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REVIEW

Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learnt in the last 20 years?

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Abstract

Agricultural lands occupy about 40–50% of the Earth's land surface. Agricultural practices can make a significant contribution at low cost to increasing soil carbon sinks, reducing greenhouse gas (GHG) emissions and contributing biomass feedstocks for energy use. Considering all gases, the global technical mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030 is estimated to be ca. 5500–6000 Mt CO_2-eq. yr^{-1}. Economic potentials are estimated to be 1500–1600, 2500–2700 and 4000–4300 Mt CO_2-eq. yr^{-1} at carbon prices of up to $US20, 50 and 100 t CO_2-eq.$^{-1}$, respectively. The value of the global agricultural GHG mitigation at the same three carbon prices is $US32 000, 130 000 and 420 000 million yr^{-1}, respectively. At the European level, early estimates of soil carbon sequestration potential in croplands were ca. 200 Mt CO_2 yr^{-1}, but this is a technical potential and is for geographical Europe as far east as the Urals. The economic potential is much smaller, with more recent estimates for the EU27 suggesting a maximum potential of ca. 20 Mt CO_2-eq. yr^{-1}. The UK is small in global terms, but a large part of its land area (11 Mha) is used for agriculture. Agriculture accounts for about 7% of total UK GHG emissions. The mitigation potential of UK agriculture is estimated to be ca. 1–2 Mt CO_2-eq. yr^{-1}, accounting for less than 1% of UK total GHG emissions.

Keywords: agriculture, climate change, Europe, global, greenhouse gas, mitigation, UK

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Introduction

Greenhouse gas emissions from agriculture

Agricultural lands occupy about 40–50% of the Earth's land surface (Smith *et al.*, 2007a). In 2005, agriculture accounted for 5100–6100 Mt CO_2-eq. yr^{-1}, or 10–12% of total global greenhouse gases (GHGs) [60% of global nitrous oxide (N_2O), 50% of methane (CH_4) and less than 1% of carbon dioxide (CO_2); Smith *et al.*, 2007a]. If one accounts for GHG emissions from deforestation for agriculture, usually accounted for as deforestation in the forest sector, agriculture may contribute 17–30% of total global anthropogenic GHG emissions (Bellarby *et al.*, 2008). These emissions have increased by 17% from 1990 to 2005 (60 Mt CO_2-eq. yr^{-1}; Smith *et al.*, 2007a). Non-Annex I countries (i.e. developing countries) have increased agricultural GHG emissions by 32% (representing 75% of global agricultural GHGs in 2005), whereas Annex I (industrialized) countries showed a decrease of 12% (Smith *et al.*, 2007a). Global agricultural non-CO_2 GHG emissions are expected to increase to 8200 Mt CO_2-eq. in 2030 (Smith *et al.*, 2007a). The main sources of GHG emissions from agriculture are N_2O from soils (38%), CH_4 from enteric fermentation (32%), N_2O and CH_4 from biomass burning (12%), CH_4 from rice production (11%), and N_2O and CH_4 from manure management (7%). There are significant regional differences in the relative importance of sources (Smith *et al.*, 2007a). There are a number of drivers of emissions. Factors causing increases include population pressure (a 10% increase in extension of agricultural land over the last 40 years), dietary changes (increased demand of livestock products) and technological changes (increased use of N fertilizers, increased use of irrigation and intensification of animal production systems). Factors causing decreases include increased productivity of agricultural land, adoption of conservation tillage and climate and nonclimate policies in industrialized countries (Smith *et al.*, 2007a).

Mitigation technologies and practices for GHG mitigation in agriculture

Despite accounting for a significant proportion of global GHG emissions, agricultural practices can make a significant contribution at low cost to increasing soil carbon sinks, reducing GHG emissions and contributing biomass feedstocks for energy use (Smith *et al.*, 2008). In

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agriculture, GHG mitigation is possible through emission reduction (e.g. more efficient use of N fertilizers) through enhancing sinks (e.g. cropland and grassland management to enhance soil carbon stocks; estimated historical loss of carbon from soils is ca. 50 Pg C; Houghton, 1999) and displacement of emissions (e.g. bioenergy for fossil fuel substitution; Smith *et al.*, 2007a). There are many tens of potential individual mitigation options, but these are often grouped. For the IPCC Fourth Assessment Report (Smith *et al.*, 2007a), the practices were grouped as follows:

1. Cropland management: including improved agronomy, improved nutrient management, improved tillage/residue management, improved water management, improved rice management, agroforestry and potential for land cover (use) change (e.g. setaside).
2. Grazing land management and pasture improvement: including optimized grazing intensity, increased productivity (including fertilisation), improved nutrient management, better fire management and species introduction (e.g. deep rooted species).
3. Improved management of agricultural organic/peaty soils.
4. Restoration of degraded lands.
5. Livestock management: improved feeding practices, specific agents and dietary additives, longer term management changes and animal breeding.
6. Manure management.
7. Bioenergy production.

