximum to lower, realistically achievable potentials (after Smith, 2004b).

In North America, whilst the US is not a participant in the Kyoto Protocol, it hosts multinational companies which have reduced GHG intensity as a by-product of their world-wide current Kyoto exposure, or through their activities to explore options for future climate agreements. Some of this activity has involved agricultural sector activities including pig manure management, farm tillage 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 emissions per capita, largely caused by energy conservation and the program does not deviate much from a continuation of that trend. In Canada, the agriculture sector contributes about 10% to national emissions, so mitigation (removals and emission reductions) is considered to be an important contribution to achieving Kyoto targets (and at the same time reduce risk to air, water and soil quality). Examples include: the AAFC Mitigation program which encourages voluntary adoption of GHG Mitigation practices on farms; National research programs aimed at reducing the energy intensity of crop production systems, enhancing biological sinks, and enhanced bio-energy capacity (i.e. methane capture); and the domestic offset trading system designed to encourage soil C sequestration and emission reductions.

In 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 non-commercial forestry and agro-forestry are resulting in significant afforestation of agricultural land in both Australia and New Zealand. There is a range of research being supported into 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 for mainstream policy implementation. Most countries in the region have devoted efforts to capacity building for complying with obligations under the UNFCCC, and a few of them have prepared National Strategy Studies for the CDM. Carbon sequestration in agricultural soils would be the climate change mitigation option with the highest potential in the region, and its exclusion from the CDM has hindered a wider adoption of land use management practices (e.g. zero tillage).

In Asia, China and India have policies that reduce GHG emissions, but these were implemented for reasons other than climate policy. These are discussed further in Section 5.2.

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

5.2. *Impact of non-climate policies*

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 6), 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.

5.2.1. *Non-climate related UN conventions*

In Asia, China has introduced laws to convert croplands to forest and grassland in Vulnerable Ecological Zones under the UN Convention on Desertification. This will increase carbon storage and reduce N_2O emissions. Under the UN Convention on Biodiversity, China has initiated a programme that restores croplands close to lakes, the sea or other natural lands to conservation zones for wildlife. This may increase soil C sequestration by if restored to wetland, could increase CH_4 emissions. In support of UN Sustainable Development guidelines, China has introduced a Land Reclamation Regulation in 1998 in which land degraded by construction, mining, etc. is restored for use in agriculture, increasing 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.

5.2.2. *Macroeconomic policy*

Some macro-economic changes, for example, in Latin America, the burden of a high external debt 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 5.1 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 6 provides a non-exhaustive summary of various macro-economic policies that potentially affect agricultural GHG emissions in each major world region.

Table 6
A non-exhaustive summary of various macro-economic policies that potentially affect agricultural GHG emissions

Region	Macro-economic policies potentially affecting agricultural GHG emissions	Impact on CO_2 emissions	Impact on N_2O emissions	Impact on CH_4 emissions
North America	Energy conservation and energy security policies – promote bio-energy – increase fossil fuel offsets and possibly SOC (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 and Argentina)	+		
Europe and 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 fertilization (Russia and 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 perennial grasses) (Russia)	+	+	

Table 6 (*Continued*)

Region	Macro-economic policies potentially affecting agricultural GHG emissions	Impact on CO_2 emissions	Impact on N_2O emissions	Impact on CH_4 emissions
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 N_2O) is reduced.		+	
	Continuing tightening of terms of trade for farm enterprises, as well as ongoing relaxation of requirements for agricultural imports, is likely to maintain this focus (Australia and 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)		+	+

'+', a positive effect mitigative effect; '–', a negative mitigative effect. Examples of policies are listed for each major world region and the potential impact on the emissions of each GHG is indicated.

5.2.3. 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 reduces losses from agriculture. The majority of these environmental policies also reduce GHG emissions (Table 7). Table 7 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.

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 5.1). The importance of identifying these co-benefits when formulating climate and other environmental policy was addressed in Section 3.

