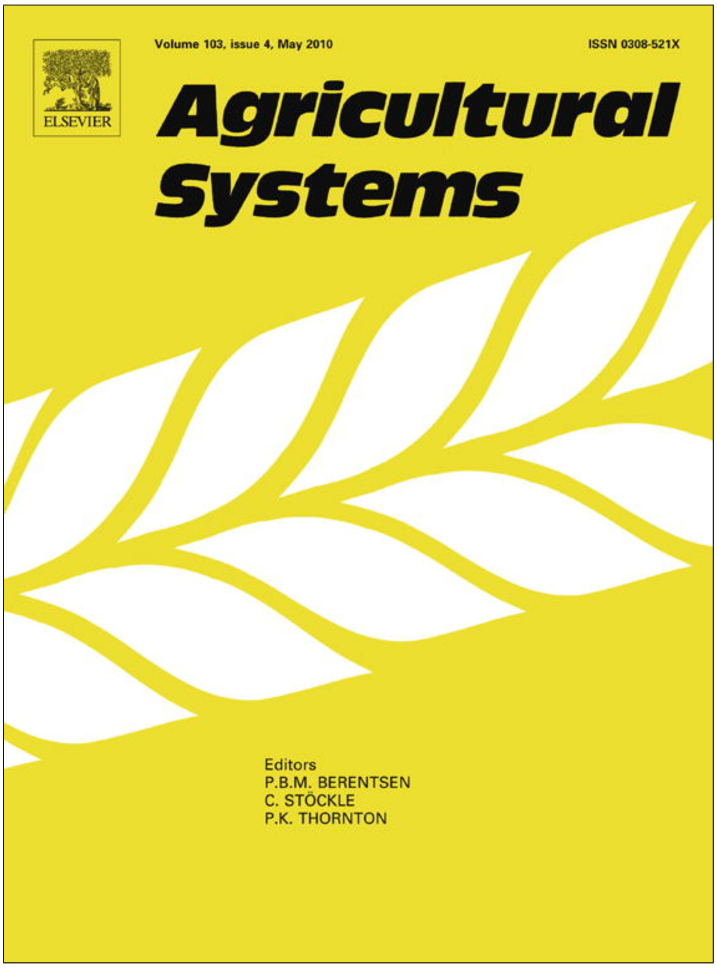

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Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK

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ABSTRACT

Emissions of greenhouse gases from agriculture are likely to come under increasing scrutiny as governments around the world develop proposals for large cuts in greenhouse gas emissions. Yet while there is a range of technically feasible measures for reducing agricultural emissions, it is not immediately apparent which options deliver the most economically efficient reductions in greenhouse gases. This paper develops a marginal abatement cost curve (MACC) for crop and soil measures applicable in UK agriculture. A range of specific abatement measures are screened for their cost-effectiveness and mitigation potential in the field. An efficient subset is identified with reference to a cost per tonne threshold of $\leqslant$£100/tCO$_2$e. Results indicate that the abatement potential by 2022 is likely to be between 1.628 and 10.164 MtCO$_2$e y^{-1} depending on the policies implemented, with a central estimate of 5.196 MtCO$_2$e y^{-1}. This represents 11.5% of the 2005 UK agricultural GHG emissions.

1. Introduction

It has been estimated that agriculture accounted for 10–12% of global anthropogenic greenhouse gas (GHG) emissions in 2005 (Smith et al., 2008). In the UK, the National Emissions Inventory reported UK agricultural emissions to be 50 MtCO$_2$e in 2005 i.e. 7.6%, of the 654 MtCO$_2$e UK total emissions for that year. Furthermore, government projections of the business-as-usual case "assume that agricultural non-CO$_2$ emissions will fall by only a further 1%, such that the overall decrease for the period 1990–2020 will be 19%" (Committee on Climate Change, 2008, p. 342). However, in order to meet the UK 2050 target (of reducing emissions by at least 80% below 1990 levels), national budgets have been set that require a 34% reduction (relative to 1990 levels) in greenhouse gas levels by 2020 (Committee on Climate Change 2008). This means that agriculture is likely to come under increasing scrutiny in order to identify ways of reducing emissions. Yet, while there is a range of technically feasible ways of reducing agricultural emissions, it is not immediately apparent which options will deliver the most economically efficient reductions in greenhouse gases within agriculture. Furthermore, in order to identify the most economically efficient reductions across the economy as a whole, methods are required that enable the comparison of the cost-effectiveness of mitigation in different sectors (e.g. agriculture, waste, transport, power, industry and domestic energy consumption). Calculating the cost-effectiveness of different mitigation options within sectors is a challenging exercise, however there is a growing literature on this (recent work on the development of agricultural emissions is reviewed briefly below). Calculating the cost-effectiveness of agricultural mitigation in ways that enable inter-sector comparisons to be made is likely to present additional challenges. This paper seeks to illustrate key challenges by outlining the findings of a recent analysis, which was undertaken in order to enable inter-sector comparison of mitigation costs.

The international literature shows several attempts to develop global Marginal Abatement Cost Curves (MACCs) (McKinsey and Company, 2008, 2009), and MACCs for agriculture in particular, using qualitative judgment (ECCP, 2001) and Weiske (2005, 2006), and more empirical methods (McCarl and Schneider, 2001, 2003; US-EPA, 2005, 2006; Weiske and Michel, 2007; Schneider et al., 2007, Smith et al., 2007a,b, 2008; Pérez and Holm-Müller, 2005; De Cara et al., 2005; Deybe and Fallot, 2003). The literature is dominated by top-down analysis, which usually employs a macroeconomic general equilibrium model taking emission reductions

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as exogenous and providing an overall cost to the economy. In contrast, bottom-up engineering based MACCs are detailed technology rich models, modelling abatement potential and costs for individual technologies and measures. For a detailed explanation of the derivation of bottom-up MACCs, see Wassman and Pathak (2007), in addition Bosello et al. (2007) provides a review of both approaches and hybrids. Global bottom-up studies (e.g. Beach et al., 2008; Mckinsey and Company 2008, 2009) offer a compelling picture of abatement possibilities, but there is still a need to drill down to more specific information that reflects regional heterogeneity in effectiveness and cost. NERA (2007) offers an interesting study for the UK as part of an assessment of the potential to extend emissions trading into the agricultural sector. However, their initial MACC exercise considered only a limited number of measures and was not specific about implementation horizons. This paper (which is based on recent work for the newly appointed UK Committee on Climate Change (CCC)) addresses this by developing MACCs for the mitigation of agricultural emissions from crops and soils. Other emissions from the agriculture, land use and land use sectors are described by Moran et al. (2008) and Moran et al. (submitted for publication). The specific objectives of the paper are to:

1. Develop MACCs for agricultural GHG emissions in a way consistent with other sectors (using an approach based on the methodological guidelines devised for the initial UK carbon budgeting undertaken during 2008).
2. Highlight the challenges encountered in developing MACCs for agriculture.
3. Outline the approaches adopted to address key challenges.
4. Outline outstanding challenges and areas requiring further development.

