

Greenhouse gas mitigation in agriculture

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Agricultural lands occupy 37% of the earth's land surface. Agriculture accounts for 52 and 84% of global anthropogenic methane and nitrous oxide emissions. Agricultural soils may also act as a sink or source for CO₂, but the net flux is small. Many agricultural practices can potentially mitigate greenhouse gas (GHG) emissions, the most prominent of which are improved cropland and grazing land management and restoration of degraded lands and cultivated organic soils. Lower, but still significant mitigation potential is provided by water and rice management, set-aside, land use change and agroforestry, livestock management and manure management. The global technical mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030, considering all gases, is estimated to be approximately 5500–6000 Mt CO₂-eq. yr⁻¹, with economic potentials of approximately 1500–1600, 2500–2700 and 4000–4300 Mt CO₂-eq. yr⁻¹ at carbon prices of up to 20, up to 50 and up to 100 US\$ t CO₂-eq.⁻¹, respectively. In addition, GHG emissions could be reduced by substitution of fossil fuels for energy production by agricultural feedstocks (e.g. crop residues, dung and dedicated energy crops). The economic mitigation potential of biomass energy from agriculture is estimated to be 640, 2240 and 16 000 Mt CO₂-eq. yr⁻¹ at 0–20, 0–50 and 0–100 US\$ t CO₂-eq.⁻¹, respectively.

Keywords: greenhouse gas; agriculture; mitigation; cropland management; grazing land; soil carbon

1. INTRODUCTION

Agriculture releases to the atmosphere significant amounts of CO₂, CH₄ and N₂O (Cole *et al.* 1997; IPCC 2001; Paustian *et al.* 2004). Carbon dioxide is released largely from microbial decay or burning of plant litter and soil organic matter (Janzen 2004;

Smith 2004b). Methane is produced when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion by ruminant livestock, stored manures and rice grown under flooded conditions (Mosier *et al.* 1998). Nitrous oxide is generated by the microbial transformation of nitrogen in soils and manures, and is often enhanced where available N exceeds plant requirements, especially under wet conditions (Smith & Conen 2004; Oenema *et al.* 2005). Agricultural greenhouse gas (GHG) fluxes are

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complex and heterogeneous, but the active management of agricultural systems offers possibilities for mitigation. Many of these mitigation opportunities use current technologies and can be implemented immediately. In this paper, we use the latest datasets and techniques to make the first estimates of agricultural GHG mitigation potential for 2030 that include all GHGs with breakdowns for all global regions and all gases.

2. MITIGATION TECHNOLOGIES AND PRACTICES

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

- (i) *Reducing emissions.* Agriculture releases to the atmosphere significant amounts of CO₂, CH₄ and N₂O (Cole *et al.* 1997; IPCC 2001; Paustian *et al.* 2004). The fluxes of these gases can be reduced by managing more efficiently the flows of carbon and nitrogen in agricultural ecosystems. For example, practices that deliver added N more efficiently to crops often suppress the emission of N₂O (Bouwman 2001) and managing livestock to make most efficient use of feeds often suppresses the amount of CH₄ produced (Clemens & Ahlgrimm 2001). The approaches that best reduce emissions depend on local conditions and therefore vary from region to region.
- (ii) *Enhancing removals.* Agricultural ecosystems hold large reserves of C (IPCC 2001), mostly in soil organic matter. Historically, these systems have lost more than 50 Pg C (Paustian *et al.* 1998; Lal 1999, 2004a), but some of this lost C can be recovered through improved management, thereby withdrawing atmospheric CO₂. Any practice that increases the photosynthetic input of C or slows the return of stored C via respiration or fire will increase stored C, thereby 'sequestering' C or building C 'sinks'. Many studies worldwide have now shown that significant amounts of soil C can be stored in this way, through a range of practices suited to local conditions (Lal 2004a). Significant amounts of vegetative C can also be stored in agroforestry systems or other perennial plantings on agricultural lands (Albrecht & Kandji 2003). Agricultural lands also remove CH₄ from the atmosphere by oxidation, but this effect is small when compared with other GHG fluxes (Smith & Conen 2004).
- (iii) *Avoiding (or displacing) emissions.* Crops and residues from agricultural lands can be used as a source of fuel, either directly or after conversion to fuels such as ethanol or diesel (Cannell 2003; Schneider & McCarl 2003). These bioenergy feedstocks still release CO₂ upon combustion, but now the C is of recent atmospheric origin (via photosynthesis), rather than from fossil C. The net benefit of these bioenergy feedstocks to the atmosphere is equal to the fossil-derived emissions displaced less any emissions from their production, transport and processing. Emissions of GHGs, notably CO₂, can also be avoided by

agricultural management practices that forestall the cultivation of new lands now under forest, grassland or other non-agricultural vegetation (Foley *et al.* 2005).

Many practices have been advocated to mitigate emissions through the mechanisms cited above. Often a practice will affect more than one gas, by more than one mechanism, sometimes in opposite ways, so that the net benefit depends on the combined effects on all gases (Robertson & Grace 2004; Schils *et al.* 2005). In addition, the temporal pattern of influence may vary among practices or among gases for a given practice; some emissions are reduced indefinitely, other reductions are temporary (Marland *et al.* 2003a; Six *et al.* 2004). Where a practice affects radiative forcing through other mechanisms such as aerosols or albedo, those impacts also need to be considered (Marland *et al.* 2003b; Andreae *et al.* 2005). The impacts of various mitigation options considered are summarized in table 1. The most important options are discussed below.

(a) Cropland management

Croplands, because they are often intensively managed, offer many opportunities to impose practices that reduce net emissions of GHGs (table 1). Mitigation practices in cropland management include the following partly overlapping categories.

(i) Agronomy

Improved agronomic practices that increase yields and generate higher inputs of residue C can lead to increased soil C storage (Follett 2001). Examples of such practices include: using improved crop varieties; extending crop rotations, notably those with perennial crops which allocate more C below-ground; and avoiding or reducing use of bare (unplanted) fallow (West & Post 2002; Lal 2003, 2004a; Freibauer *et al.* 2004; Smith 2004a,b). Adding more nutrients, when deficient, can also promote soil C gains (Alvarez 2005), but the benefits from N fertilizer can be offset by higher emissions of N₂O from soils and CO₂ from fertilizer manufacture (Schlesinger 1999; Robertson & Grace 2004; Gregorich *et al.* 2005).

Emissions can also be reduced by adopting less intensive cropping systems, which reduce reliance on pesticides and other inputs (and therefore the GHG cost of their production; Paustian *et al.* 2004). An important example is the use of rotations with legume crops (Izaurralde *et al.* 2001; West & Post 2002), which reduce reliance on inputs of N, though legume-derived N can also be a source of N₂O (Rochette & Janzen 2005).

A third group of agronomic practices are those that provide temporary vegetative cover between agricultural crops. These 'catch' or 'cover' crops add C to soils (Barthès *et al.* 2004; Freibauer *et al.* 2004) and may also extract plant-available N unused by the preceding crop, thereby reducing N₂O emissions.

(ii) Nutrient management

Nitrogen applied in fertilizers and manures is not always used efficiently by crops (Cassman *et al.* 2003; Galloway *et al.* 2003). Improving this efficiency can reduce emissions of N₂O, generated by soil microbes

Table 1. A list of proposed measures for mitigating GHG emissions from agricultural ecosystems, their apparent effects on reducing emissions of individual gases (mitigative effect) and an estimate of scientific confidence that the proposed practice can reduce overall net emissions.

measure	examples	mitigative effects ^a			net mitigation ^b (confidence)	
		CO ₂	CH ₄	N ₂ O	agreement	evidence
cropland management	agronomy	+		±	***	**
	nutrient management	+		+	***	**
	tillage/residue management	+		±	**	**
	water management (irrigation, drainage)	±		+	*	*
	rice management		+	±	**	**
	agroforestry	+		±	***	*
	set-aside, land-use change (LUC)	+	+	+	***	***
grazing land management/ pasture improvement	grazing intensity	±		±	*	*
	increased productivity (e.g. fertilization)	+		±	**	*
	nutrient management	+		±	**	**
	fire management	+		±	*	*
	species introduction (including legumes)	+		±	*	**
management of organic soils	avoid drainage of wetlands	+	—	±	**	**
	erosion control, organic amendments, nutrient amendments	+		±	***	**
livestock management	improved feeding practices		+		***	***
	specific agents and dietary additives		+		**	***
	longer term structural and management changes and animal breeding		+		**	*
manure/biosolid management	improved storage and handling		+	±	***	**
	anaerobic digestion		+	±	***	*
	more efficient use as nutrient source	+		+	***	**
bioenergy	energy crops, solid, liquid, biogas, residues	+		±	***	**

^a ‘+’ denotes reduced emissions or enhanced removal (positive mitigative effect); ‘—’ denotes increased emissions or suppressed removal (negative mitigative effect); ‘±’ denotes uncertain or variable response.

^b A qualitative estimate of the confidence in describing the proposed practice as a measure for reducing *net* emissions of GHGs, expressed as CO₂ equivalence. ‘Agreement’ refers to the relative degree of agreement or consensus in the literature (the more asterisks, the higher the agreement); ‘Evidence’ refers to the relative amount of data in support of the proposed effect (the more asterisks, the greater the amount of evidence).

largely from surplus N and it can indirectly reduce emissions of CO₂ from N fertilizer manufacture (Schlesinger 1999). Practices that improve N use efficiency include: adjusting application rates based on precise estimation of crop needs (e.g. precision farming); using slow-release fertilizer forms or nitrification inhibitors (which slow the microbial processes leading to N₂O formation); avoiding time delays between N application and plant N uptake (improved timing); placing the N more precisely into the soil to make it more accessible to crops roots; avoiding excess N applications, or eliminating N applications where possible (Cole *et al.* 1997; Dalal *et al.* 2003; Paustian *et al.* 2004; Robertson 2004; Monteny *et al.* 2006).

(iii) Tillage/residue management

Advances in weed control methods and farm machinery now allow many crops to be grown with minimal tillage (reduced tillage) or without tillage (no till). These practices are now increasingly used

throughout the world (e.g. Cerri *et al.* 2004). Since soil disturbance tends to stimulate soil C losses through enhanced decomposition and erosion, reduced- or no-till agriculture often results in soil C gain, though not always (West & Post 2002; Alvarez 2005; Gregorich *et al.* 2005; Ogle *et al.* 2005). Adopting reduced or no till may also affect emissions of N₂O, but the net effects are inconsistent and not well-quantified globally (Cassman *et al.* 2003; Smith & Conen 2004; Helgason *et al.* 2005; Li *et al.* 2005). The effect of reduced tillage on N₂O emissions may depend on soil and climatic conditions: in some areas reduced tillage promotes N₂O emissions; elsewhere it may reduce emissions or have no measurable influence (Marland *et al.* 2001).

Systems that retain crop residues also tend to increase soil C because these residues are the precursors for soil organic matter, the main store of carbon in the soil. Avoiding the burning of residues, for instance mechanizing the harvesting of sugarcane,

which eliminates the need for pre-harvest burning (Cerri *et al.* 2004), also avoids emissions of aerosols and GHGs generated from fire.

(iv) *Water management*

About 18% of the world's croplands now receive supplementary water through irrigation (Millennium Ecosystem Assessment 2005). Expanding this area or using more effective irrigation measures can enhance C storage in soils through enhanced yields and residue returns (Follett 2001; Lal 2004a). But some of these gains may be offset by CO₂ from energy used to deliver the water (Schlesinger 1999; Mosier *et al.* 2005) or from N₂O emissions from higher moisture and fertilizer N inputs (Liebig *et al.* 2005), though the latter effect has not been widely measured.

Drainage of agricultural lands in humid regions can promote productivity (and hence soil C) and perhaps also suppress N₂O emissions by improving aeration (Monteny *et al.* 2006). Any nitrogen lost through drainage, however, may be susceptible to loss as N₂O (Reay *et al.* 2003).

(v) *Rice management*

Cultivated wetland rice soils emit significant quantities of methane (Yan *et al.* 2003). Emissions during the growing season can be reduced by many practices (Yagi *et al.* 1997; Wassmann *et al.* 2000; Aulakh *et al.* 2001). For example, draining the wetland rice once or several times during the growing season effectively reduces CH₄ emissions (Smith & Conen 2004; Yan *et al.* 2003), although this benefit may be partly offset by higher N₂O emissions, and the practice may be constrained by water supply. Rice cultivars with low exudation rates could offer an important methane mitigation option (Aulakh *et al.* 2001). In the off-rice season, methane emissions can be reduced by improved water management, especially by keeping the soil as dry as possible and avoiding waterlogging (Cai *et al.* 2000, 2003; Kang *et al.* 2002; Xu *et al.* 2003).

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

(vi) *Agroforestry*

Agroforestry is the production of livestock or food crops on land that also grows trees, either for timber, firewood or other tree products. It includes shelter belts and riparian zones/buffer strips with woody species. The standing stock of carbon above ground is usually higher than the equivalent land use without trees, and planting trees may also increase the soil carbon sequestration (Guo & Gifford 2002; Paul *et al.* 2003; Oelbermann *et al.* 2004; Mutuo *et al.* 2005), though the effects on N₂O and CH₄ emissions are not well known (Albrecht & Kandji 2003).

(vii) *Land cover (use) change*

One of the most effective methods of reducing emissions is to allow or encourage the reversion of

cropland to another land cover, typically one similar to the native vegetation. The conversion can occur over the entire land area ('set-asides') or in localized spots such as grassed waterways, field margins or shelterbelts (Follett 2001; Ogle *et al.* 2003; Falloon *et al.* 2004; Freibauer *et al.* 2004; Lal 2004a). Such land cover change often increases storage of C; for example, converting arable cropland to grassland typically results in the accrual of soil C owing to lower soil disturbance and reduced C removal in harvested products. Compared to cultivated lands, grasslands may also have reduced N₂O emissions from lower N inputs and higher rates of CH₄ oxidation, though recovery of oxidation may be slow (Paustian *et al.* 2004).

Similarly, converting drained croplands back to wetlands can result in rapid accumulation of soil carbon (removal of atmospheric CO₂), although this conversion may stimulate CH₄ emissions, because waterlogging creates anaerobic conditions (Paustian *et al.* 2004). Planting trees can also reduce emissions, but these practices are considered under agroforestry (see §2a(vi)) afforestation or reforestation.

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

(b) *Grazing land management and pasture improvement*

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

(i) *Grazing intensity*

The intensity and timing of grazing can influence the growth, C allocation and flora of grasslands, thereby affecting the amount of C accrual in soils (Conant *et al.* 2001, 2005; Conant & Paustian 2002; Freibauer *et al.* 2004; Reeder *et al.* 2004). Carbon accrual on optimally grazed lands is often greater than on ungrazed or overgrazed lands (Rice & Owensby 2001; Liebig *et al.* 2005). The effects are inconsistent, however, owing to the many types of grazing practices employed and the diversity of plant species, soils and climates involved (Schuman *et al.* 2001; Derner *et al.* 2006). The influence of grazing intensity on emission of non-CO₂ gases is not well established, apart from the indirect effects from adjustments in livestock numbers.

(ii) *Increased productivity (including fertilization)*

As for croplands, C storage in grazing lands can be improved by a variety of measures that promote productivity. For instance, alleviating nutrient deficiencies by fertilizer or organic amendments increases plant litter returns and, hence, soil C storage (Conant *et al.* 2001; Schnabel *et al.* 2001). Adding nitrogen, however, may stimulate N₂O emissions (Conant *et al.* 2005) thereby offsetting some of the benefits. Irrigating grasslands, similarly, can promote soil C gains (Conant *et al.* 2001), though the net effect of this practice depends also on emissions from energy use

and other related activities on the irrigated land (Schlesinger 1999).

(iii) *Nutrient management*

Practices that tailor nutrient additions to plant uptake, like those described for croplands, can reduce emissions of N₂O (Follett *et al.* 2001; Dalal *et al.* 2003). Management of nutrients on grazing lands, however, may be complicated by deposition of faeces and urine from livestock, which are neither easily controlled nor as uniformly applied as nutritive amendments in croplands (Oenema *et al.* 2005).

