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Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions

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Abstract

This article addresses the challenge of developing a 'bottom-up' marginal abatement cost curve (MACC) for greenhouse gas (GHG) emissions from UK agriculture. An MACC illustrates the costs of specific crop, soil and livestock abatement measures against a 'business as usual' scenario. The results indicate that in 2022 under a specific policy scenario, around 5.38 Mt CO_2 equivalent (e) could be abated at negative or zero cost. A further 17% of agricultural GHG emissions (7.85 Mt CO_2e) could be abated at a lower unit cost than the UK Government's 2022 shadow price of carbon [£34 $(tCO_2e)^{-1}$]. The article discusses a range of methodological hurdles that complicate cost-effectiveness appraisal of abatement in agriculture relative to other sectors.

Keywords: *Agriculture; climate change; marginal abatement costs.*

JEL classifications: *Q52, Q54, Q58.*

1. Introduction

Greenhouse gas (GHG) emissions from agriculture represent approximately 8% of UK anthropogenic emissions, mainly as nitrous oxide and methane. Under its Climate Change Act 2008, the UK Government is committed to an ambitious target for reducing national emissions by 80% of 1990 levels by 2050, with all significant

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sources coming under scrutiny. The task of allocating shares of future reductions falls to the Committee on Climate Change (CCC), an independent government agency responsible for setting economy-wide emissions targets (as emission 'budgets') and to report on progress.

The CCC recognises the need to achieve emission reductions in an economically efficient manner and has adopted a 'bottom-up' marginal abatement cost curve (MACC) approach to facilitate this. An MACC shows a schedule of abatement measures ordered by their specific costs per unit of carbon dioxide equivalent (CO_2e)[2] abated, where the measures are additional to mitigation activity that would be expected to happen in a 'business as usual' (BAU) baseline. Some measures can be enacted at a lower unit cost than others, whereas some are thought to be cost-saving, that is, farmers could implement some measures that could simultaneously save money and also reduce emissions.[3] Thereafter, the schedule shows unit costs rising until a comparison of the costs relative to the benefits of mitigation show that further mitigation is not worthwhile. An MACC illustrates either a cost-effectiveness (CE) or a cost-benefit assessment of measures, where the benefits of avoiding carbon emission damages are expressed by the shadow price of carbon (SPC), as developed by Defra (2007). Alternatively, unit abatement costs can be compared with the emissions price prevailing in the European Trading Scheme (ETS). An efficient 'budget' (as the target level of emissions to be achieved[4]) in a given sector, such as agriculture, is implied by the implementation of efficient measures, where efficiency considers mitigation costs in other sectors as well as the benchmark benefits defined by the SPC or the ETS price.

This article outlines the construction of a 'bottom-up' MACC for UK agriculture as an estimate of the emissions abatement potential (AP) of the industry. The methodology for estimating APs and the associated costs has been developed with guidance from the CCC so as to be consistent with MACC analysis in other sectors of the economy. The next section outlines the MACC approach adopted by the CCC to determine mitigation budgets across the main non-ETS sectors in the United Kingdom, including agriculture. Section 3 summarises the methods used to gather and estimate APs and costs to populate the CCC MACC framework for agriculture. Subsequent sections outline the specific mitigation measures identified for the agricultural sub-sectors of crop soils and livestock (beef, dairy, pigs and poultry). The application highlights several outstanding issues that complicate MACC analysis in agriculture relative to other sectors, where technologies are less variable. Section 7 presents the resulting APs and costs as MACCs, and section 8 concludes.

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[2] The release of GHG from agriculture (predominantly nitrous oxide, methane and carbon dioxide) is typically expressed in terms of a common global warming potential unit of CO_2e.

[3] The fact that some apparently cost-saving measures have not been adopted may be owing to a number of reasons, for example, farmers may not be profit-maximising, or they may be exhibiting risk aversion behaviour in response to fear of yield penalties. Alternatively, farmers may be behaving rationally, but the full costs of the measures have not been captured.

[4] The CCC defines the carbon budget as: 'Allowed emissions volume recommended by the Committee on Climate Change, defining the maximum level of CO_2 and other GHG's which the UK can emit over 5 year periods' (http://www.theccc.org.uk/glossary?task = list&glossid = 1&letter = C, accessed 17 May 2010).

2. MACC Analysis

MACC analysis is a tool for determining optimal levels of pollution control across a range of environmental media (McKitrick, 1999; Beaumont and Tinch, 2004). MACC variants are broadly characterised as either ‘top-down’ or ‘bottom-up’. The ‘top-down’ variant describes a family of approaches that typically take an externally determined emission abatement requirement that is allocated downwards through modelling assumptions based on Computable General Equilibrium models, which in turn characterise industrial/commercial sectors according to simplified production functions that are assumed to apply commonly throughout the sector (if not the whole economy). In agriculture, this approach implies substantial homogeneity in abatement technologies, their biophysical potential and implementation costs (see, e.g. De Cara *et al.*, 2005). For many industries, this assumption is appropriate. For example, power generation is characterised by fewer firms and a common set of relatively well-understood abatement technologies. In contrast, agriculture and land use are more atomistic, heterogeneous and regionally diverse, and the diffuse nature of agriculture can affect APs and CE. This suggests that different forms of mitigation measure can be used in different farm systems, and that there may be significant cost variations and ancillary impacts to be taken into account.

A ‘bottom-up’ MACC approach addresses some of this heterogeneity. A ‘bottom-up’ approach can be more technologically rich in terms of mitigation measures, and can accommodate variability in cost and AP within different land use systems. In contrast to the ‘top-down’ approach, an efficient ‘bottom-up’ mitigation budget is derived from a scenario that first identifies the variety of effective field-scale measures, and then determines the spatial extent and cost of applying these measures across diverse farm systems that characterise a country or region. In construction of the MACC, abatement measures are ordered in increasing cost per unit CO_2e abated (the vertical axis). The volumes abated (the horizontal axis) are the annual emission savings for a given year generated by adoption of the measure. As such, the emission savings and associated costs are the difference between CO_2e emitted in a baseline or BAU scenario and the emissions and costs involved in the adoption of particular technology or abatement measure. This requires the definition of a counterfactual situation, represented by the adoption rates throughout the sector, which is subject to assumptions about, *inter alia*, prevailing incentive policies and market conditions. This ranking, expressed as the MACC, compares technologies and measures at the margin (i.e. the steps of the curve, representing adoption of increasingly costly abatement measures), and provides an invaluable tool for CE analysis. Figure 1 summarises the relationship between the constructed MACC (right-hand side of the figure) and the identified emissions budget, as the difference in AP between a baseline and a scenario under which efficient measures are adopted (left-hand part of the figure).

