Mitigating climate change: energy, carbon and nitrogen on the farm

P. J. GREGORY

Scottish Crop Research Institute (SCRI), Invergowrie, Dundee, DD2 5DA

Summary

The evidence for climate change is unequivocal and attention is now focussed on adapting agriculture to the current and projected changes, and in mitigating emissions of greenhouse gases. Agriculture contributes directly only about 7% of the gases causing global warming, but it also contributes indirectly through the manufacture of fertilisers and the use of power and fuels on farm. Mitigation can be achieved by either reducing emissions (e.g. by decreasing the use of fossil fuels or the inputs manufactured from them, growing bioenergy crops, or adopting management practices that decrease net emissions of N_2O and CH_4) or adopting management practices that permit sequestration of carbon in soil or in long-lived plants. Overall, while each of the possible individual mitigation options can only make a small inroad into greenhouse gas emissions, collectively they start to make an important contribution both environmentally and economically.

Introduction

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that evidence of “warming of the climate system is unequivocal” and that there is “very high confidence” that this climatic change is a direct result of human activity (IPCC, 2007). This global warming is a result of increasing emissions of greenhouse gases principally from the burning of fossil fuels but also as a consequence of changed land use and agriculture.

Greenhouse gases (GHG) comprise carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. All are involved in retaining heat in the earth’s atmosphere but each has a different degree of effectiveness. For example, a unit of N_2O is about 300 times more active than a unit of CO_2 over a century in its radiative forcing; methane is 21 times more active. To provide a simple measure that takes account of these different activities, the relative effects are referred to as the “Global Warming Potential” (GWP) and the product of GWP and the actual emission of that gas enables estimation of the contribution of that gas to global warming. For example, the release of 1000 t CO_2 into the atmosphere would contribute 1000t CO_2 equivalent whereas the release of only 3.33 t N_2O would provide the same CO_2 equivalent (1000/300).

There is ample evidence that agricultural production is affected by climate and that agricultural systems have been influenced in the past by changing climate (Porter and Semenov, 2005). In future, the projected effects on crop productivity range from being mainly negative in areas that are already water-limited (e.g. much of sub-Saharan Africa), to positive in areas where suitable soils for crop production are present but where the growing season is temperature-limited (e.g. northern, temperate latitudes; Fischer *et al*., 2005; Fuhrer, 2006). There are options for adapting crop husbandry to cope with changed climates and climate variability, but governments are also taking seriously the need to mitigate climate change through reductions in emissions of GHGs. Farmers will be expected to play their part in these mitigation efforts.

This paper focuses on the opportunities for mitigation on the farm.

The contribution of UK agriculture to greenhouse gas emissions

Greenhouse gas (GHG) emissions from agriculture in 2005 contributed 7.0% of the total UK GHG emissions (calculated as mass of CO_2 equivalent; AEA Technology plc, 2007). While this is small in comparison with emissions from the energy sector (85.6% of the total), it is comparable with those from waste and industrial processes combined (7.7%), and attention will continue to be focussed on attempting to reduce agricultural emissions. The picture in the UK is similar to that of Europe as a whole (15 countries) where 9.2% of total emissions arise from agricultural activity, and to that of the USA where agriculture also produces 6.6% of GHG emissions (EEA, 2007; EIA, 2007). It should be noted that the methodology employed to calculate these figures does not take account of the emissions resulting from the use of energy on farms for heating and fuel.

Net GHG emissions from agriculture consist entirely of methane and N_2O because CO_2 uptake in photosynthesis is normally greater than any losses of CO_2 from, for example, soil respiration (AEA Technology plc, 2007). Agriculture is the major contributor to emissions of N_2O in all parts of the UK and to emissions of methane in Scotland, Wales and Northern Ireland where animals constitute a relatively larger component of agricultural activity (Table 1). Enteric fermentation is the major process contributing to methane emissions (typically 85-90% of the release from agriculture), so stocking levels play a major role in determining the amounts of methane released. Emissions of N_2O mainly arise from agricultural soils and result predominantly from the application of synthetic fertilisers and manures, and leaching from these sources to ground and surface waters (63-71% of the total emissions from agriculture). In England and Scotland, some 70 kt N_20 is emitted annually to the atmosphere from agricultural operations equivalent to 21.7 Mt CO_2.