2. Background

2.1. Using marginal abatement cost curves

A marginal abatement cost curve represents the relationship between the cost-effectiveness of different options and the total amount of GHG abated (see Fig. 1). Moving along the curve from left to right the cost-effectiveness worsens (i.e. each tonne of CO_2e mitigated becomes more expensive) as the total level of mitigation increases. Different mitigation measures will occupy different positions on the curve. Thus, some measures may be able to reduce emissions and save money (A), other measures may reduce emissions more, but incur a positive cost (B). The MACC enables efficient mitigation measures to be identified with reference to a threshold cost per tonne of CO_2e, such as the shadow price of carbon (SPC), or the price of allowances in emissions trading schemes. The MACC process has been adopted by the CCC to determine greenhouse gas budgets.

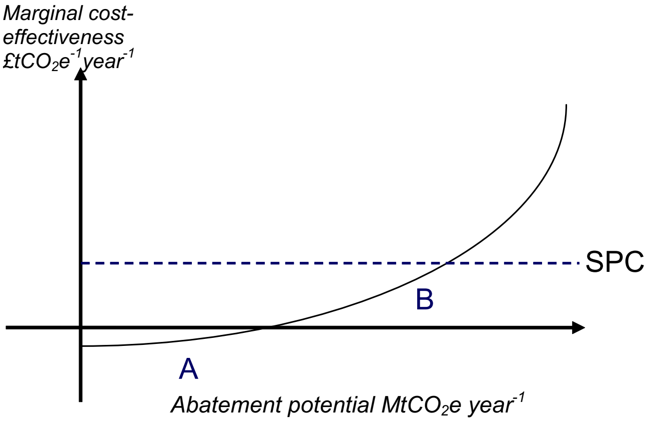

Fig. 1. Stylised marginal abatement cost curve for CO_2e.

2.2. Sources of emissions from crops and soils

Agricultural soils account for around half of the GHG emissions from agriculture (Fig. 2). Cropland and grassland are responsible for the exchange of significant quantities of greenhouse gases in the form of CO_2 and N_2O. Carbon dioxide can be removed from the atmosphere by processes of photosynthesis, which can lead to carbon sequestration in soils (Rees et al., 2004). Carbon dioxide can also be lost from soils as a consequence of land use change and soil disturbance.

Most N_2O is released from soils, and the use of nitrogen based fertilisers, manures and slurries increases losses significantly. Nitrogen is applied in fertilisers and manures in order to promote plant growth. However, the nutrient requirements of the crop and the nutrient content of the soils are not always balanced. If N is in excess supply, soil microbes can convert the excess to N_2O. Better nutrient management can therefore reduce direct N_2O emissions, and the indirect CO_2 emissions associated with fertiliser manufacture and distribution.

Methane uptake and release from agricultural soils is a relatively minor component of greenhouse gas exchange. However, the release from ruminant animals and manures is important (Moran et al., 2008).

2.3. Crops and soils mitigation measures

The derived mitigation potentials take into account changes in the areas of cropland and grassland under agricultural production. In 2005, grasslands (including rough grazing land) occupied 12.5 Mha or 52% of the land area of the UK, while croplands occupied 4.6 Mha or 19% of the land area (Defra, 2008). The areas remain relatively constant (Table 1), although any changes in land use (including changes that occur as a consequence of changes within a rotation) can contribute significantly to changes in greenhouse gas exchange and are included in the reporting procedures used by the IPCC (IPCC, 2006).

Emissions of greenhouse gases from agriculture occur as a direct consequence of management (e.g. N_2O loss from soils that receive fertiliser, manure and slurry N), and indirect processes (such as N_2O loss from N that has leached into rivers). Both processes are accounted for in the IPCC methodology and mitigation referred to in this paper includes both. The IPCC does however acknowledge that there is considerable uncertainty in many of the emissions associated with indirect processes.

There is uncertainty about the magnitude, and spatial and temporal variability of emissions from croplands and grasslands (Janssens et al., 2003; Soussana et al., 2007). It has been estimated that

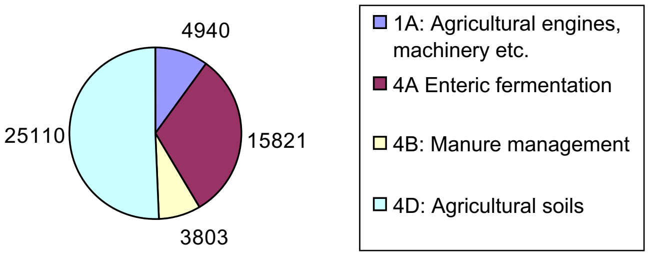

Fig. 2. The main sources of UK agricultural GHG emissions ($ktCO_2$e, 2005) (1A, 4A, 4B and 4D refer to the IPCC sectors).

Table 1
Land use projections (based on Shepherd et al. 2007).

	UK land area (ha)			
	2004	2012	2017	2022
Grassland (LFA + non-LFA)	6,885,463	6,913,765	6,952,616	6,957,736
Cereals (maize, wheat, winter barley, spring barley and other cereals, rape)	3,660,601	3,846,417	4,105,625	4,063,293
Other crops (hops, horticulture, beans, peas, linseed, flax, fallow)	330,657	339,620	339,236	334,383
Root crops (potatoes, sugar beet, turnips, swedes, fodder beet and mangolds)	339,439	326,999	325,450	332,521
Total	11,216,160	11,426,802	11,722,927	11,687,932

Note: LFA = Less Favoured Area.

improved management of the UK's agricultural land (improved tillage, fertiliser and manure management, soil management and extensification) could result in a mitigation potential of 6.1 $MtCO_2e$ y^{-1} (Smith et al., 2000). Mitigation of greenhouse gas emissions needs to take account of the collective emissions of CO_2, N_2O and CH_4, since mitigation measures taken to reduce emissions of one greenhouse gas can sometimes result in corresponding increases in emissions of non-target gases. The approach taken is therefore to measure changes the global warming potential of a system, which integrates the warming potential of CO_2, N_2O and CH_4 in a single measurement and expresses them as C equivalents. Such approaches have been successfully used to assess mitigation potential of changes to management that can involve complex interactions (Soussana et al., 2007; Sutton et al., 2007).

3. Methodology

3.1. Overall approach

Agriculture in the UK consists of more than 300,000 small and micro-sized businesses managing complex biological systems in varied physical environments. Given this, it is inevitable that the analysis of agricultural GHG mitigation presents particular challenges compared to other sectors. In their study of global agricultural GHG emissions, Beach et al. (2008) identified the main challenges of estimating mitigation costs over large spatial scales as follows:

- High degree of spatial and temporal heterogeneity in biophysical and management conditions that affect both production and emissions.
- Many agricultural activities emit multiple GHGs, and there are often complex interactions between these emissions.
- There is a paucity of regionally specific cost data.
- Estimating the expected level of implementation of the mitigation options.