The literature shows several attempts to develop MACCs for energy sector emissions and even global MACCs (McKinsey & Company, 2008, 2009). MACCs for agriculture have used qualitative judgement (ECCP, 2001; Deybe and Fallot, 2003; Weiske, 2005, 2006) and more empirical methods (McCarl and Schneider, 2001, 2003; Pérez and Holm-Müller, 2005; De Cara *et al.*, 2005; US-EPA, 2005, 2006; Weiske and Michel, 2007; Smith *et al.*, 2007a,b, 2008). This evidence does not yet provide a clear picture of the AP for UK agriculture.

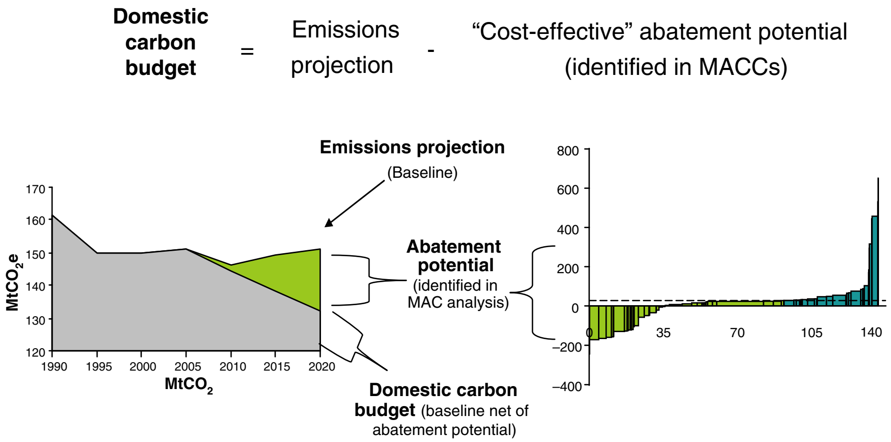

Figure 1. An illustrative marginal abatement cost curve (MACC) and its relationship to a carbon budget. The right-hand side presents an illustrative MACC comprised of bars representing individual (abatement) measure cost (height) and abatement potential (width). An externally determined threshold is placed on measured cost-effectiveness by a carbon price represented by the horizontal dashed line. The abatement potential from the application of the efficient measures (i.e. costing less than the carbon price) over and above their baseline application defines the carbon budget as represented in the left-hand side of the diagram

3. Agricultural Mitigation

UK agriculture contributes about 50 million tonnes (Mt) CO_2e, or 8% of total UK GHG emissions (654 Mt CO_2e in 2005), mainly as N_2O (54%), CH_4 (37%) and CO_2 (8%; Thomson and van Oijen, 2008). Within the farm-gate, emissions are dominated by methane from enteric fermentation by livestock, and nitrous oxide from crop and soil management. For the purposes of this analysis, the definition of 'agriculture' includes all major livestock groups, arable and field crops and soils management. Our analysis does not include the 8% CO_2 emissions that arise from energy use in heating and transportation, including the majority of emissions from horticulture, farm transportation and some machinery emissions. These emissions are counted in MACCs developed by the CCC for the energy and transportation sectors. This analysis also ignores other CO_2 emissions related to the prefarm-gate or postfarm-gate activities involving agricultural inputs and products.

The CCC has signalled a desire for the agricultural sector to contribute to reducing the UK's emissions of GHGs to at least 80% below 1990 levels by 2050. The first challenge in determining a feasible budget for the agricultural sector is to identify which measures might be implemented, how these measures are ordered in terms of the volume of GHG emissions that could be abated by each measure and the estimated cost per tonne of CO_2e of implementing each measure.

There is an extensive list of technically feasible measures for mitigating emissions in agriculture. For example, ECCP (2001) identified a list of 60 possible options, Weiske (2005) considered around 150 and Moorby *et al.* (2007) identified 21. Smith *et al.* (2008) considered 64 agricultural measures, grouped into 14 categories. Measures may be categorised as: improved farm efficiency, including selective breeding of livestock and use of nitrogen; replacing fossil fuel emissions *via* alternative energy sources; and enhancing the removal of atmospheric CO_2 *via* sequestration into soil and vegetation sinks. Some abatement options, typically current best management practices, deliver improved farm profitability as well as lower emissions, and thus might be adopted in the baseline without specific intervention, beyond continued promotion/revision of benchmarking and related advisory and information services. Estimated emissions in the sector have already fallen by around 6% since 1990, largely because of falling livestock numbers. Further reductions are anticipated over the next decade as animals become more productive through improved breeding and genetic selection (Amer *et al*., 2007).

However, many mitigation options entail additional cost to farmers. This raises questions about which measures can be implemented effectively in what conditions, and at what cost. The list of CE mitigation measures is likely to be significantly smaller than the technically feasible measures.

4. Methodological Steps for Developing an MACC for UK Agriculture

In outline, the main steps of the MACC exercise are as follows:

(a) Identify the baseline BAU abatement emission projections for the specified budgetary dates: 2012, 2017 and 2022.[5] The BAU used in this study was based on an existing set of projections for the United Kingdom to 2025, provided by ADAS, SAC, IGER and AFBI (2007). This is outlined in section 6.

(b) Identify potential *additional* abatement for each period, above and beyond the abatement forecast in the BAU, by identifying an abatement measures inventory. This includes measure adoption assumptions corresponding to: (i) maximum technical potential (MTP), as the maximum physical extent to which a measure could be applied; (ii) central feasible potential (CFP); (iii) high feasible potential (HFP); (iv) low feasible potential (LFP), with varying adoption rates reflecting alternative plausible policy and market scenarios offering varying adoption incentives).

(c) Quantify (i) the maximum technical potential abatement, and (ii) CE in terms of £/tCO_2e of each measure (based on existing data, expert group reviews and the National Atmospheric Emissions Inventory) for each budget period, using the following process (Figure 2):

(i) generate an initial (long) list of all the potential mitigation measures within each sub-sector (a, crops/soils; b, livestock);

(ii) screen the initial list by removing measures that: (a) have low additional AP in United Kingdom; (b) are unlikely to be technically feasible or acceptable to the industry. Also, some measures are aggregated at this stage;

(iii) calculate the MTP of the remaining measures by estimating their abatement rate (based on available evidence, e.g. Smith *et al*., 2008), and the areas or animal numbers to which measures could be applied in addition to their likely BAU uptake (see step b). Remove measures with a reduction potential of $< 2\%$ UK agricultural emissions, to generate a *short list* of measures. This threshold is arbitrary and

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[5] Five-year budgetary periods have been determined by the CCC as a basis for periodic progress reporting on overall targets. For the purposes of this analysis the focus is on the achievable abatement by the third budget 2017–2022, a period deemed sufficient to allow the accommodation of new technologies.

