Marginal abatement cost curves for UK agriculture, forestry, land-use and land-use change sector out to 2022

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Abstract

Greenhouse gas emissions from agriculture, land use, land use change and forestry (ALULUCF) are a significant percentage of UK industrial emissions. The UK Government is committed to ambitious targets for reducing emissions and all significant industrial sources are coming under increasing scrutiny. The task of allocating shares of future reductions falls to the newly appointed Committee on Climate Change (CCC), which needs to consider efficient mitigation potential across a range of sectors.

Marginal abatement cost curves are derived for a range of mitigation measures in the agriculture and forestry sectors over a range of adoption scenarios and for the years 2012, 2017 and 2022. The results indicate that in 2022 around 6.36 $MtCO_2e$ could be abated at negative or zero cost. Further, in same year over 17% of agricultural GHG emissions (7.85$MtCO_2e$) could be abated at a cost of less than the 2022 Shadow Price of Carbon (£34tCO_2e).

1 Introduction

Greenhouse gas emissions from agriculture, land use, land use change and forestry (ALULUCF) represent approximately 8% of UK industrial emissions, mainly as nitrous oxide and methane. Under the Climate Change Act 2008, the UK Government is committed to ambitious targets for reducing national emissions by 80% of 1990 levels by 2050, and all significant industrial sources are coming under increasing scrutiny. The task of allocating shares of future reductions falls to the newly appointed Committee on Climate Change (CCC), which needs to consider efficient mitigation potential across a range of sectors.

The CCC recognises the need to achieve emissions reductions in an economically efficient manner where the cheapest units of greenhouse gas should be abated first. As with other sectors, ALULUCF emissions abatement or mitigation needs to be achieved at least cost. More technically, there exists a notional schedule of costs of implementing mitigation measures, which shows that some measures can be enacted at a lower cost than other measures. Indeed some measures are thought to be cost saving, i.e. farmers could implement some measures more efficiently such that they would simultaneously save money and reduce emissions. Thereafter costs rise until some calculation of the costs relative to the benefits of abatement show that further mitigation is less worthwhile. This is the essence of the Marginal abatement cost curve (MACC) approach, which enables a comparison of cost with the benefit of avoided carbon emission damages - the so-called shadow price of carbon (SPC). Alternatively unit abatement costs can be compared with the emissions price prevailing in the European Trading Scheme (ETS). Notionally as shown in Figure 1 an efficient budget can be derived from implementation of measures with reference to mitigation costs in other sectors and that cost less than the notional benchmark of the SPC or the ETS price.

This paper describes the derivation of MACC's to depict abatement potential for ALULUCF for the UK. In the next section the paper scopes the aims of the MACC approach that has been adopted by the CCC as a basis for determining notional mitigation budgets across the main non traded sectors in the UK including ALULUCF. We then outline the methodological approach to deriving

the relevant data on abatement potential and costs to populate the CCC MACC framework. Subsequent sectors outline the specific mitigation measures available in the sub sectors of crops and soils, livestock, land use and land use change and forestry. The application of these gives rise to a range of outstanding issues that complicate the application of MACC analysis in ALULUCF relative to other sectors where technologies are relatively well understood. The penultimate sections present resulting abatement potential and costs before a discussion.

2 The committee on climate change and MACC analysis

The Committee on Climate Change was established as an independent body to provide expert analysis and advice on how the UK can meet its climate change goals (i.e. 80% reduction in CO_2e by 2050). The CCC is responsible for advising on the UK's carbon budgets for the periods to 2012, 2017 and 2022 as part of the journey to reach the 2050 target, and for reporting on progress in reducing emissions to meet these budgets. The CCC is the first body of its kind in the world and is being set up under the Climate Change Act.

To inform its sectoral budgeting process the CCC has adopted Marginal Abatement Cost curves. There exist two main types of MAC curve; this exercise used a bottom up engineering based MACCs, which are detailed technology rich models modelling abatement potential and costs for individual technologies and measures. The alternative approach that dominates the abatement cost literature can use a top-down macroeconomic general equilibrium models that typically take emission reductions as exogenous and provide an overall cost to the economy.

The bottom up MACC provides a static 'snap shot' illustration of the annual potential to reduce emissions and average costs of doing so for a wide variety of technologies and abatement measures for a given year relative to an assumed baseline. Ranking abatement measures in order of decreasing cost effectiveness - such that measures to the left of the curve and below the x-axis indicate negative costs (i.e. benefits, either private or social), and costs the right and above the x-axis illustrate costs - permits technologies and measures to be compared at the margin (i.e. the steps of the curve) and provides an invaluable tool for cost-effectiveness analysis. These volumes are taken as annual emission savings for a given year, additional from initial fixed baseline (which the CCC has chosen to be consistent with BERR Updated Emissions Projections 29 – baseline used for EWP analysis). As such the emission savings should be constructed from the difference between CO_2e emitted in the baseline or business as usual scenario and emissions in the abatement scenario where a particular technology or abatement measure is employed across a likely adoption profile within a reasonable policy environment

3 Agricultural mitigation

Total GHG emissions in the UK in 2005 (654 Mt CO_2e); ALULUCF contributes approximately 8% or 50 Mt CO_2e mainly as N_2O (54%) and CH_4 (37%). The CCC has already signaled a desire for ALULUCF to work towards the notional 80% target, which has been met with skepticism by the industry, which feels that this is too radical given current technology and practice. This is largely because of the absence of any systematic route map showing what is possible.