(iv) *Fire management*

Biomass burning (not to be confused with bioenergy, where biomass is combusted off-site for energy) contributes to climate change in several ways. Firstly, it releases GHGs, notably CH₄, and to a lesser extent, N₂O (the CO₂ released is of recent origin, is reabsorbed by vegetation and is usually not counted). Secondly, it generates hydrocarbon and reactive nitrogen emissions, which react to form tropospheric ozone. Smoke contains a range of aerosols which can have either warming or cooling effects on the atmosphere, though the *net* effect is thought to be positive radiant forcing (Andreae 2001; Andreae & Merlet 2001; Menon *et al.* 2002; Anderson *et al.* 2003; Jones *et al.* 2003; Andreae *et al.* 2005; Venkataraman *et al.* 2005). Thirdly, fire blackens the land surface, reducing its albedo for several weeks, causing a warming (Beringer *et al.* 2003). Fourthly, burning can affect the proportions of woody versus grass cover, notably in savannas, which occupy approximately one-eighth of the global land surface. Reducing the frequency or intensity of fires typically leads to increased tree and shrub cover, resulting in higher landscape C density in soil and biomass (Scholes & van der Merwe 1996). This woody plant encroachment mechanism is higher initially, but saturates over 20–50 years, whereas avoided CH₄ and N₂O emissions are ongoing as long as the fires are suppressed.

Mitigation of radiant forcing involves reducing the frequency or extent of fires through more effective fire suppression (Korontzi *et al.* 2003); reducing the fuel load by vegetation management; and burning at a time of year when less CH₄ and N₂O are emitted (Korontzi *et al.* 2003). Although most agricultural-zone fires are ignited by humans, there is evidence that the area burned is ultimately under climatic control (van Wilgen *et al.* 2004). In the absence of human ignition, the fire-prone ecosystems would be lit by other agents.

(v) *Species introduction*

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

also reduce N₂O emissions if the biological N₂ fixation displaces the need for fertilizer N.

Lands used for grazing also emit GHGs from the livestock, notably CH₄ from ruminants and their manures. Practices for reducing these emissions are considered under §2e below.

(c) *Management of organic soils*

Organic soils contain high densities of C, accumulated over many centuries, because decomposition is suppressed by absence of oxygen under flooded conditions. To be used for agriculture, these soils are drained, which aerates the soil, favouring decomposition and therefore high fluxes of CO₂ and N₂O. Methane emissions are usually suppressed after draining, but this effect is far outweighed by pronounced increases in N₂O and CO₂ (Kasimir-Klemedtsson *et al.* 1997). Emissions on drained organic soils can be reduced to some extent by practices such as avoiding row crops and tubers, avoiding deep ploughing and maintaining a more shallow water table, but the most important mitigation practice, probably, is avoiding the drainage of these soils in the first place, or re-establishing a high water table where GHG emissions are still high (Freibauer *et al.* 2004).

(d) *Restoration of degraded lands*

A large fraction of agricultural lands have been degraded by erosion, excessive disturbance, organic matter loss, salinization, acidification or other processes that curtail productivity (Batjes 1999; Lal 2001, 2003, 2004b; Foley *et al.* 2005). Often the C storage in these soils can be at least partly restored by practices that reclaim productivity including: revegetation (e.g. planting grasses); improving fertility by nutrient amendments; applying organic substrates such as manures, biosolids and composts; reducing tillage and retaining crop residues; and conserving water (Bruce *et al.* 1999; Lal 2001, 2004b; Olsson & Ardo 2002; Paustian *et al.* 2004). Where these practices involve higher nitrogen amendments, the benefits of C sequestration may be partly offset by higher N₂O emissions.

(e) *Livestock management*

Livestock, predominantly ruminants such as cattle and sheep, are important sources of CH₄, accounting for approximately 18% of global anthropogenic emissions of this gas (US-EPA 2006). The methane is produced primarily by enteric fermentation and voided by eructation (Murray *et al.* 1976; Kennedy & Milligan 1978; Crutzen 1995). Practices for reducing CH₄ emissions from this source fall into three general categories: improved feeding practices, use of specific agents or dietary additives, and longer term management changes and animal breeding.

(i) *Improved feeding practices*

Methane emissions can be reduced by feeding more concentrates, normally replacing forages (Blaxter & Clapperton 1965; Johnson & Johnson 1995; Lovett *et al.* 2003; Beauchemin & McGinn 2005). Although concentrates may increase daily methane emissions, emissions per kilogram feed intake and per kilogram

product are almost invariably reduced. The net benefit, however, depends on reduced animal numbers or younger age at slaughter for beef animals and on how the practice affects emissions when producing and transporting the concentrates (Phetteplace *et al.* 2001; Lovett *et al.* 2006).

Other practices that can reduce CH₄ emissions include: adding oils to the diet (e.g. Machmüller *et al.* 2000; Jordan *et al.* 2004); improving pasture quality, especially in less developed regions, because it improves animal productivity and reduces the proportion of energy lost as CH₄ (Leng 1991; McCrabb *et al.* 1998; Alcock & Hegarty 2005); and optimizing protein intake to reduce N excretion and N₂O emissions (Clark *et al.* 2005).

(ii) *Specific agents and dietary additives*

A wide range of specific agents, mostly aimed at suppressing methanogenesis, have been proposed as dietary additives to reduce CH₄ emissions as follows:

- Ionophores are antibiotics that can reduce methane emissions (Benz & Johnson 1982; Van Nevel & Demeyer 1995; McGinn *et al.* 2004), but their effect may be transitory (Rumpler *et al.* 1986) and they have been banned in the EU.
- Halogenated compounds inhibit methanogenic bacteria (Wolin *et al.* 1964; Van Nevel & Demeyer 1995) but their effects, too, are often transitory and they can have side effects such as reduced intake.
- Probiotics, such as yeast culture, have shown only small, insignificant effects (McGinn *et al.* 2004), but selecting strains specifically for methane reducing ability could improve results (Newbold & Rode 2005).
- Propionate precursors such as fumarate or malate reduce methane formation by acting as alternative hydrogen acceptors (Newbold *et al.* 2002), but they elicit response only at high doses and are therefore expensive (Newbold *et al.* 2005).
- Vaccines against methanogenic bacteria are being developed but are not yet commercially available (Wright *et al.* 2004).
- Bovine somatotrophin (bST) and hormonal growth implants do not specifically suppress CH₄ formation, but by improving animal performance (Bauman 1992; Schmidely 1993), they can reduce emissions per kilogram of animal product (Johnson *et al.* 1991; McCrabb 2001).

(iii) *Longer term management changes and animal breeding*

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

(f) *Manure management*

Animal manures can release significant amounts of N₂O and CH₄ during storage, but the magnitude of these emissions varies. Methane emissions from manure stored in lagoons or tanks can be reduced by cooling or covering the sources, or by capturing the CH₄ emitted (Clemens & Ahlgrimm 2001; Monteny *et al.* 2001, 2006; Paustian *et al.* 2004). The manures can also be digested anaerobically to maximize retrieval of CH₄ as an energy source (Clemens & Ahlgrimm 2001; Clemens *et al.* 2006). Storing and handling the manures in solid rather than liquid form can suppress CH₄ emissions, but may increase N₂O formation (Paustian *et al.* 2004). Preliminary evidence suggests that covering manure heaps can reduce N₂O emissions (Chadwick 2005). For most animals worldwide, there is limited opportunity for manure management, treatment or storage—excretion happens in the field and handling for fuel or fertility amendment occurs when it is dry and methane emissions are negligible (Gonzalez-Avalos & Ruiz-Suarez 2001). To some extent, emissions from manure might be curtailed by altering feeding practices (Külling *et al.* 2003) or by composting the manure (Pattey *et al.* 2005), but these mechanisms and the system-wide influence have not been widely explored. Manures also release GHGs, notably N₂O, after application to cropland or deposition on grazing lands, but the practices for reducing these emissions are considered above in §2*a,b*.

(g) *Bioenergy*

Increasingly, agricultural crops and residues are seen as sources of feedstocks for energy to displace fossil fuels. A wide range of materials have been proposed for use, including grain, crop residue, cellulosic crops (e.g. switchgrass, sugarcane) and various tree species (Cerri *et al.* 2004; Edmonds 2004; Paustian *et al.* 2004; Sheehan *et al.* 2004; Dias de Oliveira *et al.* 2005; Eidman 2005). These products can be burned directly, but often are processed further to generate liquid fuels such as ethanol or diesel fuel (Richter 2004). These fuels release CO₂ when burned, but this CO₂ is of recent atmospheric origin (via photosynthesis) and displaces CO₂ which otherwise would have come from fossil C. The net benefit to atmospheric CO₂, however, depends on energy used in growing and processing the bioenergy feedstock (Spatari *et al.* 2005).

The interactions of an expanding bioenergy sector with other land uses, and impacts on agro-ecosystem services such as food production, biodiversity, soil and nature conservation, and carbon sequestration have not yet been adequately studied, but bottom up approaches (Smeets *et al.* 2007) and integrated assessment modelling (Hoogwijk 2004; Hoogwijk *et al.* 2005) offer opportunities to improve understanding. Latin America, sub-Saharan Africa and Eastern Europe are promising regions for bioenergy, with additional long-term contributions from Oceania and East and NE Asia. The technical potential for biomass production may be developed at low production costs in the range of 2 US\$ GJ⁻¹ (Rogner *et al.* 2000; Hoogwijk 2004).

Major transitions are required to exploit the large potential for bioenergy. Improving agricultural efficiency in developing countries is a key factor. It is

Table 2. Per-area annual mitigation potentials for each climate region for non-livestock mitigation options.

climate zone	activity	practice	CO ₂ (t CO ₂ ha ⁻¹ yr ⁻¹)			CH ₄ (t CO ₂ -eq. ha ⁻¹ yr ⁻¹)			N ₂ O (t CO ₂ -eq. ha ⁻¹ yr ⁻¹)			all GHG (t CO ₂ -eq. ha ⁻¹ yr ⁻¹)		
			mean estimate			mean estimate			mean estimate			mean estimate		
			low	high	low	low	high	low	low	high	low	low	high	high
cool-dry	croplands	agronomy	0.29	0.07	0.51	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.20	0.71
	croplands	nutrient management	0.26	-0.22	0.73	0.00	0.00	0.00	0.00	0.00	0.07	0.01	0.32	1.05
	croplands	tillage and residue management	0.15	-0.48	0.77	0.00	0.00	0.00	0.00	0.00	0.02	-0.04	0.09	0.86
	croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.82
	croplands	set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	0.00	0.00	2.30	0.00	4.60	7.90
	croplands	agroforestry	0.15	-0.48	0.77	0.00	0.00	0.00	0.00	0.00	0.02	-0.04	0.09	0.86
	grasslands	grazing, fertilization, fire	0.11	-0.55	0.77	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.79
	organic soils	restoration	36.67	3.67	69.67	-3.32	-0.05	-15.30	0.16	0.05	0.28	33.51	3.67	54.65
	degraded lands	restoration	3.45	-0.37	7.26	0.08	0.04	0.14	0.00	0.00	0.00	3.53	-0.33	7.40
	manure/biosolids	application	1.54	-3.19	6.27	0.00	0.00	0.00	0.00	0.17	1.30	1.54	-3.36	7.57
cool-moist	bioenergy	soils only	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
	croplands	agronomy	0.88	0.51	1.25	0.00	0.00	0.00	0.10	0.00	0.20	0.98	0.51	1.45
	croplands	nutrient management	0.55	0.01	1.10	0.00	0.00	0.00	0.07	0.01	0.32	0.62	0.02	1.42
	croplands	tillage and residue management	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	croplands	set-aside and LUC	3.04	1.17	4.91	0.02	0.00	0.00	2.30	0.00	4.60	5.36	1.17	9.51
	croplands	agroforestry	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	grasslands	grazing, fertilization, fire	0.81	0.11	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.11	1.50
	organic soils	restoration	36.67	3.67	69.67	-3.32	-0.05	-15.30	0.16	0.05	0.28	33.51	3.67	54.65
	degraded lands	restoration	3.45	-0.37	7.26	1.00	0.69	1.25	0.00	0.00	0.00	4.45	0.32	8.51
warm-dry	manure/biosolids	application	2.79	-0.62	6.20	0.00	0.00	0.00	0.00	-0.17	1.30	2.79	-0.79	7.50
	bioenergy	soils only	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	croplands	agronomy	0.29	0.07	0.51	0.00	0.00	0.00	0.10	0.00	0.20	0.39	0.07	0.71
	croplands	nutrient management	0.26	-0.22	0.73	0.00	0.00	0.00	0.07	0.01	0.32	0.33	-0.21	1.05
	croplands	tillage and residue management	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	croplands	set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	2.30	0.00	4.60	3.93	-0.07	7.90
	croplands	agroforestry	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	grasslands	grazing, fertilization, fire	0.11	-0.55	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.11	-0.55	0.77
	organic soils	restoration	73.33	7.33	139.33	-3.32	-0.05	-15.30	0.16	0.05	0.28	70.18	7.33	124.31
warm-moist	degraded lands	restoration	3.45	-0.37	7.26	0.00	0.00	0.00	0.00	0.00	0.00	3.45	-0.37	7.26
	manure/biosolids	application	1.54	-3.19	6.27	0.00	0.00	0.00	0.00	-0.17	1.30	1.54	-3.36	7.57
	bioenergy	soils only	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	croplands	agronomy	0.88	0.51	1.25	0.00	0.00	0.00	0.10	0.00	0.20	0.98	0.51	1.45
	croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	croplands	set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	2.30	0.00	4.60	3.93	-0.07	7.90

(Continued.)

Table 2. (Continued.)

climate zone	activity	practice	CO ₂ (t CO ₂ ha ⁻¹ yr ⁻¹)			CH ₄ (t CO ₂ -eq. ha ⁻¹ yr ⁻¹)			N ₂ O (t CO ₂ -eq. ha ⁻¹ yr ⁻¹)			all GHG (t CO ₂ -eq. ha ⁻¹ yr ⁻¹)		
			mean			mean			mean			mean		
			estimate	low	high	estimate	low	high	estimate	low	high	estimate	low	high
croplands	croplands	nutrient management tillage and residue man- agement	0.55	0.01	1.10	0.00	0.00	0.00	0.07	0.01	0.32	0.62	0.02	1.42
			0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89
croplands	croplands	water management set-aside and LUC	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
			3.04	1.17	4.91	0.02	0.00	0.00	2.30	0.00	4.60	5.36	1.17	9.51
croplands	croplands	agroforestry grazing, fertilization, fire restoration	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89
			0.81	0.11	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.11	1.50
organic soils	degraded lands	restoration	73.33	7.33	139.33	-3.32	-0.05	-15.30	0.16	0.05	0.28	70.18	7.33	124.31
			3.45	-0.37	7.26	0.00	0.00	0.00	0.00	0.00	0.00	3.45	-0.37	7.26
manure/biosolids	bioenergy	application soils only	2.79	-0.62	6.20	0.00	0.00	0.00	0.00	-0.17	1.30	2.79	-0.79	7.50
			0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89

still uncertain to what extent, and how fast, such transitions can be realized in different regions. Under less favourable conditions the (regional) bioenergy potential(s) could be quite low. In addition, it should be noted that technological developments (in conversion, as well as long-distance biomass supply chains such as those involving intercontinental transport of biomass-derived energy carriers) can dramatically improve competitiveness and efficiency of bioenergy (Hamelinck *et al.* 2004; Faaij 2006).

It is theoretically possible to increase the storage of carbon in long-lived agricultural products (e.g. strawboards, wool, leather and bioplastics) but with an increase in C held in these products from 37 to 83 Mt C yr⁻¹ over the past 40 years and assuming a first-order decay rate of 10–20% per year, this is estimated to be a global net annual removal of 3–7 Mt CO₂ from the atmosphere which is negligible when compared with other mitigation measures, and the option is not considered further here.