There is no universally applicable list of mitigation practices. The proposed practices need to be evaluated for individual agricultural systems according to the specific climatic, edaphic, social settings and historical land use and management. For nonlivestock mitigation options, mitigation potentials per unit land area for different climate regions (cool–dry, cool–moist, warm–dry, warm–moist) can be defined (Smith *et al.*, 2008). For livestock options, mitigation potentials for CH_4 from enteric fermentation can be defined for different livestock groups in different regions. In the following sections entitled 'GHG mitigation potential in global agriculture', 'GHG mitigation potential in European agriculture' and 'GHG mitigation potential in UK agriculture', the mitigation potential of agriculture at global scale, European scale and for the UK is outlined.

GHG mitigation potential in global agriculture

Global technical potential for GHG mitigation in agriculture

Considering all gases, the global technical mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030 is estimated to be ca. 5500–6000 Mt CO_2-eq. yr^{-1} (Smith *et al.*, 2007a, 2008). The range of the standard deviation and the 95% confidence interval about the mean are 3000–8700 and 300–11400 Mt CO_2-eq. yr^{-1}, respectively, where the range is largely determined by uncertainty in per-area estimate of the mitigation measure (Smith *et al.*, 2008). The regions with the highest potential are Southeast Asia (922 Mt CO_2-eq. yr^{-1}), South America (707 Mt CO_2-eq. yr^{-1}), China (622 Mt CO_2-eq. yr^{-1}), India (480 Mt CO_2-eq. yr^{-1}) and Eastern Africa (434 Mt CO_2-eq. yr^{-1}). The practices with the highest technical potential are cropland management (1550 Mt CO_2-eq. yr^{-1}), grazing land management (1450 Mt CO_2-eq. yr^{-1}), restoration of cultivated organic soils (1250 Mt CO_2-eq. yr^{-1}) and restoration of degraded land (650 Mt CO_2-eq. yr^{-1}; Smith *et al.*, 2007a, 2008).

Global economic potential for GHG mitigation in agriculture

The economic mitigation potential is based on social cost and social discount rates, but excludes many externalities (McCarl & Schneider, 2001; Moran *et al.*, 2011). It is intended to estimate the achievable mitigation potential for a range of carbon prices, given the cost of implementing each mitigation measure (Smith *et al.*, 2008).

Estimates of economic potential can be made by multisectoral 'top-down' models, which look across the whole economy but have limited details of individual sectors and spatial disaggregation, or through 'bottom-up' methods with better description of sectoral practices, but focused on fewer sectors (e.g. agriculture and forestry only), whereby levels of implementation, as a fraction of the technical potential, are estimated from the cost of implementation and the carbon price, using marginal abatement cost curves (MACCs; Beach *et al.*, 2008) often implemented within models, such as FASOM (McCarl & Schneider, 2001).

Available top-down estimates of global mitigation potential in agriculture cover only CH_4 and N_2O from cropland and livestock (i.e. they exclude non-CO_2 from grassland and organic soils, and CO_2 emissions and removals from all lands). Some models also consider emissions from burning of agricultural residues and waste, and fossil fuel combustion CO_2 emissions. Top-down estimates are: 267–1518 Mt CO_2-eq. yr^{-1} (for a carbon price of \$US20 t CO_2-eq.$^{-1}$), 643–1866 Mt CO_2-eq. yr^{-1} (for a carbon price of \$US50 t CO_2-eq.$^{-1}$) and 604 Mt CO_2-eq. yr^{-1} (for a carbon price of \$US 100 t CO_2-eq.$^{-1}$; Smith *et al.*, 2007a).