But this reaction is based on an incomplete picture of the extent of potential emissions reductions from agriculture. While the methods are understood, there has never been a concrete piece of work showing the extent to which measures can be implemented and how measures (across all ALULUCF) can be lined up in terms of the volume of greenhouse gas they reduce and, crucially, the implicit cost per tonne of CO_2e from implementing each measure in the field. Until we have this work, it is impossible for the sector to know the extent to which it can meet the 80% target efficiently – i.e. at a cost per tonne that is comparable to the cost in other industries, or relative to the benchmark of either buying an emissions permit in the European Trading Scheme (about 40

euro/tonne CO_2e) or the UK government's notional benchmark figure of around £100/tonne of CO_2e. This is the approach taken by the CCC to determine a sector budget.

MACC analysis offers a representation of cost and abatement potential that is built up from a bottom-up analysis of data on mitigation options within respective sectors. These mitigations are projected to be adopted over and above a baseline of what would normally happen, thereby giving rise to extra abatement potential.

There is an extensive list of technically possible options for mitigating emissions in ALULUCF. For example, ECCP (2001) identify a list of 60 possible options, Weiske (2005) considers around 150 and Moorby et al. (2007) identify 21. Measures may be categorised as: reducing emissions via improved farming efficiency; displacing fossil fuel emissions via alternative energy sources; and enhancing the removal of atmospheric CO_2 via sequestration into soil and vegetation sinks (see Table 1). Some mitigation options, typically current best management practices, deliver improved farm profitability as well as lower emissions and thus might be adopted without government intervention beyond continued promotion/revision of benchmarking and related advisory information services. Estimated emissions have already fallen by around 6% since 1990 – largely due to falling livestock numbers - and further spontaneous cuts are anticipated to deliver similar savings over the next decade or so.

However, the majority of mitigation options entail additional cost to farmers. This raises questions regarding: Which measures can be implemented on farm? Where, when, and at what cost? What effect will different measures have on emissions? The derivation of efficient mitigation options requires some understanding of the relative cost of measures in terms of cost per tonne of CO_2e. This information defines the marginal abatement cost curves which show higher emission savings becoming increasingly expensive to achieve in terms of extra effort or income foregone. Consequently, cost-effective mitigation is likely to be significantly less than the technically feasible potential: the absolute size of emissions from a particular activity is less important than the cost of reducing its size since it is avoidable rather than total emissions that are of interest.

International literature on Marginal abatement costs

The international literature shows various attempts to estimate the cost-effectiveness of different mitigation options, both individually and to trace-out MACC's. Some, such as ECCP (2001) and Weiske (2005, 2006), offer qualitative judgements. Others, such as McCarl and Schneider (2001), US-EPA (2005, 2006), Weiske & Michael (2007), Smith et al. (2007a,b,c) and AEA (2008) offer quantitative estimates. NERA (2007) offers an interesting study for the UK as part of an assessment of extending greenhouse gas trading into the agricultural sector. However, an initial MACC exercise considered only a limited number of measures. We are unaware of a similarly comprehensive assessment of the range of technologies to that presented in this paper. The methodology for deriving abatement potentials and the derivation of associated cost curves was developed in light of guidance provided by the Office of Climate Change/CCC to be consistent with MACC analysis in other sectors of the economy. The methodology allows for abatement potentials to be represented using a range of alternative cost metrics (e.g. private costs and social costs).

4 Methodological steps for developing MACC's

In this section we briefly outline key parameters needed for the analysis. We then outline the range of measures considered under the principal headings of ALULUCF. Within agriculture, these measures are broken down into crops and soils and livestock measures. Note that we deal principally with non CO_2 emissions (except for forestry). While CO_2 emissions from ALULUCF could amount to around 8% of the sector – these are predominantly from energy and transport use and also are covered in a separate MACC exercise for those areas.

In broad terms the main steps of the MACC exercise are as follows:

a. Identify Business As Usual (BAU) abatement or baseline emissions projection for the specified budgetary dates 2012, 2017, 2022
b. Identify potential *additional* abatement for each period, above and beyond the abatement forecast in the BAU scenario, by comparing the BAU abatement with the constructed abatement measures inventory, which includes measure adoption scenarios corresponding to maximum technical potential and central, high and low feasible potentials
c. Quantify (i) the maximum technical potential abatement and (ii) Cost-effectiveness (CE) in terms of £/tCO_2e of each measure that can contribute additional abatement (based on measures inventory, existing data, expert groups review and NAEI) for each period, by the following process:
    i. quantify the costs and benefits, and the timing of costs and benefits
    ii. calculate the net present value (NPV) using either a private or a social discount rate
    iii. express costs in £2006
    iv. list cost breakdowns used to calculate the CE; note which BAU working assumptions were used, and list any new assumptions made
    v. identify the potential global emissions impact of the measure, i.e. the extent to which mitigation might displace production (and associated emissions) from the UK rather than reducing the global emissions.
d. Draw initial MACCs varying the discount rate (to derive social, private and hybrid metrics)
e. Adjust CE to take into account (a) reduced/increased CE resulting from interaction of measures[1] and (b) granularity in the MACCs to reflect different average costs as penetration becomes more demanding
f. Redraw MACC
g. Identify feasible uptake
h. Quantify feasible potentials in terms of central, low and high estimates, based on a review of the levels of compliance/uptake associated with existing policies
i. Disaggregate into feasible potentials by devolved administration (DA) and gas
j. Report in output summary sheet format
k. Carry out stand alone MACC check

This process is outlined in Figure 2 below, which shows an example for crop and soil measures. The information was compiled in spreadsheets that allow transparency and flexibility in altering assumptions in several key data inputs.