3. PER AREA/ANIMAL ESTIMATES OF AGRICULTURAL MITIGATION POTENTIAL

Many mitigation practices (§2) affect more than one GHG and the best available data have been used to estimate the impact on all GHGs of each practice. When assessing the impact of agriculture on changes in GHG emissions, it is important to consider the impacts on all GHGs together (Robertson *et al.* 2000; Smith *et al.* 2001; Gregorich *et al.* 2005). For the non-livestock-based options, ranges for per-area mitigation potentials for each practice are given for each GHG (in t CO₂-eq. ha⁻¹ yr⁻¹) for each of four climate regions in table 2. For soil carbon, estimates of soil C storage, CO₂ mitigation potential and the low and high values for the 95% confidence interval were derived using mixed-effect modelling on a large dataset of long-term agricultural soil carbon experiments from a variety of countries, though temperate studies were more prevalent in the database (Ogle *et al.* 2005). Estimates were made using this method for all land-based mitigation options except estimates for soils under bioenergy crops and agroforestry which are assumed to derive their mitigation potential mainly from cessation of soil disturbance; the figures for soils under bioenergy crops and agroforestry are therefore assumed to be the same as for no till within the same climatic region, and for organic soil estimates which are derived using estimated emissions under drained conditions from International Panel on Climate Change (IPCC) guidelines (IPCC 1997, 2003). Soil methane and nitrous oxide emission reduction potentials were derived as follows: (i) for organic soils, the mean of low- and high-nutrient status organic soil N₂O emission factors were used from the IPCC good practice guidelines for land use, land-use change and forestry (GPG LULUCF; IPCC 2003), where low and high values correspond to best estimates for low- and high-nutrient status organic soils and for CH₄, low, high and median emission values are taken from Le Mer & Roger (2001), (ii) N₂O figures for nutrient management were derived from US-EPA (2006) assuming a reduction in N to 80% current N

Table 3. Summary of biophysical reduction potential (proportion of an animal's enteric methane production) for enteric methane emissions due to (i) improved feeding practices, (ii) specific agents and dietary additives and (iii) longer term structural/management change and animal breeding.^a

AEZ regions	improved feeding practices ^b				specific agents and dietary additives ^c				longer term structural/management change and animal breeding ^d						
	dairy cows	beef cattle	sheep	dairy buffalo	non-dairy buffalo	dairy cows	beef cattle	sheep	dairy buffalo	non-dairy buffalo	dairy cows	beef cattle	sheep	dairy buffalo	non-dairy buffalo
North Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
South Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
West Europe	0.18	0.12	0.04			0.08	0.04	0.004			0.04	0.03	0.003		
East Europe	0.11	0.06	0.03			0.04	0.01	0.002			0.03	0.07	0.003		
Russian Federation	0.10	0.05	0.03			0.03	0.04	0.002			0.03	0.06	0.003		
Japan	0.17	0.11	0.04			0.08	0.09	0.004			0.03	0.03	0.003		
South Asia	0.04	0.02	0.02	0.04	0.02	0.01	0.01	0.0005	0.01	0.002	0.01	0.01	0.001	0.01	0.02
East Asia	0.10	0.05	0.03	0.10	0.05	0.03	0.05	0.002	0.03	0.012	0.03	0.06	0.003	0.03	0.07
West Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Southeast Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Central Asia	0.06	0.03	0.02	0.06	0.03	0.01	0.02	0.001	0.01	0.004	0.01	0.02	0.001	0.02	0.03
Oceania	0.22	0.14	0.06			0.08	0.08	0.004			0.05	0.03	0.004		
North America	0.16	0.11	0.04			0.11	0.09	0.004			0.03	0.03	0.003		
South America	0.06	0.03	0.02			0.03	0.02	0.001			0.02	0.03	0.002		
Central America	0.03	0.02	0.02			0.02	0.01	0.001			0.01	0.02	0.002		
East Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
West Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
North Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
South Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		
Middle Africa	0.01	0.01	0.01			0.003	0.004	0.0002			0.004	0.006	0.0004		

^a Values have been adjusted for non-additivity of individual practices.^b Includes replacing roughage with concentrate (Blaxter & Clapperton 1965; Moe & Tyrrell 1979; Johnson & Johnson 1995; Yan *et al.* 2000; Mills *et al.* 2003; Beauchemin & McGinn 2005; Lovett *et al.* 2006), improving forages/inclusion of legumes (Leng 1991; McCrabb *et al.* 1998; McCaughy *et al.* 1999; Woodward *et al.* 2001; Waghorn *et al.* 2002; Pinares-Patino *et al.* 2003; Alcock & Hegarty 2005) and feeding extra dietary oil (Dohme *et al.* 2000; Machmüller *et al.* 2000, 2003; Lovett *et al.* 2003; McGinn *et al.* 2004; Beauchemin & McGinn 2005; Jordan *et al.* 2006a,b).^c Includes bST (Johnson *et al.* 1991; Bauman 1992), growth hormones (McCrabb 2001), ionophores (Benz & Johnson 1982; Rumpel *et al.* 1986; Van Nevel & Demeyer 1996; McGinn *et al.* 2004), propionate precursors (McGinn *et al.* 2004; Beauchemin & McGinn 2005; Newbold *et al.* 2005; Wallace *et al.* 2005).^d Includes lifetime management of beef cattle (Johnson *et al.* 2002; Lovett & O'Mara 2002) and improved productivity through animal breeding (Ferris *et al.* 1999; Hansen 2000; Robertson & Waghorn 2002; Miglier *et al.* 2005).

application, (iii) N₂O figures for tillage and residue management were derived from US-EPA (2006 using figures for no-till), and (iv) global rice figures were taken directly from US-EPA (2006) so per area figures are not given.

For the livestock-based options, mitigation potentials (dairy cows, beef cattle, sheep, dairy buffalo and other buffalo) for reducing enteric methane emissions through improved feeding practices, specific agents and dietary additives, and longer term structural and management changes/animal breeding are shown in table 3. These estimates were derived using a model similar to that described in US-EPA (2006). The proportional reduction due to the application of each practice was estimated from reports in the scientific literature (see footnotes to table 3 for main references). These were adjusted for (i) the proportion of the animal's life where the practice was applicable, (ii) the technical adoption feasibility in a region, i.e. whether the farmers have the necessary knowledge, equipment, extension services, etc., to apply the practice (average dairy cow milk production in each region over the period 2000–2004 was used as an index of the level of technical efficiency in the region and to score a region's technical adoption feasibility), (iii) the proportion of animals in a region to which the measure can be applied (i.e. if the measure is already being applied to some animals as in the case of bST use in North America, it is considered to be applicable only to the proportion of animals not currently receiving the product), and (iv) non-additivity of simultaneous application of multiple measures. There is evidence in the literature that some measures are not additive when applied simultaneously, such as the use of dietary oils and ionophores, but this is probably not the case with most measures. However, we did account for the fact that once one measure is applied, the emissions base for the second measure is reduced and so on, and we also incorporated a further 20% reduction in mitigation potential to account for unknown non-additivity effects. Only measures considered feasible for a region were applied in that region (e.g. bST was not considered for European regions due to the ban on its use in the EU). It was assumed that total production of milk or meat was not affected by application of the practices, so that if a measure increased animal productivity, animal numbers were reduced in order to keep production constant.

As can be seen from tables 2 and 3, some of the mitigation measures operate predominantly on one GHG (e.g. dietary management of ruminants to reduce CH₄ emissions) while others have impacts on more than one (e.g. rice management). Some practices benefit more than one gas (e.g. set-aside/headland management) while others involve a trade-off between gases (e.g. restoration of organic soils). Table 2 also shows that the effectiveness of some mitigation practices differs between climate regions and can also differ within a climate region. A practice that is highly effective in reducing emissions at one site may be less effective or even counterproductive elsewhere. This means that there may be no universally applicable list of mitigation practices, but that any proposed practices will need to be tuned to individual agricultural systems present in specific climatic, edaphic and social settings.

The effectiveness of mitigation strategies also changes with time. Some practices, like those which elicit soil C gain, have diminishing effectiveness after several decades; others, such as methods that reduce energy use, may reduce emissions indefinitely. For example, Six *et al.* (2004) found a strong time dependency of emissions from no-till agriculture, in part owing to changing influence of tillage on N₂O emissions.

4. GLOBAL AND REGIONAL ESTIMATES OF AGRICULTURAL GHG MITIGATION POTENTIAL

The per-area/per-animal values for mitigation potential for each climate region, summarized in tables 2 and 3, were used to scale-up to regions and to the world by multiplying by the appropriate area under each climate in each region. The regions, climate zones within each region, areas of crop, crop mix and grassland in each climate zone in each region, area of cultivated organic soils within each climate zone in each region, the area of degraded land in each climate zone in each region and the total area of rice cultivation for each region were derived from the FAO Global Agro-Ecological Zones (AEZ; FAO/IIASA 2000), FAO Digital Soils Map of the World (FAO/UNESCO 2002) and FAO statistical (FAOSTAT 2006) databases as follows (figure 1):

- *Areas of each region:* Area of each region in the FAO AEZ database.
- *Areas of climate zones within each region.* Geographic information system (GIS) overlay of FAO AEZ regions with climate regions defined as follows: 'warm' for use with the mitigation factors in table 2 is defined by 'tropical' and 'subtropical' categories of the thermal climate dataset and 'cool' is defined by the 'temperate' categories of the thermal climate dataset. Boreal climates were excluded as little agriculture takes place in these zones. 'Dry' climates are defined by areas with 'severe moisture constraints or moisture constraints' in the climate constraints dataset with all other areas defined as 'moist'. The GIS overlay gives the areas in region in the cool-dry, cool-moist, warm-dry and warm-moist climate categories used in table 2.
- *Areas of crop, crop mix and grassland in each climate zone within each region in 2030.* The areas under these land uses in 2030 were projected by taking the proportional change in each area in 2030 in each region as projected by the IMAGE v. 2.2 model for the four IPCC Special Report on Emissions Scenarios (SRES) scenarios (Strengers *et al.* 2004). The area defined as 'mixture including crops' was added 50:50 to 'crops' and 'grassland' areas from the 'dominant land cover' dataset of FAO AEZ. This proportional change was then applied to the current areas of crops and grassland areas using a GIS overlay of the regional and climate data described above. This was done to normalize the areas between IMAGE v. 2.2 and FAO AEZ, since differences in classification between the two schemes could lead to misleading changes in land use.
- *Areas of cultivated organic soils in each climate zone within each region.* GIS overlay of areas under crops

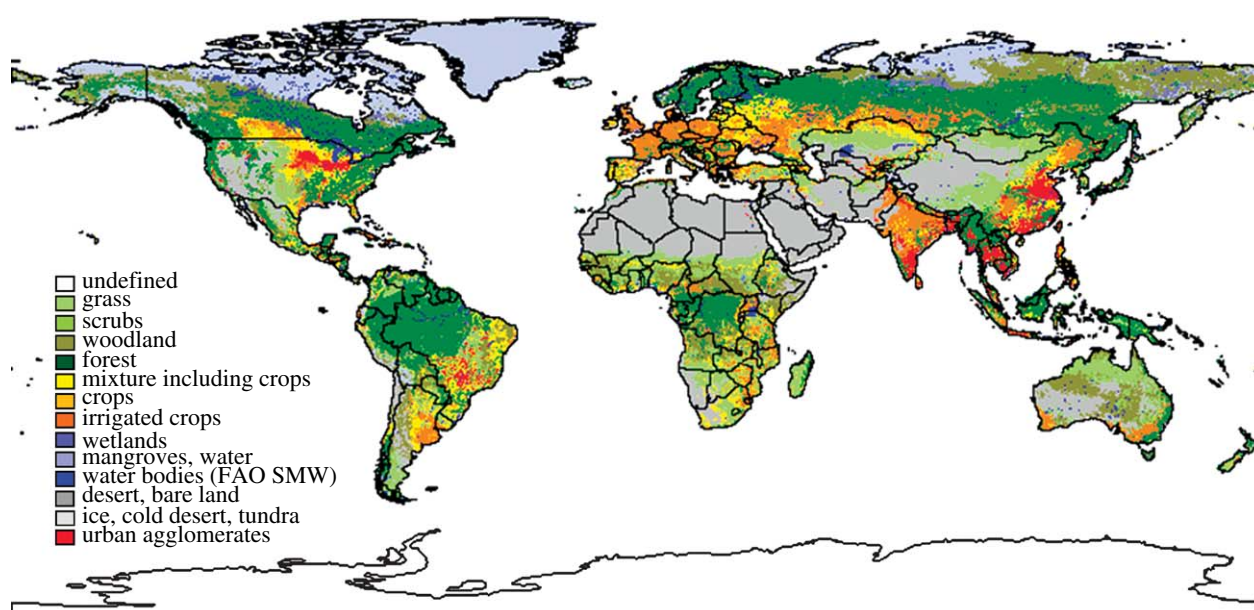


Figure 1. FAO AgroEcological Zones (AEZ) database; example of data held showing predominant land cover in each grid cell mapped onto the globe.

of the dominant land cover dataset of FAO AEZ and the FAO soils database, with organic soils defined by soil carbon contents greater than 30 kg m^{-2} to 100 cm depth.

- *Area of degraded land in each climate zone within each region.* GIS overlay of areas under crops from the dominant land cover dataset of FAO AEZ with the 'severe fertility constraints' and 'unsuitable for agriculture' categories of the 'soil fertility constraints' dataset of the FAO AEZ database.
- *Areas of rice cultivation within each region in 2030.* The proportional changes in rice area for each region, as projected by the IMPACT model (Rosegrant *et al.* 2001) for 2020 (the closest year to 2030 for which data were available), were used to project changes in harvested rice area for each region using 2004 areas given in the FAOSTAT database.

All data were converted to real-area projections and the areas in square metre were converted to hectare. Cropland mitigation options were applied to the total crop area (minus those under rice cultivation, irrigation, set-aside or on organic soils or degraded soils, since other mitigation occurred on these lands), total mitigation was taken as the mean of the agronomy, nutrient management and tillage/residue management effects on 95% of the land, plus improved biosolid management on 5% of the land. Grazing land management was applied on all grassland, restoration of organic soils and degraded lands on the croplands occurring on these areas as calculated above, bioenergy on the land projected to be available for bioenergy production in 2030 by the IMAGE v. 2.2 model (Strengers *et al.* 2004; Hoogwijk *et al.* 2005). Water management was applied only on the irrigable area identified in the FAO AEZ database, and agroforestry and set-aside only on projected surplus cropland in 2030. The total area of cropland and grassland for each region in 2030 for each SRES scenario is shown in table 4.

For emissions from livestock, total cattle, sheep and buffalo numbers in the various regions were obtained from FAOSTAT (2006). The cattle numbers for each region were broken down into numbers of dairy cattle and other cattle (owing to the different reduction potentials of both types) using FAOSTAT (2006). The biophysical emissions reduction potentials of the various practices were determined as described above. Estimated marginal costs of implementing each mitigation practice are shown in table 5.

In agriculture, there is a relationship between the amount paid for GHGs (i.e. the price of CO_2 equivalents) and the level of mitigation realized. The amount of mitigation achieved for a given carbon price can be used to define a marginal abatement curve (MAC) for each practice for each region. We used the MACs from US-EPA (2006) to define the level of implementation (economic potential) for each practice in each region, for carbon prices up to 20, up to 50 and up to 100 US\$ t $\text{CO}_2\text{-eq.}^{-1}$ practices as described below:

- The global soil carbon MACs were used for soil C changes under cropland management, grassland management, set-aside/agroforestry/land-use change, organic soil management and restoration of degraded lands for all regions, except North America where the US soil carbon MAC was used (Antle *et al.* 2001; McCarl & Schneider 2001; Lee *et al.* 2005; US-EPA 2006).
- The global soil N_2O MACs were used for N_2O emissions under cropland management, grassland management, set-aside/agroforestry/land-use change, organic soil management and restoration of degraded lands for all regions, except for North America where the US soil N_2O MAC was used, Europe where the EU-15 soil N_2O MAC was used, the Russian Federation where the soil N_2O MAC for the Former Soviet Union was used and East Asia where the soil N_2O MAC for China was used (US-EPA 2006).

Table 4. The total crop area and grassland area for each region for each SRES scenario as used in the mitigation analysis.