5.3. Greenhouse gas inventories

Effective policy making in relation to agricultural GHG emissions will be highly dependent on information that enables decision makers to deal with four key questions (Howden and Reyenga, 1999):

- What is the current status of agriculture in regards to GHG emissions?
- To what degree do they want to change these emissions?
- What is the best pathway to achieving those changes?
- How will they know when they have reached the target level of change?

The current instruments used to address these points are the national GHG inventories established in accordance with the IPCC Inventory Guidelines (IPCC, 1997, 2003). These Guidelines can be completed to three different levels of complexity (or Tiers). The default, simplest level essentially uses agricultural activity data (e.g. livestock numbers, area cropped, etc.) and simple, fixed emissions factors (e.g. methane emissions per head, etc.) and hence has severely limited capacity to incorporate the agricultural mitigation activities and policies discussed above. For example, even if there is widespread adoption of improved livestock feeding practices, enhanced genetics or use of anti-methanogenic additives or vaccines, there will be no reported change in GHG emissions from this sector. The only option to reduce inventory-recorded emissions is to reduce the agricultural activities themselves: a challenging prospect in many economies. Even in the progressively more complex Tier Two and Tier Three methods, there is limited scope to include the activities and policies described in this paper. For example, the Tier Three livestock inventory has scope to describe the effect of improved feeding practices and changes in animal size and other characteristics on feed intakes but currently no method for systematic, evidence-based variation in methane emissions due to feed

Table 7
A non-exhaustive summary of various environmental policies that were not implemented specifically to address GHG emissions but that potentially affect agricultural GHG emissions

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 N_2O emissions (Canada)	+	+	
Latin America	Increasing adoption of environmental policies driven by globalization, consolidation of democratic regimes (all Latin America and The Caribbean)			
	Fourteen countries have introduced environmental regulations over the last two 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)	+	?	
Europe and 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., 2005a) (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’ and ‘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 N_2O 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, 1988)	+	+	+

Table 7 (*Continued*)

Region	Other environmental policies potentially affecting agricultural GHG emissions	Impact on CO_2 emissions	Impact on N_2O emissions	Impact on CH_4 emissions
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—bans straw burning, thus reducing CO_2 (and CH_4 and N_2O) emissions (China)	+	+	+
	"Township Enterprises" and "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 and other ecosystems (Australia and 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 and NZ)	+	−	−
	Policy responses are being developed that include monitoring, regulatory, research and extension components (Australia and 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)	+	+	+

'+', a positive effect mitigative effect; '−', a negative mitigative effect. Examples of policies are listed for major world region and the potential impact on the emissions of each GHG is indicated.

characteristics, animal genetics or anti-methanogenic treatments. Similar constraints operate in other inventory sectors. Additionally, there are often significant limitations in the data required to make more complex inventories operational. Consequently, there is a need to consider progressive enhancement of inventory structures, methods and data inputs so as to be able to more effectively inform policymakers of the links between the adoption of new technologies and activities to changes in agricultural GHG emissions.

6. Implications for sustainable development

There are various potential impacts of agricultural GHG mitigation on sustainable development. Table 8 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 suggests of the likely impact, but the exact magnitude will depend upon the scale and intensity of the mitigation measures and where they are undertaken.

Agriculture contributes 24% of global GDP (World Bank, 2003) and provides employment to 1.3 billion people; 22% of the world population (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.

Table 8
Potential sustainable development consequences of mitigation options

Activity category	Sustainable development			Notes
	Social	Economic	Environmental	
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. Agro-forestry	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	
10. Management of oreanic soils	Uncertain	Uncertain		8
11. Land restoration	Positive	Likely to be positive	Positive	9
12. Bio-energy	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

Notes: (1) Economic benefits might decline but other benefits will increase; (2) technology-based production increases fertilizer efficiency, which leads to decreasing 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.