5 Measure screening for ALULUCF in the UK.

The separate sub sectors comprising ALULUCF have a corresponding body of research evaluating mitigation potentials. From this literature and existing mitigation research conducted in the UK, a range of sub-sector specific abatement measures were identified with some applicability to UK agricultural and land use conditions. Expert opinion was then used to further refine abatement potentials; specifically the extent to which measures would be additional to a business as usual baseline and the extent to which a measure could work as stand alone technology or whether its wider use would interact with other measures when applied in the field. Information on implementation costs was also collected and subsequently augmented by modelling decision-making at the farm scale. A full description of the measures considered can be found in Moran *et al*. (2008)

[1] The CE of a measure is dependent on the measures that are implemented prior to it, e.g. the CE of decreasing herd size is lowered if the herd has already been switched to lower GHG feed.

5.1 Crops and soils

Agricultural soils account for around half of the GHG emissions from agriculture. Croplands (i.e. those areas producing arable crops) and grasslands, 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 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.

Developing multiple MACCs for the crops and soils sub-sector was challenging for a range of reasons, not least of which were: (a) the large number of potential mitigation measures, (b) the lack of secondary data, particularly on the costs of measures, and (c) the fact that the effectiveness of a measure depends on how it interacts with other measures. These were dealt with by reducing the range of measures to a more manageable number through a scoping exercise, using expert groups to provide data in the absence of existing data, and undertaking simple modelling of the interactions between the measures.

An initial list of measures was drawn up based on a literature review and input from the project team. This was reviewed by the steering group and policy officials within Defra, who added further measures. The resulting long list had a total of 97 measures. The long list was discussed at an expert meeting, and measures were removed that were considered (a) likely to have very low additional abatement potential in UK (e.g. already current practice, only applicable to very small % of land) or (b) unlikely to be technically feasible or acceptable to the industry. In addition some measures were aggregated, giving an interim list of 35 measures. The abatement potential of these measures was calculated so that measures with small abatement potential could be identified. The interim list was reduced to a short list of 15 (see Table 2). Several measures with small (<2%) abatement potentials were included in the short list, in particular some measures between 1 and 2% likely to have negative costs were included. Short descriptions of the measures are given in Table 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 Figure 2.

Costs

Secondary data about costs were used where appropriate (e.g. Defra 2002), however, there was a lack of up to date cost data for most measures. In order to tackle this, each measure was discussed with experts, who identified the on-farm implications and likely costs and benefits. The costs and benefits were translated into terms that could be inputted into the farm scale model to calculate each measures' impact on the gross margins. The model and the assumptions underpinning it are described in detail in section 3 of Moran *et al*. (2008).

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/y)
- the additional area (over and above the present area) that the measure could be applied to in the given period.

The additional areas for the maximum technical potential were derived from expert judgement. The three feasible potentials (high, central and low) were calculated based on a review of uptake/compliance with existing policies. It was assumed that measures are adopted at a linear rate over time.

Existing evidence on the abatement rates (see in particular Smith *et al*. 2007) was combined with expert judgement to derive estimates of the abatement rates of each of the measures on the interim list. (see Table 3). 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.

Cost-effectiveness (CE) and 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/y) by the abatement rate (tCO_{2e}/ha/y). However, when measures are applied in combination, they interact and their abatement rates and cost effectiveness change in response to the measures that they combine with. 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). Each time a measure is implemented, the abatement rates of all of the remaining measures are recalculated by multiplying them by the appropriate IF. In order to perform this repeated calculation, a routine was written in PERL. Note that the 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, while above the x-axis they are ordered according to their height, i.e. the unit cost-effectiveness of each measure.

5.2 Livestock

Livestock are an important source of methane (CH_4) and nitrous oxide (N_2O). Methane is mainly produced from ruminant animals by the enteric fermentation of roughages. A secondary source is from the anaerobic breakdown of slurries and manures. Both ruminant and monogastric species produce N_2O from manure due to the excretion of nitrogen in faeces and urine. The main abatement options from the livestock sector, independent of grazing/pasture management, are through the efficiencies with which ruminant animals utilise their diet and manure management. The following describes the mode of action of the main options.

A review of the literature highlighted a vast array of abatement options from the livestock industry (see Annex A5 of Moran *et al*., 2008), which fell into two broad categories, those options that focus on animal management options and those that focus on manure management. These options were reviewed and ranked on their likely uptake and feasibility over the 3 time points. 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 studied further as traditional sheep management systems would mean that an abatement option would be difficult 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 BAU3 scenario, were also eliminated as there is a need to avoid displacing domestic demand overseas. Livestock land management options (e.g., spreading of manures to crop/grassland) are dealt with in the crop/land management section of this report. The final table of abatement options examined for livestock are shown in Table 4 and detailed below.