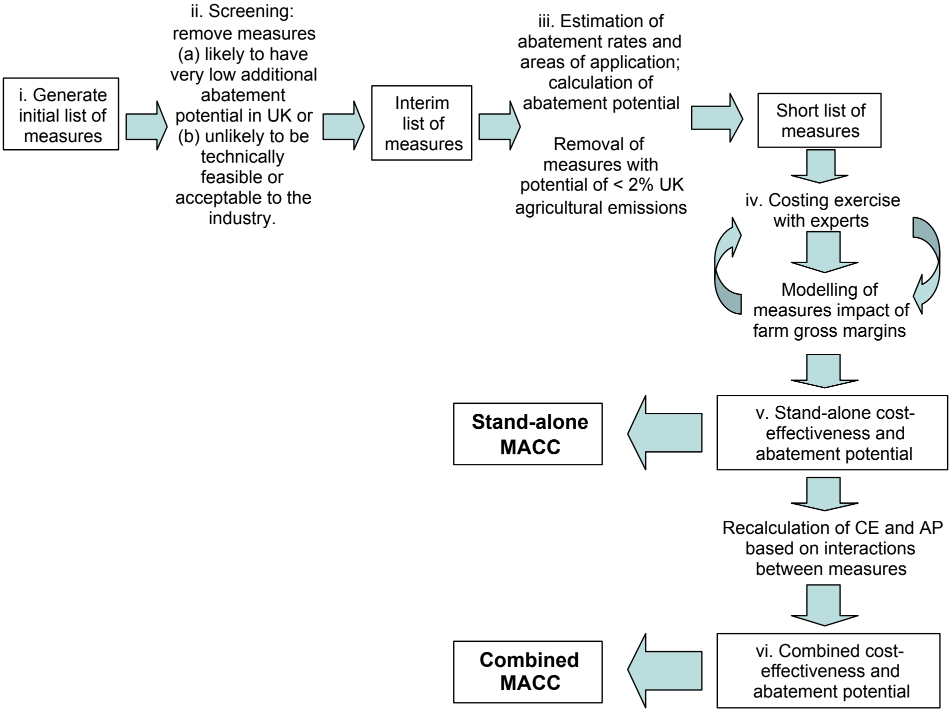

Figure 2. Marginal abatement cost curve development process

reduced the number of measures that could be considered within the time and resource constraints of this exercise;

(iv) identify and quantify the costs and benefits and their timing, and calculate the effect of measures on farm gross margins using a representative farm scale optimisation model;

(v) calculate the 'stand-alone' CE and AP of each measure (i.e. assuming that measures do not interact) to generate 'stand-alone' MACCs;

(vi) recalculate the CE and AP based on an analysis of the interactions between measures and produce a 'combined' MACC;

(vii) qualify the MTP MACC in terms of central, low and high estimates, based on a review of the likely levels of compliance/uptake associated with existing policies and alternative market conditions for agricultural commodities.

5. Inventory of Abatement Measures for UK Agriculture

A range of sub-sector-specific abatement measures were identified from the literature that appear to be applicable to UK agricultural and land use conditions. Abatement estimates from these measures were then discussed and screened in a series of expert meetings using six scientists[6] covering livestock, crop and soil

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[6] Scientists used in the stages of estimation were drawn from the Scottish Agricultural College, and North Wyke Research. Estimates were subsequently reviewed separately by ADAS and scientists from the University of Reading.

science. Experts were asked to refine the estimates of AP: specifically, the extent to which measures would be additional to a 'BAU' baseline, the extent to which a measure could work as a stand-alone technology or whether its wider use would interact with other measures when applied in the field, and implementation issues.

5.1. Crops and soils

Agricultural soils account for around half of the GHG emissions from agriculture. Crops and grass are responsible for the exchange of significant quantities of GHGs in the form of CO_2 and N_2O. Carbon dioxide is removed from the atmosphere by photosynthesis, which may 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.

An initial list of measures was drawn up from the literature review and input from the project team (further details of the method and results for the crops/soils sub-sector is given in MacLeod *et al*., 2010a). This was reviewed by Defra scientists, who added further measures. The resulting long list had a total of 97 measures (Appendix 1 and Table 1). The initial list was discussed at an expert meeting, and measures were screened and reduced following step c (ii) before.

Developing MACCs for the crops and soils sub-sector was particularly challenging for a number of reasons, including: (a) the large number of potential mitigation measures; (b) the lack of relevant data, particularly on the costs of measures; (c) the fact that the effectiveness of many measures depend on interaction with other measures. To cope with these problems, the range of measures was reduced to a more manageable number through the screening exercises, with scientists providing best estimates in the absence of existing data, and providing informed judgements on the extent of interactions between the measures. In addition some measures were aggregated especially to internalise the interactions, giving an interim list of 35 measures. The AP of these measures was estimated so that measures with small AP could be identified. The interim list was then reduced to a short list of 15 (see Table 1) by eliminating measures with minor to insignificant AP. However, several measures with small (< 2% of sub-sector potential) AP were retained in the crop/soil short list; in particular, some measures between 1% and 2% which are likely to have negative costs were included.

5.1.1. Costs

Existing estimates of abatement measure costs were used where available (e.g. Defra 2002). But there is a lack of up-to-date cost estimates for most measures. As an alternative, each measure was discussed with the same scientific experts, who identified the on-farm implications and likely costs and benefits. The costs and benefits were translated into terms that could be entered into a farm-scale Linear Programme (LP) model, used to provide a consistent opportunity cost estimate of the adoption of measures into specific farm types (SAC, 2005). This model has over 200 activities and nearly 100 constraints and provides flexibility for modelling farming systems across the United Kingdom.

