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Low carbon agriculture: Objectives and policy pathways ☆

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ABSTRACT

The threat of long-term climate change has driven a number of international and national bodies to call for a re-direction of development pathways so that they are more resource efficient and use less carbon (C) in the form of fossil fuel per unit of economic growth and cause lower greenhouse gas emissions (GHGs). Agriculture is one of the largest anthropogenic sources of GHG emissions yet few authorities take account of this fact in their proposals and programmes for low C development. Hence this policy review examines the case for promoting strategies and policies for low C agricultural growth. Most of the policy and technological options that it considers have already been put forward by the Intergovernmental Panel on Climate Change (IPCC) and others in the context of climate change mitigation, but constraints to their implementation have often been underestimated. This review reassesses their potential contribution in the light of known bio-physical, socio-economic and institutional limitations. It concludes that there is a very strong case for greatly increasing the priority given to policies for low C growth which can be true win–win–win responses. Many of them are more cost-effective than the responses available to other sectors. They can be pro-poor and have other socio-economic benefits. They not only limit GHG emissions but also provide a range of other environmental and ecosystem benefits. However there can be significant barriers to implementation that must be overcome by national policies shaped to meet the needs of different farmer groups and agricultural systems.

☆ The narrow definition of agriculture is used here which excludes forestry and in this review only deals with direct and indirect carbon use to the farm gate. This is not to ignore the fact that forestry plays a major role in the carbon cycle (IPCC, 2007) nor that carbon use between the farm gate and the consumers plate is of major significance and can be greater than that up to the farm (Garnett, 2010).

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1. Introduction

Since the publication of the Stern Review on the Economics of Climate Change (2006) and its follow-up report on moving to a low carbon economy (HM Treasury, 2007) increasing attention has been focused on the concepts of and strategies for clean growth (UNCTAD, 2009), the green economy (UNEP, 2011) green growth (OECD, 2011), and low emission growth (Foresight, 2011). Although the main descriptive of these proposals varies they are all centred on reducing the carbon content of economic growth through policies that restructure economic, technological and social systems of production and consumption to slow down climate change, increase natural resource use efficiency and improve environmental protection. They should therefore be considered as a central and well focused component of sustainable development rather than an alternative pathway.

The term low C agriculture is used here to cover actions to reduce the energy inputs to and GHG emissions from agriculture, with progress being a good indicator of improving environmental sustainability. Carbon (C) is used as short-hand for all greenhouse gases. Direct C inputs to agriculture as fuel for tractors, energy for milking machinery, crop drying, etc., tend to be a small fraction of a country's energy use and carbon dioxide (CO_2) emissions ($<2\%$ in the UK, $>3\%$ in China) though at the enterprise level may exceed 25%, e.g. as in the case of diesel and electricity for dairy farms in New Zealand (Fraser et al., 2008). However, agriculture's GHG emissions, which are as much nitrogen (N) related as they are C related, are of major significance. They are predominantly of methane (CH_4) and nitrous oxide (N_2O), which are 21 and 310 times more powerful, respectively, than CO_2 as regards their greenhouse warming effect (IPCC, 2007). Globally, agriculture's share (excluding emissions from fertilizer production) of total anthropogenic GHG emissions was about 13% in the mid-2000s (Fig. 1) compared with 9% in the UK (MacCarthy et al., 2011) and 15–19% in China (SAIN, 2010). Moreover, CH_4 and N_2O emissions are projected to grow by 30–60% by 2030 even under relatively favourable policy and technological assumptions (Bruinsma, 2003), and the bulk of this growth will be in developing countries.

Low C agriculture must therefore be a key thrust in strategies to achieve green growth. However, although most developed countries are endeavouring to lower their GHG emissions from agriculture very few (notably the UK and New Zealand) have explicitly adopted the recommendations of the Stern Review and the IPCC and started to implement measures to shift their agricultural sector on to

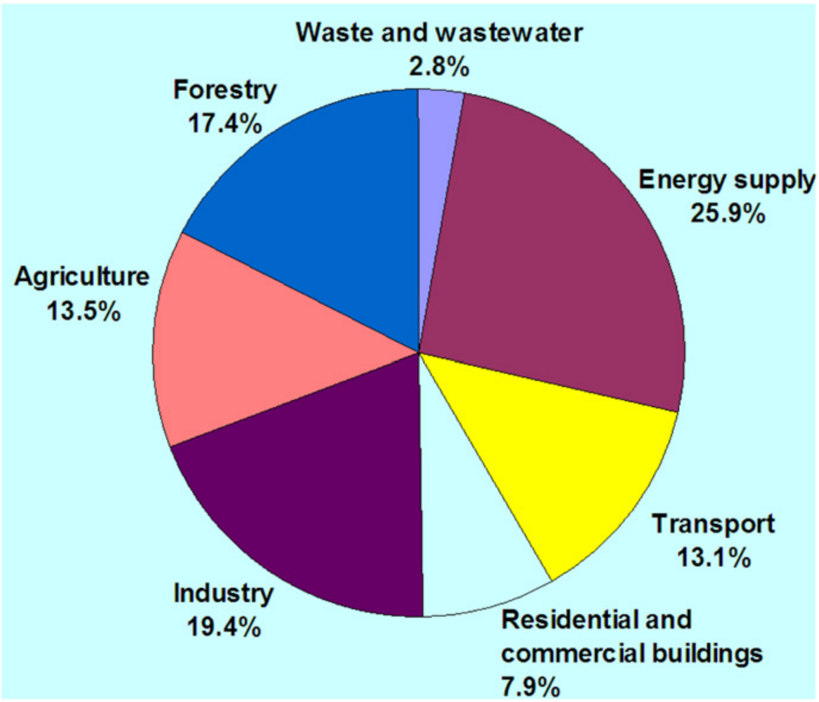

Fig. 1. Contribution of different sectors to global GHG emissions.
Source: IPCC (2007).