5.3 Forestry

Forest biomass trees and soil sequester carbon, and biomass may be used to displace emissions in other sectors. We have undertaken an indicative analysis of the associated potential and the estimates presented here come with a number of important caveats.

The definition of appropriate measures in forestry presented specific problems in relation to the adoption of a life cycle approach that was not addressed in other sub sectors. Specifically the forestry abatement potential inherent in sequestration is largely inflated depending on the *substitution* assumptions that can be made in relation to the subsequent use of wood products, specifically into construction and in energy end uses. Use of timber in these products has the potential to displace emissions from more carbon intensive fuels and materials.

Data on direct abatement in the forestry sector may be considered fairly reliable. Current estimates of substitution potential are contested and therefore were not eventually reported for the national carbon budget. We nevertheless demonstrate their significance here.

Baseline

As with the agricultural analysis, abatement potential needs to be determined relative to a business as usual baseline, which in this case was provided by CEH projections for LULUCF activities (Thomson & Van Oijen, 2007).

Afforestation measure

The analysis concentrates on conifer forests (Sitka Spruce) as an established species in the UK, where management practices are also well established. Afforestation involves planting new forests on land previously used for other purposes (or not used at all). We assumed that all trees planted will be harvested (and then replanted) after 49 years. We assumed that an increased planting regime begins in 2009 and continues through the carbon budget periods. Afforestation is a source of CO_2 emissions for several years after planting. This is reflected in the projections. However, the first years after planting, which is presented in the MAC curves, do not reflect accurately what the carbon balance of afforestation is over the lifetime of the measure, where later forest growth offsets emissions due to planting. A longer time horizon offers even greater potential to offset initial emissions.

For afforestation, CEH use three scenarios for forestry (see Table 5). Projections deal with the period 2006-2020. A high emissions scenario does not consider any new planting. A second scenario projects the 2005 planting rate to occur every year between 2006 and 2020 (8,500 ha/year). This is the mid emissions scenario and this is considered as the baseline for afforestation. The third scenario anticipates a high planting rate (30,000 ha/year). It is described as the low emissions scenario and is taken as our abatement option for afforestation. This level of planting is below what could be deemed as a full technical potential, which in turn is dependent on the availability of alternative land classes. But the achievable annual rate of afforestation is likely to be limited by a range of factors including environmental constraints, licensing regulations and requirements and the practicable ability to carry out the necessary administrative functions, including Environmental Impact Assessments. A figure with which to constrain the potential extent of afforestation is more difficult to arrive at. In England, the extent of poor agricultural land (Grade 4 land class) currently without woodland cover and on mineral or organo-mineral soils is 1.6 million

hectares. This clearly provides little constraint on the abatement potential, although could be reduced further through more detailed constraint analysis.

The maximum area of forest planted in the UK in any one year was 42,600 ha in 1971, covering the period 1920 to the present day. At that time, policy levers favoured woodland creation and the environmental and regulatory framework were less demanding than at present. It could therefore be assumed that this implies a maximum technical potential that is below this limit, which is the rationale behind the 30,000 hectares. This is arguably a conservative approach, given that the MACCs are constructed with an open mind to changes in policy stance. Within this area, the species mix is more difficult to determine. Although the analysis will use sitka spruce, the demand for other public good benefits from forestry will likely mandate a mix of coniferous and broadleaf species. This in turn will influence abatement potentials.

Shorter rotation measure

The analysis again concentrates on conifer forests. For the broadleaf forest, changes in rotation lengths do not have a major impact over the next 50 years, for three major reasons:

- slow growth rates
- a well balanced age structure
- planting rates have been relatively low until the 90s (Thomson & Van Oijen, 2007). As the main impact of the implementation of short rotations is offered by wood products and substitution, low planting rates mean low harvest rates as well and finally few substitution possibilities.

While broadleaf planting has been at low levels in the last 50 years, the same is not the case for the conifers. This implies that a strategy aiming at some significant results by 2020 should focus on the conifers forest because of

- the faster growth rates
- the high plantation rates in the 60s, 70s.

Shortening rotation length means that existing forests of 49 years old will be harvested in each year the measure is implemented, instead of harvesting 59-year old forests, as would occur in the baseline. The forests will be replanted after each harvest. Although implementing shorter rotations result in net emissions due to the decrease in the biomass, possible benefits in the energy sector and in product substitution mean high direct plus indirect abatement potential for this measure.

5.4 Land use and land use change

Land use change can result in both emissions and removals of greenhouse gases, which can be widely dispersed in space and highly variable in time. The factors governing these emissions and removals can be both natural and anthropogenic (direct and indirect) and it can be difficult to clearly distinguish between causal factors. Land-use change is often associated with a change in land cover and an associated change in carbon stocks. For example, if a forest is cleared, the carbon stocks in aboveground biomass are either removed as products, released by combustion, or decay back to the atmosphere through microbial decomposition. Stocks of carbon in soil will also be affected, although this effect will depend on the subsequent treatment of the land. Cropland soils can lose carbon as a consequence of soil disturbance (e.g., tillage). Tillage increases aeration and soil temperatures, making soil aggregates more susceptible to breakdown and physically protected organic material more available for decomposition. Conversion of cropland back into grassland can result in a build-up in the level of carbon in the soil again, but this usually takes considerably longer than the loss of soil carbon resulting from conversion of grassland into cropland.