Bottom-up estimates of global economic potentials are estimated to be 1500–1600, 2500–2700 and 4000–

4300 Mt CO_2-eq. yr^{-1} at carbon prices of up to \$US20, 50 and 100 t CO_2-eq.$^{-1}$, respectively (Smith *et al.*, 2008). The value of the global agricultural GHG mitigation at the same three carbon prices is \$US32 000, 130 000 and 420 000 million yr^{-1}, respectively (Smith & Olesen, 2010). About 70% of the potential lies in nonindustrialized countries, 20% in industrialized countries and 10% in countries with economies in transition (Smith *et al.*, 2007a). In the long-term (post-2050), climate change may affect the mitigation potential of soil carbon sinks, but the direction and magnitude of this effect is uncertain (Smith *et al.*, 2007a,b). Agricultural mitigation options are cost-competitive with mitigation options in other sectors. Agriculture shows similar potential to forestry, industry and energy supply and has higher potential than the transport and waste sectors (Barker *et al.*, 2007). A large proportion (ca. 90%) of the economic mitigation potential (at \$US100 t CO_2-eq.$^{-1}$ and excluding bioenergy) arises from soil carbon sequestration, which has strong synergies with sustainable agriculture and generally reduces vulnerability to climate change (Smith *et al.*, 2007b). In the long-term (post-2050), climate change may affect the mitigation potential of soil carbon sinks, but the direction and magnitude of this effect are uncertain.

Carbon sequestration (removing atmospheric CO_2) largely drives the estimated global mitigation potential, rather than a reduction in non-CO_2 GHGs, which largely drive current agricultural GHG emissions. However, significant potential is also available from reductions in methane and nitrous oxide emissions, and such emission reductions are permanent.

There is no universally applicable list of mitigation practices; practices need to be evaluated for individual agricultural systems and settings (Smith *et al.*, 2007b). The composition of the portfolio of mitigation practices changes with the price level (Smith *et al.*, 2008; Fig. 1). At low carbon price (\$US20 t CO_2-eq.$^{-1}$), the practices with highest mitigation potential are cropland management (750 Mt CO_2-eq. yr^{-1}, 46% of total), restoration of organic soils (220 Mt CO_2-eq. yr^{-1}, 13% of total), rice management (160 Mt CO_2-eq. yr^{-1}, 10% of total) and grazing land management (150 Mt CO_2-eq. yr^{-1}, 10% of total). At medium carbon prices (\$US50 t CO_2-eq.$^{-1}$), the practices with highest mitigation potential are cropland management (850 Mt CO_2-eq. yr^{-1}, 32% of total), restoration of organic soils (600 Mt CO_2-eq. yr^{-1}, 22% of total), grazing land management (400 Mt CO_2-eq. yr^{-1}, 15% of total) and restoration of degraded lands (350 Mt CO_2-eq. yr^{-1}, 13% of total). At high carbon prices (\$US100 t CO_2-eq.$^{-1}$), the practices with highest mitigation potential are restoration of organic soils (1250 Mt CO_2-eq. yr^{-1}, 29% of total), cropland management (830 Mt CO_2-eq. yr^{-1}, 19% of total), grazing land management (800 Mt CO_2-eq. yr^{-1}, 18% of total) and restoration of degraded lands (650 Mt CO_2-eq. yr^{-1}, 15% of total).

Biomass from agricultural residues or dedicated crops can be an important biomass feedstock, but its contribution to mitigation depends on demand for bioenergy from transport and energy supply, on water availability and on requirements of land for food and fibre production (Sims *et al.*, 2006; Smith *et al.*, 2007a). Widespread use of agricultural land for biomass production may compete with other land uses and have other environmental impacts (Searchinger *et al.*, 2008; Smith *et al.*, 2010a). The economic mitigation potential for agricultural bioenergy in 2030 is estimated to be 70–1260, 560–2320 and 2720 Mt CO_2-eq. yr^{-1} at prices up to \$US20, 50 and above 100 t CO_2-eq.$^{-1}$, respectively. These potentials represent mitigation of 5–90% of all other agricultural mitigation measures combined (Smith *et al.*, 2007a, 2008). An additional mitigation of 770 Mt CO_2-eq. yr^{-1} could be achieved by 2030 by improved energy efficiency in agriculture (Smith *et al.*, 2007a; Schneider & Smith, 2009). The mitigation potential in agriculture is significant in relation to the potential available in other sectors (Fig. 2; Barker *et al.*, 2007), and needs to form part of a portfolio of measures to tackle climate change.

Estimates of global agricultural GHG mitigation potential since the IPCC Fourth Assessment Report

Since the IPCC Fourth Assessment Report, there has been one further comprehensive assessment of GHG mitigation potential in global agriculture. In an assessment across all sectors, McKinsey & Co (2009) used a bottom-up approach similar to that used by Smith *et al.*

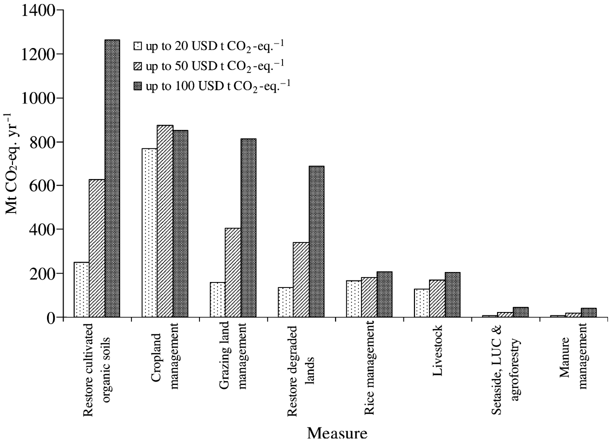

Fig. 1 Global mitigation potential in agriculture for 2030, at low, medium and high carbon price. Data from Smith *et al.* (2008).