In addition to these challenges (which are relevant to analysis at the UK level) could be added:

- The large number of potential mitigation techniques.
- The interactions between mitigation techniques targeted at the same gas.
- The need to avoid the displacement of emissions.
- Accounting for the ancillary costs and benefits of mitigation.

These challenges had to be addressed pragmatically by, for example, systematically reducing the number of measures considered, using the input of expert judgement and adopting a simplified consideration of interaction effects.

Expert judgement involved an assessment by relevant subject experts of the published data on mitigation options overlaid with a judgement of the effectiveness of these different options at a national scale. It should be noted that individual mitigation options are often reported in the literature on a site specific basis (i.e. they are based on experiments at a limited number of sites). In order to upscale to a national level, experts that are familiar with UK conditions have made a prediction of the likely national contribution.

3.2. Screening the measures

An initial long list of mitigation measures was drawn up based on a literature review (Ball et al., 2008; Bates, 2001; Godwin et al., 2003; IGER, 2001; Keller et al., 2006; King et al., 2004; Moorby et al., 2007; Moxey, 2008; NERA, 2007; O'Hara et al., 2003; Smith et al., 2007a,b, 2008; US-EPA, 2006; Weiske, 2005, 2007; Weiske and Michel, 2007). The initial list was circulated to twelve members of the project team who reviewed it and also forwarded in onto relevant colleagues for further review. The list was also sent to policy staff in Defra (the UK Government's Department for Environment, Food and Rural Affairs) and the CCC for circulation to relevant colleagues. The purpose of this exercise was to identify any potential mitigation measures missed during the initial literature review. This exercise produced a list of 97 mitigation measures applicable to the crops/soils sub-sector. These measures were then screened by four experts (two soils scientists, a cereals specialist and an agricultural systems modeller). Each of the experts was asked to independently assess the extent to which each measure was likely to be an (a) technically feasible and (b) industry-acceptable means of abatement. The measures were ranked from 1–5, where: 1 = will almost certainly be feasible and acceptable; 2 = will probably be feasible and acceptable; 3 = will possibly be feasible and acceptable; 4 = will probably be unfeasible or unacceptable; 5 = will almost certainly be unfeasible and/or unacceptable. A meeting of the experts was then convened, and the independent rankings compared, and an agreed ranking for each measure reached. During this meeting the list was reviewed, and measures removed where they were considered (a) probably or almost certainly likely to be unfeasible and/or unacceptable (b) likely to have very low additional abatement potential in UK (e.g. already current practice, only applicable to very small% of land). In addition some measures were aggregated, giving an interim list of 35 measures.

Abatement potential was calculated for each of the measures on the interim list by multiplying (a) the abatement rate of the measure by (b) the area of land it could be applied to. The abatement rates were based on published data (Ball et al., 2008; Bates, 2001; Godwin et al., 2003; IGER, 2001; Keller et al., 2006; King et al., 2004; Moorby et al., 2007; Moxey, 2008; NERA, 2007; O'Hara et al., 2003; Smith et al., 2007a,b, US-EPA, 2006; Weiske, 2005, 2007; Weiske and Michel, 2007) interpreted and adjusted for UK conditions. The areas of application were obtained by multiplying the land use projections in Shepherd et al. (2007) by the expert group's estimation of the maximum technically feasible additional proportion of each land category (grassland; cereals and oil seeds; root crops; other crops) that each measure could be applied to by 2022. Once the measures with small abatement potentials (defined as <2% of UK agricultural emissions) had been removed, the outcomes of the scoping exercise were presented to the project steering group and policy experts within Defra and the CCC. A final short list of 15 measures was drawn up in light of feedback (for example, several measures with small abatement were reinstated, in particular those likely to have negative costs). The measures on the interim and short lists are shown in Table 2. Short descriptions of the measures can be found in Table 3. It should be noted that the measures listed in Tables 2 and 3 are essentially forms of technological adaptation. However, as Wassman and Pathak (2007) note, "apart from this technological adaptation there may also be structural changes to adjust to an emission constraint (e.g. diverting to another crop)". However, these structural changes are not considered in this paper, as the focus is on quantifying the mitigation that could be achieved as a result of technological adaptation in response to policy.

3.3. Calculating the abatement potential and costs-effectiveness of the measures

The methodology used to calculate the abatement potential (AP) and cost-effectiveness of the measures is summarised in Fig. 3. The relevant terminology for interpreting the stages is set out in Table 4.

It is important to note the following assumptions and clarifications:

1. Current estimates of costs and abatement rates represent typical values, and are based on estimates of the averages across the UK.
2. The estimates of cost and cost-effectiveness are based on the private costs/benefits; they do not yet include ancillary costs/benefits such as impacts on diffuse water pollution or animal welfare.
3. The abatement rate is for on farm direct emissions, averaged across all sectors. It does not include wider life cycle impacts, for example CO_2 emitted during the manufacture of fertiliser, but does include indirect N_2O emissions from N applied on farm (e.g. N_2O loss from N that has leached into rivers).
4. It has been assumed that the interaction of measures will affect the abatement rates but not the costs of measures.

Recent and on-going structural change in UK agricultural production makes the determination of a reliable baseline particularly challenging. For this exercise the main source of baseline information is a recent exercise developing a UK Business as Usual projection (BAU3, see Table 1 and Shepherd et al., 2007). BAU3 covers the

Table 2
Measures on the interim list and reasons for inclusion/exclusion from short list.