Within this category we distinguished potential of residual measures that have already been addressed in agriculture and forestry, specifically peat land restoration, halting liming of organic soils and land use transitions between grassland transitions and other agricultural uses. We do not report any significant stand alone abatement potentials arising from analysis of land uses and land use change as they are defined in this chapter. Measures are discounted on the basis of either small abatement potential and or relatively high cost. Peatland restoration may offer small volume of cost-effective abatement potential but there is scientific uncertainty about the volume.

The Land Use, Land Use Change, and Forestry (LULUCF) sector is estimated to have been a net sink since 1999, amounting in 2006 to some 1.95 Mt CO_2 equivalent (Choudrie *et al.*, 2008). However, most of this is due to the uptake of CO_2 by forestry – if this is excluded, then land use and land use change emits 13.7 Mt $CO_2e\ y^{-1}$ (calculated from Table 1-27 in Thomson & van Oijen, 2008).

6 Modelling assumptions

A range of common assumptions define the additional abatement potential across ALULUCF.. 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 ALULUCF sectors.

Different baselines are applicable across the sub sectors but since these all apply to a limited amount of UK land area, the assumptions necessarily need to be consistent in order to avoid double counting abatement potential.

Agricultural baselines attempted to account for recent and on-going structural change in UK agricultural production. For this exercise the main source of baseline information is a recent exercise developing a UK Business as Usual projection (BAU3) (ADAS *et al.*, 2007). BAU3 covers the periods 2004 to 2025, choosing discrete blocks of time to provide a picture of change over this period, and to accommodate the implementation of major policy changes. The BAU3 base year was 2004; a period where the most detailed data could be gathered for the 4 countries of the UK at a spatial level. 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 projections cover the years 2010, 2015, 2020 and 2025. 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.

Cost assumptions

The cost of the measures was calculated as the negative of the net present value (NPV) of implementing the measure, i.e. by defining the cash flow over the lifetime of the measure (accounting for anticipated future price changes) and discounting them back to 2006 values (2006 was chosen as a base year for all financial calculations). This usually meant estimating the annual recurring costs (and incomes, where applicable) and the capital expenditure in the first year of implementation.

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 anyway for more than one year. Other measures, mainly in manure management and obviously the forestry measures require longer term commitments.

For the crops and soil measures the SAC Farm Level Model was used to estimate the annual cost of the options. This linear programming model is 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 to the baseline farm activities. The annualised cost data were then fed into the cost panel of the MAC spreadsheet.

The cost of implementing each animal management abatement option was estimated using the annual cost of administering the abatement option per treated animal (mainly based on IGER, 2001) and multiplied by the number of animals treated. The costs of the nutrition options (e.g., increasing proportion of maize silage) accounted for the number of days that the abatement option would be administered and change in the cost of the diet compared to previous options. The assumed dairy cattle milk quota system causes the reduction of the national herd if milk yield increases, so the total cost decreases as the number of animals decreases. Regarding beef cattle, efficiency improvement results in more meat to be sold, and this additional income was included in the NPV calculations.

The costs of the manure management options were calculated by estimating the investment required to implement the measure and the associated annual running cost per storage unit. The numbers of storage units was estimated from the proportion of manure volume and from the average storage capacities in each manure management system. The lifetime of the equipments installed is assumed to be 20 years.

The anaerobic digestion options have slightly more complicated NPV calculations. For on farm anaerobic digestion plants the capital cost, the annual operating cost, and the incomes from electricity (including Renewable Obligation Certificate (ROC)) and heat sold were considered. Centralised plants have an additional cost element: the transport cost of the slurry. Again, the lifetime of the plants are set to 20 years.

The afforestation measure has two cost elements: purchase of land and planting, while generates income through the whole lifetime (thinning four times and falling the trees). The NPV of the shortening rotation length measure is calculated by the difference between the baseline and the abatement option arising from the different timing of the same events (planting, thinning four times and felling the trees).

The model will produce a snapshot of potential against the baseline for each year to 2022. Each abatement option is evaluated with respect to the baseline. The difference between the baseline and the volume of emissions abated by the MAC curves gives the new abated emissions projection.

Each column of the MAC curve is calculated as follows:

$$Abatement\ Potential\ Volume_{year} = GHG\ emissions_{baseline} - GHG\ emissions_{abatement\ option}$$

$$Cost\ Effectiveness = \frac{Lifetime\ cost_{abatement\ option} - Lifetime\ cost_{baseline}}{Lifetime\ GHG\ emissions_{baseline} - Lifetime\ GHG\ emissions_{abatement\ option}}$$

Abatement potential volume = $MtCO_2$ baseline – $MtCO_2$ abated

$$\text{Abatement costs} = \frac{\text{full cost of abatement option} - \text{full cost of baseline option}}{CO_2 \text{ emissions in baseline} - CO_2 \text{ emissions with abatement option}}$$

The resulting abatement potentials are clearly influenced by levels of expected adoption of these measures. Accordingly, the analysis considers a range of technical potentials that might set the limits on abatement. A full technical potential determined the absolute upper limit that might result form the highest technically feasible level of adoption or measure implementation in the subsectors. For example, it is technically possible to commit the majority of UK land area to forestry, though this is unlikely to happen. Similarly, 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. A maximum technical potential therefore sets a limit on the abatement potential, but this limit is not informed by the reality of non-adoption or likely regulatory policy or social constraints. The analysis therefore derived high, central and low feasible potential abatements (Figure 2), which are the levels thought most likely to emerge in the time scales and policy contexts under consideration.