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

— The global MACs for livestock GHG emissions were used for all regions except for North America where the US MAC was used, East Asia where the MAC for China was used, South America where the MAC for Brazil was used and South Asia where the MAC for India was used (US-EPA 2006).

At low prices, the dominant strategies are those consistent with existing production such as change in tillage practice, fertilizer application, diet formulation and manure management, while higher prices elicit land use changes that displace existing production, such as biofuels (and afforestation), and allow the use of more costly animal feed-based mitigation options. The portfolio of mitigation strategies also varies over time owing to (i) the limited ecological capacity of the sequestration related strategies (i.e. their approach to a new carbon equilibrium over time) and (ii) the limited market penetration potential of capital intensive strategies like biofuels (which are constrained by the rate of turnover in energy processing plants, prospects and costs of retrofits, and energy product growth; Lee *et al.* 2005). It is important to note that while the most prevalent cost-mitigation quantity schedules are for single strategies (i.e. the amount of sequestration obtained as prices increase; as in Antle *et al.* 2001), it is not valid to sum these to gain a total mitigation potential due to resource competition among strategies. For example, Schneider & McCarl (2006) show that at higher prices, adding individual strategies can yield a total mitigation estimate that is as much as five times too large.

The global technical mitigation potential from agriculture by 2030, considering all gases, is estimated to be approximately 5500–6000 Mt CO₂-eq. yr⁻¹, with cumulative economic potentials of 1500–1600,

2500–2700 and 4000–4300 Mt CO₂-eq. yr⁻¹ at carbon prices of up to 20, up to 50 and up to 100 US\$ t CO₂-eq.⁻¹ (table 6). To put these figures in context, annual CO₂ emissions during the 1990s were approximately 29 000 Mt CO₂-eq. yr⁻¹, so agriculture could offset, at full biophysical potential, about 20% of total annual CO₂ emissions, with offsets of approximately 5, 9 and 14% at CO₂-eq. prices of up to 20, up to 50 and up to 100 US\$ t CO₂-eq.⁻¹.

Of these total mitigation potentials, approximately 89% is from reduced soil emissions of CO₂, approximately 9% from mitigation of methane and approximately 2% from mitigation of soil N₂O emissions (figure 2). For each region, the biophysical potential is defined by the sum of the potential due to (i) improvements in cropland management (mean of cropland management, tillage practice, nutrient and manure management and water management) for the whole cropland area in 2030, (ii) improved grazing land management for the whole grassland area in 2030, (iii) reduction of soil GHG emissions under bioenergy cropping, (iv) improved rice management of the whole rice area, (v) restoration of native ecosystems on currently cultivated organic soils, (vi) restoration of all degraded lands, (vii) improved livestock management (mean of mitigation due to feeds/inocula/breeding and systems) and (viii) improved manure management. Figure 3 shows the total mitigation potential per region using the mean per-area estimates of potential for all practices and GHGs considered together.

The low, mean and high regional estimates of the biophysical mitigation potential are shown in figure 4. The low and high estimates about the mean (e.g. low and high estimates are approximately 400 and

Table 5. Estimated costs (US\$ per t CO₂-eq.) of each mitigation option. (Nutrient management excludes precision farming, slow release fertilizers and nitrification inhibitors. Livestock additives exclude propionate precursors and halogenated compounds. Organic soil restoration includes the cost of restoration (est. 40 US\$ ha⁻¹) plus an opportunity cost associated with the crop that could be grown on the land of 300 US\$ ha⁻¹ (based on costs of 120 US\$ t dry grain⁻¹ and mean US wheat yields during the 1990s of 2.5 t dry grain ha⁻¹; FAOSTAT 2006); cost t CO₂-eq.⁻¹ is not very sensitive to these costs as the per-area mitigation is large (table 2).)

climate zone	activity	practice	\$ ha ⁻¹ yr ⁻¹	\$ t CO ₂ -eq. ⁻¹ yr ⁻¹
cool-dry	croplands	agronomy	20	51
	croplands	nutrient management	5	15
	croplands	tillage and residue management	5	30
	croplands	water management	—	2500
	croplands	rice management	10	1
	croplands	set-aside and LUC	10	3
	croplands	agroforestry	20	119
	grasslands	grazing, fertilization, fire	—	5
	organic soils	restoration	340	10
	degraded lands	restoration	50	14
	manure/biosolids	soil application	—	10
	bioenergy	soils only	—	15
	livestock	feeding	—	60
	livestock	additives	—	5
	livestock	breeding	—	50
	manure management	storage, biogas	0	200
cool-moist	croplands	agronomy	20	20
	croplands	nutrient management	5	8
	croplands	tillage and residue management	5	9
	croplands	water management	—	2500
	croplands	rice management	10	1
	croplands	set-aside and LUC	10	2
	croplands	agroforestry	20	38
	grasslands	grazing, fertilization, fire	—	5
	organic soils	restoration	340	10
	degraded lands	restoration	50	11
	manure/biosolids	soil application	—	10
	bioenergy	soils only	—	15
	livestock	feeding	—	60
	livestock	additives	—	5
	livestock	breeding	—	50
	manure management	storage, biogas	0	200
warm-dry	croplands	agronomy	20	51
	croplands	nutrient management	5	15
	croplands	tillage and residue management	5	14
	croplands	water management	—	2500
	croplands	rice management	10	1
	croplands	set-aside and LUC	10	3
	croplands	agroforestry	20	58
	grasslands	grazing, fertilization, fire	—	5
	organic soils	restoration	340	5
	degraded lands	restoration	50	15
	manure/biosolids	soil application	—	10
	bioenergy	soils only	—	15
	livestock	feeding	—	60
	livestock	additives	—	5
	livestock	breeding	—	50
	manure management	storage, biogas	0	200
warm-moist	croplands	agronomy	20	20
	croplands	nutrient management	5	8
	croplands	tillage and residue management	5	7
	croplands	water management	—	2500
	croplands	rice management	10	1
	croplands	set-aside and LUC	10	2
	croplands	agroforestry	20	28
	grasslands	grazing, fertilization, fire	—	5
	organic soils	restoration	340	5
	degraded lands	restoration	50	15

(Continued.)

Table 5. (Continued.)

climate zone	activity	practice	\$ ha ⁻¹ yr ⁻¹	\$ t CO ₂ -eq. ⁻¹ yr ⁻¹
	manure/biosolids	soil application	—	10
	bioenergy	soils only	—	15
	livestock	feeding	—	60
	livestock	additives	—	5
	livestock	breeding	—	50
	manure management	storage, biogas	0	200

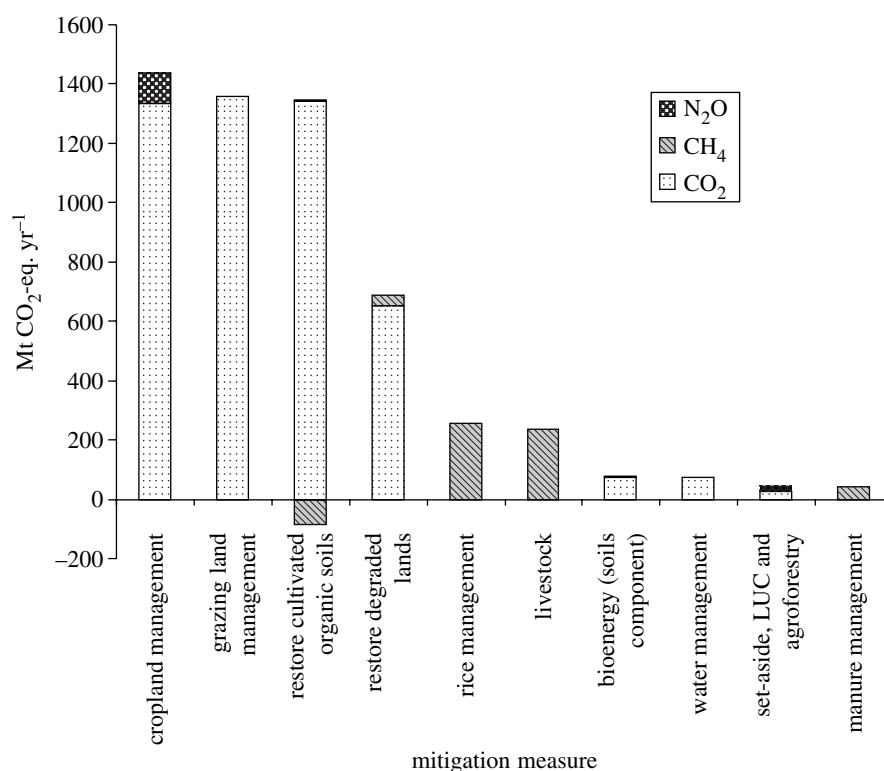


Figure 2. Global biophysical mitigation potential (Mt CO₂-eq. yr⁻¹) by 2030 of each agricultural management practice showing the impacts of each practice on each GHG stacked to give the total for all GHGs combined (B1 scenario shown though the pattern is similar for all SRES scenarios).

10 600 Mt CO₂-eq. yr⁻¹, respectively about the mean estimate of 5500 Mt CO₂-eq. yr⁻¹) are largely determined by uncertainty in the per-area estimate for the mitigation measure. For soil CO₂ emission reduction, this arises from the mixed linear effects model used to derive the mitigation potentials, accounting for approximately 89% of the total potential. It is important to note that the most appropriate agricultural mitigation response will vary at the regional level and different portfolios of strategies will be developed in different regions and in countries within a region.

Estimates in the IPCC Second Assessment Report (SAR; IPCC 1996) suggested that 400–800 Mt C yr⁻¹ (equivalent to approximately 1400–2900 Mt CO₂-eq. yr⁻¹) could be sequestered in global agricultural soils with a finite capacity saturating after 50–100 years. In addition, the SAR concluded that 300–1300 Mt C (equivalent to approximately 1100–4800 Mt CO₂-eq. yr⁻¹) from fossil fuels could be offset by using 10–15% of agricultural land to grow energy crops, with crop residues potentially contributing 100–200 Mt C (equivalent to approximately 400–700 Mt CO₂-eq. yr⁻¹) to fossil fuel offsets if recovered and burned.

Table 6. Estimates of the global agricultural GHG mitigation potential (Mt CO₂-eq. yr⁻¹) by 2030 at a range of prices of CO₂-eq. for the four SRES scenarios.

scenario	price range (US\$ t CO ₂ -eq. ⁻¹)			biophysical potential
	up to 20	up to 50	up to 100	
B1	1540	2530	4030	5480
A1b	1590	2600	4170	5670
B2	1630	2670	4330	5840
A2	1640	2690	4340	5950

It was noted that burning residues for bioenergy might increase N₂O emissions but this effect was not quantified. The SAR concluded that CH₄ emissions from agriculture could be reduced by 15–56%, mainly through improved nutrition of ruminants and better management of paddy rice. It was also estimated that improvements in agricultural management could reduce N₂O emissions by 9–26%. The SAR noted that GHG mitigation techniques will not be adopted by land managers unless they improve profitability, but that some measures are adopted for reasons other than

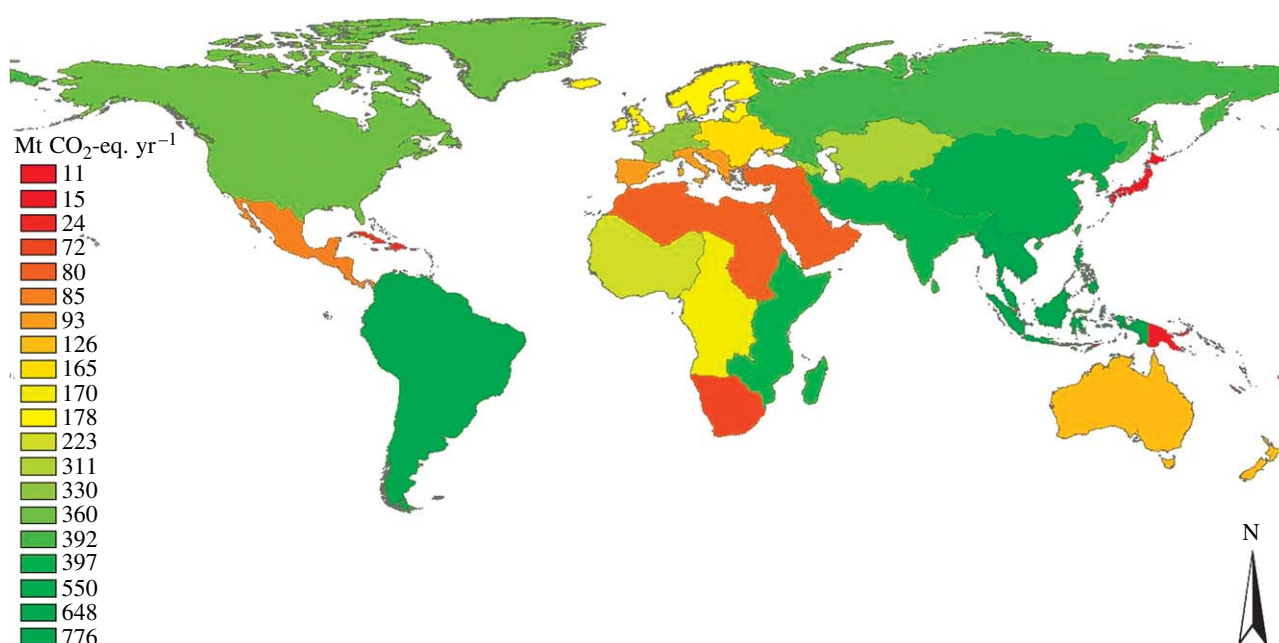


Figure 3. Total biophysical mitigation potentials (all practices, all GHGs: Mt CO₂-eq. yr⁻¹) for each region by 2030, showing mean estimates (B1 scenario shown though the pattern is similar for all SRES scenarios).

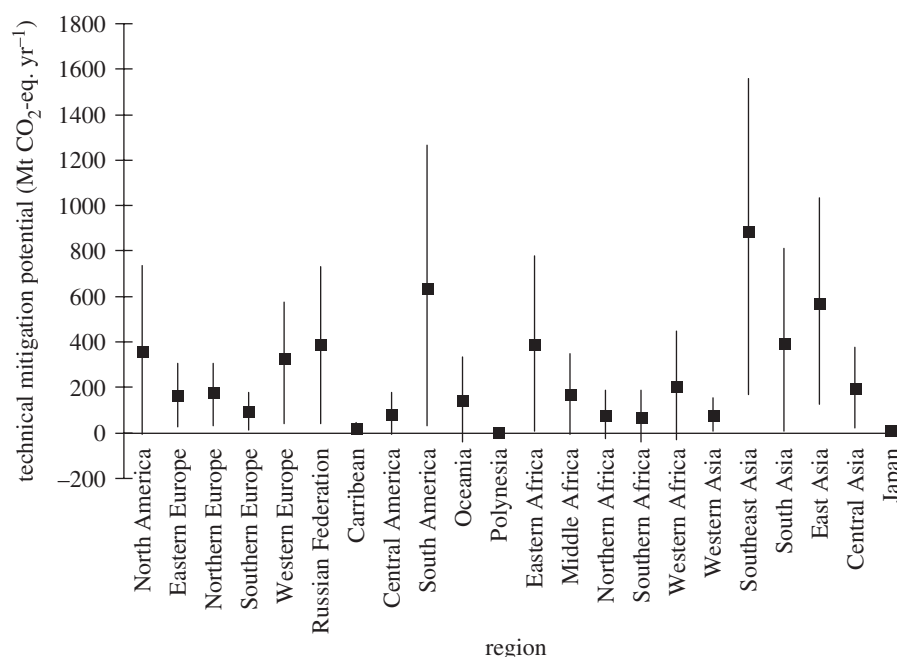


Figure 4. Total biophysical mitigation potentials (all practices, all GHGs: Mt CO₂-eq. yr⁻¹) for each region by 2030, showing the best estimate using the mean per-area mitigation potential (square) and the range of estimates derived using the low- and high-per-area mitigation potentials (line; B1 scenario shown though the pattern is similar for all SRES scenarios).

for climate mitigation. Options that both reduce GHG emissions and increase productivity are more likely to be adopted than those which only reduce emissions.