Measure	Include in short list?
Cropland management: agronomy	
Adopting systems less reliant on inputs (nutrients, pesticides, etc.)	Y
Improved crop varieties	N – small abatement potential, see plant varieties with improved N
Catch/cover crops	N – small abatement potential
Maintain crop cover over winter	N – small abatement potential
Extending the perennial phase of rotations	N – small abatement potential
Reducing bare fallow	N – small abatement potential
Changing from winter to spring cultivars	N – small abatement potential
Cropland management: nutrient management	
Using biological fixation to provide N inputs (clover)	Y
Reduce N fertiliser	Y
Avoiding N excess	Y
Fully accounting for manure/slurry N when determining fertiliser N application rates	Y
Improved management of mineral fertiliser N application	Y
Controlled release fertilisers	Y
Nitrification inhibitors	Y
Improved management of slurry and manure application	Y
Application of urease inhibitor	N – N_20 reduction small and offset by indirect N_20 emissions
Plant varieties with improved N-use efficiency	Y
Mix nitrogen rich crop residues with other residues of higher C:N ratio	N – marginal, too localised
Separate slurry/manure applications from fertiliser applications by several days	Y
Use composts, straw-based manures in preference to slurry	Y
Precision farming	N – small abatement potential
Split fertilisation (baseline amount of N fertilizer but divided into three smaller increments)	N – small abatement potential
Use the right form of mineral N fertiliser	N – small abatement potential
Placing N precisely in soil	N – small abatement potential
Cropland management: tillage/residue management	
Reduced tillage/no-till	Y
Retain crop residues	N – small abatement potential
Cropland management: water and soil management	
Improved land drainage	Y
Loosen compacted soils/prevent soil compaction	N – small abatement potential
Improved irrigation	N – small abatement potential
Grazing land management/pasture improvement: increased productivity	
Species introduction (including legumes)	Y
New forage plant varieties for improved nutritional characteristics	N – small abatement potential
Introducing/enhancing high sugar content plants (e.g. "high sugar" ryegrass)	N – small abatement potential
Grazing land management/pasture improvement: water and soil management	
Prevent soil compaction	N – small abatement potential
Management of organic soils	
Avoid drainage of wetlands	N – high level of uncertainty, also could displace significant amounts of production and emissions
Maintaining a shallower water table: peat	N – small abatement potential

Table 3
Descriptions of the measures on the short list (for more extensive descriptions see Moran et al.(2008).

Measure	Explanation of the measure
Using biological fixation to provide N inputs (clover)	Using legumes to biologically fix nitrogen reduces the requirement for N fertiliser to a minimum
Reduce N fertiliser	An across the board reduction in the rate at which fertiliser is applied will reduce the amount of N in the system and the associated N_2O emissions
Improving land drainage	Wet soils can lead to anaerobic conditions favourable to the direct emission of N_2O. Improving farmland drainage can therefore reduce N_2O emissions by increasing soil aeration
Avoiding N excess	Reducing N application in areas where it is applied in excess reduces N in the system and therefore reduces N_2O emissions
Fully accounting for manure/slurry N	This involves using manure N as far as possible. The fertiliser requirement is adjusted for the manure N, which potentially leads to a reduction in fertiliser N applied
Species introduction (including legumes)	The species that are introduced are either legumes (see comment regarding biological fixation above) or they are taking up N from the system more efficiently and there is therefore less available for N_2O emissions
Improved management of mineral fertiliser N application	Matching the timing and amount of N fertiliser applied with crop requirement will ensure a better match between supply and demand and reduces the likelihood of N_2O emissions as a result of surplus N
Controlled release fertilisers	Controlled release fertilisers supply N more slowly than conventional fertilisers, ensuring that microbial conversion of the mineral N in soil to nitrous oxide and ammonia is reduced
Nitrification inhibitors	Nitrification inhibitors slow the rate of conversion of fertiliser ammonium to nitrate, decreasing the rate of reduction of nitrate to nitrous oxide (or dinitrogen)
Improved management of slurry and manure application	See improved management of mineral N
Adopting systems less reliant on inputs (nutrients, pesticides, etc.)	Moving to less intensive systems that use less input can reduce the overall greenhouse gas emissions
Plant varieties with improved N-use efficiency	Adopting new plant varieties that can produce the same yields using less N would reduce the amount of fertiliser required and the associated emissions
Separate slurry applications from fertiliser applications by several days	Applying slurry and fertiliser together brings together easily degradable carbon and nitrogen sources in the slurry and increased water contents, which can greatly increase the denitrification of available N and thereby the emission of nitrous oxide
Reduced tillage/no-till	No tillage, and to a lesser extent, minimum (shallow) tillage reduces release of stored carbon in soils because of decreased rates of oxidation. The lack of disturbance by tillage can also increase the rate of oxidation of methane from the atmosphere
Use composts, straw-based manures in preference to slurry	Composts provide a more steady release of N than slurries which increase anaerobic conditions and thereby loss of nitrous oxide

periods 2004–2025, choosing discrete blocks of time to provide a picture of change over this period, and to accommodate the implementation of major policy changes. Projections followed headings for agricultural production contained within the Defra census, covering both livestock and crop categories, to a fairly detailed resolution of activities, e.g. beef heifers in calf, 2 years and over, etc. The project concentrated on policy commitments that were in place in 2006, including those for future implementation. As the project was looking to 2025, it also seemed reasonable to include assumptions about some policy reforms that, due to current discussions, would seem likely, although not formally agreed at the time of writing. These mainly include the abolition of set-aside and milk quotas. For a summary of the assumptions made see (Moran et al., 2008, p. 7).

The BAU abatement potential is based on largely static assumptions about abatement potential of key farm measures and fixed emissions factors (per unit of livestock or area of land), although some allowance is also made for the indirect effects of a range of legislative changes that are included within BAU and its associated abatement potential. This paper is therefore restricted in its ability to predict how evolving regulatory changes will lead to additional progressive uptake of abatement measures, or how climate change itself might affect emissions factors and abatement rates. Uncertainty about the BAU abatement means the reported mitigations are likely to be smaller to the extent that the BAU will progressively include effects on emissions arising indirectly in response to policies not specifically targeted at reducing GHG emissions.

3.4. Costs

The costs of measures were calculated using the SAC Farm Level Model, which is based on a Linear Programming framework. A brief description of the modelling approach is given below (a more detailed explanation is given in chapter 3 of Moran et al. (2008).

The model is based on a central matrix of activities and constraints. The base model (pre-parameterised for farm types) has 194 activities and 205 constraints. Activities range from hectares of cropping activity to numbers of animals of various categories, e.g. heifers in calf, etc., born, bought and sold. Constraints range over the main variable and fixed costs that are present on most UK farming systems, e.g. land area, N, P and K applications, etc. The objective function is to maximise gross margins, hence it provides a response for the optimal allocation of resources. The model is based within MS Excel and has a central control panel to change the key values for these constraints. This allows each farming type, e.g. cereal, mixed, etc., to be typified and described within the model. Critically, it also allows options for changing activity mixes on the farm or constraints to accommodate particular abatement technologies. The model was used to estimate in some detail the on-farm impacts of each abatement measure. This followed the approach similar to Gibbons et al. (2006), which compared costs under each abatement scenario with optimised solutions under no abatement. Furthermore, prices and costs were forecast, following a linear trend up to the years 2022 and a number of runs of the model were undertaken for discrete time periods to understand this impact.

In order to calculate the costs using the SAC Farm Level Model, the one-off and recurring costs of each measure were identified. This was done using secondary data where possible (e.g. Smith and Dobbie, 2002), however, there was a lack of up-to-date cost data for many measures. In order to tackle this, each measure was discussed with experts, who identified the on-farm implications. These were converted into variables that could be entered into the SAC Farm Level Model (for example, effects on yields, input purchase costs, labour and machinery costs, capital purchases). The model was then used to calculate each measure's impact on the gross margins of a representative (a) cereal and (b) mixed farm. The assumptions made in calculating the cost of the measures are given in Table 5.