a low C growth path even though there is a wide range of GHG mitigation options available (Stern, 2007; HM Treasury, 2007; Smith and Martino, 2007b). Furthermore, the few that are actively trying to adopt a low C growth path are not placing it in the wider environmental development context. Instead they are focusing their attention on lowering the fossil energy intensity of growth in their industrial and transport sectors and on breaking the link between CO_2 emissions and economic output. They are not focusing on the agricultural sector where the unit costs of C reduction (including transaction costs) are generally lower and the associated socio-economic and environmental benefits can be greater (McKinsey, 2009a; SAIN, 2010, 2011; Norse et al., 2011). Moreover, their focus on energy intensity is too simplistic for the agricultural sector. First, because the direct energy inputs tend to be low as indicated above whereas the indirect ones can be very high, particularly those associated with the production of synthetic nitrogen fertilizers (Table 1). And

Table 1
Agricultural GHG emissions by main source[a] (Mt CO_2eq with shares of total on-farm emissions in brackets).
Source: Bellarby et al. (2008 (col.1)), SAIN (2011(col.2)), Chadwick et al. (2011 (col.3)) and INCCA (2010 (col.4)).

	Global for 2005	China for 2007	UK for 2007	India 2007
N_2O from soil	2128(38)	263(23–29%)	25	43(13)
CH_4 from enteric fermentation	1792(32)	467–701 Incl. manure(41–51%)	16	212(63)
CO_2 from biomass incineration	672(12)		Not available	7(2)
CH_4 from rice	616(11)	170(15–19)	0	70(21)
CH_4 from manure	413(7)		3	2(1)
Total of above on-farm emissions	5621	900–1134		334
CO_2 from fertilizer production	410	292		
CO_2 from farm machinery and irrigation	527	190		
Total of the above	6558	1382–1636		

[a] Excluding emissions from land conversions.

secondly, because the main agricultural (excluding forestry) driver for climate change is emissions of non-CO_2 gases rather than of carbon dioxide.

Consequently this paper undertakes two tasks. First, it presents the case for greater national and international efforts to move onto a lower C agricultural growth path. Second, it assesses the main strategy and policy options for achieving such growth. These tasks are illustrated by the contrasting cases of the UK (one of the few countries with a fairly comprehensive strategy for agricultural GHG mitigation) and China (a transition economy responsible for $>20\%$ of global agricultural GHG emissions, which has started to prepare a strategy). As stated in footnote 1 the analysis is restricted to actions on agriculture up to the farm gate, but this is not to deny that complimentary actions will be needed along the remainder of the food processing, distribution and consumption chain (including demand management) if the full potential for low C growth is to be realised (Garnett, 2010). The aim is not to be comprehensive but to expand the debate on strategy formulation and on policy development and selection.

2. The case for low C agricultural growth

2.1. Agriculture's large and growing contribution to global GHG emissions

Agriculture's share of total global anthropogenic GHG emissions in 2005 (excluding those associated with the production of fertilizers and other agro-chemicals) was about 13% (Fig. 1), and similar to that of the transport sector, but only about half of the energy supply sector (IPCC, 2007). The distribution around this mean is considerable. It ranges from 1% to 2% in some developing countries such as Tanzania and Madagascar with low C intensity farming systems to 15–19% in China with very intensive cropping systems using high inputs of nitrogen fertilizer inefficiently and a rapidly growing livestock sector with low average feed use efficiency (Ma et al., 2010; SAIN, 2011). Most of these emissions are of CH_4 and N_2O of which agriculture's global share is ~47% and ~58%, respectively, though with appreciable uncertainties in these estimates (IPCC, 2007).

Much of this uncertainty stems from limits to our understanding about the magnitude and role of indirect emissions of N_2O from soils and surface waters (via N leaching and runoff and N deposition). The IPCC has recently revised downwards (as has the UK) its recommended default values for these indirect emissions to 0.33–0.43% of synthetic fertilizer use that are based on field estimates primarily from temperate farming systems (IPCC, 2007, 2010). This proposal has been challenged using global top-down analysis. Crutzen et al. (2007) in the context of a study on N_2O emissions from agro-biofuel production concluded that these N fertilizer related emissions could be as much as 4% of the fixed N input. A similar conclusion was reached by a historical reconstruction of atmospheric N_2O levels since 1860 (Davidson, 2009). He extended the analysis to consider the role of the livestock sector in more detail and estimated that ~2% of manure N is converted to N_2O. The IPCC acknowledges that there are major uncertainties in reconciling top-down and bottom-up estimates, possibly due to underestimates of N_2O emissions from animal wastes and slow moving rivers in the Tropics (IPCC, 2010). These conclusions could have important implications for the policy priorities for low C agriculture.