Table 1. The contributions of methane and nitrous oxide from agricultural sources to total national emissions, and the contributions of the major processes for these gases to the agricultural emissions (2005 data; AEA Technology plc, 2007)

Country	Methane		Nitrous oxide	
	% total emissions	Enteric fermentation (% agric. emissions)	% total emissions	Fertilisers & manures (% agric. emissions)
England	28	84	61	64
Scotland			77	63
Wales	60	90	82	71
N. Ireland	78	86	79	69

Again, this picture in the UK is broadly similar across Europe as a whole where the agricultural emissions of GHGs comprise: direct soil emissions (26%), cattle (CH_4, 26%), indirect emissions (N_2O, 18%), animal production (N_2O, 7%), cattle (CH_4, 5%), pigs (CH_4, 5%), sheep (CH_4, 5%), solid stores and drylots (N_2O, 5%) and other (4%; EEA, 2007).

What is mitigation?

Mitigation of climate change essentially involves the adoption of practices which either reduce emissions of GHGs to the atmosphere and/or remove GHGs from the atmosphere into long-term stores. Farmers can contribute to the mitigation of climate change in the following ways:

1. Decrease the use of fossil fuel for farm operations or in inputs having large emissions from fossil fuels during their manufacture (e.g. N fertiliser).

2. Grow bioenergy crops or utilise agricultural wastes to partially replace fossil fuels for electricity production, heating or transport.

3. Adopt management practices that decrease net emissions of N_2O and CH_4

4. Adopt management practices that permit sequestration of carbon (from CO_2) in soil or in long-lived plants.

Mitigation through reduced emissions

1. Reduce the use of fossil fuel

Crop production results in the short-term net fixation of carbon but there are several emissions of C during the production process that can be managed. For comparison with the emission values, a winter wheat crop yielding 7 t grain dry matter ha^{-1} (8.05 t ha^{-1} at 15% water content) will contain about 6.8 t C ha^{-1} (assuming harvest index of 0.5, roots are 10% of total crop mass, and 1 t dry matter contains 440 kg C).The main indirect contributor of CO_2 emissions in crop production comes about through the manufacture of nitrogen fertiliser because of the amount of energy expended to capture atmospheric N. There is variation in the estimates of the amount of energy required for this process. West and Marland (2002) calculated an emission of 0.86 kg CO_2-C kg^{-1} N while data provided by The Fertiliser Institute for the production of ammonia from natural gas suggest a lower value of 0.56 kg CO_2-C kg^{-1} N. This means, for example, that if 150 kg N fertiliser ha^{-1} is applied to a crop of winter wheat then the equivalent of 84 - 129 kg of CO_2-C has been emitted during the manufacturing process. In the UK, the CO_2 “cost” of N fertiliser represents about 45% of total CO_2 emissions during the production of a winter wheat crop (Turley *et al*., 2005; Table 2) compared to about 60% in the USA (West and Marland, 2002). This is another reason for using N fertilisers efficiently. In terms of the energy used to manufacture N fertiliser relative to the energy gain by the crop, the additional harvested biomass due to N fertilisation of a range of winter wheat and sugar beet crops across Europe exceeded by a least five times the energy input of the N fertiliser itself (Kuesters and Lammel, 1999).

Emissions can, of course, be reduced if N is supplied from legumes or from the use of organic manures. However, as Powlson *et al*. (2005) point out, it does not necessarily follow that organic systems of production are preferable from the viewpoint of reducing emissions of C per unit of grain produced. Yields of cereals in organic systems are typically 20-30% less than in “conventional” systems and usually also rely on several years of a mixed ley so that the effective production of grain per year is even lower. This means that the average C emission per unit of grain can be similar in both production systems.