The effectiveness of measures is influenced by interactions between measures and their environment. We have tried to reduce this uncertainty by explicit consideration of interactions, but we stress that further work is required to derive more targeted abatement potentials e.g. across a variety of farm types and on a regional basis.

There are several ways to present the resulting MACC information for the CCC budget periods 2012, 2017 and 2022. In addition to the differing levels of abatement related to adoption, MACC variants can be created using private or social costs or a hybrid of both. The key distinctions here are the different discounting assumptions and whether or not the analysis reflects private or social costs. (7.0% and 3.5% discount rate was used for calculating private cost and social costs, respectively.) Abatement potentials have also been estimated for the separate UK devolved administrations, i.e. England, Scotland, Wales and Northern Ireland. This information was compiled in spreadsheets that allow transparency and flexibility in altering assumptions in several key data inputs.

MAC curves present a 'snap-shot' for a single year of abatement potential against a baseline. This means that the conventional MAC curve approach would not take account of abatement measures additional to the baseline which had already implemented in MAC curves generated for previous years. The CCC approach of producing annual MAC curves (i.e. a MAC curve for each year) should help to introduce some dynamics.

7 Results and discussion

We estimate significant abatement potential in crop and soil measures and in livestock management. Estimated total abatement in ALULUCF is clearly influenced by the forestry potential, which is significantly enhanced by the extent to which wood products are assumed to displace carbon intensive construction materials and energy sources. We do not identify any specific significant abatement opportunities in land-use change, but note that scientific uncertainty, and that small opportunities may exist in terms of peat land restoration. But these opportunities may be relatively costly compared to any reasonable cost threshold such as the current UK Shadow Price of Carbon.

The combined total central feasible abatement potential estimates for 2012, 2017 and 2022 (social discount rate) are 2.66 MtCO_2e, 6.58 MtCO_2e and 10.83 MtCO_2e respectively. In other words, by 2012, and assuming a feasible policy environment, ALULUCF could be mitigating around 6% of

current greenhouse gas emissions (which the NAEI reported to be 45.253MtCO_2e in 2005 – not including emissions from agricultural machinery). By 2022 this rises to nearer 25%. The combined total MTP abatement estimates for 2012, 2017 and 2022 (social discount rate) are 5.83 MtCO_2e, 14.91 MtCO_2e and 23.86 MtCO_2e respectively.

The estimated CFP and MTP potentials for 2022 are demonstrated in Tables 6 and 7, respectively, where the final column of cumulative abatement potential defines the MACC curve shown in Figures 3 and 4.

For illustrative purposes, using the 2022 MACC this total central feasible potential can be divided between crop and soil measures 6.46 MtCO_2e, livestock measures 3.40 MtCO_2e, and forestry measures 0.98 MtCO_2e.

Table 6 also suggests that all three sub sectors offer measures capable of delivering abatement at zero or low cost (expressed in 2006 prices) below thresholds set by the Shadow Price of Carbon (currently about £36/t CO_2e projected for 2025). Indeed around 6.34 MtCO_2e could possibly be abated at negative or zero cost. As demonstrated by Table 6 and associated MACC, costs then rise progressively. After measure AC (crop-soils drainage) there is a steep rise in the abatement cost per tonne.

For agriculture alone, the central feasible potential of 7.85MtCO_2e (at <£100/t) represents 17.3% of the 2005 UK agricultural NAEI GHG emissions. Although there are no similar benchmark studies, the results presented here partly corroborate conclusions on abatement potential identified in IGER (2001) and CLA/AIC/NFU (2007) in relation to N_2O. The MACC curves presented here provide more detail that builds on a preliminary MACC exercise set out in Nera (2007).

We also quantify the indirect abatement potential that afforestation and short rotation forestry biomass substitution provides in substituting in energy generation and in other product end uses. This latter potential could be a significant addition to the ALULUCF potential, i.e. as high as 11.90 MtCO_2e from short rotation biomass substitution into other end uses (2022 CFP). But this potential is not included in the main figures for two reasons. Firstly, it is not clear that these savings will accrue in the UK. Secondly, our analysis is based on the costs of production of this biomass and does not make any assumptions about costs entailed in its use.

An horizon scan of likely 2050 technologies that could conceivably increase this potential significantly. A precise estimate of how far emissions can be reduced is speculative pending further research. However, a cautious assessment is that the high feasible abatement potential identified in the full MAC curves (17 MtCO_2e) could be achieved by 2050. This would imply emissions from agriculture in 2050 of around 50% below 1990 levels.

A number of caveats need to be stressed on the results as they are currently presented. The first is that the results do not include a quantitative assessment of ancillary benefits and costs, i.e. other positive and negative external impacts likely to arise when implementing some greenhouse gas abatement measures. Reduced water pollution related to more efficient use of nitrogen fertiliser is a classic example. While emissions abatement and water pollution may be positively correlated, the same is not always true for the effect of some abatement measures on biodiversity. Some ancillary impacts will be significant, and they ideally need to be quantified and added to the cost estimates. Work is currently underway to include estimates of these largely non-market impacts. For now we note that these will tend to make crops and soils measures more attractive and livestock measures less so.