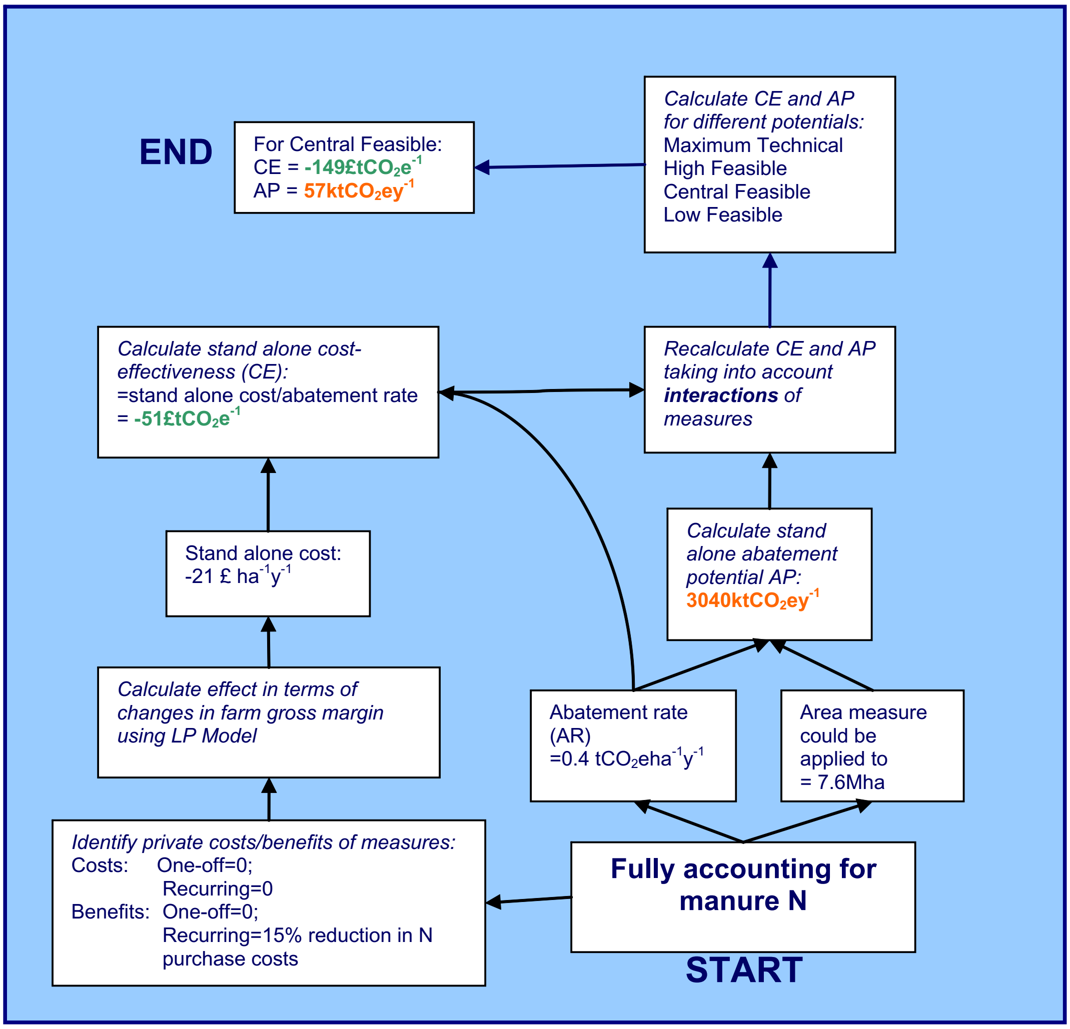

Fig. 3. Flow diagram showing the stages involved in the calculation of each measures' cost-effectiveness and abatement potential.

Table 4
Definitions of key terms.

Term	Meaning	Unit
Cost	The cost per hectare (or per animal) of implementing a measure, per hectare, per year	£ha^{-1} year^{-1}
Cost-effectiveness (CE)	The cost of reducing GHG emissions	£tCO_2 e^{-1}
Abatement rate (AR)	The rate at which a measure can reduce emissions, per hectare	tCO_2e ha^{-1}
Abatement potential (AP)	The total amount that GHG emissions can be reduced by (usually per year)	tCO_2e
Stand alone	The AR, AP or CE of a measure when applied in isolation	Not applicable
Combined	The AR, AP or CE of a measure when applied in conjunction with other measures	Not applicable

The calculation of abatement costs delivered by some measures requires the consideration of cost profiles that stretch over a number of years. A consistent treatment of alternative cost streams involves time discounting and the treatment of discount rates can make significant differences to the cost effectiveness of abatement options. In this analysis unless otherwise stated we present all results using a discount rate of 7%.

The results from the model were used to calculate the weighted mean cost of each measure by multiplying the cost (£ ha^{-1} y^{-1}) for different farm types by the amount of land in the UK to which the measure could be applied. The stand alone cost-effectiveness was then obtained by dividing the cost (£ ha^{-1} y^{-1}) by the abatement rate (tCO_2e ha^{-1} y^{-1}).

3.5. Abatement rate and potential

In order to calculate the total UK abatement potential for each measure over a given time period, the following information is required:

- the measure's abatement rate (tCO_2e ha^{-1} y^{-1}),
- the additional area (over and above the present area) that the measure could be applied to in the given period.

Some measures can in theory be applied to a large proportion of the available land. However, the extent to which mitigation measures are adopted in practice depends on the specifics of the

Table 5
Assumptions used in calculating the costs of measures.

	Private costs		Private benefits	
Measure	One off	Recurring	One off	Recurring
Using biological fixation to provide N inputs (clover)	0	Yield reduced by 30%	0	N purchase cost reduced by 60%; labour and machine costs reduced by 5%
Reduce N fertiliser	0	Yield reduced by 20%	0	N purchase costs reduced by 30%; labour and machine costs reduced by 5%
Improving land drainage	£1850/ha to build, then £250/ha every 5 years to clean[a]	0 – maintenance costs low	0	Increased yield of 10%
Avoiding N excess	0	No yield reduction	0	N purchase costs reduced by 10%, N limit reduced by 10%
Fully accounting for manure/slurry N	0	0	0	Reduce N purchase costs by 15%
Species introduction (including legumes)	0	Possibly an extra sowing so mech and labour costs increased by 5%; yields reduced by 7%	0	Reduction in N purchase costs by 10%
Controlled release fertilisers	0	Fertiliser purchase costs increased by 50%	0	Yield increase 2% Ball et al. (2004), half the number of applications – so machine and labour reduced by 5%
Nitrification inhibitors	0	Fertiliser purchase costs increased by 50%	0	Yield increase of 2%; machine and labour reduced by 5%
Improved management of mineral fertiliser N application	0	0	0	Small yield increase (∼5%), no N reductions
Improved management of slurry and manure application	0	0	0	Small yield increase (∼3%), no N reductions
Adopting systems less reliant on inputs (nutrients, pesticides, etc.)	0?	Yield down by 10%	0	N purchase costs reduced by 25%
Plant varieties with improved N-use efficiency	0	Yield unaffected	0	N purchase costs down 30%
Separate slurry/manure applications from fertiliser applications by several days	0	Yield unaffected	0	0
Reduced tillage/No-till	£20,000 for a power harrow, lifespan 20 years[a]	0	0	Overall cultivation costs (spraying, ploughing, drilling, harvesting, etc.) reduced by 16% (Ball 1985, p40)
Use composts, straw-based manures in preference to slurry	0	0	0	0

[a] Beaton et al. (2007).