Controlling overgrazing through pasture improvement has a favourable impact on livestock productivity (greater income from the same number of the 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, 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 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.

7. Interactions between agricultural GHG mitigation, adaptation and vulnerability

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 5.1 and 5.2) 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 livestock herds and rates of sequestration are variables affected by climate change. 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). 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; (c) increased microbial decomposition under higher temperatures will lower soil carbon sequestration potential. Interactions also occur with adaptation. Butt et al. (in press) 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.

8. Future outlook

8.1. Technology, research, development, deployment, diffusion and transfer

There is much scope for technological developments in the agriculture sector to reduce GHG emissions. 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. Thus, better management, genetically modified crops, improved cultivars, fertilizer recommendation systems, precision agriculture, improved animal breeds, improved animal nutrition, dietary additives and growth promoters, improved animal fertility, 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 involve employment of existing technology (e.g. crop management, livestock feeding—replace roughage with concentrates). With such strategies, the main issue is technology transfer, diffusion and deployment. Other strategies involve new use of existing technologies. For example, oils have been used in animal diets for many years to increase dietary energy content, but their role as a methane suppressant is relatively new, and the parameters of the technology in terms of scope for methane reduction are only now being defined. Other strategies still require 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.

Geopolitical 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 regions than in the developing world because of cost, opportunity (i.e. it is much easier to administer products to animals in confinement systems than in free ranging or nomadic systems), availability of the technology, etc. (US-EPA, 2006a). 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.

8.2. Long-term versus short-term outlook

There is a large potential for mitigating GHG emissions in the agricultural sector in future. Trends in GHG emissions in the agricultural sector are mainly dependent on the level and rate of socio-economic development, application of adequate technologies, climate and non-climate policies, and future climate change.

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 globalization 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 several climate and non-climate policies as described in Section 5, most of which are believed to have direct effects or synergistic effects on mitigating GHG emissions from agricultural sector. Global sharing of innovated technologies for efficient use of land resources and agricultural chemicals, to eliminate poverty and malnutrition, will significantly mitigate GHG emissions from the agricultural sector.

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. It has been estimated that 10–15% of total arable lands could potentially be used to grow energy crops. However, there are still significant barriers in technologies and economics to using agricultural wastes, and in converting energy crops into commercial fuels. The development of innovative technologies is a critical factor in realizing the potential for agricultural wastes and energy crops. Government investment for the development of these technologies, and subsidies for using these forms of energy, is essential.

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 very large uncertainties due to sparse data and incomplete knowledge. Before the options for mitigating GHG emissions from agricultural sectors can be recommended as measures, their socio-economic aspects need to be fully evaluated.

Climate and global change are expected to influence agricultural in different ways. It has been demonstrated that elevated atmospheric CO_2 concentration alone, on average, increases crop yield 10–15%. This feedback effect will increase crop production per land unit, hence 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 and Christensen, 2004; 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.

9. Conclusions

GHG emissions from agriculture have large uncertainties and it is difficult to assess the effectiveness of GHG mitigation measures under the changing conditions of the future. This makes a consensus difficult to achieve and hinders policy-making. For sustainable development and environment quality improvement, some countries have initiated several climate and non-climate policies, most of which are believed to have direct effects or synergistic effects on mitigating GHG emissions from agriculture. 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 agriculture.

Smith et al. (in press) showed that economic constraints might limit implementation of agricultural GHG mitigation to less than 35% of the total biophysical potential by 2030. Other barriers may limit this further. The challenge for successful agricultural GHG mitigation will be to remove these barriers by implementing creative policies. Identifying policies that provide benefits for climate, as well as for aspects of economic, social and environmental sustainability, will be critical for ensuring that effective GHG mitigation options are widely implemented in the future.

References

Agriculture of Russia, 2004. Available at: http://www.gks.ru/scripts/regl/1c.exe?XXXX38R.5.1.