In addition to N fertiliser, other sources of CO_2 emissions include fuel use in the manufacture of P and K fertilisers, in drying grain, for machinery operations such as cultivating and harvesting (plus pumping where crops are irrigated), for the production and distribution of seed, and for the manufacture of herbicides and insecticides. Table 2 shows some typical values of CO_2-C emissions in the production of winter wheat crops in the UK and for a maize crop in the USA. In the UK, fuel emissions appear as a significant contributor to total emissions so that minimum or reduced tillage may be one way by which some farmers can significantly reduce energy use in some years and on some soils. There is no standard methodology for these calculations so precise comparisons between crops and production methods are difficult.

Table 2. Typical CO_2-C emissions resulting from fossil fuel inputs in the production of a winter wheat crop in the UK and a rainfed maize crop in the USA. Data for the winter wheat crop are from Elsayed *et al*. (2003) and Turley *et al*. (2005), and those for the maize crop from http://csp.unl.edu/Public/G_energy.htm. Embodied emissions represent the emissions associated with the manufacture of equipment; n.i. = not included.

Source	Winter wheat		Rainfed maize	
	kg C ha^{-1}	%	kg C ha^{-1}	%
N fertiliser	102	44	109.5	45.4
P + K fertilisers	19	8	n.i.	n.i.
Grain drying	n.i.	n.i.	64.8	26.8
Machinery	80	35	24.8	10.3
Embodied	n.i.	n.i.	8.2	3.4
Seed	18	8	23.6	9.8
Herbicide + insecticide	11	5	10.4	4.3
Total	230	100	241	100

2. Bioenergy crops

Recent rises in the price of oil above $50 per barrel (and now to almost $100 per barrel), together with legislation in both the USA and Europe, have increased the focus on plants as a source of energy for transport and electricity generation. The 2005 Energy Policy Act in the USA mandated production of 28 billion litres of ethanol by 2012, and the Renewable Transport Fuels Obligation of the EU requires all member states to achieve a 5.75% contribution of biofuels (ethanol and diesel) to transport fuels by 2010. For the UK, this is equivalent to about 2.5 Mt of biofuel requiring 3 Mt wheat and 3Mt rape to produce. Substitution of biofuels for petrol and diesel is being promoted politically as a means of reducing GHG emissions with various studies estimating a net reduction of 13-35% for ethanol from maize (Cassman and Liska, 2007). Moreover, the switch in USA maize production to ethanol has already had substantial beneficial effects on the economic returns available to arable farmers for their products because it has driven a fundamental change in the valuation of cereal grains.

Biomass can be burnt and used directly for electricity generation. Powlson *et al*. (2005) estimated the potential contribution of biomass crops to UK electricity requirements (in 2002) based on a dry matter yield of 12 t ha^{-1} for all biomass crops, and demonstrated that if 10% of current grassland and 80% of the then set-aside area (480,000 ha) were converted to biomass crops, then these would provide 3.7% and 2.7%, respectively, of UK electricity. If 50% of wheat straw were used for generation this would provide a further 3.7% of UK electricity. However, agricultural residues, while large in quantity, are often currently used as livestock feed to provide proteins for the human diet. A recent analysis in the Netherlands suggests that from the perspective of effective land use, it is better to produce energy from dedicated energy crops and to use agricultural residues such as straw for animal feed (Nonhebel, 2007). Perennial biomass crops such as *Miscanthus* can not only mitigate carbon emissions by substituting for fossil fuels but can also sequester C in soils (see below). For example, *Miscanthus* grown in southern Ireland over a 15-year period increased soil C by 8.9 ± 2.4 t ha^{-1} which when combined with biomass yields gave an estimated carbon mitigation of 5.2 – 7.2 t C ha^{-1} a^{-1}(Clifton-Brown *et al*., 2007).