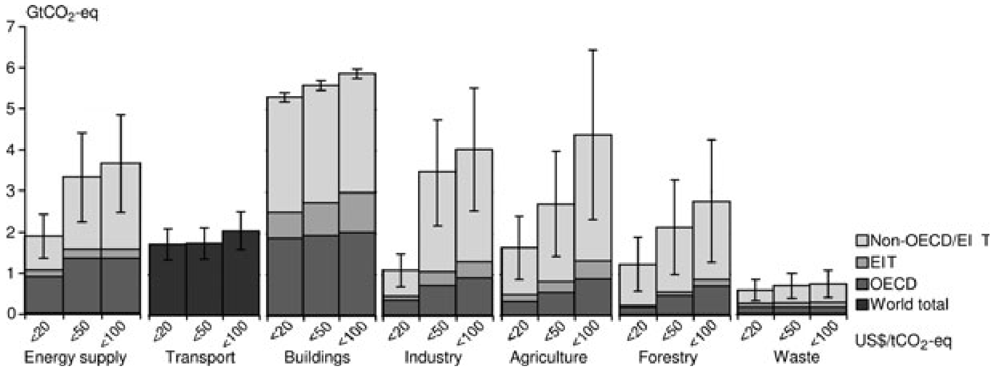

Fig. 2 Global economic mitigation potential for different sectors at different carbon prices (Barker *et al.*, 2007).

(2008), but made different assumptions about the baseline projections for GHG emissions in agriculture and the policy levers for encouraging mitigation. In that assessment, new global MACCs were derived, but the global potential was somewhat larger than that estimated in the IPCC Fourth Assessment Report at 4600 Mt CO_2-eq. yr^{-1} in 2030, and was estimated to be possible at lower cost ($US <70 t CO_2-eq.$^{-1}$; Fig. 3).

The Mitigation Volume of the IPCC Fifth Assessment Report (AR5) will be structured slightly differently, with agriculture, forestry and other land use all dealt with in a single chapter. This makes sense as different land uses compete for the same land base (Smith *et al.*, 2010a) and inevitably affect one another. One aim for the agriculture, forestry and other land use chapter is to provide a more comprehensive assessment and comparison of 'bottom-up' and 'top-down' estimates of mitigation potential. Another aim is to align the estimates of potentials with the land use projections associated with the Representative Concentration Pathway (RCP) scenarios of climate change that will be used in AR5. Detailed work is underway in the Land Use Harmonization (LUH) project using the Message, MiniCam, AIM and IMAGE models providing land use change projections under each RCP at 0.5 degree scale, providing a more consistent basis for comparison and assessment in the land-based sectors (LUH, 2011).

GHG mitigation potential in European agriculture

Early estimates of the GHG mitigation potential in agriculture in Europe focused largely on soil C sequestration and focused on croplands. The first estimates (Smith *et al.*, 1997, 1998) did not consider a baseline and examined technical potential only, with estimated soil C sequestration potentials of ca. 30–140 Mt CO_2-eq. yr^{-1}. Later developments included baseline estimates (Smith *et al.*, 2000a) and examined combined scenarios using different options on different pieces of land, with combined estimates of up to 200 Mt CO_2-eq. yr^{-1}, enough to meet Europe's emission reduction targets under the Kyoto Protocol. A later study gave some consideration to N_2O and CH_4 (Smith *et al.*, 2001), but the extent to which these could be included was limited by