Although the share of total GHGs will generally fall in coming decades as the agricultural sector declines in size relative to the manufacturing and service sectors, actual GHG emissions will continue to rise as a result of greater agricultural intensification (Bruinsma, 2003; US-EPA, 2006a). For example, rising incomes in developing countries and the increasing demand for livestock products will lead to greater emissions of CH_4 from enteric fermentation and poor manure management and of N_2O through the application of nitrogen fertilizers and manure to feed grains. It follows from the latter that it is important to disaggregate total GHG emissions into their main sources as an aid to priority setting at both the international and national level and the selection of mitigation options. Globally, the main sources are N_2O from soils (largely from inorganic fertilizer) and CH_4 from enteric fermentation (Table 1) and this predominance is found in the UK, the EU, the USA, China, India and most other developing countries (US-EPA, 2006a). Thus, for example, there is a strong case for international organisations like the FAO and the CGIAR to focus more of their climate change mitigation activities on these two GHG sources.

Three preliminary conclusions can be drawn from the above. First, that unless agriculture is included in strategies and policies for low C growth there will be substantial increases in non-CO_2 GHG emissions during the next 2–3 decades. Second, that it may be possible for low C intensity farming systems in some developing countries to substitute for production in other countries with more intensive systems. Third, the relative importance of low C agricultural growth and agricultural GHG mitigation opportunities may rise if concerns about the underestimation of indirect GHG emissions prove to be correct.

2.2. Other environmental costs of high input agricultural systems

High input agriculture in developed countries has been the cause of widespread environmental damage and economic losses for more than 60 years and less extensively in developing countries for at least the past 40 years (Alexandratos, 1988; Bruinsma, 2003). Global estimates of these economic costs are hedged with so many uncertainties that they are not very meaningful but national estimates may be at least indicative of the correct order of magnitude. Those for the UK agriculture have been estimated to be ~US$ 5.6 bn. (Pretty et al., 2005) and in China those for rice production alone could be US$ 8 bn. (Norse et al., 2001 but updated to current prices and exchange rates).

Most of the environmental costs arise from the agricultural activities, which are also the main source of GHGs, notably N fertilizer use, enteric fermentation and manure management (Table 1). More specifically, there is the cost of nitrate accumulation in ground and surface water systems because of poor synthetic N fertilizer and manure management. This has negative consequences for human health – though these may have been overestimated (Powlson et al., 2008) – and for aquatic ecosystems because of eutrophication and the enhanced development of harmful algal blooms (Li et al., 2009).

Fortunately many of the mitigation options to be discussed in Section 3 have multiple benefits and lower both GHG emissions and these environmental costs. Furthermore, policies and technologies to address these other environmental costs were first introduced in developed countries before climate change mitigation became a major issue and so measures to promote low C agriculture can build on past experience on policy implementation. In the UK, for example, early attempts to reduce the accumulation of nitrates from agriculture in the water system underestimated the size and complexity of the problem. Consequently, the EU Nitrates Directive (EC, 1991) was initially applied to a relatively small proportion of England's cropland, but this was insufficient to control nitrate pollution of ground and surface waters. Consequently, it has now been extended to cover $>65\%$ of the farmland. In addition, the controls on N management have become tighter and tighter (Defra, 2009) but nitrate pollution remains a problem with one-third of the rivers showing high nitrate levels and a quarter of groundwater bodies failing the nitrate objectives of the EU Water Framework Directive (OECD, 2009; Environment Agency, 2010). This experience has important implications regarding the rate at which the mitigation options in Section 3 may lower GHG emissions.

2.3. *Low C agriculture and pro-poor development*

This can be examined from several aspects but notably from the point of view of higher farm incomes and lower food prices for all low income consumers. These arise mainly from:

- Productivity increases particularly those associated with greater nutrient and water use efficiency, for example, precision placement of fertilizers and drip-irrigation that lower C inputs and GHG emissions. Such gains in productivity reduce the unit costs of production and may lower both food prices and food price inflation.
- Increases in net farm incomes from measures to limit the overuse of synthetic N fertilizers (and livestock manure) that are commonly the major purchased production of small farmers. These measures can (a) lower the costs of production and (b) raise yields by lowering pest attacks (Cu et al., 1996; Long et al., 2011). In China, action against N overuse can give low-income farmers a $\sim$10% increase in net farm incomes with no reduction in crop yields (in fact many farmers get a 5–10% increase in yields) though only a 2–3% increase for other farmers obtaining most of their income from off-farm employment (Norse et al., 2011 and Table 2). Similar income gains seem possible in other countries like India, Indonesia, Mexico, Malaysia and Thailand where there are areas of overuse even though national average use is more modest.
- Improvements in the stability of food and cash crop production where reduced tillage and other measures to build up SOC raise the moisture holding capacity of soils and decrease the vulnerability to drought

Table 2
Potential income gains from reducing synthetic N overuse in Shaanxi Province, China.
Source: Norse et al. (2011).