In the IPCC Third Assessment Report (TAR; IPCC 2001), estimates of agricultural mitigation potential by 2020 were 350–750 Mt C yr⁻¹ (approximately 1300–2750 Mt CO₂ yr⁻¹). It was noted that the range was mainly caused by large uncertainties about CH₄, N₂O and soil-related emissions of CO₂ and that most reductions will cost between US\$ 0 and 100 tC-eq.⁻¹ (approximately US\$ 0–27 t CO₂-eq.⁻¹) with limited opportunities for negative net direct cost options. The analysis of agriculture in the TAR included only conservation tillage, soil C sequestration, nitrogen

fertilizer management, enteric methane reduction and rice paddy irrigation and fertilizers. The estimate for global mitigation potential was not broken down by region or practice.

These estimates, based on the best data currently available, are comparable with previous estimates, but give for the first time, an assessment of the agricultural mitigation potential for all gases, for all regions, at a range of potential carbon costs. The comparison of previous estimates of agricultural mitigation potential with comparable figures from this study is summarized in table 7. Given the differences in areas considered and the different assumptions made in previous studies, the estimates in this study are strikingly similar.

Table 7. Comparison of the estimates of agricultural GHG mitigation potential (Mt CO₂-eq. yr⁻¹) by 2030 with previous global and regional estimates, for combinations of practices, gases considered and different marginal costs assumed.

study	region—practice	gas considered	price of CO ₂	previous mitigation potential estimate (Mt CO ₂ -eq. yr ⁻¹)	equivalent mitigation potential estimate from this study (Mt CO ₂ -eq. yr ⁻¹)
IPCC (1996; TAR) ^a	globe—soil sequestration	CO ₂ only	biophysical potential	1400–2900	1370–3880
Lal (2003, 2004a) ^a	globe—soil sequestration	CO ₂ only	biophysical potential	3300 ± 1100	1370–3880
IPCC (2000; SR-LULUCF) ^b	globe—soil sequestration	CO ₂ only	biophysical potential	1470	1370–1470
Manne & Richels (2004) ^c	globe—soil sequestration	CO ₂ only	US\$ 27 t CO ₂ -eq. ⁻¹	1700	1370–1470
IPCC (2001; TAR) ^d	globe—all measures	CO ₂ , CH ₄ and N ₂ O	US\$ 27 t CO ₂ -eq. ⁻¹	1300–2750	1540–1640
Caldeira <i>et al.</i> (2004) ^e	globe—all measures	CO ₂ , CH ₄ and N ₂ O	biophysical potential	4510	4300–5950
Lal & Bruce (1999) ^f	globe—croplands only	CO ₂ only	biophysical potential	1580–2090	1980–2140
Conant <i>et al.</i> (2001) ^g	globe—permanent pastures only	CO ₂ only	biophysical potential	6860	1360–1560
Squires <i>et al.</i> (1995) ^h	globe—desertification control only	CO ₂ only	biophysical potential	3670	approximately 650
Lal (2001) ^h	globe—desertification control only	CO ₂ only	biophysical potential	730–1470	approximately 650
US-EPA (2006) ⁱ	globe—soil N ₂ O only	N ₂ O only	US\$ 100 t CO ₂ -eq. ⁻¹	200	120
US-EPA (2006) ⁱ	globe—rice CH ₄ only	CH ₄ only	US\$ 100 t CO ₂ -eq. ⁻¹	230	230
US-EPA (2006) ⁱ	globe—livestock CH ₄ only	CH ₄ only	US\$ 100 t CO ₂ -eq. ⁻¹	200–300	210
US-EPA (2006) ⁱ	US—livestock CH ₄ only	CH ₄ only	US\$ 20 t CO ₂ -eq. ⁻¹	40	32
US-EPA (2006) ⁱ	China—livestock CH ₄ only	CH ₄ only	US\$ 50 t CO ₂ -eq. ⁻¹	45	42
US-EPA (2006) ⁱ	India—livestock CH ₄ only	CH ₄ only	US\$ 10 t CO ₂ -eq. ⁻¹	17	12
US-EPA (2006) ⁱ	Brazil—livestock CH ₄ only	CH ₄ only	US\$ 30 t CO ₂ -eq. ⁻¹	23	46 (for all South America)
Smith <i>et al.</i> (2000) ^j	Europe (excluding Russia)	CO ₂ only	limited by suitability	205	120, 160, 240
Lal <i>et al.</i> (2003) ^k	US—croplands only	CO ₂ only	biophysical potential	165–360	140
Lal <i>et al.</i> (2003) ^k	US—grasslands only	CO ₂ only	biophysical potential	48–257	60
Lal <i>et al.</i> (2003) ^k	US—land conversion only	CO ₂ only	biophysical potential	77–282	—
Lal <i>et al.</i> (2003) ^k	US—land restoration only	CO ₂ only	biophysical potential	92–220	30
Sperow <i>et al.</i> (2003) ^k	US—croplands only	CO ₂ only	biophysical potential	220–257	140
Boehm <i>et al.</i> (2004) ^l	Canada—all agriculture	CO ₂ only	biophysical potential	16.5–29.9	—
Boehm <i>et al.</i> (2004) ^l	Canada—all agriculture	CO ₂ , CH ₄ and N ₂ O	biophysical potential	4–15.6	—
Lal (2004c) ^m	China	CO ₂ only	biophysical potential	436–829	425
Lal (2004d) ^l	Central Asia	CO ₂ only	biophysical potential	approx. 60 ± 30	—
Lal (2004e) ⁿ	India	CO ₂ only	biophysical potential	approx. 160 ± 18	330 (for all South Asia)
Lal (2005) ^o	Brazil	CO ₂ only	biophysical potential	400	570 (for all South America)

^a Economic potentials estimated here at up to 20 US\$ t CO₂-eq.⁻¹ of approximately 1300–1400 Mt CO₂-eq. yr⁻¹ rising to 2200–2400 and 3600–3900 Mt CO₂-eq. yr⁻¹ at up to 50 and up to 100 US\$ t CO₂-eq.⁻¹, respectively.

^b IPCC LULUCF (2000) estimate is based on C stock change in croplands, grazing lands, agroforestry, rice paddies and urban lands. Compared to estimates here at 0–20 US\$ t CO₂-eq.⁻¹.

^c Manne & Richels (2004) estimates for 2010 assuming a marginal cost of US\$ 100 t C⁻¹ (equivalent to US\$ 27 t CO₂-eq.⁻¹); figures from this study are from closest comparable price range of 0–20 US\$ t CO₂-eq.⁻¹.

^d IPCC TAR (2001) estimates for 2020 assuming a marginal cost of US\$ 100 t C⁻¹ (equivalent to US\$ 27 t CO₂-eq.⁻¹); figures from this study are from closest comparable price range of 0–20 US\$ t CO₂-eq.⁻¹.

^e Caldeira *et al.* (2004) estimates are for all gases for practices: enteric fermentation, rice cultivation, biomass burning, animal waste treatment and agricultural soils over a 0–20 year time horizon; estimates here are between the estimates at 0–100 US\$ t CO₂-eq.⁻¹ and total biophysical potential (up to 6000 Mt CO₂-eq. yr⁻¹).

^f Estimate for croplands only; comparable figure is for the biophysical potential of cropland management, plus restoration of degraded croplands.^{67g}

(Continued.)

Table 7. (Continued.)

^g	The Conant <i>et al.</i> (2001) estimate for permanent pasture only is much larger than many estimates for all agricultural mitigation measures combined; as such, it may be unrealistically high.
^h	Comparable estimates for this study are for restoration of degraded lands.
ⁱ	All US-EPA (2006) estimates are for 2020. Global estimates are for prices of 100 US\$ t CO ₂ -eq. ⁻¹ . US-EPA (2006) estimate for Brazil should be equivalent to approximately 60% the estimate from this study for South America. Rice figures are taken directly from US-EPA (2006).
^j	Comparable figures for this study are quoted for prices of up to 20, up to 50, up to 100 US\$ t CO ₂ -eq. ⁻¹ , respectively. Other studies from individual countries are not included as there is no comparable area in the present study.
^k	From this study, biophysical potentials used for all North America (US plus Canada) from cropland management, grassland management and restoration of degraded lands.
^l	No comparable area in the present study.
^m	Estimate in this study for East Asia.
ⁿ	Estimate in this study for South Asia; covers a larger area than just India.
^o	Lal (2005) estimates that 180 Mt CO ₂ yr ⁻¹ could be sequestered in the soils of Brazil, plus a further 220 Mt CO ₂ yr ⁻¹ mitigated by erosion prevention; estimate from this study from South America; covers a larger area than just Brazil.

In addition to GHG emission reduction, agricultural land can provide feedstock for bioenergy production. Bioenergy to replace fossil fuels can be generated from agricultural feedstocks including by-products of agricultural production and dedicated energy crops. For residues from agriculture, the energy production and GHG mitigation potentials depend on yield/product ratios and the total agricultural land area, as well as type of production system. Less intensive management systems require reuse of residues for maintaining soil fertility. Intensively managed systems not only allow for higher usage rates of residues but also usually deploy crops with lower crop-to-residue ratios. Estimates of energy production potential from agricultural residues vary between 15 and 70 EJ yr⁻¹. The latter figure is based on the regional *production* of food (in 2003) multiplied by harvesting or processing factors and the assumed recoverability factors. These figures do not subtract the potential alternative use for agricultural residues. As indicated by Junginger *et al.* (2001), competing applications can reduce the net availability of agricultural residues for energy or materials significantly. In addition, the expectations about future availability of residues from agriculture vary widely among the studies. Dried dung can also be used as an energy feedstock. The total estimated contribution could be 5–55 EJ yr⁻¹ worldwide, with the range defined by current global use at the low end, to technical potential at the high end. Usage in the longer term is uncertain because dung is considered a 'poor man's fuel'.

Organic wastes and residues together could supply 20–125 EJ yr⁻¹ by 2050, with organic wastes potentially having an important role. The potential fossil fuel offset for 2050 from agricultural organic wastes and residues when used for energy production, assuming that it replaces gas, its energy content is 20 GJ t⁻¹ of dry biomass (IPCC 2001) and 1 t of dry biomass used to generate electricity prevents 0.28 t C from gas from being emitted to the atmosphere (Cannell 2003), is 1000–6000 Mt CO₂-eq. yr⁻¹. If we assume linear uptake, a rough estimate of the potential by 2030 is 600–4000 Mt CO₂-eq. yr⁻¹.

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

Energy cropping on current agricultural land could, with projected technological progress, deliver over 800 EJ yr⁻¹ without jeopardizing the world's food supply. Various studies have arrived at differing figures for the potential contribution of biomass to future global energy supplies ranging from below 100 EJ yr⁻¹ to above 400 EJ yr⁻¹ in 2050. A recent study (Sims *et al.* 2006), using lower per-area yield assumptions and bioenergy crop areas projected by the IMAGE v. 2.2 model, suggests more modest potentials by 2025. The differences among studies are largely attributable to

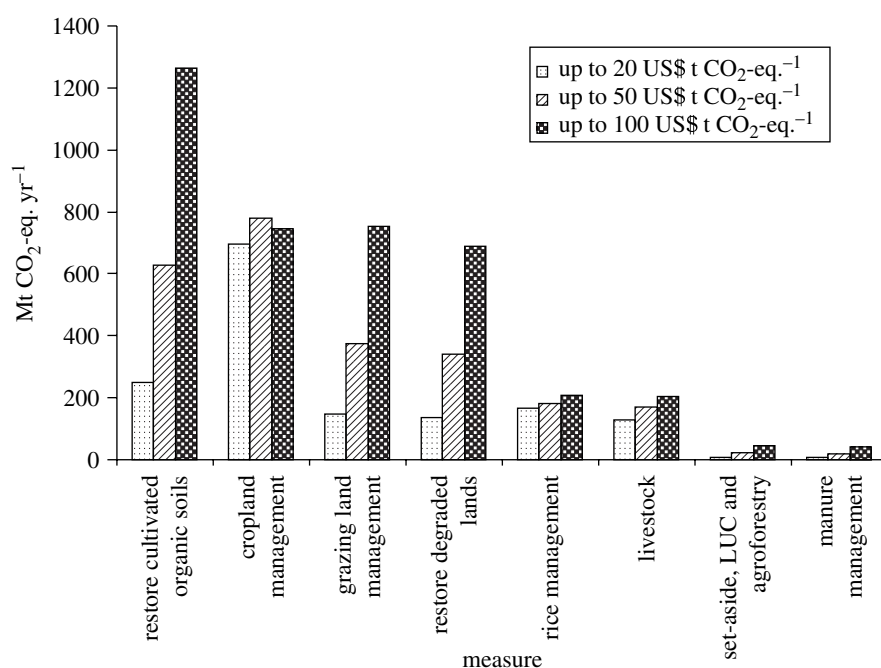


Figure 5. Potential for agricultural GHG mitigation (excluding bioenergy and improved energy efficiency) at a range of prices of CO₂-eq. (B1 scenario shown though the pattern is similar for all SRES scenarios).

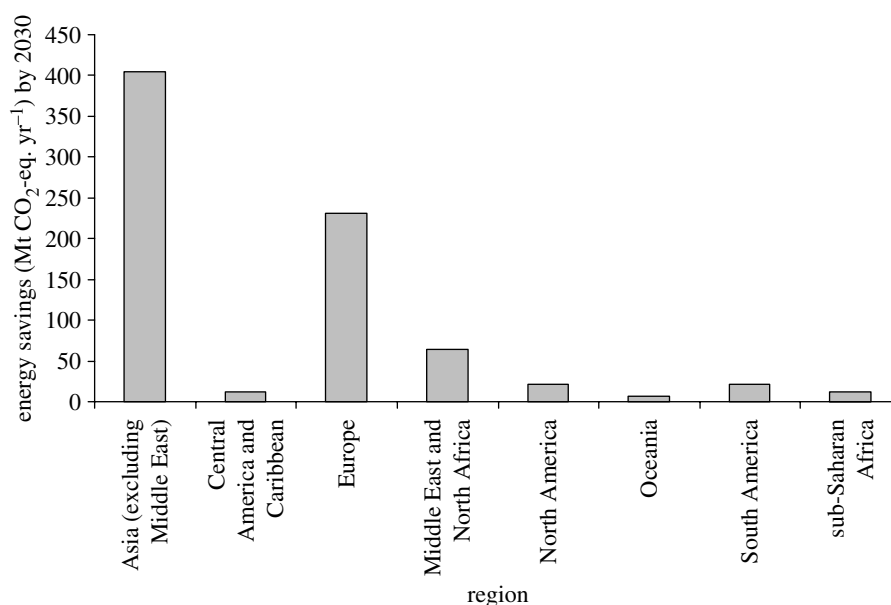


Figure 6. Potential for GHG mitigation through improved energy efficiency in agriculture by 2030, though the mitigation is usually counted in the user sectors.

uncertainty in land availability and yield levels. The potential fossil fuel offset from dedicated energy crops by 2050, if assumed to supply 100–400 EJ yr⁻¹ by replacing gas, and assuming 20 GJ t⁻¹ of dry biomass (IPCC 2001) and that 1 t of dry biomass used to generate electricity prevents 0.28 t C from gas from being emitted to the atmosphere (Cannell 2003), is 5000–20 000 Mt CO₂-eq. yr⁻¹. If we assume linear uptake, a rough estimate of the potential by 2030 is 3000–12 000 Mt CO₂-eq. yr⁻¹.

Total GHG mitigation potential from agricultural bioenergy by 2030, including dedicated energy crops and agricultural wastes and residues is 4000–16 000 Mt CO₂-eq. yr⁻¹. The economic analysis presented above, using figures for bioenergy uptake from Lee *et al.* (2005),

suggests that 4, 14 and 100% of the biophysical potential would be implemented at 0–20, 0–50, 0–100 US\$ t CO₂-eq., respectively. Assuming that 16 000 Mt CO₂-eq. yr⁻¹ represents the total biophysical potential, economic mitigation potential of biomass energy from agriculture at 0–20, 0–50, 0–100 US\$ t CO₂-eq. is estimated to be 640, 2240 and 16 000 Mt CO₂-eq. yr⁻¹ accounting for 30, 90–100 and 500% of all other agricultural GHG mitigation measures combined, respectively. The bioenergy mitigation potential is compared to other agricultural GHG mitigation options at a range of prices of CO₂-eq. in figure 5.