Balmford, A., Green, R.E., Scharlemann, J.P.W., 2005. Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. Global Change Biol. 11, 1594–1605.

Barak, P., Jobe, B.O., Krueger, A.R., Peterson, L.A., Laird, D.A., 1997. Effects of long-term soil acidification due to nitrogen fertilizer inputs in Wisconsin. Plant Soil 197, 61–69.

Berndes, G., 2002. Bio-energy and water—the implications of large-scale bio-energy production for water use and supply. Global Environ. Change 12, 253–271.

Berndes, G., Börjesson, P., 2002. Multi-functional biomass production systems. Available at: http://www.elkraft.ntnu.no/eno/konf_pub/ISES2003/full_paper/6%20MISCELLANEOUS/O6%204.pdf (last accessed 31 May 2006).

Berndes, G., Fredrikson, F., Borjesson, P., 2004. Cadmium accumulation and Salix-based phytoextraction on arable land in Sweden. Agriculture. Ecosyst. Environ. 103, 207–223.

Bhatia, A., Pathak, H., Aggarwal, P.K., 2004. Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. Curr. Sci. 87, 317–324.

Binfield, J., Donnellan, T., Hanrahan, K., Westhoff, P., 2006. World Agricultural Trade Reform and the WTO Doha Development Round: Analysis of the Impact on EU and Irish Agriculture. Teagasc, Athenry, Galway, Ireland, p. 79.

Börjesson, P., Berndes, G., 2006. The prospects for willow plantations for wastewater treatment in Sweden. Biomass Bioenergy 30, 428–438.

Bouwman, A., 2001. Global Estimates of Gaseous Emissions From Agricultural Land. FAO, Rome.

Butt, T.A., McCarl, B.A., Kergna, A.O., in press. Policies for reducing agricultural sector vulnerability to climate change in Mali. Climate Pol.

Cannell, M.G.R., 2003. Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass Bioenergy 24, 97–116.

Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H., 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Resour. 28, 315–358.

Cerri, C.C., Bernoux, M., Cerri, C.E.P., Feller, C., 2004. Carbon cycling and sequestration opportunities in South America: the case of Brazil. Soil Use Manage. 20, 248–254.

Cohen, J.E., 2003. Human population: the next half century. Science 302, 1172–1175.

Connor, D.J., 2004. Designing cropping systems for efficient use of limited water in southern Australia. Eur. J. Agron. 21, 419–431.

Conway, G., Toenniessen, G., 1999. Feeding the world in the twenty-first century. Nature 402, C55–C58.

Dalal, R.C., Wang, W., Robertson, G.P., Parton, W.J., 2003. Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. Aust. J. Soil Res. 41, 165–195.

Dean, T., 2000. Development: Agriculture Workers Too Poor to Buy Food. UN IPS, New York.

DeFries, R.S., Foley, J.A., Asner, G.P., 2004. Land-use choices: balancing human needs and ecosystem function. Front. Ecol. Environ. 2, 249–257.

de Oliveira, M.E.D., Vaughan, B.E., Rykiel Jr., E.J., 2005. Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. BioScience 55, 593–602.

Diaz-Zorita, M., Duarte, G.A., Grove, J.H., 2002. A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina. Soil Till. Res. 65, 1–18.

Díez, J.A., Hernaiz, P., Muñoz, M.J., de la Torre, A., Vallejo, A., 2004. Impact of pig slurry on soil properties, water salinisation, nitrate leaching and crop yield in a four-year experiment in Central Spain. Soil Use Manage. 20, 444–450.

Elbakidze, L., McCarl, B.A., in press. Sequestration offsets versus direct emission reductions: consideration of environmental co-effects. Ecol. Econ.

European Climate Change Programme, 2003. Working Group 7—Agriculture. Mitigation Potential of Greenhouse Gases in the Agricultural

Sector. Final Report. COMM(2000)88. European Commission, Brussels.