Income level	Total household income (US$)	Savings from 30% fertilizer use reduction		Savings from 50% fertilizer use reduction	
		Savings (US$)	% Of household income	Savings (US$)	% Of household income
1st Quartile	252	23	9	39	15
2nd Quartile	983	38	4	63	6
3rd Quartile	1582	34	2	57	4
4th Quartile	3070	34	1	56	2
Average	1474	32	2	53	4

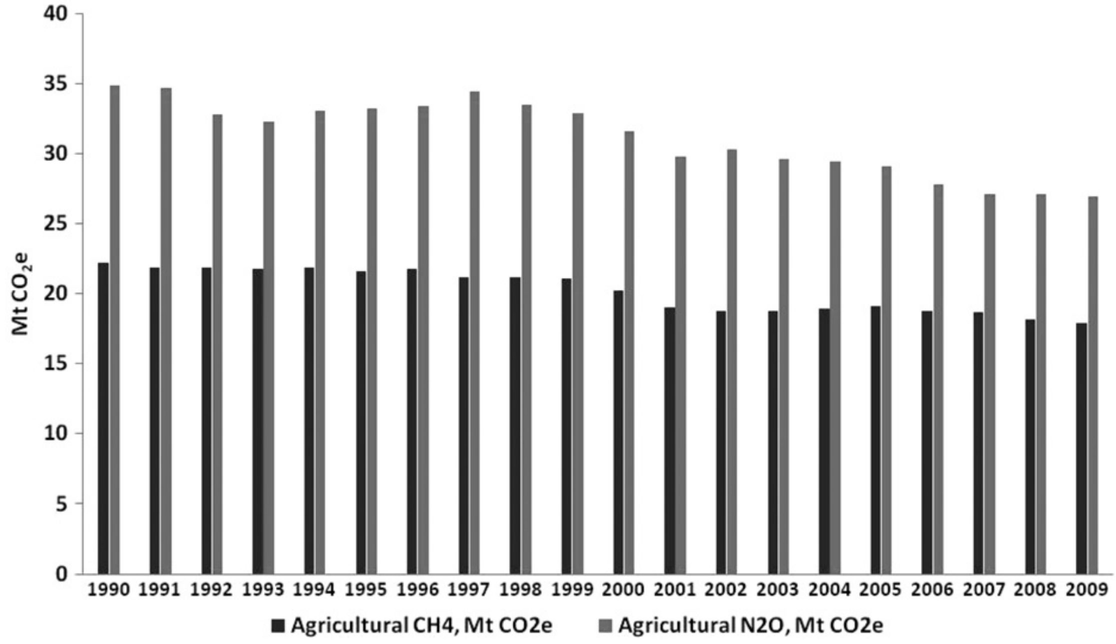

Fig. 2. GHG emissions from UK agriculture, 1990–2009.

2.4. *High cost-effectiveness of low C agriculture*

Many of the policy and technology options to be considered in Section 3 involve management changes and evolutionary changes in technology which can be introduced at low or negative economic cost (US-EPA, 2006b; Smith and Martino, 2007b; McKinsey, 2009a). The potential is substantial. Studies for the IPCC have estimated that at the lower end of the mitigation cost range (up to US\$20/tCO_2-eq) the total potential reduction in GHG emissions is 1500 Mt CO_2-eq/year (Fig. 2).

Moreover, average costs per tonne of CO_2 removed in the agricultural sector can be significantly less than in the power, manufacturing and service sectors. In China, for example, the chemical and cement industries provide the greatest potential for GHG abatement (930 Mt CO_2-eq by 2030) and one of the promising technologies for this is carbon capture and storage but at an average cost of US$ 90–100 per tonne of CO_2-eq removed (McKinsey, 2009b). This is in contrast to many of the improved cropland and fertilizer management techniques, such as better timing and placement of synthetic N fertilizers and integrated nutrient management. These are amongst the most promising agricultural GHG mitigation measures, and have negative abatement costs of –US\$30 to –US\$60 primarily because of the production cost savings they provide. Moreover, technological development is increasing the range of cost-effective measures. For example, slow release fertilizers and nitrification inhibitors have been available for many years but have been too expensive for most crops. R&D in China, however, has improved their performance and lowered their cost such that they may add only 5–10% to the cost of the conventional fertilizer, but provide a 50% or more reduction in N_2O emissions (see further discussion in Section 3.3). Thus there are strong economic arguments for giving priority to low C agriculture in national plans for low C growth.

3. Strategies and policy options for low C growth

3.1. *Strategy setting*

The foregoing analysis of the case for accelerating the adoption of low C agriculture has identified a number of objectives that should be included in most if not all national strategies for low C growth.

These objectives should include:

- Focusing on the largest sources of GHGs with the lowest unit mitigation costs (Moran et al., 2008).
- Maximising the social, economic and environmental benefits by giving emphasis to those low C and GHG mitigation policies that take account of the multifunctional characteristics of agriculture.
- Giving priority to those measures that are pro-poor and improve food security by raising food supply and increasing food purchasing power.

The validity of these objectives is strong for both developed countries like the UK where agricultural GHG emissions are only ~8% of total anthropogenic emissions and have been declining for the past 20 year (Fig. 2) and China where agriculture's share of total emissions is now ~18% (excluding emissions from fertilizer production), but agricultural GHGs have been rising for the past 25 years (Gao et al., 2011) and are projected to increase by about 20% over the next 10 years. This follows because (a) all countries have to lower their total GHG emissions and agricultural GHG mitigation is one of the cheapest options for doing this, and (b) they all need to raise agricultural productivity and food security, and decrease the non-GHG related environmental costs of agriculture (Foresight, 2011).