Like mitigation from bioenergy, where the mitigation effect is usually counted in the user sector, enhanced energy efficiency (i.e. through reduced fossil fuel) is also

possible in the agricultural sector. Figure 6 shows the potential for energy savings by 2030 in different world regions, derived by summing estimates from individual countries. These were calculated as emission savings which were calculated as follows:

- Primary crop and country specific production data collated from FAO statistics
- Calories contained in primary crop production computed by multiplying production by calories per primary crop commodity using coefficients from FAO
- Fertilizer emissions computed by multiplying fertilizer quantities (FAO, country specific) with emission coefficients from Schneider & McCarl (2006) and World Resources Institute (<http://earthtrends.wri.org/>)
- Machinery emissions computed by multiplying tractor and harvester numbers (FAO, country specific) with respective emission coefficients from Schneider & McCarl (2006) and World Resources Institute (<http://earthtrends.wri.org/>)
- Labour emissions computed by multiplying agricultural labour numbers (FAO, country specific) with residential carbon emission coefficients from Schneider & McCarl (2006) and World Resources Institute (<http://earthtrends.wri.org/>)
- Emission intensity per calorie computed by summing fertilizer, machinery and labour emissions and dividing those by the total calories contained in primary crop products
- Emissions intensity targets computed. These targets are different for different regions and reflect the lowest observed emission intensities within a group of similar countries. However, emission intensity targets are constrained to be not below 40% of the actual emission intensity
- Emission savings from lower emission intensities computed by multiplying emission intensity differences with the total calories contained in primary crop products. Aggregate to macroregions.

Improved energy efficiency potentially delivers an additional global GHG mitigation potential of 770 Mt CO₂-eq. yr⁻¹ by 2030.

5. FURTHER CONSIDERATIONS

Many agricultural mitigation activities show synergy with the goals of sustainability, and many explicitly influence the constituents of sustainable development, including social, economic and environmental indicators. Other mitigation options have more uncertain impact on sustainable development. There are interactions between mitigation and adaptation in the agricultural sector. Mitigation and adaptation may occur simultaneously, but differ in their spatial and geographical characteristics. The main climate change benefits of mitigation actions taken now will emerge only over decades, but where the drivers achieve other policy objectives (e.g. to meet air or water quality standards) there may also be short-term benefits. Conversely, actions to enhance adaptation to climate change impacts, even in the short term, will have consequences at all timescales from short- to long term (Smith *et al.* 2007).

In many regions, non-climate policies, including macroeconomic, agricultural and environmental policies, have greatest impact on agricultural mitigation options. These are reviewed elsewhere (Smith *et al.* 2007). Some evidence suggests that, despite significant biophysical potential for GHG mitigation in agriculture, very little progress has been made since 1990 and little is expected by 2010. There are barriers to implementation which may not be overcome without policy/economic incentives (Smith *et al.* 2005a).

Many agricultural mitigation options have both co-benefits (in terms of improved efficiency, reduced cost and environmental co-benefits) and trade-offs. Balancing the co-benefits with potential adverse effects is necessary for successful implementation. Many agricultural GHG mitigation options could be implemented immediately without further technological development, but a few options are still undergoing technological development. Technological development has been shown to be a key driver in ensuring the efficacy of agricultural mitigation measures (Smith *et al.* 2005b). Communication and capacity building is also important. In particular, it is important that farm managers understand the issue of climate change or potential opportunities so as to be motivated to act, the technologies and their application, and the costs and benefits of mitigation actions. The long-term outlook for GHG mitigation in agriculture suggests that there is significant potential, but many uncertainties, both price- and non-price related, will determine the level of implementation. These further considerations are discussed in detail elsewhere (Smith *et al.* 2007).

6. CONCLUDING REMARKS

There are significant opportunities for GHG mitigation in agriculture, but for the potential to be realized numerous barriers need to be overcome. Many recent studies have shown that actual levels of GHG mitigation are far below the technical potential for these measures (e.g. Smith *et al.* 2005a). The gap between technical potential and realized GHG mitigation occurs due to barriers to implementation, including climate and non-climate policy, and institutional, social, educational and economic constraints. The mix of agricultural mitigation options that are adopted in the future will also depend upon the price of carbon dioxide equivalents. The total biophysical potential of approximately 5500–6000 Mt CO₂-eq. yr⁻¹ would never be realized due to these constraints, but with appropriate policies, education and incentives, it may be possible for agriculture to make a significant contribution to climate mitigation by 2030. To put the figures calculated here in context, annual CO₂ emissions during the 1990s were approximately 29 000 Mt CO₂-eq. yr⁻¹, so agriculture could offset, at full biophysical potential, about 20% of total annual CO₂ emissions, with offsets of approximately 5, 9 and 14% at CO₂-eq. prices of up to 20, up to 50 and up to 100 US\$ t CO₂-eq.⁻¹.

REFERENCES

- Albrecht, A. & Kandji, S. T. 2003 Carbon sequestration in tropical agroforestry systems. *Agric. Ecosyst. Environ.* **99**, 15–27. (doi:10.1016/S0167-8809(03)00138-5)

- Alcock, D. & Hegarty, R. S. 2005 Effects of pasture improvement on productivity, gross margin and methane emissions of grazing sheep enterprises. In *Second Int. Conf. on Greenhouse Gases and Animal Agriculture, Working Papers* (eds C. R. Soliva, J. Takahashi & M. Kreuzer), pp. 127–130. Zurich, Switzerland: ETH.
- Alvarez, R. 2005 A review of nitrogen fertilizer and conservative tillage effects on soil organic storage. *Soil Use Manage.* **21**, 38–52. (doi:10.1079/SUM2005291)
- Anderson, T. L., Charlson, R. J., Schwartz, S. E., Knutti, R., Boucher, O., Rodhe, H. & Heintzenberg, J. 2003 Climate forcing by aerosols—a hazy picture. *Science* **300**, 1103–1104. (doi:10.1126/science.1084777)
- Andreae, M. O. 2001 The dark side of aerosols. *Nature* **409**, 671–672. (doi:10.1038/35055640)
- Andreae, M. O. & Merlet, P. 2001 Emission to trace gases and aerosols from biomass burning. *Global Biogeochem. Cycles* **15**, 955–966. (doi:10.1029/2000GB001382)
- Andreae, M. O., Jones, C. D. & Cox, P. M. 2005 Strong present-day aerosol cooling implies a hot future. *Nature* **435**, 1187. (doi:10.1038/nature03671)
- Antle, J. M., Capalbo, S. M., Mooney, S., Elliott, E. T. & Paustian, K. H. 2001 Economic analysis of agricultural soil carbon sequestration: an integrated assessment approach. *J. Agric. Resour. Econ.* **26**, 344–367.
- Aulakh, M. S., Wassmann, R., Bueno, C. & Rennenberg, H. 2001 Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. *Plant Soil* **230**, 77–86. (doi:10.1023/A:1004817212321)
- Barthès, B., Azontonde, A., Blanchart, E., Girardin, C., Villenave, C., Lesaint, S., Oliver, R. & Feller, C. 2004 Effect of a legume cover crop (*Mucuna pruriens* var. *utilis*) on soil carbon in an Ultisol under maize cultivation in southern Benin. *Soil Use Manage.* **20**, 231–239. (doi:10.1079/SUM2004235)
- Batjes, N. H. 1999 Management options for reducing CO₂-concentrations in the atmosphere by increasing carbon sequestration in the soil. Dutch National Research Programme on Global Air Pollution and Climate Change report 410-200-031 and ISRIC technical paper 30, International Soil Reference and Information Centre, Wageningen, The Netherlands.
- Bauman, D. E. 1992 Bovine somatotropin: review of an emerging animal technology. *J. Dairy Sci.* **75**, 3432–3451.
- Beauchemin, K. & McGinn, S. 2005 Methane emissions from feedlot cattle fed barley or corn diets. *J. Anim. Sci.* **83**, 653–661.
- Benz, D. A. & Johnson, D. E. 1982 The effect of monensin on energy partitioning by forage fed steers. *Proc. West Section Am. Soc. Anim. Sci.* **33**, 60.
- Beringer, J., Hutley, L. B., Tapper, N. J., Coutts, A., Kerley, A. & O'Grady, A. P. 2003 Fire impacts on surface heat, moisture and carbon fluxes from a tropical savanna in northern Australia. *Int. J. Wildland Fire* **12**, 333–340. (doi:10.1071/WF03023)
- Berndes, G., Hoogwijk, M. & van den Broek, R. 2003 The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass Bioenergy* **25**, 1–28. (doi:10.1016/S0961-9534(02)00185-X)
- Blaxter, K. L. & Clapperton, J. L. 1965 Prediction of the amount of methane produced by ruminants. *Br. J. Nutr.* **19**, 511–522. (doi:10.1079/BJN19650046)
- Boadi, D., Benchaar, C., Chiquette, J. & Massé, D. 2004 Mitigation strategies to reduce enteric methane emissions from dairy cows: update review. *Can. J. Anim. Sci.* **84**, 319–335.
- Boehm, M., Junkins, B., Desjardins, R., Kulshreshtha, S. & Lindwall, W. 2004 Sink potential of Canadian agricultural soils. *Clim. Change* **65**, 297–314. (doi:10.1023/B:CLIM.0000038205.09327.51)
- Bouwman, A. 2001 *Global estimates of gaseous emissions from agricultural land*. Rome, Italy: FAO.
- Bruce, J. P., Frome, M., Haïtes, E., Janzen, H., Lal, R. & Paustian, K. 1999 Carbon sequestration in soils. *J. Soil Water Conserv.* **54**, 382–389.
- Cai, Z. C. & Xu, H. 2004 Options for mitigating CH₄ emissions from rice fields in China. In *Material circulation through agro-ecosystems in East Asia and assessment of its environmental impact* (ed. Y. Hayashi) *NIAES Series*, no. 5, pp. 45–55. Tsukuba, Japan: NIAES.
- Cai, Z. C., Tsuruta, H. & Minami, K. 2000 Methane emissions from rice fields in China: measurements and influencing factors. *J. Geophys. Res.* **105**, 17 231–17 242. (doi:10.1029/2000JD900014)
- Cai, Z. C., Tsuruta, H., Gao, M., Xu, H. & Wei, C. F. 2003 Options for mitigating methane emission from a permanently flooded rice field. *Global Change Biol.* **9**, 37–45. (doi:10.1046/j.1365-2486.2003.00562.x)
- Caldeira, K., Morgan, M. G., Baldocchi, D., Brewer, P. G., Chen, C. T. A., Nabuurs, G. J., Nakicenovic, N. & Robertson, G. P. 2004 A portfolio of carbon management options. In *The global carbon cycle. Integrating humans, climate, and the natural world* (eds C. B. Field & M. R. Raupach), pp. 103–129. Washington DC: Island Press.
- 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. (doi:10.1016/S0961-9534(02)00103-4)
- 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. (doi:10.1146/annurev.energy.28.040202.122858)
- 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. (doi:10.1079/SUM2004237)
- Chadwick, D. R. 2005 Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. *Atmos. Environ.* **39**, 787–799. (doi:10.1016/j.atmosenv.2004.10.012)
- Clark, H., Pinares, C. & de Klein, C. 2005 Methane and nitrous oxide emissions from grazed grasslands. In *Grassland—a global resource* (ed. D. McGilloway), pp. 279–293. Wageningen, The Netherlands: Wageningen Academic Publishers.
- Clemens, J. & Ahlgrimm, H. J. 2001 Greenhouse gases from animal husbandry: mitigation options. *Nutr. Cycl. Agroecosyst.* **60**, 287–300. (doi:10.1023/A:1012712532720)
- Clemens, J., Trimborn, M., Weiland, P. & Amon, B. 2006 Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agric. Ecosyst. Environ.* **112**, 171–177. (doi:10.1016/j.agee.2005.08.016)
- Cole, C. V. *et al.* 1997 Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutr. Cycl. Agroecosyst.* **49**, 221–228. (doi:10.1023/A:1009731711346)
- Conant, R. T. & Paustian, K. 2002 Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochem. Cycles* **16**, 90–1–90–9. (doi:10.1029/2001GB001661)
- Conant, R. T., Paustian, K. & Elliott, E. T. 2001 Grassland management and conversion into grassland: effects on soil carbon. *Ecol. Appl.* **11**, 343–355. (doi:10.1890/1051-0761(2001)011[0343:GMACIG]2.0.CO;2)