A similar caveat applies to the need to extend the consideration of costs to the life cycle impact of some measures. A qualitative assessment of these impacts and we suggest that the analysis does need to be extended to consider selected life cycles assessments (LCA), which could change the MACC ordering. The qualitative analysis suggests that crops and soils measures will have co-benefits in reducing emissions from fertiliser production.

A third point to note is that there is some uncertainty about the extent to which some of the identified measures are counted directly in the current UK national emissions inventory format. As currently compiled, some measures may only reduce emissions indirectly[2] and it is important to try and identify how a measure can qualify as being of direct mitigation potential. Removing indirect measures can have the effect of reducing abatement potential by around two thirds.

For example, the removal of indirect potential from the central feasible potential estimate for 2022 reduced the cumulate abatement from 10.83 $MtCO_2e$ to 3.3 $MtCO_2e$. All of this reduction is in the crop and soil and livestock abatement potentials. Crop and soil abatement potential would reduce from 5.17 $MtCO_2e$ to only 154.74 $ktCO_2e$. Livestock measures reduce from 3.40 $MtCO_2e$ to 2.17 $MtCO_2e$. There is clearly a need to clarify how measures qualify for inclusion in national inventory formats.

This exercise raises a number of other complicating factors that increase the uncertainty inherent in the definition of MACC's, and that distinguish the ALULUCF exercise from that undertaken in other sectors characterised by fewer firms and a common, relatively well-understood set of abatement technologies. In comparison, agriculture and land use are more atomistic, heterogeneous and regionally diverse. These factors can alter the abatement potentials and the cost-effectiveness outlined here. We have tried to reduce this uncertainty by explicit consideration of interactions between measures, but we stress that further work is required to derive more targeted abatement potentials e.g. across a variety of farm types and on a regional basis. This modelling exercise proved representative MACC for the UK. Ideally this exercise needs to drill down to develop regional and farm specific abatement costs curves

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[2] 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 hence in an indirect way, but may not be recognised.

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Table 1 Selected examples of agricultural mitigation options (source Moxey, 2008)

Category	General Example	Specific Examples	Technical feasibility	Potential emission reductions	Private Cost effectivene	Social Cost effectivene	Co-benefit effects
Reducing Emissions	Energy efficiency	Adoption and maintenance of modern machinery	High	Low	Medium	Medium	?
		Adoption and maintenance of modern building design	High	Low	Medium	Medium	?
	Nutrient management	Improved utilisation of nutrients for plant growth	High	Low	High	High	+
		Improved manure storage	High	Low	Medium	High	+
	Livestock management	Reduced roughage intake/improved dietary controls	High	Low	Medium	Medium	-
		Dietary supplements/ faster maturing breeds	Medium	Low	Medium	Medium	-
	Different agriculture	Fewer livestock (*)	High	Medium	High?	Medium?	-
		Switch to non-ruminant livestock (*)	High	Medium	Low	Medium?	-
Displacing emissions	Bioenergy	Bioethanol/biodiesal: from crops, recycled veg oils etc.	Medium	Medium	Medium	Low	+/-
		Biomass: from SRC, farm residues, municipal waste	Medium	Medium	Medium	Medium	+/-
		Biogass: from anaerobic digestion or housed livestock	Medium	Medium	Low	Low	?
Enhancing removals	Soil restoration/protection	Land idling (e.g. set-aside) (*)	High	Medium	Low?	High?	+
		Prescriptive restorative management	High	Medium	Low	High	+
		Reduced tillage	Medium	Low	Medium	Medium	+/-
	Afforestation	Afforestation	High	Medium	Low	High	+/-

Sources: derived from ECCP (2001), Weiske (2005), Weiske (2006), USEPA (2005), Weiske & Michel (2007), Smith et al. (2007a), ADAS et al. (2007), Bell et al. (2007), Booth et al. (2007), Hanley et al. (2007a), Doornbosch & Steenblik (2007), Moorby et al. (2007), NERA (2007).

Table 2 Crops/soils measures 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
Full allowance of manure N supply	Y
Improved timing of mineral fertiliser N application	Y
Controlled release fertilisers	Y
Nitrification inhibitors	Y
Improved timing of slurry and poultry 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 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 Abatement rates of the short listed measures

Measure	Estimate of measures abatement rate t CO_2e/ha/y [1]	Explanation of the measure
Using biological fixation to provide N inputs (clover)	0.5	Using legumes to biologically fix nitrogen reduces the requirement for N fertiliser to a minimum.
Reduce N fertiliser	0.5	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	1	Wet soils can lead to anaerobic conditions favourable to the direct emission of N_20. Improving drainage can therefore reduce N_2O emissions by increasing soil aeration.
Avoiding N excess	0.4	Reducing N application in areas where it is applied in excess reduces N in the system and therefore reduces N_2O emissions.
Full allowance of manure N supply	0.4	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)	0.5	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 timing of mineral fertiliser N application	0.3	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	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	0.3	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	See improved timing of mineral N
Adopting systems less reliant on inputs (nutrients, pesticides etc)	0.2	Moving to less intensive systems that use less input can reduce the overall greenhouse gas emissions.
Plant varieties with improved N-use efficiency	0.2	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	0.1	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 N and thereby the emission of nitrous oxide.
Reduced tillage / No-till	0.15	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	Composts provide a more steady release of N than slurries which increase anaerobic conditions and thereby loss of nitrous oxide.