3.2. *Policy options: general considerations*

There is no single pathway for achieving the shift to low C agriculture, but many of the policy and technological requirements and response options are common to most countries, although the appropriate mix will vary as will the time path for implementation. The GHG mitigation options have been comprehensively reviewed in recent years (Smith et al., 2007a; Bellarby et al., 2008; UNCTAD, 2009; Garnett, 2010; Foresight, 2011) so this section will take a more general approach focussing on certain issues. Most of the options fall into four groups according to their dominant impact:

- measures that increase C sequestration or limit soil organic matter (SOC) loss;
- technical or regulatory measures to directly limit C inputs to or improve the efficiency of C inputs in to agriculture including improved N use efficiency and improvements in livestock diets to reduce enteric fermentation;
- substitution for C inputs to agriculture or by agriculture for C inputs to other sectors (biogas and certain C neutral or C negative biofuels, Woods et al., 2010);
- awareness raising.

3.2.1. *Raising awareness of the issues and opportunities*

There are five key target groups:

- Decision makers in central or local government responsible for strategy formulation and policy design and implementation.
- Farmers who must be convinced that a shift to low C agriculture is in their interests and within their capacity to adopt (and adapt to their personal circumstances).
- Agricultural input producers, wholesalers and retailers who need to generate new products and services and improve the advice they give to farmers.
- Public and private extension workers and technical advisors who need to offer consistent and comprehensive advice.
- Consumers who can influence how foods are produced and the sourcing policies of retailers (particularly supermarkets).

For example, decision makers in central or local government are commonly not aware that the shift to low C agriculture is a win–win–win change that can be justified in terms of short-term economic, social and environmental benefits and not just its contribution to the mitigation of uncertain temporal and spatial climate change impacts There is no doubt that the shift will involve some policy tradeoffs – these can seldom be avoided when a government makes a significant shift in their national development path – but none of these justify blocking the overall objective. In China, for example, some members of the National Development and Reform Committee[1] (NDRC, 2004b) have questioned the adoption of one of the most cost-effective agricultural GHG mitigation measures, namely the reduction of the current ~30–50% overuse of N fertilizer on crops (Chen et al., 2011). They did so on the grounds that such a reduction would put national food security at risk, which is key priority of the Chinese Government. Such concerns are not justified. There is widespread experimental and on-farm research, which clearly shows that N fertilizer use can be reduced substantially without any fall in yields, in fact yields frequently rise 5% or more because of the way overuse of N increases pest and disease attacks, constrains root development and disrupts biological fixation and other soil processes (SAIN, 2010; Long et al., 2011; Cheng et al., 2009).

For farmers it can be argued that the key awareness issue is that of the profitability and feasibility of GHG mitigation measures. This can be as true for the many UK and EU medium to large-scale farmers, who have been facing declining profit margins and incomes for a number or years, as for small famers in China with agricultural incomes of > US$3/day. In the UK, as in the rest of the EU and OECD, farmers are very responsive to economic arguments and cost saving opportunities so the switch to low C agriculture message is commonly promoted to farmers in these terms (Defra, 2010). Chinese farmers are also price responsive and particularly to changing crop prices, but appear to be less responsive to input prices. The reasons for the latter are complex and expose weaknesses in our understanding of farm behaviour and in policy formulation and implementation (Lu et al., 2006). It has been clear from thorough economic analysis that many Chinese farmers have been overusing N fertilizers since the late 1980s at least resulting in net income losses to them and additional costs to the wider community from off-farm environmental damage (Zhang et al., 2006; Zhu et al., 2006). Yet this fact is not apparent in the policies of central or local government and the writer is not aware of it being used as a key message by extension agents anywhere in China. It follows that understanding, informing and guiding the decision process of farmers and local agricultural officials must play a central role in the promotion of low C agriculture.

3.2.2. Reducing embodied fossil fuel C in production inputs

Embodied fossil fuel C in the form of nitrogen fertilizer is one of the largest energy inputs to agriculture (over 60% in UK and USA) and hence should be a major target for GHG mitigation. The potential for reduction is substantial particularly in China and some other transition or developing countries where the energy efficiency of N fertilizer and ammonia (commonly the main raw material) production and pesticide production is low. It is even an option in the EU and other developed countries where average primary energy consumption performance is > 17–36% higher than best available technology (BAT) and average GHG emissions/kg product can be double that with BAT (Brentrup and Palliere, 2008). In China, the NDRC has set the target of a 17% increase in energy use efficiency of ammonia production by 2020, but this seems quite modest compared with BAT and furthermore it might be quicker to persuade and/or regulate the 230 or so medium to large scale ammonia producers to improve their performance than persuade most of the 200 million or more farmers to raise their N fertilizer use efficiency not withstanding the fact that the latter is profitable to the farmer (although labour constraints may be the overriding factor – see Section 2.3 and Norse et al., 2011) and cost negative to the country.