The model was parameterised and validated for the main robust farming types operating within UK agriculture, as defined by Defra (2004), using a combination of agricultural census, farm accounts data and input from farming consultants from

Table 1

The abatement rates of the short-listed crops/soils measures

Measure	Estimated abatement rate (t CO_2e/ha/y)	Estimated maximum area that measure could be applied to by 2022 (mha)	Explanation of the measures
Using biological fixation to provide nitrogen inputs (clover)	0.5	6.4	Using legumes to biologically fix nitrogen reduces the requirement for nitrogen fertiliser to a minimum.
Reduce nitrogen fertiliser	0.5	9.9	An across the board reduction in the rate at which fertiliser is applied will reduce the amount of nitrogen in the system and the associated N_2O emissions.
Improving land drainage	1	4.0	Wet soils can lead to anaerobic conditions favourable to the direct emission of N_2O. Improving drainage can therefore reduce N_2O emissions by increasing soil aeration.
Avoiding nitrogen excess	0.4	8.8	Reducing nitrogen application in areas where it is applied in excess reduces nitrogen in the system and therefore reduces N_2O emissions.
Full allowance of manure nitrogen supply	0.4	7.6	This involves using manure nitrogen as far as possible. The fertiliser requirement is adjusted for the manure nitrogen, which potentially leads to a reduction in the nitrogen fertiliser applied.
Species introduction (including legumes)	0.5	5.8	The species that are introduced are either legumes (see comment regarding biological fixation before) or they are taking up nitrogen from the system more efficiently and there is therefore less available for N_2O emissions.
Improved timing of mineral fertiliser nitrogen application	0.3	8.1	Matching the timing of application with the time the crop will make most use of the fertiliser reduces the likelihood of N_2O emissions by ensuring there is a better match between supply and demand.
Controlled release fertilisers	0.3	8.1	Controlled release fertilisers supply nitrogen more slowly than conventional fertilisers, ensuring that microbial conversion of the mineral nitrogen in soil to nitrous oxide and ammonia is reduced.

Table 1
(*Continued*)

Measure	Estimated abatement rate (t CO_2e/ha/y)	Estimated maximum area that measure could be applied to by 2022 (mha)	Explanation of the measures
Nitrification inhibitors	0.3	8.1	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 timing of slurry and poultry manure application	0.3	7.3	See improved timing of mineral nitrogen.
Adopting systems less reliant on inputs (nutrients, pesticides, etc.)	0.2	5.8	Moving to less-intensive systems that use less input can reduce the overall greenhouse gas emissions.
Plant varieties with improved nitrogen use efficiency	0.2	3.8	Adopting new plant varieties that can produce the same yields using less nitrogen would reduce the amount of fertiliser required and the associated emissions.
Separate slurry applications from fertiliser applications by several days	0.1	7.3	Applying slurry and fertiliser together brings together easily degradable compounds in the slurry and increased water contents, which can greatly increase the denitrification of available nitrogen and thereby the emission of nitrous oxide.
Reduced tillage/no-till	0.15	2.0	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	0.1	5.5	Composts provide a more steady release of nitrogen than slurries which increase anaerobic conditions and thereby loss of nitrous oxide.

the four UK countries. Separate models were run for the three super-regions of England, that is, North, East and West, plus one region for each of Wales, Scotland and Northern Ireland. The model aims to optimise gross margins subject to detailed constraints and activities. Hence, the LP is first calibrated against gross margins expected by farm type in the start year of 2006. Then, dependant on each measure, a combination of constraints, technical (input/output) coefficients, costs and yields are adjusted to reflect the impact at farm scale of each mitigation measure. When optimised this gives a comparison to provide the opportunity cost of adoption.

To calculate costs for the relevant future budget periods, price forecasts were provided by the BAU scenario (BAU3; ADAS, SAC, IGER and AFBI, 2007). Hence, the models were run for each farm type by each mitigation measure for the four discrete time periods. The advantage of the LP approach is that it allows a consistent metric, that is, gross margins, for each mitigation measure compared against the BAU scenario. The adoption of price forecasts attempts to capture some of the predicted market and policy conditions of future periods and farms will optimise subject to these price forecasts. But a common criticism of LP, and related approaches, is that they fail to capture new activity mixes which may appear attractive under future scenarios (Kanellopoulos *et al*., 2010). This area is under-represented in the literature and requires further investigation.

5.1.2. Abatement rate and potential

To calculate the total UK AP for each measure over a given time period, the following information is required:

- the measure's abatement rate (tCO_2e/ha/year);
- the additional area (over and above the present area) that the measure could be applied to in the period considered.

The additional areas for the MTP were based on the judgements of the (same) scientific experts. An MTP identifies the maximum upper limit that would result from the highest technically feasible[7] level of adoption or measure implementation in the sub-sectors. Most crop/soil or livestock measures are only ever likely to be adopted by some percentage of all producers that could technically adopt the measures. An MTP therefore sets a limit on the AP, but this limit is not informed by the reality of non-adoption (or the associated regulatory policy or socio-economic conditions and contexts). Our procedures therefore also identified high, central and low potential abatements, as an indication of the levels thought most likely to emerge in the time scales and policy contexts under consideration.

The assumed potentials were based on a consideration of potential uptake/compliance with existing policies such as nitrate vulnerable zones. For the purposes of specifying abatement possibilities at specific dates in the future, we assume that measures are adopted at a linear rate between current levels of adoption and the MTP. Thus, LFPs are defined relative to this trajectory.

Existing global evidence on the abatement rates (see, in particular Smith *et al*., 2008) was combined with expert judgement to generate estimates of the abatement rates of each of the measures on the shortlist (see Table 1). Where measures lead to abatement of CO_2 emissions over a period of years (e.g. as a consequence of a new

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[7] Where relevant assumptions were developed using the scientific expert groups.

rotational management), emission reductions are expressed on an average annual basis.

5.1.3. CE and the effect of interactions between measures

An abatement measure can be applied on its own, that is, stand-alone, or in combination with other measures. The stand-alone CE of a measure can be calculated by simply dividing the weighted mean opportunity cost (£/ha/year) by the abatement rate (tCO_{2e}/ha/year). However, when measures are applied in combination, they can interact, and their abatement rates and CE change in response to the measures with which they combine. For example, if a farm implements biological fixation, then less nitrogen fertiliser will be required, lessening the extent to which nitrogen fertiliser can be reduced. The extent to which the efficacy of a measure is reduced (or in some cases, increased) can be expressed using a simple interaction factor (IF). Each time a measure is implemented, the abatement rates of all the remaining measures are recalibrated by the relevant IF. It is clearly possible to define a variety of IFs to reflect the biophysical complexity that is both measure- and context-specific. For the purpose of this exercise, IFs were initially defined based on known pair-wise interactions with recalculation of remaining APs accruing to successive measures that remain feasible in application.[8] Appendix 2 provides further details on the IF assumptions.

5.2. Livestock

Livestock are an important source of CH_4 and N_2O. Methane is mainly produced from ruminant animals by the enteric fermentation of roughages. A secondary source is the anaerobic breakdown of slurries and manures. Both ruminant and monogastric species produce N_2O from manure because of the excretion of nitrogen in faeces and urine. The main abatement options for the livestock sector, independent of grazing/pasture management (dealt with under the crops and soils element of the exercise), are through efficiencies in ruminant animal utilisation of diets, and manure management.