European Environment Agency, 2005. How much biomass can Europe use without harming the environment? EEA Briefing 2/2005. Available at: http://www.reports.eea.europa.eu/briefing_2005_2/en (last accessed 31 May 2006).

Ewert, F., Rounsevell, M.D.A., Reginster, I., Metzger, M., Leemans, R., 2005. Future scenarios of European agricultural land use. I. Estimating changes in crop productivity. Agric. Ecosyst. Environ. 107, 101–116.

Falloon, P., Smith, P., Powlson, D.S., 2004. Carbon sequestration in arable land—the case for field margins. Soil Use Manage. 20, 240–247.

Fang, C., Smith, P., Moncrieff, J.B., Smith, J.U., 2005. Similar response of labile and resistant soil organic matter pools to changes in temperature. Nature 433, 57–59.

FAO, 2001. Soil carbon sequestration for improved land management. World Soil Resources Reports No. 96. FAO, Rome.

FAO, 2003. World agriculture: towards 2015/2030. An FAO perspective. FAO, Rome.

FAOSTAT, 2006. FAOSTAT Agricultural Data. http://www.faostat.fao.org/faostat/collections?version=ext&hasbulk=0&subset=agriculture (last accessed 30 May 2006).

Fedoroff, N.V., Cohen, J.E., 1999. Plants and population: is there time? Proc. Natl. Acad. Sci. U.S.A. 96, 5903–5907.

Foley, J.A., DeFries, R., Asner, G., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Dailey, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Follett, R.F., Shafer, S.R., Jawson, M.D., Franzluebbers, A.J., 2005. Research and implementation needs to mitigate greenhouse gas emissions from agriculture in the USA. Soil Till. Res. 83, 159–166.

Freibauer, A., Rounsevell, M., Smith, P., Verhagen, A., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122, 1–23.

Galloway, J.N., 2003. The global nitrogen cycle. Treatise Geochem. 8, 557–583.

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B., Cosby, B.J., 2003. The nitrogen cascade. Bioscience 53, 341–356.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vörösmarty, C.J., 2004. Nitrogen cycles: past, present, and future. Biogeochemistry 70, 153–226.

Gehl R.J., Rice, C.W., in press. Emerging technologies for in situ measurement of soil carbon. Climatic Change.

Gilland, B., 2002. World population and food supply. Can food production keep pace with population growth in the next half-century? Food Policy 27, 47–63.

Green, R.E., Cornell, S.J., Scharlemann, J.P.W., Balmford, A., 2005. Farming and the fate of wild nature. Science 307, 550–555.

Henry, H.A.L., Cleland, E.E., Field, C.B., Vitousek, P.M., 2005. Interactive effects of elevated CO_2, N deposition and climate change on plant litter quality in a California annual grassland. Oecologia 142, 465–473.

Howden, S.M., Reyenga, P.J., 1999. Methane emissions from Australian livestock: implications of the Kyoto Protocol. Aust. J. Agric. Res. 50, 1285–1291.

Huang, J., Pray, C., Rozelle, S., 2002. Enhancing the crops to feed the poor. Nature 418, 678–684.

Huston, M.A., Marland, G., 2003. Carbon management and biodiversity. J. Environ. Manage. 67, 77–86.

IPCC, 1997. Revised 1996 IPCC Guidelines for National Greenhouse Inventories. IPCC/OECD/IEA, Paris.

IPCC, 2003. Good practice guidance for land use, land-use change and forestry. NGES, IPCC NGGI Office, Kanagawa, Japan.

Izaurralde, R.C., Rice, C.W., 2006. Methods and tools for designing pilot soil carbon sequestration projects. In: Lal, et al. (Eds.), Carbon Sequestration in Soils of Latin America. CRC Press, Boca Raton, pp. xx–xx.

Janzen, H.H., 2005. Soil carbon: a measure of ecosystem response in a changing world? Can. J. Soil Sci. 85, 467–480.