Table 3 shows estimates of the potential of wheat and rape to supply UK transport fuels (Powlson *et al*., 2005); of course, if the land is used for this purpose it cannot also contribute to biomass production for electricity at the quantities estimated above. For Europe as a whole, a 10% substitution of petrol and diesel fuel is estimated to require 38% of current cropland. At present, increased prices for cereal grains have rendered obsolete many of the assumptions made until fairly recently about the likely increased area available in the UK for non-food and biofuel crops. For example, set-aside land which might have been used in future to grow biomass for power generation has been ploughed in autumn 2007 and sown to winter grain crops.

Table 3. The potential for wheat and rape crops to supply UK demand for petrol (19.8 Mt in 2002) and diesel (17.7 Mt in 2002). Assumes wheat grain yield of 8 t ha^{-1} and 276 kg ethanol t^{-1} grain, and rape yield of 3.33 t ha^{-1} with 37% oil (from Powlson *et al*., 2005).

Scenario	UK petrol (%)	UK diesel (%)
Convert 480,000 ha of set-aside land to biofuels	5.5	3.4
Convert all sugar beet area (169, 000 ha) to biofuels	1.8	1.2

There is considerable potential to enhance further the beneficial reductions in GHG emissions resulting from the production of bioenergy crops both through adoption of environmentally sound management practices and improved design of power and bioethanol plants (Cassman and Liska, 2007). Furthermore, as research expands to increase hydrocarbon production from cellulosic biomass crops, the competition for space between food and fuel crops should diminish. Finally, though, it is important that the move into the production of bioenergy crops is not achieved at the expense of cultivating old woodlands and pastures. Cultivation results in the release of substantial quantities of CO_2 from soil organic matter negating by many years any potential savings from the use of biofuels. Righelato and Spracklen (2007) estimate that while the conversion of wheat to ethanol might save 11 t C ha^{-1} over 30 years, conversion of the same area into forest would save about 100 t C ha^{-1}. So, if the prime policy objective is mitigation, better outcomes would be achieved in the next 30 years by focussing on improving the efficiency of fossil fuel use, the conservation of existing forests and grasslands, and the conversion of cropland not required for food to grassland and forests, rather than producing biofuels. The importance of crops grown to produce solid fuels was recognised by Defra in establishing the Bio-energy Capital Grants and Infrastructure schemes in 2006 (http://www.defra.gov.uk/farm/crops/industrial/energy/energy2.htm).

3. Reduce N_2O and CH_4 emissions

Agriculture is the main anthropogenic source of N_2O emissions which arise as a consequence of the microbial processes of aerobic nitrification and anaerobic denitrification in soils. The amount of N_2O emitted is directly related to the amount of N applied being typically 1.25 ± 1.0 % of fertiliser N (IPCC, 1997). So, application of 150 kg N ha^{-1} to a crop will typically produce 1.88 kg N_2O ha^{-1} with a GWP of 564 kg CO_2 equivalent (or 171 kg C i.e. more than the fossil fuel C used to manufacture the fertiliser [Table 2]; see also Turley *et al*., 2005).

Appropriate fertiliser management can substantially reduce emissions. Smith *et al*. (1997) suggest four management practices likely to contribute to this:

1. Match N supply with crop demand (split applications, soil/plant testing etc).
2. Tighten N cycles (reuse manures effectively, retain plant residues on site).
3. Employ advanced fertilisation techniques (e.g. controlled release fertilisers, nitrification inhibitors, placement etc).
4. Optimise tillage, irrigation and drainage to avoid anaerobic soil zones.

Changing land use is one of the major factors influencing both N_2O and CH_4 emissions. For example, ploughing of a grass sward in southeast Scotland resulted in 449 kg N ha^{-1} from mineralisation with an associated 2.0 kg N_2O-N ha^{-1} over 18 months, while ploughing a grass-clover sward gave corresponding values of 244kg N ha^{-1} and 4.5 kg N_2O-N ha^{-1} (Davies *et al*., 2001). These N_2O emissions, equivalent to 0.45% and 1.6%, respectively, of N mineralised fall within the IPCC range quoted above. Similarly, conversion of land to rice production substantially enhances CH_4 emissions, but in the UK the main emissions of CH_4 from agriculture arise from ruminant production.