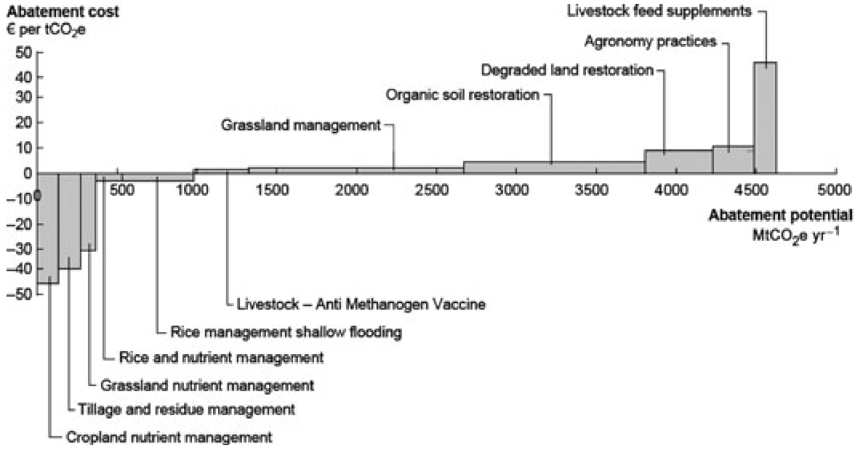

Fig. 3 Global mitigation marginal abatement cost curve for agriculture for 2030 (McKinsey & Co, 2009).

lack of available data, and estimates were still of technical, rather than of economic potential. Other estimates during the same period derived even higher estimates (70–600 Mt CO_2-eq. yr^{-1}) for technical potential of soil C sequestration in agriculture (Vleeshouwers & Verhagen, 2002).

By the middle of the decade (2000s), no new measures had been introduced in Europe to encourage C sequestration and it was clear that soil C sequestration would play a minimal role in meeting the then upcoming targets of the Kyoto Protocol first commitment period (2007–2012). Smith *et al.* (2005) examined the level of soil C sequestration in four European countries, and for EU15, and showed that it was almost negligible. This led to the distinction between *potential* sequestration and *likely* sequestration with a conceptual framework to compare these potentials proposed (Smith *et al.*, 2005). In light of more recently adopted terminology, we can recast these potentials in terms of technical, economic and market potential, as shown in Fig. 4.

Since the mid-2000s, new assessments of agricultural mitigation potential have been made, using bottom-up mitigation factors similar to those used by Smith *et al.* (2008) and also using systems models based on IPCC methodologies, such as MITERRA. In the PICCMAT project, a range of cropland mitigation activities were examined for their impact on soil C and on N_2O emissions in EU27 (PICCMAT 2008). For individual measures on croplands and grazing lands, the potential was estimated to be much lower (20 Mt CO_2-eq. yr^{-1}) than the earlier estimates of technical potential made in the late 1990s. The lower potentials are partly due to a smaller geographical area considered (EU27 compared with geographical Europe as far East as the Urals), and also due to more limited application of the measures (e.g. 5–15% increases in practices compared to full implementation when assessing technical potential). Figure 5 summarizes the mitigation potential for a range of practices for EU27 (PICCMAT 2008).

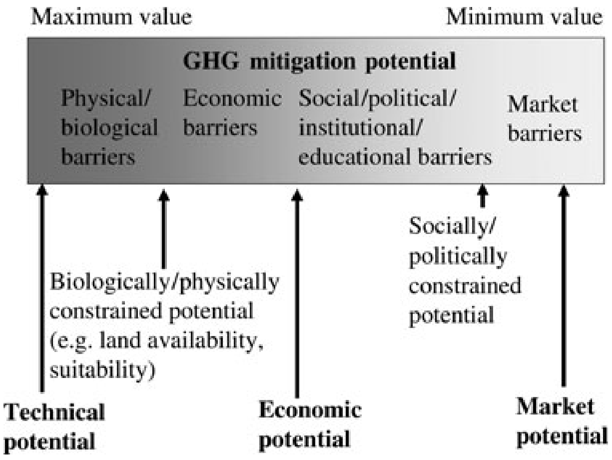

Fig. 4 Relationship between technical, economic and market greenhouse gas (GHG) mitigation potential. Different categories of barriers to implementation (Smith *et al.*, 2007b), which each reduce the realized potential, are shown. Technical potential is the full biophysical potential of a mitigation measure if all barriers could be overcome. Economic potential is the potential that could be realized at a given carbon price. Market potential is the potential actually seen under current market conditions. Policy can be used to move the market potential closer to the economic potential. Figure adapted from figures used by Smith *et al.* (2005) and adapted by Smith & Olesen (2010).