Jensen, B., Christensen, B.T., 2004. Interactions between elevated CO_2 and added N: effects on water use, biomass, and soil ^{15}N uptake in wheat. Acta Agric. Scand. Sect. B 54, 175–184.

Knorr, W., Prentice, I.C., House, J.I., Holland, E.A., 2005. Long-term sensitivity of soil carbon turnover to warming. Nature 433, 298–301.

Kumar, P., 2001. Valuation of Ecological Services of Wetland Ecosystems: A Case Study of Yamuna Floodplains in the Corridors of Delhi, Mimeograph. Institute of Economic Growth, Delhi, India.

Kurkalova, L., Kling, C.L., Zhao, J., 2004. Multiple benefits of carbon-friendly agricultural practices: empirical assessment of conservation tillage. Environ. Manage. 33, 519–527.

Lal, R., 2001. World cropland soils as a source or sink for atmospheric carbon. Adv. Agron. 71, 145–191.

Lal, R., 2004a. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.

Lal, R., 2004b. Soil carbon sequestration to mitigate climate change. Geoderma 123, 1–22.

Lal, R., 2004c. Offsetting China's CO_2 emissions by soil carbon sequestration. Climatic Change 65, 263–275.

Lal, R., Follett, R.F., Kimble, J.M., 2003. Achieving soil carbon sequestration in the United States: a challenge to the policy makers. Soil Sci. 168, 827–845.

Lutz, W., Sanderson, W., Scherbov, S., 2001. The end of world population growth. Nature 412, 543–545.

Machado, P.L.O.D., Silva, C.A., 2001. Soil management under no-tillage systems in the tropics with special reference to Brazil. Nutr. Cycl. Agroecosyst. 61, 119–130.

McCarl, B.A., Kim, M.-K., Lee, H.-C., Murray, B.C., Sands, R.D., Schneider, U.A., in press. Insights from agricultural and forestry GHG offset studies that might influence IAM modelling. In: Schlesinger, M., Kheshgi, H., Smith, J., de la Chesnaye, F., Reilly, J., Wilson, T., Kolstad, C. (Eds.), Integrated Assessment of Human Induced Climate Change. Cambridge University Press, Cambridge.

Millennium Ecosystem Assessment, 2005. Findings From the Conditions and Trend Working Group. Island Press, Washington, DC.

Mooney, S., Antle, J.M., Capalbo, S.M., Paustian, K., 2004. Influence of project scale on the costs of measuring soil C sequestration. Environ. Manage. 33 (S1), S252–S263.

Mooney, H., Cropper, A., Reid, W., 2005. Confronting the human dilemma. Nature 434, 561–562.

Mosier, A.R., 2001. Exchange of gaseous nitrogen compounds between agricultural systems and the atmosphere. Plant Soil 228, 17–27.

Mosier, A.R., 2002. Environmental challenges associated with needed increases in global nitrogen fixation. Nutr. Cycl. Agroecosyst. 63, 101–116.

Mosier, A., Kroeze, C., 2000. Potential impact on the global atmospheric N_2O budget of the increased nitrogen input required to meet future global food demands. Chemosphere-Global Change Sci. 2, 465–473.

Murray, B.C., McCarl, B.A., Lee, H.-C., 2004. Estimating leakage from forest carbon sequestration programs. Land Econ. 80, 109–124.

NEPAD (New Partnership for Africa's Development), 2005. The NEPAD Framework Document. Available at: http://www.uneca.org/nepad/ (last accessed 30 May 2006).

Norby, R.J., Cotrufo, M.F., Ineson, P., O'Neill, E.G., Canadell, J.G., 2001. Elevated CO_2, litter chemistry, and decomposition: a synthesis. Oecologia 127, 153–165.

Oenema, O., Wrage, N., Velthof, G.L., van Groenigen, J.W., Dolfing, J., Kuikman, P.J., 2005. Trends in global nitrous oxide emissions from animal production systems. Nutr. Cycl. Agroecosyst. 72, 51–65.