A literature review highlighted an array of abatement options for the livestock industry. These fall into two broad categories: animal and nutrition management; manure management. Measures were reviewed and ranked on their likely uptake and feasibility over the three budget periods. Certain options were considered similar in mode of action and likely outcome, and were therefore reduced to a single option. Animal management options for sheep/goats were not considered in the present exercise, as traditional sheep management systems mean that any potential abatement measures would be virtually impossible to apply across the UK flock. Options that included a simple reduction in animal numbers and/or product output, above and beyond those assumed by the BAU scenario, were also ignored, on the grounds that reducing livestock output domestically would simply displace GHG emissions overseas (albeit with some unestimated consequences for global emissions). Livestock land management options (e.g. spreading of manures on crop/grassland) are dealt with in the crop/soil management options. The final table

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[8] To perform this repeated calculation, a routine was written in PERL http://www.perl.org/.

of 15 abatement options examined here for livestock are shown in Table 2a–c. Livestock measures were screened using a similar process as outlined for crop and soil measures, with a key distinction being the application to current livestock numbers rather than crop areas.

5.3. On-farm anaerobic digestion and centralised anaerobic digestion

The estimated abatement from anaerobic digestion is based on avoided CH_4 emissions from manures/slurries plus CO_2 avoided from displaced electricity generation [based on typical 0.43 kg CO_2 per kilowatt hour of electricity (kWhe)], less CO_2 emissions from the digester (40% of biogas, based on 1 t $CO_2 = 556.2\ m^3$) and CO_2 emissions from methane combustion (based on 0.23 kg CO_2/kWh). Cost per tonne CO_2e avoided over project lifetime is calculated as net emission saving divided by net project cost for each farm size band.

The on-farm anaerobic digestion (OFAD) calculations were built up from the average herd size for each holding size category (small, medium or large) based on projected livestock and holding numbers (ADAS, SAC, IGER and AFBI, 2007). Emissions from the UK Greenhouse Gas Inventory (Baggott *et al.*, 2005) were used to determine the CH_4 emissions for the average holding and from that the potential AD-generating potential was determined. Costs, incomes and APs were then calculated for the average holding.

The calculation of CAD potential takes a different starting point to that used for OFAD. In the case of central anaerobic digestion (CAD) the starting point was a range of possible generator capacities between 1 and 5 MWh. This range of generating capacities allows an exploration of the scale efficiencies of CAD plants, primarily because of the reduction in per unit capital costs for larger plants. For each generator size the required volume of CH_4 was calculated and IPCC emission factors used to determine the number of livestock of each category required to produce that volume of CH_4. Average herd sizes were then used to determine the number of farms required to supply one CAD plant of each capacity and also the total number of CAD plants that could be supported by each sector.

The CAD calculations also include the installation of CHP under the assumption that 50% of the heat generated by the plant will be exported to a local district heating installation. This provides a further income stream for each CAD plant.

6. Further Modelling Assumptions

A range of common assumptions define the additional AP across the agricultural sector. In each sub-sector, mitigation potential for the budgetary periods needs to be based on a projected level of production activity that constitutes the basis for estimating current (or 'business as usual') abatement associated with production, and for determining the potential extent of additional abatement above this level. The choice of baselines is therefore crucial, and it is important to determine whether the baseline is an accurate reflection of the changing production environment across agriculture.

The agricultural baseline attempts to account for recent and on-going structural change in UK agricultural production. For this exercise, the main source of baseline information is a project that developed a UK 'BAU' projection (BAU3; ADAS, SAC, IGER and AFBI, 2007). BAU3 covers the periods 2004–2025, choosing

Table 2a

Applicable livestock abatement measures

	Estimated abatement rate (% of emitted GHG)					Increase in yield (%)				
	For measures where abatement rate is consistent across animal categories			For measures where abatement rate is consistent over time but varies between animal categories		For measures where yield increase is consistent across animal categories			For measures where yield increase is consistent over time but varies between animal categories (%)	
Measure	2012 (%)	2017 (%)	2022 (%)	Cows and heifers in milk (%)	Heifers in calf (%)	2012 (%)	2017 (%)	2022 (%)		
Increasing concentrate in the diet – dairy	7	7	7			–	–	–	14*	9†
Increasing maize silage in the diet – dairy	−2	−2	−2			7	7	7	–	–
Propionate precursors – dairy	22	22	22			15	15	15	–	–
Probiotics – dairy				7.5	0	10	10	10	–	–
Ionophores – dairy	25	25	25			25	25	25	–	–
Bovine somatotropin – dairy				−10	0	17.5	17.5	17.5	–	–
Genetic improvement of production – dairy	0	0	0			7.5	15	22.5	–	–
Genetic improvement of fertility – dairy	2.5	5.0	7.5			3.25	8	11.25	–	–
Use of transgenic offsprings – dairy	20	20	20			10	10	10	–	–
Increasing concentrate in the diet – beef	7	7	7			9	9	9	–	–
Increasing maize silage in the diet – beef	−2	−2	−2			7	7	7	–	–
Propionate precursors – beef	22	22	22			15	15	15	–	–
Probiotics – beef	7.5	7.5	7.5			10	10	10	–	–
Ionophores – beef	25	25	25			25	25	25	–	–
Genetic improvement of production – beef	2.5	5.0	7.5			5	10	15	–	–

*Cows and heifers in milk housed in cubicles.

†All other animals.

GHG, greenhouse gas.

Table 2b

Applicability of animal management measures and the explanation of the measures

Measure	Estimated maximum number of animals that measure could be applied to by 2022 (m)	Explanation of the measures
Increasing concentrate in the diet – dairy	2.2	Increasing the proportion of high starch concentrates in the diet makes animals to produce more and/or reach final weight faster.
Increasing maize silage in the diet – dairy	2.2	Increasing the proportion of maize silage in the diet makes animals to produce more and/or reach final weight faster.
Propionate precursors – dairy	2.2	By adding propionate precursors (e.g. fumarate) to animal feed, more hydrogen is used to produce propionate and less CH_4 is produced.
Probiotics – dairy	2.0	Probiotics (e.g. *Saccharomyces cerevisiae* and *Aspergillus oryzae*) are used to divert hydrogen from methanogenesis towards acetogenesis in the rumen, resulting in a reduction in the overall methane produced and an improved overall productivity (acetate is a source of energy for the animal).
Ionophores – dairy	2.0	Ionophore antimicrobials (e.g. monensin) are used to improve efficiency of animal production by decreasing the dry matter intake and increasing performance and decreasing CH_4 production.
Bovine somatotropin (bST) – dairy	2.0	Administering bST to the cattle has been shown to increase production, and at the same time to increase CH_4 emissions per animal.
Genetic improvement of production – dairy	2.2	Selection on production traits.
Genetic improvement of fertility – dairy	2.0	Selection on fertility traits.
Use of transgenic offsprings – dairy	2.2	Using the offspring of genetically modified animals, with improved productivity and less CH_4 emission.
Increasing concentrate in the diet – beef	5.5	Increasing the proportion of high starch concentrates in the diet makes animals to produce more and/or reach final weight faster.