3.2.3. Substituting for high C inputs

A range of substitution possibilities have been proposed many of which are feasible, cost-effective, and justified on wider agricultural sustainability or ecosystem health grounds, for example,

[1] The National Development and Reform Committee is the premier development strategy and policy formulation body of the Chinese Government and responsible for coordination of measures to shift the energy, industry and agricultural sectors on to a low C pathway.

anaerobic digestion, organic fertilizers and green manures in place of synthetic N fertilizers and integrated pest management in place of pesticides. The question for debate is how much reduction in GHG emissions could they provide and over what time frame, since some of the estimates seem to be unrealistically high. There is a strong consensus that anaerobic digestion is generally a win–win intervention with a large potential to generate biogas as a substitute for fossil fuels, and to recycle crop nutrients, but this may not be the case for other interventions. For example, some have argued that a substantial conversion to organic farming is possible, and could make world agriculture almost GHG neutral (Hoffman, 2009). Similar conclusions have been made for China (Ho, 2010). FAO has explored this possibility through scenario analysis, and concluded that the adoption of a minimum set of measures could lower global agricultural GHG emissions by about 40%, and additional measures could boost the reduction by a further 25–45% (FAO, 2009). Two questions arise from this. First, can organic agriculture meet food security needs? Some scientists argue that there is a major trade-off issue here and that such a switch from conventional farming would result in reduced production (Mader et al., 2002) Others argue that organic farming need not result in lower yields (Pimentel et al., 2005) though it can be questioned whether this is the case for large-scale mechanised farming. Secondly, although organic farming has been strongly advocated for the past 20 years or so, and there is now a premium price market for organic fruit and vegetables, the present area is ~37 Mha (FiBL, 2011) up from about 11 Mha in 1999 so if the past rate of expansion was maintained it would have little impact on GHG emissions from the worlds ~1500 Mha of arable land and nor the even greater area of grazing land.

However, much could be achieved without switching to organic farming. Inter-cropping with legumes, agro-forestry, and leguminous catch or cover crops are biophysically suitable for large areas and could substitute for synthetic N fertilizer. In practice, however, there are a number of constraints, which will limit the uptake of this potential, for example:

- inter-cropping can be very labour intensive, which may be a disincentive for both smallholders dependent on family labour and for highly mechanised large farms;
- a switch to green manure crops could substitute for synthetic N but this must put pressure on land availability unless the green manure crop can substitute for a fallow period or be introduced as a very short duration catch crop. It will seldom be possible to replace a food crop by a green manure crop without endangering food security.
- Organic fertilizers, composts and farm yard manure generally have a much lower N content than synthetic fertilizers. Therefore applications rates can be 25 t/ha or more, which may exceed the labour supply available to smallholders, and that is why traditionally they have commonly applied their manure to vegetable plots close to their homes.

3.2.4. *C sequestration*

Estimates made for the IPCC Fourth Assessment Report indicate that improved cropland and grazing land management provide the largest and most cost effective measures for GHG mitigation (Smith et al., 2007a). Over 95% of this technical potential is for increased C sequestration through the build up of soil organic matter (SOC) and much of this is likely to be a secondary result of measures to raise crop and grassland productivity by improvements in fertilizer use efficiency, tillage practices, and grazing land management (Fig. 3). Specific measures to increase C sequestration through the restoration of degraded lands and the re-incorporation of crop residues can have more direct and longer-term benefits (Smith et al., 2007a; Lu et al., 2009; Lal, 2011). There are a number of points to consider here.

First, the term C sequestration tends to be used quite broadly and does not necessarily result in a net transfer of C from the atmosphere to the land (Powlson et al., 2011). Consequently, for example, some of the earlier estimates of the gains from reduced tillage were too high (including some by the author). Second, the build up of SOC in croplands is generally slow and in some farming systems it may plateau out after as little as 10–20 years of improved management. Third, C sequestration may involve tradeoffs, for example, between removing CO_2 as SOC and increasing N_2O emissions (Powlson et al., 2011). Fourth, one needs to examine this potential holistically and with reference to the other mitigation options. For