GHG mitigation potential in UK agriculture

As for Europe, early estimates of GHG mitigation potential in agriculture in the UK focused on soil C sequestration in croplands (Smith *et al.*, 2000b,c). These estimates suggested a technical potential of ca. 14 Mt CO_2-eq. yr^{-1} (Smith *et al.*, 2000b). More recent estimates, examining the impact on all GHGs of feasible land use change within the agricultural sector for Great Britain (excluding Northern Ireland for which county level land use change data were unavailable), suggest a maximum potential of ca. 11 Mt CO_2-eq. yr^{-1} (Smith *et al.*, 2010b), but with potential to lose 14 Mt CO_2-eq. yr^{-1} if 20% if current grassland were ploughed out to cropland. A study of mitigation potential on agricultural land remaining in the same use (i.e. without land use change) suggests a mitigation potential of ca. 1–2 Mt CO_2-eq. yr^{-1} (Fitton *et al.*, 2011), which is less than 1% of UK GHG emissions. Another recent study of cropland and soil mitigation measures in the UK (MacLeod *et al.*, 2010) suggests a higher mitigation potential by 2022 of 1.6–10.2 Mt CO_2-eq. yr^{-1} (Fig. 6) at costs equal to or less than 100 euro t CO_2-eq.$^{-1}$ (ca. \$US130–140 t CO_2-eq.$^{-1}$). An extended analysis also including livestock options and other components of the Agriculture, Forestry and Other Land Use sector suggested a potential of ca. 10.8 Mt CO_2-eq. yr^{-1} by 2022 (using social discount rates; Moran *et al.*, 2011) comprising 6.5 Mt CO_2-eq. yr^{-1} from soils and crops, 3.4 Mt CO_2-eq. yr^{-1} from livestock measures and 1.0 Mt CO_2-eq. yr^{-1} from forestry measures. This is equivalent to ca. 6% of current UK GHG emissions.

Other considerations for agricultural GHG mitigation

Mitigation and sustainable development

Agricultural mitigation measures often have synergy with sustainable development policies. Smith *et al.* (2007b) evaluated the effect of different mitigation

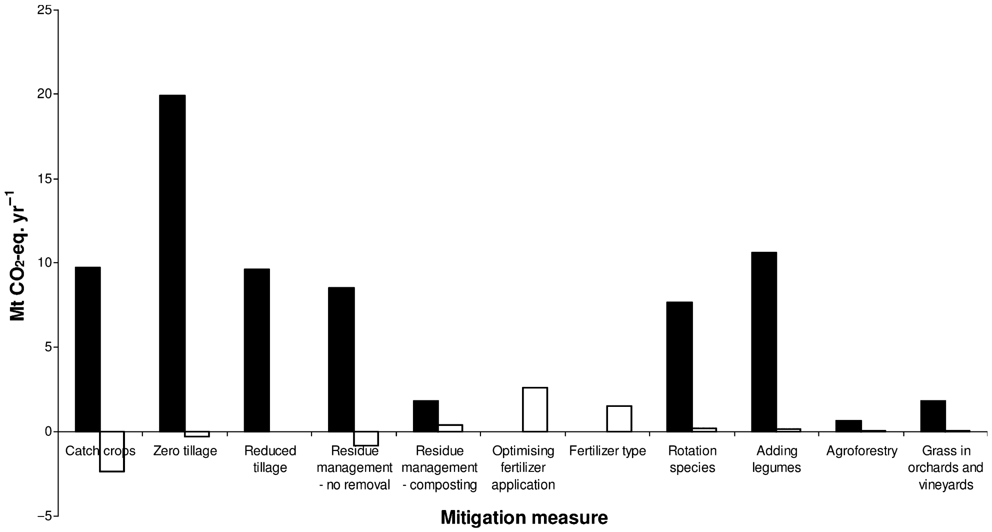

Fig. 5 Mitigation potential of agricultural measures in EU27. Mitigation from carbon soil C sinks (CO_2) in black and from reduced N_2O emissions in white (data from PICCMAT, 2008).