Table 2b

(*Continued*)

Measure	Estimated maximum number of animals that measure could be applied to by 2022 (m)	Explanation of the measures
Increasing maize silage in the diet – beef	5.5	Increasing the proportion of maize silage in the diet makes animals to produce more and/or reach final weight faster.
Propionate precursors – beef	5.5	By adding propionate precursors (e.g. fumarate) to animal feed, more hydrogen is used to produce propionate and less CH_4 is produced.
Probiotics – beef	6.5	Probiotics (e.g. *Saccharomyces cerevisiae* and *Aspergillus oryzae*) are used to divert hydrogen from methanogenesis towards acetogenesis in the rumen, resulting in a reduction in the overall methane produced and an improved overall productivity (acetate is a source of energy for the animal).
Ionophores – beef	6.5	Ionophore antimicrobials (e.g. monensin) are used to improve efficiency of animal production by decreasing the dry matter intake and increasing performance and decreasing CH_4 production.
Genetic improvement of production – beef	2.9	Selection on production traits.

Table 2c

Assumed effects of manure management measures on greenhouse gas abatement, their applicability and the explanation of the measures

Measure	Estimated abatement rate (% of emitted CH_4)	Additional CO_2 emission (kg/storage/year)	Estimated maximum volume of manure/slurry that measure could be applied to by 2022 (m^3)	Estimated maximum number of storages that measure could be applied to by 2022	Explanation of the measures
Covering slurry tanks – dairy	20		4,435,573	5,544	Covering existing slurry tanks.
Covering lagoons – dairy	20		4,292,490	2,862	Covering existing lagoons.
Switch from anaerobic to aerobic tanks – dairy	20	5,200	4,435,573	5,544	Aerating slurry and manure while being stored.
Switch from anaerobic to aerobic lagoons – dairy	20	6,900	4,292,490	2,862	Aerating slurry and manure while being stored.
Covering slurry tanks – beef	20		524,895	656	Covering existing slurry tanks.
Covering lagoons – beef	20		454,909	303	Covering existing lagoons.
Switch from anaerobic to aerobic tanks – beef	20	5,200	524,895	656	Aerating slurry and manure while being stored.
Switch from anaerobic to aerobic lagoons – beef	20	6,900	454,909	303	Aerating slurry and manure while being stored.
Covering slurry tanks – pigs	20		894,059	1,118	Covering existing slurry tanks.
Covering lagoons – pigs	20		715,247	477	Covering existing lagoons.
Switch from anaerobic to aerobic tanks – pigs	20	5,200	894,059	1,118	Aerating slurry and manure while being stored.
Switch from anaerobic to aerobic lagoons – pigs	20	6,900	715,247	477	Aerating slurry and manure while being stored.

discrete blocks of time to provide a picture of change. The BAU3 base year was 2004; a period where the most detailed data could be gathered for the four countries of the United Kingdom. Projections were made for the different categories of agricultural production contained within the Defra June census,[9] covering both livestock and crop categories, to a detailed resolution of activities (e.g. beef heifers in calf, two years and over). The projections cover the years 2010, 2015, 2020 and 2025. The exercise concentrated on general agricultural policy commitments that were in place in 2006, including those for future implementation. As BAU extended to 2025, the exercise also accommodated assumptions about some policy reforms that, as a result of current discussions, seemed probable, although not formally agreed at the time of writing. These mainly include the abolition of set-aside and the eventual removal of milk quotas.

6.1. Cost assumptions

Most of the crops and soil measures and the animal management measures are annual measures, which mean that they do not require the farmer to commit himself in any way for more than one year. Other measures, specifically in manure management and drainage require longer-term commitments and capital outlays additional to baseline costs. For these measures, recurrent future investment costs were converted to an equivalent annual cost after converting flows to a present value.

Further annual adoption costs derive from the displacement of agricultural production, which was estimated by using a representative farm-scale linear programme used to calculate these costs consistently over farm types. This model was based on a central matrix of activities and constraints for different farm types, and calculates the change in the gross margin of implementing a measure in the three time periods compared with the baseline farm activities. The model produced a snapshot of potential against the baseline for each year to 2022. Each abatement measure is evaluated with respect to the baseline. The difference between the baseline and the volume of emissions abated in the MACC gives the new abated emissions projection.

Each measure (representing a step of the MACC) is calculated by combining separate data on AP and costs as follows:

$$\text{Abatement potential}_{\text{year}} = \text{GHG emissions}_{\text{baseline}} - \text{GHG emissions}_{\text{abatementoption}},$$

$$\text{Cost effectiveness} = \frac{\text{lifetime cost}_{\text{abatementoption}} - \text{lifetime cost}_{\text{baseline}}}{\text{lifetime GHG emissions}_{\text{baseline}} - \text{lifetime GHG emissions}_{\text{abatementoption}}}.$$

MACCs present a picture for a single year of AP against a cumulative baseline. This means that the approach adopted here takes account of abatement measures additional to the baseline which had already implemented in MACCs generated for previous years. The CCC approach of producing annual MACCs (i.e. a MACC for each year) should help to introduce some dynamics.

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[9] http://www.defra.gov.uk/esg/work_htm/publications/cs/farmstats_web/default.htm.

The resulting APs are clearly influenced by levels of expected adoption of these measures. Accordingly, the analysis considers a range of adoption rates to approximate likely bounds on AP.

7. Results[10]

The combined (i.e. crop and livestock) sector total central AP estimates for 2012, 2017 and 2022 (discount rate 3.5%) are 2.68, 6.27 and 9.85 Mt CO_2e, respectively. In other words, by 2012, and assuming a feasible policy environment, agriculture could abate around 6% of its current GHG emissions (which the UK National Atmospheric Emissions Inventory[11] reported to be 45.3 Mt CO_2e in 2005, not including emissions from agricultural machinery). By 2022 this rises to nearly 22%, as adoption rates increase.

The estimated CFP for 2022 is shown in Table 3 and Figure 3. The MACC shows a significant AP below the *x*-axis, and further significant abatement just above the *x*-axis until measure EB [OFAD –dairy (medium)], after which the CE worsens markedly. The results suggest that both sub-sectors offer measures capable of delivering abatement at zero or low cost below thresholds set by the shadow price of carbon (currently £36/tCO_2e for 2025). Given a higher SPC of £100/tCO_2e, greater emission abatement becomes economically sensible, though would clearly need appropriate market conditions and policies for actual achievement. Importantly, this analysis shows that 5.38 Mt CO_2e (12% of current emissions) might be abated at negative or zero cost, although this estimate raises the obvious question of why this is not already likely in the baseline projection.