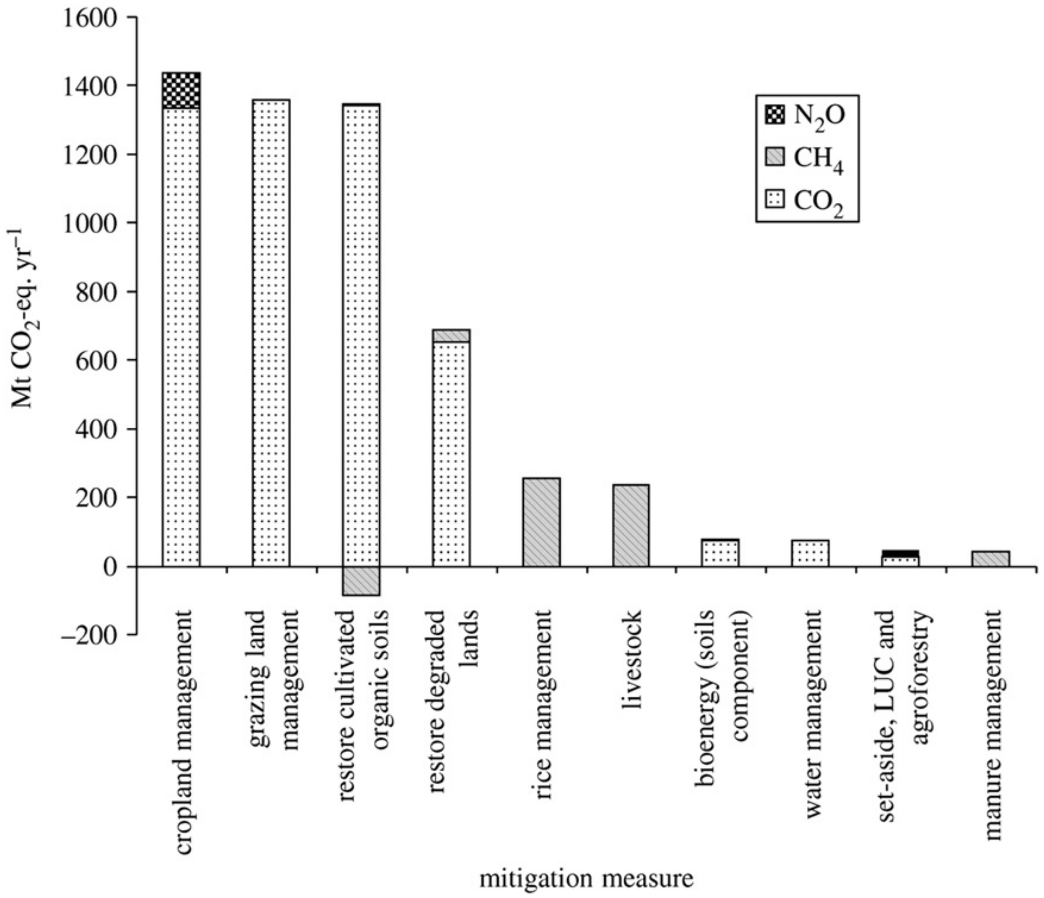

Fig. 3. GHG mitigation potential.
Source: Smith et al. (2007a).

example, cropland top soil C in China during the period 1980–2000 has been estimated to have increased by 300–740 Tg (Piao et al., 2001). However, the GHG cost of N fertilizer production and use over the same period was >10 times greater than this increase in top soil C.

So if the priority is to slow down climate change as quickly as possible then there is a very strong case for a strategy that focuses on (a) raising energy use efficiency in N fertilizer factories (see next section) and (b) increasing nitrogen use efficiency not just in crop production, but also in the livestock sector, which is becoming the largest source of agricultural GHGs (Table 1 and FAO, 2006, US-EPA, 2006a, 2006b), and in the aquaculture sector, which is now thought to be a significant source of indirect N_2O emissions (Williams and Crutzen, 2010). This is not to ignore the importance of measures that are directly aimed at increasing C sequestration in currently cropped and grazed land nor to deny the importance of restoring degraded land but to argue that they tend to be more costly and/or slower to implement than (a) and (b) above.

3.3. *Removing perverse subsidies and introducing or refining price incentives*

The majority of OECD countries have removed direct fertilizer subsidies but still have extensive producer supports which in 2007 totalled over US$ 250 billion (OECD, 2009) that have implications for GHG emissions.

Some developing countries, however, still have large direct subsidies for fertilizer and other production inputs that have important implications for low C agricultural growth and GHG emissions. In China and India, for example, they were about US$ 3.7 and 5.3 bn., respectively in 2007. A significant proportion of the Chinese subsidy is for the energy costs of N fertilizer production. This subsidy has two negative impacts on GHG emissions. First, it lowers the incentive for fertilizer manufactures to improve their energy use efficiency. Second, it encourages farmers to overuse N fertilizer (see Section 3.2.1). There is therefore a strong case in China for the removal of all subsidies for the production of N fertilizers.

It is important, however, to recognise the Chinese Governments central objectives of maintaining food security and raising or at least maintaining farmer's incomes. Removal of the subsidies might be thought to endanger both objectives. This is not the case for reasons given in Section 2.3. Moreover, it may be very beneficial to re-allocate some of the funds currently used to lower the energy costs of N fertilizer production to make payments for environmental services (PES). These payments could in the form of subsidies for either the surface coating of fertilizer to turn them into slow-release formulations or for the addition of nitrification inhibitors to fertilizers. Both of these measures can lower GHG emissions by up to 50% or more (though their efficacy varies between crops and agro-ecosystems) and reduce the accumulation of nitrate in ground and surface water, thereby limiting the incidence and severity of eutrophication and harmful algal blooms. But these measures increase the price of the fertilizer to Chinese farmers by about 5–10% compared with the conventional product (and possibly much more in other countries). The total cost of a PES to compensate for this price difference would be about US$3 billion (author's estimate), which is significantly less than China's current fertilizer subsidy bill.

3.4. *Setting policy priorities*

Policy formulation and priority setting are almost invariably country and context specific varying with political structures, farming systems, agro-climatic conditions, and farm household characteristics. Furthermore, additional constraints and requirements can arise from the conflicting objectives of different stakeholders. In China, for example, the central government was quick to formulate a strategy for low C growth, which is partly enshrined in law, and the Ministry of Agriculture has formulated an action plan for low C agriculture (Box 1). However, the predominance of the interests of the fertilizer manufacturing sector and its sponsoring ministry have led to huge energy and other production subsidies for N fertilizer, which contributes to their overuse (see Section 2.2). Similarly, whereas limiting overuse of N fertilizer in China would provide substantial net income gains to many small farmers (see Section 2.3) it may provide little incentive to larger farmers who tend to have different priorities and cost/income structures. They commonly gain most of their incomes from

Box 1–China and circular agriculture.