Table 6
Abatement rates of the short listed measures.

Measure	Estimate of measures abatement rate $tCO_2e\ ha^{-1}\ y^{-1}$ [a]	Experts agreement with the estimated abatement rate[b]	Experts ranking of the uncertainty regarding the abatement rate[c]
Using biological fixation to provide N inputs (clover)	0.5	h	m
Reduce N fertiliser	0.5	h	l
Improving land drainage	1	m	m
Avoiding N excess	0.4	h	m
Fully accounting for manure/slurry N	0.4	h	h
Species introduction (including legumes)	0.5	h	h
Improved management of mineral fertiliser N application	0.3	h	m
Controlled release fertilisers	0.3	h	m
Nitrification inhibitors	0.3	h	l
Improved management of slurry and manure application	0.3	h	h
Adopting systems less reliant on inputs (nutrients, pesticides, etc.)	0.2	m	h
Plant varieties with improved N-use efficiency	0.2	h	m
Separate slurry/manure applications from fertiliser applications by several days	0.1	h	l
Reduced tillage/No-till	0.15	h	m
Use composts, straw-based manures in preference to slurry	0.1	h	m

[a] This value is averaged across all sectors. C mitigation is restricted to on farm reduction without accounting for C input to fertiliser manufacture, etc.
[b] Mode of the experts ranking of their agreement with the estimate of the measures abatement rate (high, medium, low, do not know).
[c] Mode of the experts ranking of the uncertainty regarding the abatement rate of this measure (high, medium, low, do not know).

measure and the policy framework. MACCs can be constructed to reflect abatement potentials in terms of these different levels of adoption. This analysis distinguishes between four potential abatement scenarios: maximum technical; high feasibility; central feasibility; low feasibility. *Maximum technical* abatement potential is the amount by which it is possible to reduce GHG emissions if

Table 7
Calculating the abatement rate of combinations of measures.

Measure implemented	Measure	Stand alone abatement rate $tCO_2e\ ha^{-1}\ y^{-1}$	Abatement rate when interaction is taken into account (IFs underlined)	Combined abatement rate $tCO_2e\ ha^{-1}\ y^{-1}$
First	Biological fixation	**1**	**1**	**1**
Second	Avoiding excess N	**0.4**	0.4 ∗ 0.55 = **0.22**	0.22
Third	Species introduction	**0.5**	0.5 ∗ 0.9 ∗ 0.9 = **0.40**	0.40
Fourth	Controlled release fertilisers	**0.3**	0.3 ∗ 0.55 ∗ 0.75 ∗ 0.6 = **0.07**	0.07
...	...	...	...	...

everyone who is technically able to implement a measure (that has already been demonstrated) does so as far as possible. For a given measure this potential represents the upper limit on abatement, although it is unlikely to be realised. Instead, some lower level of adoption is likely, depending on the prevailing cost and policy environment. Below this adoption rate we assume *a high feasible* level of adoption, which is the percentage of uptake if the government made the measure mandatory through regulation. We define the *central feasible* uptake as the likely percentage arising if there were a policy to subsidise the cost of implementing mitigation measures or penalise emissions. This might result in compliance amongst 50% of those who are technically able to retrofit. Finally a *low feasible* adoption percentage is the level of uptake if the government encourages adoption through education/information. We assume this may result in something below the central adoption level, e.g. as low as 10%. The three feasible potentials were calculated based on a review of uptake/compliance with existing policies. In addition, it was assumed that measures are adopted at a linear rate over time.

Existing evidence on the abatement rates (Ball et al., 2008; Bates, 2001; Godwin et al., 2003; IGER, 2001; Keller et al., 2006; King et al., 2004; Moorby et al., 2007; Moxey, 2008; NERA, 2007; O'Hara et al., 2003; Pollok, 2008; Rees et al., 2004; Rochette and Janzen, 2005, Smith and Dobbie, 2002; Smith et al., 2007a, 2008; US-EPA, 2006; Weiske, 2005, 2007; Weiske and Michel, 2007) was reviewed to derive estimates of the abatement rates of each of the measures on the interim list. These rates were then reviewed independently by another two experts, who ranked the uncertainty of the estimated abatement rate and their agreement with it (see Table 6). Where measures lead to abatement of CO_2 emissions over a period of years (for example as a consequence of a new rotational management), emissions reductions are expressed on an average annual basis.

3.6. The effect of interactions between measures

An abatement measure can be applied on its own, i.e. stand alone, or in combination with other measures. The stand alone CE of a measure can be calculated by simply dividing the weighted mean cost (£ $ha^{-1}\ y^{-1}$) by the abatement rate ($tCO_2e\ ha^{-1}\ y^{-1}$). However, when applied in combination, measures interact and their abatement rates and cost effectiveness change in response to the measures with which they combine. For example, if a farm implements measure A (biological fixation), then less N fertiliser will be required, lessening the extent to which N fertiliser can be reduced (measure B). The extent to which the efficacy of a measure is reduced (or in some cases, increased) can be expressed using an interaction factor (IF):

$$\mathrm{IF(AB)} = \frac{\text{abatement rate of measure B when applied after A}}{\text{stand alone abatement rate of measure B}}$$

For example, measures AB have an IF of 0.55, that is to say, that abatement rate of measure B ("reducing N fertiliser") is multiplied by 0.55 when applied after measure A. Each time a measure is implemented, the abatement rates of all of the remaining measures are recalculated by multiplying them by the appropriate IF, i.e. if measure A is implemented first, than all the remaining measures are multiplied by the IF (see Table 7). Therefore, after each measure is implemented, the abatement rates and CE of each remaining measure has to be recalculated, and the "next best" measure (in terms of CE) selected.

The IFs for the measures were discussed and estimated by a group of experts. The analysis undertaken in this study was restricted to looking at 2-way interactions. Multiple interactions are likely to occur in practice, but the affect of these could only adequately be assessed using more complex process-based models. For the purposes of this study multiple interactions are captured as the product of cumulative two-way interaction factors.