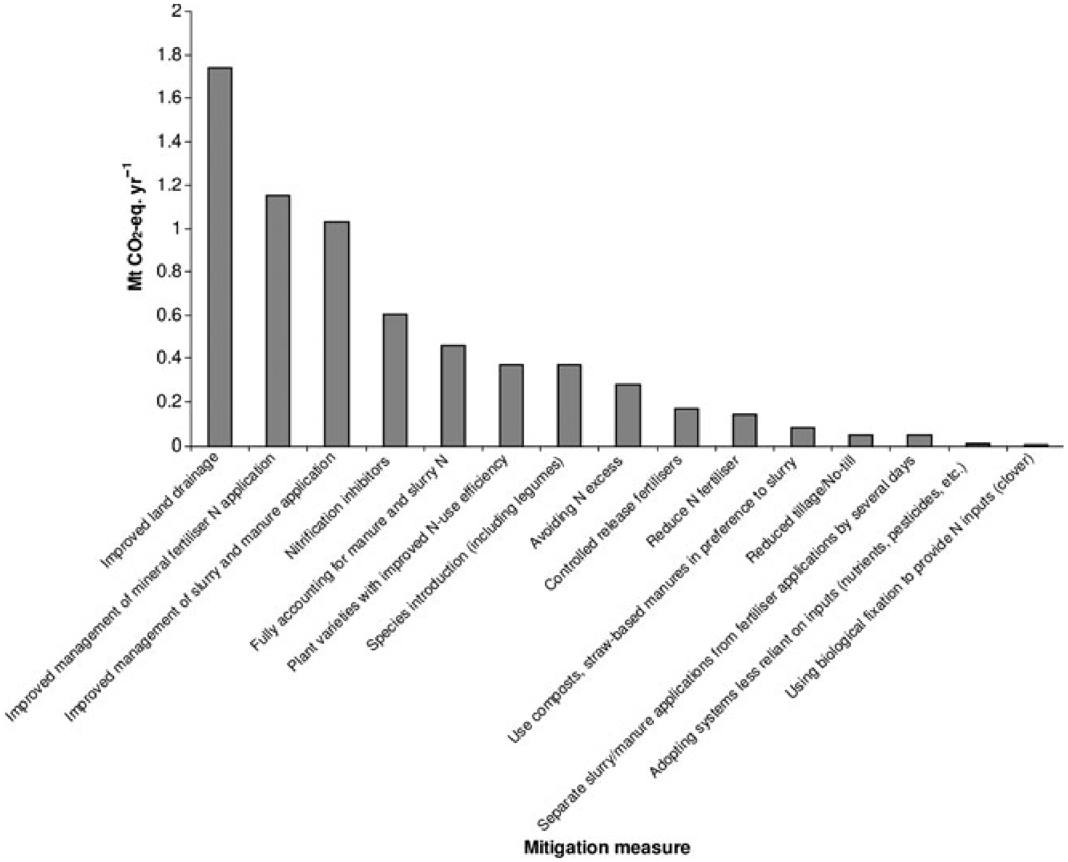

Fig. 6 Mitigation potential (Central Feasible Potential in 2022) for soil and crop mitigation measures in the UK (MacLeod *et al.*, 2010).

activities in the agricultural sector on the pillars of sustainable development; that is, the social, economic and environmental factors. A number of activities were found to provide cobenefits. For example, agriculture contributes more than half of the world's emissions of CH_4 and N_2O and nutrient, water and tillage management can help mitigate these GHGs, especially in rice crops. By careful drainage and effective institutional support, methane emissions and irrigation costs for farmers can be reduced, thereby improving farmer incomes. An appropriate mix of rice cultivation with livestock – known as integrated annual crop-animal systems and traditionally found in West Africa, India, Indonesia and Vietnam – can increase net income, improve cultivated agro-ecosystems and enhance human well-being. Such combinations of livestock and cropping, especially for rice, can improve income generation, even in semiarid and arid areas of the world.

In agriculture in general, groundwater quality may be enhanced and the loss of biodiversity slowed by careful use of farmyard manure and more targeted use of pesticides. The impact on social and economic aspects of this mitigation measure remains uncertain. Better nutrient management can improve environmental sustainability.

Pasture improvement by the control of overgrazing favourably impacts livestock productivity (creating greater income from the same number of the livestock) and slows or halts soil loss and desertification, thereby providing other environmental benefits. It also provides social security to the poorest people during extreme events such as drought and other crises, especially in Sub-Saharan Africa.

Changes in land cover and tillage management could promote both mitigation and adaptation. A mix of horticulture crops with optimal crop rotations would promote carbon sequestration and could also improve agro-ecosystem function. Societal well-being would also be enhanced through provisioning of water and enhanced productivity. While the environmental benefits of tillage and residue management are clear, other impacts are less certain.

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

Mitigation and adaptation

There are interactions between mitigation and adaptation in the agricultural sector, which may occur simultaneously, but differ in their spatial and geographical characteristics. Most mitigation measures are likely robust to future climate change, but a subset will likely be vulnerable (e.g. irrigation in regions becoming more arid). It may be possible for a vulnerable practice to be modified as the climate changes and to maintain the efficacy of a mitigation measure. Further synergies and trade-offs between mitigation and adaptation measures have been explored recently by Smith & Olesen (2010) and therefore are not described further here.

Tackling the drivers of increased GHG emissions

Most estimates of GHG emissions and mitigation potential have some underlying assumptions about increases in population and increases in demand for livestock products in developing countries. Many of these trends may be difficult to influence, and it may take a long time for policy to change these drivers. Nevertheless, they should perhaps be considered when designing policy to reduce emissions. Stehfest *et al.* (2009) showed that, hypothetically, global food demand in 2050 could be met with reduced land and emissions if livestock products were eliminated from the human diet. Similarly, Audsley *et al.* (2010) showed that some dietary change would be necessary for the UK to get close to meeting its GHG reduction targets in agriculture. Addressing the drivers of GHG emissions (i.e. the consumption side of the equation) may be as important as reducing GHG emissions from the agricultural production.