China started to formulate a strategy for a low C economy and low C agriculture several years before the publication of the Stern Review though it was more at the conceptual level and by political bodies rather than government ministries. It was formulated in terms of the development of a circular economy aimed at promoting resource-efficient production and consumption (Central Economic Work Conference on 3 December 2004) and ''accelerating progress towards a resource-efficient, environmentally-friendly society, energetically developing a circular economy, bolstering efforts to protect the environment, ensuring practical protection of natural ecosystems; striving to overcome environmental problems affecting economic and social development and putting in place models for improving resource efficiency and encouraging healthy consumption throughout society'' (Fifth Plenum of the 16th CPC Central Committee 11 October 2005). The latter also proposed that the principles of the circular economy should be applied to the full agricultural production and consumption chain so as to reduce material and resource inputs as well as waste outputs, and achieve a circle that is both ecologically and economically benign. It was not until 2007 that the MOA started to actively promote circular agriculture and formulate an ''Action Plan for the Promotion of Circular Agriculture'', which included measures to raise energy use efficiency and lower GHG emissions, enhance the development of rural biogas, and reduce the overuse of fertilizers and pesticides. These objectives are to be given added strength in the 12th 5 year Plan, which will set binding targets for the reduction of ammonia and N_2O emissions (NDRC, 2011).

off-farm work and N fertilizer account for only small fraction of their production costs (2–3%), and their main concern is to minimise labour costs (see next section).

3.4.1. *Improving the knowledge base for decision making*

Very few countries and policy formulators know where the greatest reductions in agricultural GHGs can be made at the lowest cost, nor do they generally appreciate that such actions to implement a low C agriculture strategy have other social and environmental benefits as discussed in Section 2.2. Several actions are needed to overcome this constraint, but three are of particular importance. First, it is necessary to prepare for agriculture a cradle-to-grave life-cycle analysis of direct and embodied energy inputs and GHG emissions. This should be undertaken all the way from raw material mining e.g. coal for ammonia generation for N fertilizer production, to commodity delivery to the farm gate (including crop storage) and on through processing, retailing and household consumption, and waste disposal. Such analyses have played a major role in the selection and formulation of low C agricultural policies in the UK, New Zealand, and some other OECD countries though are less common in developing countries. Second, having identified the key needs and opportunities for reducing agricultural GHGs, it is important to undertake comprehensive feasibility analysis to identify those policy measures that are cost-effective, appropriate to the country's physical and institutional setting and to the target dates for GHG reduction as discussed in Section 3.2.2. Third, and in support of the first and second, the development of sound GHG inventories and methodologies for the measurement, reporting, and verification of GHG emissions. There has been significant progress regarding the latter action with the establishment of the Global Research Alliance on Agricultural Greenhouse Gases (Shafer et al., 2011), which is actively promoting the sharing of information on GHG mitigation and inventories.

4. Conclusions

This policy review argues that there is a strong case for giving greater priority to shifting agriculture on to a low C growth path by adopting a range of complementary technological and institutional measures. Most of these measures involve non-CO_2 GHG mitigation rather than specific actions on the reduction of carbon inputs. The main measures concern:

(a) reducing fossil fuel C embodied in production inputs and particularly synthetic N fertilizers;
(b) substituting organic sources of N in manure, residues from anaerobic digesters, and leguminous crops for synthetic N fertilizer;
(c) lowering the overuse and misuse of N from both synthetic fertilizers and manure;
(d) increasing C sequestration by improving cropland and grazing land management that commonly form part of (c) above and by returning more straw and other crop residues to the soil.

They will provide multiple economic, social, and environmental benefits. Notably these measures can be cost-effective, pro-poor, reduce GHG emissions, and provide a range of other environmental and ecosystem benefits.

Uncertainties in the speed and magnitude of climate change are not a justification for delaying the implementation of many of the policy options considered here. The options will be economically, socially, and environmentally beneficial even in the absence of climate change.

If the key objective of low C strategies is to reduce C intensity by 10–20% by 2020 and limit climate change to a 2 °C rise in temperature by 2050 then priority needs to be given to GHG mitigation policies that can have a substantial impact during the next 10–20 years. Such priorities need to be clearly defined particularly in terms of:

(a) the magnitude and nature of the sources of agricultural GHGs at the national level,
(b) the dependence or sensitivity of GHG mitigation policies to decisions made outside agriculture, e.g. in the case of China, those by the Ministries of Industry or Energy regarding raising energy

efficiency in the agro-chemical industry, or outside the country e.g. transport infrastructure development in many parts of Sub-Saharan Africa, which needs international aid that is not currently being provided, and

(c) realistic assessments of how quickly (i) farmers will respond to opportunities for GHG mitigation, (ii) institutional barriers to their adoption can be removed, and (iii) research will deliver robust and more cost-effective mitigation technologies to the market place.

These three requirements will not be easy to achieve. The first can be met by improving the knowledge base for decision making as discussed in Section 3.4.1.

The second will be much more difficult given the prevailing poor co-ordination of decision making of different ministries and departments, and general decline in international aid. At least part of the solution might be to promote farming systems, which are less dependent on off-farm production inputs.

The third requirement is also multi-dimensional but must include (i) policy research which goes beyond bio-physical and economic analysis to consider behavioural science aspects; (ii) more farmer involvement in research, support services, and information transfer, e.g. farmer trains farmer schemes in place of or to complement conventional extension systems; (iii) greater sharing of experience, skills and technologies between countries and particularly between developed and developing countries. The developed countries started to intensify agricultural production much earlier than the developing countries and hence have had longer experience with the technologies and policies that can contribute to low C agriculture. None the less this sharing of experience must also include increased south–south technology transfer, because few developed countries have the types of agro-ecosystems that tend to predominate in developing countries. These proposals are not new. They have been made many times before and widely supported but progress on them has been at best piece-meal.

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