Olesen, J.E., Schelde, K., Weiske, A., Weisbjerg, M.R., Asman, W.A.H., Djurhuus, J., 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agric. Ecosyst. Environ. 112, 207–220.

Paustian, K., Babcock, B.A., Hatfield, J., Lal, R., McCarl, B.A., McLaughlin, S., Mosier, A., Rice, C., Robertson, G.P., Rosenberg, N.J., Rosenzweig, C., Schlesinger, W.H., Zilberman, D., 2004. Agricultural Mitigation of Greenhouse Gases: Science and Policy Options, Council on Agricultural Science and Technology (CAST) Report, R141 2004, ISBN 1-887383-26-3, 120 pp.

Rao, C.H., 1994. Agricultural Growth, Rural Poverty and Environmental Degradation in India. Oxford University Press, Delhi.

Rees, W.E., 2003. A blot on the land. Nature 421, 898.

Reilly, J.M., Tubiello, F., McCarl, B.A., Melillo, J., 2001. Climate change and agriculture in the United States. In: Climate Change Impacts on the United States: US National Assessment of the Potential Consequences of Climate Variability and Change: Foundation, Cambridge University Press, pp. 379–403 (Chapter 13).

Rockström, J., 2003. Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture. Phil. Trans. Roy. Soc. Lond. B 358, 1997–2009.

Romanenkov, V., Romanenko, I., Sirotenko, O., Shevtsova, L., 2004. Soil carbon sequestration strategy as a component of integrated agricultural sustainability policy under climate change. In: Proceedings of the Russian National Workshop on Research Related to the IHDP on Global Environmental Change, Moscow, IHDP, November 10–12, pp. 180–189.

Rosegrant, M.W., Cline, S.A., 2003. Global food security: challenges and policies. Science 302, 1917–1919.

Rosegrant, M., Paisner, M.S., Meijer, S., 2001. Long-Term Prospects for Agriculture and the Resource Base. The World Bank Rural Development Family. Rural Development Strategy Background Paper #1. World Bank, Washington, DC.

Rounsevell, M.D.A., Reginster, I., Araújo, M.B., Carter, T.R., Dendoncker, N., Ewert, F., House, J.I., Kankaanpää, S., Leemans, R., Metzger, M.J., Schmit, C., Smith, P., Tuck, G., 2006. A coherent set of future land use change scenarios for Europe. Agric. Ecosyst. Environ. 114, 57–68.

Roy, R.N., Misra, R.V., Montanez, A., 2002. Decreasing reliance on mineral nitrogen—yet more food. Ambio 31, 177–183.

Sanchez, P.A., 2002. Soil fertility and hunger in Africa. Science 295, 2019–2020.

Sanchez, P.A., Swaminathan, M.S., 2005. Cutting world hunger in half. Science 307, 357–359.

Sands, R.D., McCarl, B.A., 2005. Competitiveness of terrestrial greenhouse gas offsets: are they a bridge to the future? In: Abstracts of USDA Symposium on Greenhouse Gases and Carbon Sequestration in Agriculture and Forestry, Baltimore, Maryland, March 22–24.

Schlesinger, W.H., 1999. Carbon sequestration in soils. Science 284, 2095.

Scholes, R.J., Biggs, R., 2004. Ecosystem Services in Southern Africa: A Regional Assessment. CSIR, Pretoria.

Sleutel, S., 2005. Carbon sequestration in cropland soils: recent evolution and potential of alternative management options. PhD. Thesis, Ghent, Belgium, Ghent University.

Smith, J.U., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I., Ewert, F., 2005b. Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. Global Change Biol. 11, 2153–2163.

Smith, P., 2004a. Carbon sequestration in croplands: the potential in Europe and the global context. Eur. J. Agron. 20, 229–236.