Because of its GWP, Smith and Conen (2004) drew attention to the need to take full account of N_2O emissions when weighing up the benefits of various land management practices for carbon mitigation. They suggest that in many soils the increase in C sequestration (see below) by adopting no-till systems may be largely negated by associated increases in N_2O emission resulting from compaction, reduced porosity and increased denitrification. For example, emissions from spring-sown barley in Scotland were considerably higher under no-till than under conventional tillage (Vinten *et al*., 2002). Similarly, the suggested benefits of producing biofuels to replace fossil fuels are substantially reduced when the extra N_2O emissions associated with N fertiliser additions to rape and maize crops are taken into account (Crutzen *et al*., 2007).

Sequester GHGs from the atmosphere

Sequestration of carbon involves its transfer from atmospheric CO_2 into a storage pool thereby mitigating the effects of GHG emissions. Two potential biological pools for sequestering carbon are perennial plants (especially trees) and soils. On a global scale, there is more than twice as much C in soils as there is in the atmosphere, so that increasing attention is being paid to the capacity of soils both to contribute to GHG emissions when they are cultivated and to reduce atmospheric CO_2 through sequestration. Since the widespread cultivation of new land for agriculture in the 1850s, it is reckoned that the $C0_2$ release from changes in land use worldwide has contributed 20 - 25% of the increased CO_2 in the atmosphere.

In the UK, the Royal Society (2001) concluded that there were opportunities for sequestration of C in agricultural soils because the organic C content of arable soils tends to be low. Change of vegetation to woodland or pasture would result in a slow increase in soil C until a new maximum content is reached; field margins or other areas might also be used for this purpose. However, C sequestration is also reversible so that if land is cultivated again, the C accumulated will be released. In practice, then, the scope for substantial C sequestration in arable soils is very limited. Smith *et al*. (2001) estimated that if sequestration measures were utilised on all European agricultural land then the C sequestered would mitigate 1-4% of total European CO_2 emissions. This increased to 5% if biofuels were grown on former arable land because fossil fuel emissions were reduced.

Use of no-till and conservation tillage systems have been promoted as a means of increasing the C content of soils, but a range of other land management options such as rotational changes, improved residue management, introduction of leys, introduction of bioenergy crops may also have similar effects. Potential rates of sequestration of 0.3 to 0.8 t C ha^{-1} a^{-1} are typical for a range of management practices. On a global basis, C sequestration by soils could meet about one-third, at best, of the current yearly increase in atmospheric CO_2-C. Moreover, the effect would be of limited duration with significant impacts lasting only 20-50 years (Smith, 2004). In summary, sequestration by soil and vegetation is not a very effective way of mitigating GHG emissions but has a role to play as part of a portfolio of measures. There may, though, be other reasons for wishing to increase soil C such as the likely positive influences on soil fertility and improved structural stability leading to less susceptibility to erosion.

Concluding remarks

While GHG emissions from agriculture are only about 7% of the total CO_2 equivalent emissions, agriculture will be under political pressure to contribute towards mitigation. While each of the possible individual mitigation options outlined can only make a small inroad into CO_2 emissions, collectively they start to make an important contribution. Schneider *et al*. (2007) analysed the economic GHG mitigation strategies for US agriculture and forestry and concluded that the most appropriate options depended, perhaps not surprisingly, on the price attributed to C. For low C prices the preferred strategies involved reduced tillage systems (though possible increases in N_2O were not included), reduced fertiliser inputs, improved manure management and some afforestation. At higher C prices, bioenergy generation was favoured.

Overall, adoption of a suite of mitigation options is likely to provide the best way forward for farmers because single options will depend on market prices and, perhaps, be volatile. If food prices in future are more closely coupled to the oil price as international agriculture uses more land to produce biofuels, then there will be even greater economic incentives for those farmers that use carbon, nitrogen and energy efficiently on their farms.

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