The CFP of 7.85 Mt CO_2e (at a higher cut-off of £100/t) represents 17.3% of the 2005 UK agricultural NAEI GHG emissions. These results partly corroborate more speculative APs identified in IGER (2001) and CLA/AIC/NFU (2007) in relation to N_2O.

8. Discussion

This exercise is the first attempt to derive an economically efficient GHG emissions budget for the agricultural sector in the United Kingdom. The 'bottom-up' exercise raises a number of issues about the construction of agricultural MACCs.

As noted, relative to other industries, the sector is biologically complex, with considerable heterogeneity in terms of implementation cost and measure AP. This suggests considerable scope for conducting sensitivity analysis of a range of variables that have been used to generate the abatement point estimates. It also suggests that rather than one UK MACC based on a limited set of farm types, several MACCs can be defined to cover categories of farm types and regional environments. The CCC has indicated that this is a longer-term objective for refining an agricultural mitigation budget.

Such disaggregation does, however, raise a further challenge in relation to data availability, which in turn highlights the weakness of the 'bottom-up' approach. This process relied on documented evidence from experimental trials that frequently

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[10] Data and estimation spreadsheets are available from the corresponding author upon request.

[11] (http://www.naei.org.uk/).

Table 3

2022 abatement potential: Central feasible estimate

Code	Measure	Abatement per measure ($ktCO_2e$)	Cumulative abatement ($ktCO_2e$)	Cost-effectiveness (£2006/tCO_2e)
CE	Beef animal management – ionophores	347	347	−1,748
CG	Beef animal management – improved genetics	46	394	−3,603
AG	Crops – soils – mineral N timing	1,150	1,544	−103
AJ	Crops – soils – organic N timing	1,027	2,571	−68
AE	Crops – soils – full manure	457	3,029	−149
AN	Crops – soils – reduced till	56	3,084	−1,053
BF	Dairy animal management – improved productivity	377	3,462	0
BE	Dairy animal management – ionophores	740	4,201	−49
BI	Dairy animal management – improved fertility	346	4,548	0
AL	Crops – soils – improved N-use plants	332	4,879	−76
BB	Dairy animal management – maize silage	96	4,975	−263
AD	Crops – soils – avoid N excess	276	5,251	−50
AO	Crops – soils – using composts	79	5,330	0
AM	Crops – soils – slurry mineral N delayed	47	5,377	0
EI	On-farm anaerobic digestion – pigs (large)	48	5,425	1
EF	On-farm anaerobic digestion – beef (large)	98	5,523	2
EH	On-farm anaerobic digestion – pigs (medium)	16	5,539	5
EC	On-farm anaerobic digestion – dairy (large)	251	5,790	8
HT	Centralised anaerobic digestion – poultry (5 mW)	219	6,009	11
AC	Crops – soils – drainage	1,741	7,750	14
EE	On-farm anaerobic digestion – beef (medium)	51	7,801	17
EB	On-farm anaerobic digestion –dairy (medium)	44	7,845	24
AF	Crops – soils – species introduction	366	8,211	174
BG	Dairy animal management – bovine somatotropin	132	8,343	224
AI	Crops – soils – nitrification inhibitors	604	8,947	294
AH	Crops – soils – controlled release fertiliser	166	9,113	1,068
BH	Dairy animal management – transgenics	504	9,617	1,691
AB	Crops – soils – reduce N fertiliser	136	9,753	2,045
CA	Beef animal management – concentrates	81	9,834	2,704
AK	Crops – soils – systems less reliant on inputs	10	9,844	4,434
AA	Crops – soils – biological N fixation	8	9,853	14,280

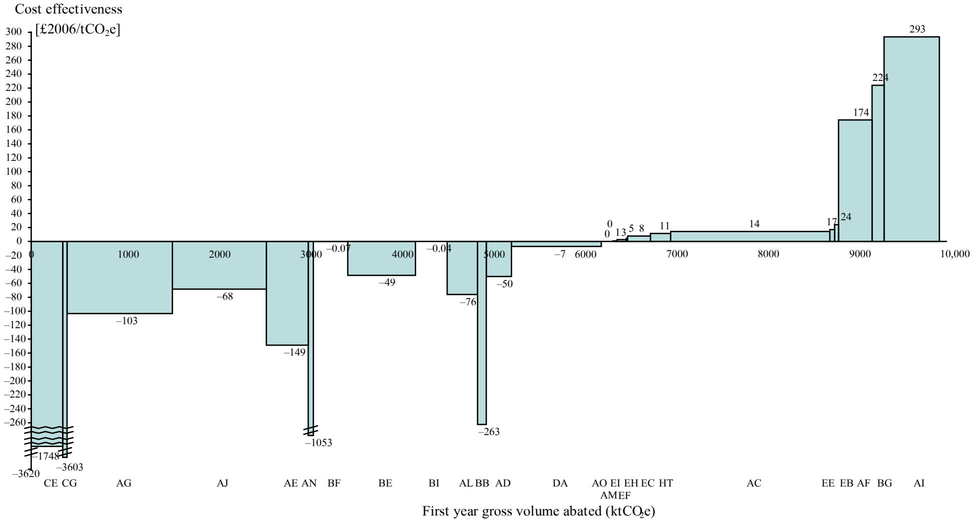

Figure 3. Total UK agricultural marginal abatement cost curve (MACC), central feasible potential 2022 (discount rate = 3.5%, codes refer to measures in Table 3, measures with CE > 1,000 are not shown). See Appendix 2 for an explanation of why the measures below the *x*-axis are not in order of cost-effectiveness

covered limited field conditions for defining AP. It revealed numerous data gaps that could only be filled with scientific opinion, often unsubstantiated with published evidence. The ability to extrapolate and validate this evidence in non-experimental conditions will be an increasing challenge for the construction of disaggregated MACCs. This challenge of extracting and gaining consensus on these data is evidently a multi-disciplinary endeavour, which might include the development of a systematic review process of field-level estimates. Reducing uncertainty by improving the evidence base for the MACCs is an on-going process; see MacLeod *et al.* (2010b).