Smith, P., 2004b. Engineered biological sinks on land. In: Field, C.B., Raupach, M.R. (Eds.), The Global Carbon Cycle. Integrating Humans, Climate, and The Natural World. Scope 62. Island Press, Washington, DC, pp. 479–491.

Smith, P., 2004c. Monitoring and verification of soil carbon changes under Article 3.4 of the Kyoto Protocol. Soil Use Manage. 20, 264–270.

Smith, P., Powlson, D.S., Glendining, M.J., Smith, J.U., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Global Change Biol. 3, 67–79.

Smith, P., Powlson, D.S., Smith, J.U., Falloon, P.D., Coleman, K., 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Global Change Biol. 6, 525–539.

Smith, P., Goulding, K.W., Smith, K.A., Powlson, D.S., Smith, J.U., Falloon, P.D., Coleman, K., 2001. Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in estimates of carbon mitigation potential. Nutr. Cycl. Agroecosyst. 60, 237–252.

Smith, P., Andrén, O., Karlsson, T., Perälä, P., Regina, K., Rounsevell, M., van Wesemael, B., 2005a. Carbon sequestration potential in European croplands has been overestimated. Global Change Biol. 11, 2153–2163.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H.H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, R.J., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J.U., in press. Greenhouse gas mitigation in agriculture. Phil. Trans. Roy. Soc. B

South Africa, 1988. Fire Act. Pretoria: Government Printer.

Strengers, B., Leemans, R., Eickhout, B., ve Vries, B., Bouwman, L., 2004. The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. GeoJournal 61, 381–393.

Tejo, P., 2004. Public Policies and Agriculture in Latin America During the 2000s. CEPAL (Comisión Económica para América Latina) Serie Desarrollo Productivo, vol. 152. Santiago de Chile (in Spanish).

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284.

Totten, M., Pandya, S.I., Janson-Smith, T., 2003. Biodiversity, climate, and the Kyoto Protocol: risks and opportunities. Front. Ecol. Environ. 1, 262–270.

Trewavas, A., 2002. Malthus foiled again and again. Nature 418, 668–670.

Unkovich, M., 2003. Water use, competition, and crop production in low rainfall, alley farming systems of south-eastern Australia. Aust. J. Agric. Res. 54, 751–762.

US-EPA, 2006a. Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2020. United States Environmental Protection Agency, Washington, DC, EPA 430-R-06-003.

US-EPA, 2006b. Global Mitigation of Non-CO_2 Greenhouse Gases. United States Environmental Protection Agency, Washington, DC, EPA 430-R-06-005.

van Groenigen, K.-J., Gorissen, A., Six, J., Harris, D., Kuikman, P.J., van Groenigen, J.W., van Kessel, C., 2005. Decomposition of ^{14}C-labeled roots in a pasture soil exposed to 10 years of elevated CO_2. Soil Biol. Biochem. 37, 497–506.

Van Oost, K., Govers, G., Quine, T.A., Heckrath, G., 2004. Comment on "Managing soil carbon" (I). Science 305, 1567.

Wander, M., Nissen, T., 2004. Value of soil organic carbon in agricultural lands. Mitigat. Adapt. Strat. Global Change 9, 417–431.

Wang, B., Neue, H., Samonte, H., 1997. Effect of cultivar difference on methane emissions. Agric. Ecosyst. Environ. 62, 31–40.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.

West, T.O., Marland, G., 2003. Net carbon flux from agriculture: carbon emissions, carbon sequestration, crop yield, and land-use change. Biogeochemistry 63, 73–83.

World Bank, 2003. World Development Indicators. World Bank, Washington, DC (CD-ROM).

Wright, A.D.G., Kennedy, P., O'Neill, C.J., Troovey, A.F., Popovski, S., Rea, S.M., Pimm, C.L., Klein, L., 2004. Reducing methane emissions in sheep by immunization against rumen methanogens. Vaccine 22, 3976–3985.