4. Results

4.1. Overall abatement potentials and costs

The low, central and high abatement potentials ($MtCO_2e\ y^{-1}$) at a cost of ⩽£100 per tCO_2e are summarised in Table 8. This table also shows the projected growth in (central) abatement potential over time, assuming a linear uptake of measures, and taking into account changing land use patterns. The abatement potential by 2022 is likely to be between 1.628 and 10.164 $MtCO_2e\ y^{-1}$ depending on the policies implemented. In principle, only abatement costing less than the shadow price of carbon (SPC) is economically efficient. The SPC is forecast to be £35 per tCO_2 in 2022 (2007 prices, see Defra, 2007), however using this as the threshold risks excluding abatement that costs more than this at the moment, but could become cheaper by 2022. In order to avoid to avoid this, a higher notional threshold of ⩽£100 per tCO_2e was used.

4.2. Measures required to achieve the abatement

The MACC for the central feasible potential in 2022 (Fig. 4 and Table 9) shows that a central feasible potential abatement of 5.196 $MtCO_2e\ ha^{-1}\ y^{-1}$ can be achieved with measures costing <£100 tCO_2e^{-1}. After this the cost of abatement increases rapidly due to the effects of interactions between the measures, i.e. the cost per ha remains constant but the amount of CO_2e abated per ha by each measure (in most cases) decreases. The following measures can achieve an annual abatement of 3.330 $MtCO_2e$ at negative cost (i.e. <£0 tCO_2e^{-1}):

- Improved management of mineral fertiliser N application.
- Improved management of slurry and manure application.

Table 8
Total annual abatement potential ($MtCO_2e\ y^{-1}$) at a cost of < £100 tCO_2e^{-1} and discount rate 7%.

Potential	2012	2017	2022
High feasible	–	–	10.164
Central feasible	1.426	3.289	5.196
Low feasible	–	–	1.628

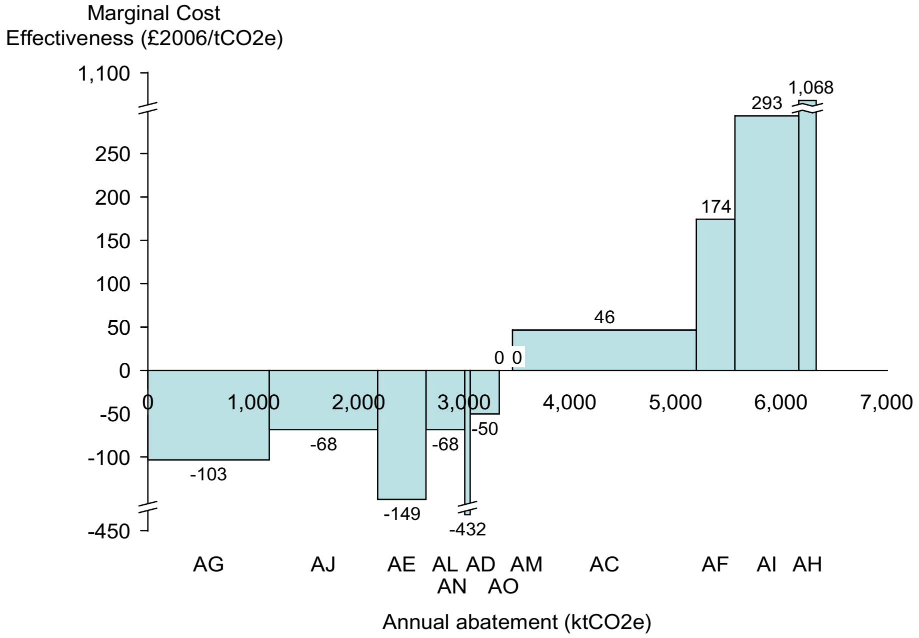

Fig. 4. Crops and soils combined MACC, central feasible potential 2022 (*Note*: measures with CE > £2000 tCO$_2$e^{-1} – i.e. AA, AB, AK – not included in the curve).

Table 9
Results underpinning the crops and soils MACC, Central Feasible Potential 2022.

Measure	Annual abatement ktCO$_2$e	Cost Effectiveness[a] £(2006) tCO$_2$e^{-1}	Cumulative annual abatement ktCO$_2$e
Improved management of mineral fertiliser N application	1150	−103	1150
Improved management of slurry and manure application	1027	−68	2178
Fully accounting for manure and slurry N	457	−149	2635
Plant varieties with improved N-use efficiency	369	−68	3003
Reduced tillage/No-till	50	−432	3054
Avoiding N excess	276	−50	3330
Use composts, straw-based manures in preference to slurry	78	0.00	3408
Separate slurry/manure applications from fertiliser applications by several days	47	0.00	3455
Improved land drainage	1741	46	5196
Species introduction (including legumes)	366	174	5562
Nitrification inhibitors	604	294	6166
Controlled release fertilisers	166	1068	6332
Reduce N fertiliser	136	2045	6468
Adopting systems less reliant on inputs (nutrients, pesticides, etc.)	10	4434	6478
Using biological fixation to provide N inputs (clover)	8	14,280	6487

[a] The cost-effectiveness of each measure when applied in combination with the other measures.

Table 10
Comparison of stand-alone and combined cost-effectiveness (CE), central feasible potential, 2022.

Measure	Stand alone CE[a] £(2006) tCO$_2$e^{-1}	Combined CE[b] £(2006) tCO$_2$e^{-1}
Improved management of mineral fertiliser N application	−103	−103
Improved management of slurry and manure application	−68	−68
Fully accounting for manure/slurry N	−49	−149
Plant varieties with improved N-use efficiency	−68	−68
Reduced tillage/No-till	−76	−432
Avoiding N excess	−33	−50
Use composts, straw-based manures in preference to slurry	0.00	0.00
Separate slurry/manure applications from fertiliser applications by several days	0.00	0.00
Improved land drainage	43	46
Species introduction (including legumes)	47	174
Nitrification inhibitors	152	294
Controlled release fertilisers	152	1068
Reduce N fertiliser	118	2045
Adopting systems less reliant on inputs (nutrients, pesticides, etc.)	82	4434
Using biological fixation to provide N inputs (clover)	41	14,280

[a] The cost-effectiveness of each measure when applied on its own.

[b] The cost-effectiveness of each measure when applied in combination with the other measures.

- Fully accounting for manure/slurry N when determining fertiliser N application rates.
- Plant varieties with improved N-use efficiency.
- Reduced tillage.
- Avoiding N excess.

In addition, the curve shows that 0.125 $MtCO_2e$ can be abated at £0 tCO_2e^{-1} using the following measures:

- Use composts, straw-based manures in preference to slurry.
- Separate slurry/manure applications from fertiliser applications by several days.

Finally, an additional 1.741Mt of abatement can be achieved at a cost of between 0 and £100 tCO_2e^{-1} by improving land drainage.