Metrics for accounting for GHG mitigation measures in agriculture

Reduction in GHG emissions from agriculture in a particular area will only have a climate benefit as long as emissions in other areas do not increase. If reduced emissions in one area lead to more GHG intensive production in other regions, the climate benefit is negated. This displacement of emissions from one area to another is termed 'leakage' (Smith, 2008). It is not sufficient therefore simply to reduce emissions at the expense of agricultural production, as increased production will be required elsewhere to meet demand. Instead, the GHG emissions per unit of agricultural product need to be considered. This impacts the metrics used to assess the efficacy of GHG mitigation in agriculture: rather than assessing GHG emission reduction per unit of land (e.g. kg CO_2-eq. ha^{-1} yr^{-1}) or per animal, GHG emissions need to be assessed against units of agricultural production (e.g. kg CO_2-eq. kg $product^{-1}$, g CO_2-eq. $kcal^{-1}$ or $joule^{-1}$ or kg CO_2-eq. kg $protein^{-1}$).

Barriers to implementation of GHG mitigation measures

Smith *et al.* (2007b) discussed some of the barriers that prevent mitigation measures being applied, and these were further examined in the context of a developing country by Trines *et al.* (2007), Smith & Trines (2007) and Smith & Wollenberg (2011). These barriers are economic, risk-related, political/bureaucratic, logistical and educational/societal, and need to be overcome if the mitigation potential available in agriculture is to be realized. In developed countries, mechanisms need to be defined that encourage farmers and land managers to implement mitigation measures. In developing countries, global sharing of innovative technologies for efficient use of land resources and agricultural chemicals, to eliminate poverty and malnutrition, will significantly help remove barriers that currently prevent implementation of mitigation measures in agriculture (Smith *et al.*, 2007b). Capacity building and education in the use of innovative technologies and best management practices would also serve to reduce barriers. More broadly, macroeconomic policies to reduce debt and to alleviate poverty in developing countries would serve to lower or remove barriers: farmers can only be expected to consider climate mitigation when the threat of poverty and hunger is removed. Mitigation measures that also improve food security and profitability (such as improved use of fertilizer) would be more favourable than those which have no economic or agronomic benefit. Such practices are often referred to as 'win–win' options, and strategies to implement such measures can be encouraged on a 'no regrets' basis (Smith & Powlson, 2003), that is they provide other benefits even if the mitigation potential is not realized. Maximizing the productivity of existing agricultural land and applying best management practices would help reduce greenhouse gas emissions (Smith *et al.*, 2007b).

Agricultural mitigation measures need to be considered within a broader framework of sustainable development. Policies to encourage sustainable development will make agricultural mitigation in developing countries more achievable. Current macroeconomic frameworks do not support sustainable development policies at the local level. Policies to reduce debt and to alleviate poverty in developing countries, through encouraging sustainable economic growth and sustainable development, are desperately needed. Potential negative impacts on the consumption side, due to changes in diet and energy use arising from improved economic growth, are likely to be more than offset by the benefits. Ideally, policies associated with fair trade, reduced subsidies for agriculture in the developed world and less onerous interest rates on loans and foreign debt all need to be considered.

Concluding remarks

Estimates of mitigation potential in agriculture have improved greatly in the last two decades in a number of ways: (i) the measurement of non-CO_2 GHGs has improved greatly allowing all three biogenic GHGs to be considered together, compared with early estimates based largely on soil C, (ii) there are better conceptual frameworks to allow estimates of technical potential to be refined, to assess realistic potentials, (iii) there are new economic frameworks (such as MACCs) to allow the cost effectiveness of mitigation measures to be assessed, (iv) models and networks of experiments with observations of GHG emissions (from soils and livestock) and soil C change have improved (e.g. the data presented in Ogle *et al.*, 2005 and the network described in Richter *et al.*, 2007) and (v) a better appreciation of the synergies and trade-offs between mitigation and adaptation, sustainable development needs and impacts on other ecosystem services. Whilst the science of GHG mitigation is not completely settled, enough is known to recommend practices that will reduce GHG emissions or create C sinks. The great challenge remaining is to find the policy mechanisms to incentivize and deliver these mitigation practices, by overcoming the barriers discussed in 'Other considerations for agricultural GHG mitigation'.

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