In its initial budget report (Committee on Climate Change, 2008), the Committee recognised the specific challenges in the agricultural sector and indicated a need for further research to reduce the uncertainties that affect the shape and position of the MACC. Some of the major issues have been alluded to in other hybrid and ‘bottom-up’ exercises (e.g. McCarl and Schneider, 2001; DeAngelo *et al.*, 2006). The first is that the results do not include a quantitative assessment of ancillary benefits and costs, that is, other positive and negative external impacts likely to arise when implementing some GHG abatement measures. An obvious example would be to consider the simultaneous water pollution benefits derived from reduced diffuse run-off of excessive nitrogen application to land. These impacts, both positive and negative, should be included in any social cost estimates.

Second, as noted, there is an issue as to whether the consideration of AP should go beyond the farm gate and extend to the significant lifecycle impacts implicit in the adoption of some measures. Such an extension complicates the MACC exercise considerably, as some may occur beyond the United Kingdom. However, for some measures (e.g. reduced use of nitrogen fertiliser), these impacts are likely to be particularly significant.

A third point is that there is uncertainty about the extent to which some of the currently identified measures are counted directly in the current UK national emissions inventory format. As currently compiled, the inventory procedure is good at recognising direct reductions (e.g. from livestock populations reduction) but does not credit measures which only reduce emissions indirectly.[12] This means that some CE measures identified here are not counted under current inventory reporting rules. Using the livestock example, a reduction in UK emissions will most likely be offset by 'demand leakage' – a corresponding increase in imports and emissions generated elsewhere. Not recognising indirect measures can have the effect of reducing sector AP by around two-thirds. The extent to which measures are captured under different inventory methodologies is explored in more detail in MacLeod *et al.* (2010c).

A final point to note is that the potentials have been developed against a baseline that warrants further scrutiny on at least two counts. First, in terms of the extent to which abatement would be occurring owing to technical change, for example, in terms of accelerated breeding. Although there is some literature on generic rates of change (e.g. Amer *et al.*, 2007), these assumptions were not explicitly included in the baseline used in this exercise. But the extent of adopted technical change does represent a potential confounding affect that could be netted out of our estimates. Second, the analysis largely ignores other important elements of the climate change agenda that are unlikely to remain constant. Specifically, mitigation potential will be vulnerable to warming and climate extremes. There is currently very little research that addresses how mitigation measures can be made more resilient to these potential impacts.

Despite these outstanding issues, the mitigation budgets estimated by this exercise have been endorsed by the CCC and have largely been accepted by industry stakeholders who now have a clearer view of the relevant high abatement and low cost measures. In practical terms, the estimates are currently being used as a basis of discussion for the development of a policy route map with Defra and key industry stakeholders in the shape of a Rural Climate Change Forum. Relevant policies include the development of voluntary approaches (i.e. improved farm advice and codes), and the exploration of the potential for emissions trading within the sector. The Scottish government has adopted key elements from the MACC directly into a five-point plan on abatement, which is currently being extended to the sector.[13] Meanwhile, further research is currently investigating alternative strategies to unlock additional emission reductions through the accelerated development and deployment of existing abatement measures, and through the development of new techniques. The identification of apparent win–win measures also suggests that there is a need for a better understanding of farmer behaviours in relation to the management of GHG emissions.

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[12] Here, 'indirect' refers to a measure that reduces emissions, but which is not currently recognised under inventory protocol. As an example, a reduction in herd populations is a direct measure that is recognised as an emissions reduction. Making an alteration to the animal (e.g. genetics), may deliver the same reduction in an indirect way, but may not be recognised.

[13] Farming for a Better Climate, http://www.sac.ac.uk/climatechange/farmingforabetterclimate/.

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Appendix 1

Table A1

Crops/soil measures and reasons for exclusion from short list

Measure	Included in short list (Y – yes, N – no)
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 nitrogen
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 nitrogen inputs (clover)	Y
Reduce nitrogen fertiliser	Y
Avoiding nitrogen excess	Y
Full allowance of nitrogen manure supply	Y
Improved timing of mineral nitrogen fertiliser application	Y
Controlled release fertilisers	Y
Nitrification inhibitors	Y

Table A1 (*Continued*)

Measure	Included in short list (Y - yes, N - no)
Improved timing of slurry and poultry manure application	Y
Application of urease inhibitor	N – N_2O reduction is small and is offset by indirect N_2O emissions
Plant varieties with improved nitrogen-use efficiency	Y
Mix nitrogen-rich crop residues with other residues of higher C : N ratio	N – marginal, too localised
Separate slurry 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 nitrogen fertiliser but divided into three smaller increments)	N – small abatement potential
Use the right form of mineral nitrogen fertiliser	N – small abatement potential
Placing nitrogen 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

Appendix 2: The Effect of Interactions on the Ordering of Measures

Measures are treated differently above and below the *x*-axis: below (i.e. when costs are negative) they are ordered according to the total savings accruing from the measure, whereas above the *x*-axis they are ordered according to their height, that is, the unit CE of each measure.

In a model MACC, in which measures do not interact, the measures can easily be arranged in order of CE, regardless of whether they have negative or positive costs; measures to the left have the greatest CE (i.e. negative costs), whereas those to the right have poorer CE and positive costs. However, when the CE of each measure is recalculated after the implementation of each measure, measures with negative costs behave differently from those with positive costs. The IF reduces the amount of GHG mitigated (in most cases), effectively increasing the length of the bar. If a measure has a positive cost, this makes the measure more expensive (i.e. less CE); however, if the measure has a negative cost, this makes the measure appear more negative, that is, less expensive and therefore more CE. The length of the bars for measures with positive costs increases as we move from left to right and the effect of the IFs is simply to increase the rate at which the costs/length of the bars increase; this means that after each measure is applied no subsequent measure will have a shorter bar (though it is theoretically possible if the IF >1 and more than the increase between bars). However, for measures with negative costs the bars shorten as we move from left to right, but the IF lengthens the bars, which means that the bars will not necessarily get shorter (i.e. CE will not decrease). For example, in Table A2 the effect of the IFs makes it impossible to order measures with negative costs according to their CE. Instead, measures with negative costs were ordered according to their potential savings, that is, the (negative) cost per hectare multiplied by the area the measure could be applied to. This approach has the advantages that (i) the potential savings are unaffected by the effects of measures interacting, and (ii) it is consistent with profit-maximising behaviour.

Table A2
Example showing the effects of measure interaction on cost-effectiveness (CE)

Measure	*X*	*Y*	*Z*
Stand-alone CE	**−7**	−6	−5
Interaction factor with *X*	NA	0.7	0.7
CE after *X* is implemented	−7	−8.6	−7.1
Interaction factor with *Y*	NA	NA	0.9
CE after *X* and *Y* are implemented	−7	−8.6	−7.9
Combined CE of *X*, *Y* and *Z*	−7	−8.6	−7.9

Notes: NA, not applicable.