4.3. Effect of the interactions between measures

The cost-effectiveness (CE), abatement rates (AR) and abatement potential (AP) of the measures are influenced by whether the measure is applied on a stand alone basis or in combination with other measures. The more measures that are implemented, the more likely it becomes that subsequent measures will interact with previous measures in ways that alter their CE, AR and AP. In most cases, interaction reduces the abatement rate of subsequent measures, and therefore increases the magnitude of the CE (see Table 10). This is particularly notable once we get to measures with positive costs, where the differences between the stand-alone and combined CE becomes highly exaggerated due to multiple interactions. The large discrepancies between some of the stand alone and combined CE emphasises the importance of taking into account interactions when developing MACCs.

5. Discussion

The central feasible potential of 5.196 $MtCO_2e\ ha^{-1}\ y^{-1}$ (at a cost of <£100 tCO_2e^{-1}) represents 11.5% of the 2005 UK agricultural GHG emissions and 20.7% of emissions from agricultural soils (the National Atmospheric Emissions Inventory reported these as 45 $MtCO_2e$ and 25 $MtCO_2e$, respectively, excluding LUC, see Choudrie et al., 2008). By way of comparison, Pollock (2008, p. 23) made the following conclusion regarding UK agricultural GHG emissions: "overall reductions using currently viable approaches are likely to be modest (maximally some 10–15% of current emissions assuming similar levels of production)". While these results are similar, direct comparison is difficult as it is not clear what% of the 10–15% is accounted for by crops/soils measures, the time scale for achieving the 10–15% or what cost of measure was used in measuring viable levels of uptake.

IGER (2001) concluded that UK agricultural "N_2O emissions could be reduced by 32.5% (maximum feasible reduction) at a cost of £97 billion. Cost effective reduction potential, determined by the point at which the cost curve becomes exponential, is approximately 18%, with total on farm savings of £916 million. However, a reduction of 20% could also be achieved at a negligible net cost." CLA/AIC/NFU (2007) reached a similar conclusion, and suggested that "combined improvements in livestock and crop nitrogen efficiencies could mitigate (N_2O) emissions by up to 20%". These results appear consistent with our estimate of a 20.7% reduction in emissions from agricultural soils.

It should be noted that if emissions are reduced by simply reducing levels of production, then there is a danger of displacing production (and the associated emissions) to other countries. Of the measures on the short list, four are likely to lead to reduced yields: using biological fixation to provide N inputs (clover), reducing N fertiliser; species introduction (including legumes), adopting systems less reliant on inputs. However, none of these measures are included in the abatement potentials achieved at a cost of <£100 tCO_2e^{-1}, so it is therefore unlikely that there will be significant changes in production levels associated with this level of abatement.

The results suggest that there is significant potential win–win abatement, i.e. scope for uptake of measures that can reduce emissions while providing a financial saving. Fig. 4 shows that 3.330 $MtCO_2e\ ha^{-1}\ y^{-1}$ could be achieved at negative costs (which represents 13.2% of the emissions from agricultural soils in 2005). If implemented, these win–win measures would result in savings of £317 m (£2006), which is equivalent to approximately £1000 per farm in the UK. Several possible explanations as to why these apparent unrealised savings exist are outlined below. Firstly, it has been suggested that many farmers are not profit maximising, and that their behaviour is influenced by a range of factors in addition to market conditions (i.e. input and output prices). For example, Pike (2008) notes that market conditions are part of a wider set of factors that influence farm decision making, which includes: internal factors (e.g. cognition, habit and attitude), social factors (e.g. norms and roles), the policy environment; and other farm business constraints. Secondly, farmers may be exhibiting risk aversion behaviour in response to yield penalties. Some farmers, for example, use too much fertilizer given average circumstances, just to be sure that also in extreme circumstances the amount of fertilizer is high enough. Alternatively it may be that farmers are behaving rationally, and that the apparent unrealised savings are due to shortcomings in the model. As Dowlatabadi (2003, p. 6) notes: "when a model identifies the world as behaving illogically, one can blame the world or recognize that something must be amiss in the model. Bottom up models describe how the world *should* be, not the way *it is*." In particular, it may be that some significant private costs, such as the administrative costs of adopting measures, are hidden and therefore not taken into account in the calculations of cost-effectiveness.

Despite these caveats, it is argued that the bottom-up modelling of abatement costs in a MACC framework is a worthwhile exercise, particularly if, as Dowlatabadi (2003, p. 8) has suggested, climate policy is treated as a long-term, iterative "learning process, where policy at any stage provides information on how to take the next step". This appears to be the approach favoured by the Committee on Climate Change which, while acknowledging the complexity regarding mitigation in the ALULUCF sector, concluded that Moran et al. (2008, p. 344) demonstrated "that there is significant potential in agriculture which merits further analysis".

One of the main lessons to be drawn from this exercise is the potential strength of adopting a dynamic approach to the modelling of mitigation. For example, the results show that failing to take into account the way in which measures interact is likely to lead to significant double-counting and over-estimation of overall abatement potential. In this paper, modelling of interactions based on Interaction Factors was used to address this. A more difficult problem is the prediction of how key variables, i.e. measures' abatement rates and cost-effectiveness, will change through time. The cost-effectiveness of mitigation measures can change in response to factors such as commodity prices, R&D investment, learning effects and economies of scale and the indirect effects of non-GHG policy. Therefore, while MACCs are useful tools in exploring the (current) cost-effectiveness of alternative mitigation options, policy formulation should include analysis of the measures' cost dynamics, i.e. how the cost-effectiveness might change through time. Without this analysis, there is the risk of the conflict between static *v* dynamic efficiency outlined in del Rio Gonzalez (2008).

6. Conclusion

We have shown that management changes that have been proposed to reduce greenhouse gas emissions are associated with widely different costs. By estimating the amount of potential mitigation and quantifying the cost of a particular measure, it is possible to create MACCs that rank potential mitigation measures in terms of their costs per unit of CO_2e saved. The results highlighted the importance of measures which increase nitrogen use efficiency while conserving crop and carbon yields.

The process of developing GHG MACCs is particularly challenging for agricultural emissions. Agriculture is a complex industry characterised by spatial and temporal heterogeneity. There are a large number of potential mitigation techniques, many of which interact and influence each other when implemented. The key challenge is to find ways of managing the complexity in ways that enable the development of MACCs without sacrificing the validity of the results. In this paper we have reported some of the approaches used in the setting of UK carbon budgets: use of experts to screen measures; simplified modelling on interactions between mitigation measures; and LP modelling of the financial impacts of mitigation measures on farm.

The approach requires further development, for example the incorporation of the ancillary costs and benefits of GHG mitigation into the calculation of cost-effectiveness, however we believe that the findings will provide policy makers with a valuable tool for implementing changes in agricultural production with a view to reducing greenhouse gas emissions.

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