- Conant, R. T., Paustian, K., Del Grosso, S. J. & Parton, W. J. 2005 Nitrogen pools and fluxes in grassland soils sequestering carbon. *Nutr. Cycl. Agroecosyst.* **71**, 239–248. (doi:10.1007/s10705-004-5085-z)
- Crutzen, P. J. 1995 The role of methane in atmospheric chemistry and climate. In *Ruminant Physiology: Digestion, Metabolism, Growth and Reproduction Proc. Eighth Int. Symp. on Ruminant Physiology* (eds W. Von Engelhardt, S. Leonhard-Marek, G. Breves, & D. Giesecke), pp. 291–316. Stuttgart, Germany: Ferdinand Enke Verlag.
- 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. (doi:10.1071/SR02064)
- Davidson, E. A., Nepstad, D. C., Klink, C. & Trumbore, S. E. 1995 Pasture soils as carbon sink. *Nature* **376**, 472–473. (doi:10.1038/376472a0)
- Derner, J. D., Boutton, T. W. & Briske, D. D. 2006 Grazing and ecosystem carbon storage in the North American Great Plains. *Plant Soil* **280**, 77–90. (doi:10.1007/s11104-005-2554-3)
- Dias de Oliveira, M. E., Vaughan, B. E. & Rykiel Jr, E. J. 2005 Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. *BioScience* **55**, 593–602. (doi:10.1641/0006-3568(2005)055[0593:EAFECD]2.0.CO;2)
- Dohme, F. A., Machmuller, A., Wasserfallen, A. & Kreuzer, M. 2000 Comparative efficiency of various fats rich in medium-chain fatty acids to suppress ruminal methanogenesis as measured with Rusitec. *Can. J. Anim. Sci.* **80**, 473–482.
- Edmonds, J. A. 2004 Climate change and energy technologies. *Mitig. Adapt. Strat. Global Change* **9**, 391–416. (doi:10.1023/B:MITI.0000038846.11924.5f)
- Eidman, V. R. 2005 Agriculture as a producer of energy. In *Agriculture as a producer and consumer of energy* (eds J. L. Outlaw, K. J. Collins & J. A. Duffield), pp. 30–67. Wallingford, UK: CAB International.
- Faaij, A. P. C. 2006 Modern biomass conversion technologies. *Mitig. Adapt. Strat. Global Change* **11**, 335–367. (doi:10.1007/s11027-005-9004-7)
- Falloon, P., Smith, P. & Powlson, D. S. 2004 Carbon sequestration in arable land—the case for field margins. *Soil Use Manage.* **20**, 240–247. (doi:10.1079/SUM2004236)
- FAO/IIASA 2000 Global Agro-Ecological Zones Database. <http://www.fao.org/ag/agl/agll/gaez/index.htm>.
- FAOSTAT 2006 FAOSTAT agricultural data. See <http://faostat.fao.org/faostat/collections?version=ext&hasbulk=0&subset=agriculture>.
- FAO/UNESCO 2002 FAO digital soils map of the world. On CD. See <http://www.fao.org/ag/agl/agll/dsmw.stm>.
- Ferris, C. P., Gordon, F. J., Patterson, D. C., Porter, M. G. & Yan, T. 1999 The effect of genetic merit and concentrate proportion in the diet on nutrient utilization by lactating dairy cows. *J. Agric. Sci. Camb.* **132**, 483–490. (doi:10.1017/S0021859699006553)
- Fisher, M. J., Rao, I. M., Ayarza, M. A., Lascano, C. E., Sanz, J. I., Thomas, R. J. & Vera, R. R. 1994 Carbon storage by introduced deep-rooted grasses in the South American savannas. *Nature* **371**, 236–238. (doi:10.1038/371236a0)
- Foley, J. A. et al. 2005 Global consequences of land use. *Science* **309**, 570–574. (doi:10.1126/science.1111772)
- Follett, R. F. 2001 Organic carbon pools in grazing land soils. In *The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect* (eds R. F. Follett, J. M. Kimble & R. Lal), pp. 65–86. Boca Raton, FL: Lewis.
- Follett, R. F., Kimble, J. M. & Lal, R. 2001 The potential of U.S. grazing lands to sequester soil carbon. In *The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect* (eds R. F. Follett, J. M. Kimble & R. Lal), pp. 401–430. Boca Raton, FL: Lewis.
- Freibauer, A., Rounsevell, M., Smith, P. & Verhagen, A. 2004 Carbon sequestration in the agricultural soils of Europe. *Geoderma* **122**, 1–23. (doi:10.1016/j.geoderma.2004.01.021)
- 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. (doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2)
- Gonzalez-Avalos, E. & Ruiz-Suarez, L. G. 2001 Methane emission factors from cattle in Mexico. *Bioresour. Technol.* **80**, 63–71. (doi:10.1016/S0960-8524(01)00052-9)
- Gregorich, E. G., Rochette, P., VandenBygaart, A. J. & Angers, D. A. 2005 Greenhouse gas contributions of agricultural soils and potential mitigation practices in eastern Canada. *Soil Till. Res.* **83**, 53–72. (doi:10.1016/j.still.2005.02.009)
- Guo, L. B. & Gifford, R. M. 2002 Soil carbon stocks and land use change: a meta analysis. *Global Change Biol.* **8**, 345–360. (doi:10.1046/j.1354-1013.2002.00486.x)
- Hamelink, C. N., Suurs, R. A. A. & Faaij, A. P. C. 2004 Techno-economic analysis of international bio-energy trade chains. *Biomass Bioenergy* **29**, 114–134. (doi:10.1016/j.biombioe.2005.04.002)
- Hansen, L. B. 2000 Consequences of selection for milk yield from a geneticist's viewpoint. *J. Dairy Sci.* **83**, 1145–1150.
- Helgason, B. L. et al. 2005 Toward improved coefficients for predicting direct N₂O emissions from soil in Canadian agroecosystems. *Nutr. Cycl. Agroecosyst.* **71**, 87–99. (doi:10.1007/s10705-004-7358-y)
- Hoogwijk, M. 2004 On the global and regional potential of renewable energy sources. PhD thesis, Copernicus Institute, Utrecht University.
- Hoogwijk, M., Faaij, A., Eickhout, B., de Vries, B. & Turkenburg, W. 2005 Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass Bioenergy* **29**, 225–257. (doi:10.1016/j.biombioe.2005.05.002)
- International Panel on Climate Change (IPCC) 1996 *Climate change 1995: the science of climate change. Contribution of working group I to the 2nd assessment report of the IPCC*. Cambridge, UK: Cambridge University Press.
- International Panel on Climate Change (IPCC) 1997 *Revised 1996 IPCC guidelines for national greenhouse gas inventories workbook*, vol. 2. Cambridge, UK: Cambridge University Press.
- International Panel on Climate Change (IPCC) 2000 *Special report on land use, land-use change and forestry*. Cambridge, UK: Cambridge University Press.
- International Panel on Climate Change (IPCC) 2001 *Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change*. Cambridge, UK: Cambridge University Press.
- International Panel on Climate Change (IPCC) 2003 *Good practice guidelines for greenhouse gas inventories for land-use, land-use change & forestry*. Kanagawa, Japan: Institute of Global Environmental Strategies (IGES).
- Izaurrealde, R. C., McGill, W. B., Robertson, J. A., Juma, N. G. & Thurston, J. J. 2001 Carbon balance of the Breton Classical plots over half a century. *Soil Sci. Soc. Am. J.* **65**, 431–441.
- Janzen, H. H. 2004 Carbon cycling in earth systems—a soil science perspective. *Agric. Ecosyst. Environ.* **104**, 399–417. (doi:10.1016/j.agee.2004.01.040)
- Johnson, K. A. & Johnson, D. E. 1995 Methane emissions from cattle. *J. Anim. Sci.* **73**, 2483–2492.
- Johnson, D. E., Ward, G. M. & Torrent, J. 1991 The environmental impact of bovine somatotropin (bST) use in dairy cattle. *J. Dairy Sci.* **74**, 209.
- Johnson, D. E., Phetteplace, H. W. & Seidl, A. F. 2002 Methane, nitrous oxide and carbon dioxide emissions from

- ruminant livestock production systems. In *Greenhouse gases and animal agriculture* (eds J. Takahashi & B. A. Young), pp. 77–85. Amsterdam, The Netherlands: Elsevier.
- Jones, C. D., Cox, P. M., Essery, R. L. H., Roberts, D. L. & Woodage, M. J. 2003 Strong carbon cycle feedbacks in a climate model with interactive CO₂ and sulphate aerosols. *Geophys. Res. Lett.* **30**, 321–324.
- Jordan, E., Lovett, D. K., Hawkins, M. & O'Mara, F. P. 2004 The effect of varying levels of coconut oil on methane output from continental cross beef heifers. In *Proc. Int. Conf. on Greenhouse Gas Emissions from Agriculture—Mitigation Options and Strategies* (ed. A. Weiske), pp. 124–130. Leipzig, Germany: Institute for Energy and Environment.
- Jordan, E., Lovett, D. K., Monahan, F. J. & O'Mara, F. P. 2006a Effect of refined coconut oil or copra meal on methane output, intake and performance of beef heifers. *J. Anim. Sci.* **84**, 162–170.
- Jordan, E., Kenny, D., Hawkins, M., Malone, R., Lovett, D. K. & O'Mara, F. P. 2006b Effect of refined soy oil or whole soybeans on methane output, intake and performance of young bulls. *J. Anim. Sci.* **84**, 2418–2425. (doi:10.2527/jas.2005-354)
- Junginger, M., Faaij, A., Koopmans, A., van den Broek, R. & Hulscher, W. 2001 Setting up fuel supply strategies for large scale bio-energy projects—a methodology for developing countries. *Biomass Bioenergy* **21**, 259–275. (doi:10.1016/S0961-9534(01)00034-4)
- Kang, G. D., Cai, Z. C. & Feng, X. Z. 2002 Importance of water regime during the non-rice growing period in winter in regional variation of CH₄ emissions from rice fields during following rice growing period in China. *Nutr. Cycl. Agroecosyst.* **64**, 95–100. (doi:10.1023/A:1021154932643)
- Kasimir-Klemedtsson, A., Klemedtsson, L., Berglund, K., Martikainen, P., Silvola, J. & Oenema, O. 1997 Greenhouse gas emissions from farmed organic soils: a review. *Soil Use Manage.* **13**, 245–250. (doi:10.1111/j.1475-2743.1997.tb00595.x)
- Kennedy, P. M. & Milligan, L. P. 1978 Effects of cold exposure on digestion, microbial synthesis and nitrogen transformation in sheep. *Br. J. Nutr.* **39**, 105–117. (doi:10.1079/BJN19780017)
- Korontzi, S., Justice, C. O. & Scholes, R. J. 2003 Influence of timing and spatial extent of savanna fires in southern Africa on atmospheric emissions. *J. Arid Environ.* **54**, 395–404. (doi:10.1006/jare.2002.1098)
- Külling, D. R., Menzi, H., Sutter, F., Lischer, P. & Kreuzer, M. 2003 Ammonia, nitrous oxide and methane emissions from differently stored dairy manure derived from grass- and hay-based rations. *Nutr. Cycl. Agroecosyst.* **65**, 13–22. (doi:10.1023/A:1021857122265)
- Lal, R. 1999 Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Prog. Environ. Sci.* **1**, 307–326.
- Lal, R. 2001 Potential of desertification control to sequester carbon and mitigate the greenhouse effect. *Clim. Change* **15**, 35–72. (doi:10.1023/A:1017529816140)
- Lal, R. 2003 Global potential of soil carbon sequestration to mitigate the greenhouse effect. *Crit. Rev. Plant Sci.* **22**, 151–184. (doi:10.1080/713610854)
- Lal, R. 2004a Soil carbon sequestration impacts on global climate change and food security. *Science* **304**, 1623–1627. (doi:10.1126/science.1097396)
- Lal, R. 2004b Soil carbon sequestration to mitigate climate change. *Geoderma* **123**, 1–22. (doi:10.1016/j.geoderma.2004.01.032)
- Lal, R. 2004c Offsetting China's CO₂ emissions by soil carbon sequestration. *Clim. Change* **65**, 263–275. (doi:10.1023/B:CLIM.0000038203.81854.7c)
- Lal, R. 2004d Carbon sequestration in soils of central Asia. *Land Degrad. Dev.* **15**, 563–572. (doi:10.1002/ldr.624)
- Lal, R. 2004e Soil carbon sequestration in India. *Clim. Change* **65**, 277–296. (doi:10.1023/B:CLIM.0000038202.46720.37)
- Lal, R. 2005 Soil carbon sequestration for sustaining agricultural production and improving the environment with particular reference to Brazil. *J. Sustain. Agric.* **26**, 23–42. (doi:10.1300/J064v26n02_04)
- Lal, R. & Bruce, J. P. 1999 The potential of world cropland soils to sequester C and mitigate the greenhouse effect. *Environ. Sci. Policy* **2**, 177–185. (doi:10.1016/S1462-9011(99)00012-X)
- 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. (doi:10.1097/01.ss.0000106407.84926.6b)
- Lee, H.-C., McCarl, B. A. & Gillig, D. 2005 The dynamic competitiveness of U.S. agricultural and forest carbon sequestration. *Can. J. Agric. Econ.* **53**, 343–357. (doi:10.1111/j.1744-7976.2005.00023.x)
- Le Mer, J. & Roger, P. 2001 Production, oxidation, emission and consumption of methane by soils: a review. *Eur. J. Soil Biol.* **37**, 25–50. (doi:10.1016/S1164-5563(01)01067-6)
- Leng, R. A. 1991 Improving ruminant production and reducing methane emissions from ruminants by strategic supplementation. EPA report, no. 400/1-91/004. US Environmental Protection Agency, Washington, DC.
- Li, C., Frolking, S. & Butterbach-Bahl, K. 2005 Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. *Clim. Change* **72**, 321–338. (doi:10.1007/s10584-005-6791-5)
- Liebig, M. A., Morgan, J. A., Reeder, J. D., Ellert, B. H., Gollany, H. T. & Schuman, G. E. 2005 Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil Till. Res.* **83**, 25–52. (doi:10.1016/j.still.2005.02.008)
- Lovett, D. K. & O'Mara, F. P. 2002 Estimation of enteric methane emissions originating from the national livestock beef herd: a review of the IPCC default emission factors. *Tearmann* **2**, 77–83.
- Lovett, D., Lovell, S., Stack, L., Callan, J., Finlay, M., Connolly, J. & O'Mara, F. P. 2003 Effect of forage/concentrate ratio and dietary coconut oil level on methane output and performance of finishing beef heifers. *Livest. Prod. Sci.* **84**, 135–146. (doi:10.1016/j.livprodsci.2003.09.010)
- Lovett, D. K., Shalloo, L., Dillon, P. & O'Mara, F. P. 2006 A systems approach to quantify greenhouse gas fluxes from pastoral dairy production as affected by management regime. *Agric. Syst.* **88**, 156–179. (doi:10.1016/j.agry.2005.03.006)
- Machmüller, A., Ossowski, D. A. & Kreuzer, M. 2000 Comparative evaluation of the effects of coconut oil, oilseeds and crystalline fat on methane release, digestion and energy balance in lambs. *Anim. Feed Sci. Technol.* **85**, 41–60. (doi:10.1016/S0377-8401(00)00126-7)
- Machmüller, A., Soliva, C. R. & Kreuzer, M. 2003 Methane-suppressing effect of myristic acid in sheep as affected by dietary calcium and forage proportion. *Br. J. Nutr.* **90**, 529–540. (doi:10.1079/BJN2003932)
- Manne, A. S. & Richels, R. G. 2004 A multi-gas approach to climate policy. In *The global carbon cycle. Integrating humans, climate, and the natural world* (eds C. B. Field & M. R. Raupach), pp. 439–452. Washington, DC: Island Press.
- Marland, G., McCarl, B. A. & Schneider, U. A. 2001 Soil carbon: policy and economics. *Clim. Change* **51**, 101–117. (doi:10.1023/A:1017575018866)

- Marland, G. *et al.* 2003a The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. *Climate Policy* **3**, 149–157. (doi:10.1016/S1469-3062(03)00028-7)
- Marland, G., West, T. O., Schlamadinger, B. & Canella, L. 2003b Managing soil organic carbon in agriculture: the net effect on greenhouse gas emissions. *Tellus B* **55**, 613–621. (doi:10.1034/j.1600-0889.2003.00054.x)
- McCarl, B. A. & Schneider, U. A. 2001 Greenhouse gas mitigation in U.S. agriculture and forestry. *Science* **294**, 2481–2482. (doi:10.1126/science.1064193)
- McCaughy, W. P., Wittenberg, K. & Corrigan, D. 1999 Impact of pasture type on methane production by lactating cows. *Can. J. Anim. Sci.* **79**, 221–226.
- McCrabb, G. C. 2001 Nutritional options for abatement of methane emissions from beef and dairy systems in Australia. In *Greenhouse gases and animal agriculture* (eds J. Takahashi & B. A. Young), pp. 115–124. Amsterdam, The Netherlands: Elsevier.
- McCrabb, G. J., Kurihara, M. & Hunter, R. A. 1998 The effect of finishing strategy of lifetime methane production for beef cattle in northern Australia. *Proc. Nutr. Soc. Aust.* **22**, 55.
- McGinn, S. M., Beauchemin, K. A., Coates, T. & Colombatto, D. 2004 Methane emissions from beef cattle: effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. *J. Anim. Sci.* **82**, 3346–3356.
- Menon, S., Hansen, J., Nazarenko, L. & Luo, Y. 2002 Climate effects of black carbon aerosols in China and India. *Science* **297**, 2250–2253. (doi:10.1126/science.1075159)
- Miglior, F., Muir, B. L. & Van Doormaal, B. J. 2005 Selection indices in Holstein cattle of various countries. *J. Dairy Sci.* **88**, 1255–1263.
- Millennium Ecosystem Assessment 2005 *Findings from the conditions and trend working group*. Washington, DC: Island Press.
- Mills, J. A. N., Kebreab, E., Yates, C. M., Crompton, L. A., Cammell, S. B., Dhanoa, M. S., Agnew, R. E. & France, J. 2003 Alternative approaches to predicting methane emissions from dairy cows. *J. Anim. Sci.* **81**, 3141–3150.
- Moe, P. W. & Tyrrell, H. F. 1979 Methane production in dairy cows. *J. Dairy Sci.* **62**, 1583–1586.
- Monteny, G. J., Groenestein, C. M. & Hilhorst, M. A. 2001 Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. *Nutr. Cycl. Agroecosyst.* **60**, 123–132. (doi:10.1023/A:1012602911339)
- Monteny, G.-J., Bannink, A. & Chadwick, D. 2006 Greenhouse gas abatement strategies for animal husbandry. *Agric. Ecosyst. Environ.* **112**, 163–170. (doi:10.1016/j.agee.2005.08.015)
- Mosier, A. R., Duxbury, J. M., Freney, J. R., Heinemeyer, O., Minami, K. & Johnson, D. E. 1998 Mitigating agricultural emissions of methane. *Clim. Change* **40**, 39–80. (doi:10.1023/A:1005338731269)
- Mosier, A. R., Halvorson, A. D., Peterson, G. A., Robertson, G. P. & Sherrod, L. 2005 Measurement of net global warming potential in three agroecosystems. *Nutr. Cycl. Agroecosyst.* **72**, 67–76. (doi:10.1007/s10705-004-7356-0)
- Murray, R. M., Bryant, A. M. & Leng, R. A. 1976 Rate of production of methane in the rumen and the large intestine of sheep. *Br. J. Nutr.* **36**, 1–14. (doi:10.1079/BJN19760053)
- Mutuo, P. K., Cadisch, G., Albrecht, A., Palm, C. A. & Verchot, L. 2005 Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. *Nutr. Cycl. Agroecosyst.* **71**, 43–54. (doi:10.1007/s10705-004-5285-6)
- Newbold, C. J. & Rode, L. M. 2005 Dietary additives to control methanogenesis in the rumen. In *Second Int. Conf. on Greenhouse Gases and Animal Agriculture, Working Papers* (eds C. R. Soliva, J. Takahashi, & M. Kreuzer), pp. 60–70. Zurich, Switzerland: ETH.
- Newbold, C. J., Ouda, J. O., Lopez, S., Nelson, N., Omed, H., Wallace, R. J. & Moss, A. R. 2002 Propionate precursors as possible alternative electron acceptors to methane in ruminal fermentation. In *Greenhouse gases and animal agriculture* (eds J. Takahashi & B. A. Young), pp. 151–154. Amsterdam, The Netherlands: Elsevier.
- Newbold, C. J., López, S., Nelson, N., Ouda, J. O., Wallace, R. J. & Moss, A. R. 2005 Propionate precursors and other metabolic intermediates as possible alternative electron acceptors to methanogenesis in ruminal fermentation *in vitro*. *Br. J. Nutr.* **94**, 27–35. (doi:10.1079/BJN20051445)
- Oelbermann, M., Voroney, R. P. & Gordon, A. M. 2004 Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. *Agric. Ecosyst. Environ.* **104**, 359–377. (doi:10.1016/j.agee.2004.04.001)
- 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. (doi:10.1007/s10705-004-7354-2)
- Ogle, S. M., Breidt, F. J., Eve, M. D. & Paustian, K. 2003 Uncertainty in estimating land use and management impacts on soil organic storage for US agricultural lands between 1982 and 1997. *Global Change Biol.* **9**, 1521–1542. (doi:10.1046/j.1365-2486.2003.00683.x)
- Ogle, S. M., Breidt, F. J. & Paustian, K. 2005 Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry* **72**, 87–121. (doi:10.1007/s10533-004-0360-2)
- Olsson, L. & Ardo, J. 2002 Soil carbon sequestration in degraded semiarid agro-ecosystems—perils and potentials. *Ambio* **31**, 471–477. (doi:10.1639/0044-7447(2002)031[0471:SCSIDS]2.0.CO;2)
- Pattey, E., Trzcinski, M. K. & Desjardins, R. L. 2005 Quantifying the reduction of greenhouse gas emissions as a result of composting dairy and beef cattle manure. *Nutr. Cycl. Agroecosyst.* **72**, 173–187. (doi:10.1007/s10705-005-1268-5)
- Paul, E. A., Morris, S. J., Six, J., Paustian, K. & Gregorich, E. G. 2003 Interpretation of soil carbon and nitrogen dynamics in agricultural and afforested soils. *Soil Sci. Soc. Am. J.* **67**, 1620–1628.
- Paustian, K., Cole, C. V., Sauerbeck, D. & Sampson, N. 1998 CO₂ mitigation by agriculture: an overview. *Clim. Change* **40**, 135–162. (doi:10.1023/A:1005347017157)
- Paustian, K. *et al.* 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, p. 120, May, 2004.
- Phetteplace, H. W., Johnson, D. E. & Seidl, A. F. 2001 Greenhouse gas emissions from simulated beef and dairy livestock systems in the United States. *Nutr. Cycl. Agroecosyst.* **60**, 9–102. (doi:10.1023/A:1012657230589)
- Pinares-Patino, C. S., Ulyatt, M. J., Waghorn, G. C., Holmes, C. W., Barry, T. N., Lassey, K. R. & Johnson, D. E. 2003 Methane emission by alpaca and sheep fed on lucerne hay or grazed on pastures of perennial ryegrass/white clover or birdsfoot trefoil. *J. Agric. Sci.* **140**, 215–226. (doi:10.1017/S002185960300306X)
- Reay, D. S., Smith, K. A. & Edwards, A. C. 2003 Nitrous oxide emission from agricultural drainage waters. *Global Change Biol.* **9**, 195–203. (doi:10.1046/j.1365-2486.2003.00584.x)
- Reeder, J. D., Schuman, G. E., Morgan, J. A. & Lecain, D. R. 2004 Response of organic and inorganic carbon and

- nitrogen to long-term grazing of the shortgrass steppe. *Environ. Manage.* **33**, 485–495. (doi:10.1007/s00267-003-9106-5)
- Rice, C. W. & Owensby, C. E. 2001 Effects of fire and grazing on soil carbon in rangelands. In *The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect* (eds R. Follett, J. M. Kimble & R. Lal), pp. 323–342. Boca Raton, FL: Lewis.
- Richter, B. 2004 Using ethanol as an energy source. *Science* **305**, 340. (doi:10.1126/science.305.5682.340b)
- Robertson, G. P. 2004 Abatement of nitrous oxide, methane and other non-CO₂ greenhouse gases: the need for a systems approach. In *The global carbon cycle. Integrating humans, climate, and the natural world* (eds C. B. Field & M. R. Raupach), pp. 493–506. Washington, DC: Island Press.
- Robertson, G. P. & Grace, P. R. 2004 Greenhouse gas fluxes in tropical and temperate agriculture: the need for a full-cost accounting of global warming potentials. *Environ. Dev. Sustain.* **6**, 51–63. (doi:10.1023/B:ENVI.0000003629.32997.9e)
- Robertson, L. J. & Waghorn, G. C. 2002 Dairy industry perspectives on methane emissions and production from cattle fed pasture or total mixed rations in New Zealand. *Proc. New Zeal. Soc. Anim. Prod.* **62**, 213–218.
- Robertson, G. P., Paul, E. A. & Harwood, R. R. 2000 Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. *Science* **289**, 1922–1925. (doi:10.1126/science.289.5486.1922)
- Rochette, P. & Janzen, H. H. 2005 Towards a revised coefficient for estimating N₂O emissions from legumes. *Nutr. Cycl. Agroecosyst.* **73**, 171–179. (doi:10.1007/s10705-005-0357-9)
- Rogner, H. *et al.* 2000 Energy resources. In *World energy assessment of the United Nations, UNDP, UNDESA/WEC* (ed. J. Goldemberg), Ch. 5, pp. 135–171. New York, NY: UNDP.
- Rosegrant, M., Paisner, M. S., Meijer, S. & Witcover, J. 2001 *Global food projections to 2020. Emerging trends and alternative futures*. Washington, DC: IFPRI Publications. ISBN 0-89629-640-7. See http://www.ifpri.org/pubs/books/global_foodprojections2020.htm.
- Rumpler, W. V., Johnson, D. E. & Bates, D. B. 1986 The effect of high dietary cation concentrations on methanogenesis by steers fed with or without ionophores. *J. Anim. Sci.* **62**, 1737–1741.
- Schils, R. L. M., Verhagen, A., Aarts, H. F. M. & Sebek, L. B. J. 2005 A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems. *Nutr. Cycl. Agroecosyst.* **71**, 163–175. (doi:10.1007/s10705-004-2212-9)
- Schlesinger, W. H. 1999 Carbon sequestration in soils. *Science* **284**, 2095. (doi:10.1126/science.284.5423.2095)
- Schmidely, P. 1993 Quantitative review on the use of anabolic hormones in ruminants for meat production. I. Animal performance. *Ann. Zootech.* **42**, 333–359.
- Schnabel, R. R., Franzluebbers, A. J., Stout, W. L., Sanderson, M. A. & Stuedemann, J. A. 2001 The effects of pasture management practices. In *The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect* (eds R. F. Follett, J. M. Kimble & R. Lal), pp. 291–322. Boca Raton, FL: Lewis.
- Schneider, U. A. & McCarl, B. A. 2003 Economic potential of biomass based fuels for greenhouse gas emission mitigation. *Environ. Resour. Econ.* **24**, 291–312. (doi:10.1023/A:1023632309097)
- Schneider, U. A. & McCarl, B. A. 2006 Implications of a carbon-based energy tax for US agriculture. *Agric. Resour. Econ. Rev.* **34**, 265–278.
- Scholes, R. J. & van der Merwe, M. R. 1996 Sequestration of carbon in savannas and woodlands. *Environ. Prof.* **18**, 96–103.
- Schuman, G. E., Herrick, J. E. & Janzen, H. H. 2001 The dynamics of soil carbon in rangelands. In *The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect* (eds R. F. Follett, J. M. Kimble & R. Lal), pp. 267–290. Boca Raton, FL: Lewis.
- Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J., Walsh, M. & Nelson, R. 2004 Energy and environmental aspects of using corn stover for fuel ethanol. *J. Ind. Ecol.* **7**, 117–146. (doi:10.1162/108819803323059433)
- Sims, R. E. H., Hastings, A., Schlamadinger, B., Taylor, G. & Smith, P. 2006 Energy crops: current status and future prospects. *Global Change Biol.* **12**, 2054–2076. (doi:10.1111/j.1365-2486.2006.01163.x)
- Six, J., Ogle, S. M., Breidt, F. J., Conant, R. T., Mosier, A. R. & Paustian, K. 2004 The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. *Global Change Biol.* **10**, 155–160. (doi:10.1111/j.1529-8817.2003.00730.x)
- Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M. & Turkenburg, W. C. 2007 A bottom up quickscan and review of global bio-energy potentials to 2050. *Prog. Energy Combust. Sci.* **33**, 56–106. (doi:10.1016/j.pecs.2006.08.001)
- Smith, P. 2004a Carbon sequestration in croplands: the potential in Europe and the global context. *Eur. J. Agron.* **20**, 229–236. (doi:10.1016/j.eja.2003.08.002)
- Smith, P. 2004b Engineered biological sinks on land. In *The global carbon cycle. Integrating humans, climate, and the natural world* (eds C. B. Field & M. R. Raupach), pp. 479–491. Washington, DC: Island Press.
- Smith, K. A. & Conen, F. 2004 Impacts of land management on fluxes of trace greenhouse gases. *Soil Use Manage.* **20**, 255–263. (doi:10.1079/SUM2004238)
- 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. (doi:10.1046/j.1365-2486.2000.00331.x)
- 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. (doi:10.1023/A:1012617517839)
- 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. (doi:10.1111/j.1365-2486.2005.01052.x)
- Smith, J. U. *et al.* 2005b Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. *Global Change Biol.* **11**, 2141–2152. (doi:10.1111/j.1365-2486.2005.001075.x)
- Smith, P. *et al.* 2007 Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. *Agric. Ecosyst. Environ.* **118**, 6–28. (doi:10.1016/j.agee.2006.06.006)
- Soussana, J.-F., Loiseau, P., Viuchard, N., Ceschia, E., Balesdent, J., Chevallier, T. & Arrouays, D. 2004 Carbon cycling and sequestration opportunities in temperate grasslands. *Soil Use Manage.* **20**, 219–230. (doi:10.1079/SUM2003234)
- Spatari, S., Zhang, Y. & Maclean, H. L. 2005 Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. *Environ. Sci. Technol.* **39**, 9750–9758. (doi:10.1021/es048293+)

- Sperow, M., Eve, M. & Paustian, K. 2003 Potential soil C sequestration on U.S. agricultural soils. *Clim. Change* **57**, 319–339. (doi:10.1023/A:1022888832630)
- Squires, V., Glenn, E. P. & Ayoub, A. T. 1995 Combating global climate change by combating land degradation. In *Proc. Workshop in Nairobi, 4–8 Sept. 1995*, p. 348. Nairobi, Kenya: UNEP.
- Strengers, B., Leemans, R., Eickhout, B., de 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. (doi:10.1007/s10708-004-5054-8)
- US-EPA 2006 *Global anthropogenic non-CO₂ greenhouse gas emissions: 1990–2020*, United States Environmental Protection Agency, EPA 430-R-06-003, June 2006. Washington, DC: US-EPA.
- Van Nessel, C. J. & Demeyer, D. I. 1995 Lipolysis and biohydrogenation of soybean oil in the rumen in vitro: inhibition by antimicrobials. *J. Dairy Sci.* **78**, 2797–2806.
- Van Nessel, C. J. & Demeyer, D. I. 1996 Influence of antibiotics and a deaminase inhibitor on volatile fatty acids and methane production from detergent washed hay and soluble starch by rumen microbes *in vitro*. *Anim. Feed Sci. Technol.* **37**, 21–31. (doi:10.1016/0377-8401(92)90117-O)
- van Wilgen, B. W., Govender, N., Biggs, H. C., Ntsala, D. & Funda, X. N. 2004 Response of savanna fire regimes to changing fire-management policies in a large African National Park. *Conserv. Biol.* **18**, 1533–1540. (doi:10.1111/j.1523-1739.2004.00362.x)
- Venkataraman, C., Habib, G., Eiguren-Fernandez, A., Miguel, A. H. & Friedlander, S. K. 2005 Residential biofuels in south Asia: carbonaceous aerosol emissions and climate impacts. *Science* **307**, 1454–1456. (doi:10.1126/science.1104359)
- Waghorn, G. C., Tavendale, M. H. & Woodfield, D. R. 2002 Methanogenesis from forages fed to sheep. *Proc. New Zeal. Soc. Anim. Prod.* **64**, 161–171.
- Wallace, R. J., Wood, T. A., Rowe, A., Price, J., Yanez, D. R., Williams, S. P. & Newbold, C. J. 2005 Encapsulated fumaric acid as a means of decreasing ruminal methane emissions. In *Second Int. Conf. on Greenhouse Gases and Animal Agriculture, Working Papers* (eds C. R. Soliva, J. Takahashi & M. Kreuzer), pp. 86–89. Zurich, Switzerland: ETH.
- Wang, M. X. & Shangguan, X. J. 1996 CH₄ emission from various rice fields in PR China. *Theor. Appl. Climatol.* **55**, 129–138. (doi:10.1007/BF00864708)
- Wassmann, R., Lantin, R. S., Neue, H. U., Buendia, L. V., Corton, T. M. & Lu, Y. 2000 Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. *Nutr. Cycl. Agroecosyst.* **58**, 23–36. (doi:10.1023/A:1009874014903)
- 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.
- Wolin, E. A., Wolf, R. S. & Wolin, M. J. 1964 Microbial formation of methane. *J. Bacteriol.* **87**, 993–998.
- Woodward, S. L., Waghorn, G. C., Ulyatt, M. J. & Lassey, K. R. 2001 Early indications that feeding Lotus will reduce methane emissions from ruminants. *Proc. New Zeal. Soc. Anim. Prod.* **61**, 23–26.
- 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. (doi:10.1016/j.vaccine.2004.03.053)
- Xu, H., Cai, Z. C., Jia, Z. J. & Tsuruta, H. 2000 Effect of land management in winter crop season on CH₄ emission during the following flooded and rice-growing period. *Nutr. Cycl. Agroecosyst.* **58**, 327–332. (doi:10.1023/A:1009823425806)
- Xu, H., Cai, Z. C. & Tsuruta, H. 2003 Soil moisture between rice-growing seasons affects methane emission, production, and oxidation. *Soil Sci. Soc. Am. J.* **67**, 1147–1157.
- Yagi, K., Tsuruta, H. & Minami, K. 1997 Possible options for mitigating methane emission from rice cultivation. *Nutr. Cycl. Agroecosyst.* **49**, 213–220. (doi:10.1023/A:1009743909716)
- Yan, T., Agnew, R. E., Gordon, F. J. & Porter, M. G. 2000 Prediction of methane energy output in dairy and beef cattle offered grass silage-based diets. *Livest. Prod. Sci.* **64**, 253–263. (doi:10.1016/S0301-6226(99)00145-1)
- Yan, X., Ohara, T. & Akimoto, H. 2003 Development of region-specific emission factors and estimation of methane emission from rice field in East, Southeast and South Asian countries. *Global Change Biol.* **9**, 237–254. (doi:10.1046/j.1365-2486.2003.00564.x)