Table 4 List of applicable livestock abatement options studied in this report

	Dairy	Beef	Pigs	Poultry
Animal Management				
Increasing concentrate in the diet	Y	Y		
Increase proportion maize silage in the diet	Y	Y		
Propionate precursors	Y	Y		
Probiotics	Y	Y		
Ionophores	Y	Y		
Bovine somatotropin	Y	Y		
Genetic improvement of production (or improved uptake)	Y	Y		
Genetic improvement of fertility	Y			
Use of transgenic offspring	Y			
Manure Management				
Covering slurry tanks	Y	Y	Y	
Covering lagoons	Y	Y	Y	
Switch from anaerobic to aerobic storage (tanks)	Y	Y	Y	
Switch from anaerobic to aerobic storage (lagoons)	Y	Y	Y	
Aerating manure	Y	Y	Y	
Anaerobic digesters (farm scale and central shared plant)	Y	Y	Y	Y

Table 5 Emissions under low, mid and high planting scenarios

	Low emissions scenario (0 kha/yr)	**Mid emissions scenario (2005 planting rate - baseline)**	**High emissions scenario (30 kha/yr)**
1990	**-12202.570**	**-12202.570**	**-12202.570**
1991	-12714.630	-12714.630	-12714.630
1992	-13340.088	-13340.088	-13340.088
1993	-13714.070	-13714.070	-13714.070
1994	-14192.631	-14192.631	-14192.631
1995	**-13948.207**	**-13948.207**	**-13948.207**
1996	-13720.064	-13720.064	-13720.064
1997	-13511.595	-13511.595	-13511.595
1998	-13406.214	-13406.214	-13406.214
1999	-13504.370	-13504.370	-13504.370
2000	**-13804.884**	**-13804.884**	**-13804.884**
2001	-14347.999	-14347.999	-14347.999
2002	-15045.160	-15045.160	-15045.160
2003	-15645.808	-15645.808	-15645.808
2004	-16302.033	-16302.033	-16302.033
2005	**-15737.997**	**-15737.997**	**-15737.997**
2006	-15205.635	-15239.353	-15259.682
2007	-14180.213	-14333.378	-14425.722
2008	-13606.969	-13790.522	-13901.187
2009	-12817.627	-12936.192	-13007.676
2010	**-10813.033**	**-10775.589**	**-10753.013**
2011	-10968.687	-10711.147	-10555.874
2012	-10460.796	-9956.893	-9653.087
2013	-9709.760	-8960.616	-8508.953
2014	-9527.819	-8546.414	-7954.718
2015	**-9033.881**	**-7835.465**	**-7112.932**
2016	-9127.373	-7725.446	-6880.215
2017	-9344.324	-7749.405	-6787.818
2018	-9531.022	-7750.499	-6677.011
2019	-8750.501	-6788.830	-5606.126
2020	**-7186.131**	**-5045.117**	**-3754.285**

Source: Table A1. 1: United Kingdom data for 2005 UK GHG Inventory: A: LULUCF GPG Format – with MID projection, B: LULUCF GPG Format – with LO projection, C: LULUCF GPG Format – with HI projection page 142
http://www.edinburgh.ceh.ac.uk/ukcarbon/docs/2007/LULUCF_2007.pdf

Table 6 2022 Abatement potential CFP

Code	Measure	First Year Gross Volume Abated [$ktCO_2e$]	Cost Effectiveness [£2006/tCO_2e]	Cumulative First Year Abatement [$MtCO_2e$]
CE	BeefAn-Ionophores	347.38	-1,747.79	0.347
CG	BeefAn-ImprovedGenetics	46.32	-3,602.93	0.394
AG	Crops-Soils-MineralNTiming	1,150.39	-103.38	1.544
AJ	Crops-Soils-OrganicNTiming	1,027.16	-68.48	2.571
AE	Crops-Soils-FullManure	457.26	-148.91	3.029
AN	Crops-Soils-ReducedTill	55.77	-1,052.63	3.084
BF	DairyAn-ImprovedProductivity	377.36	-0.07	3.462
BE	DairyAn-Ionophores	739.66	-48.59	4.201
BI	DairyAn-ImprovedFertility	346.26	-0.04	4.548
AL	Crops-Soils-ImprovedN-UsePlants	331.80	-76.10	4.879
BB	DairyAn-MaizeSilage	95.98	-262.63	4.975
AD	Crops-Soils-AvoidNExcess	276.06	-50.29	5.251
DA	Forestry-Afforestation	980.84	-7.12	6.232
AO	Crops-Soils-UsingComposts	78.51	0.00	6.311
AM	Crops-Soils-SlurryMineralNDelayed	47.17	0.00	6.358
EI	OFAD-PigsLarge	47.77	0.96	6.406
EF	OFAD-BeefLarge	97.79	2.52	6.503
EH	OFAD-PigsMedium	16.06	4.69	6.520
EC	OFAD-DairyLarge	250.81	7.96	6.770
HT	CAD-Poultry-5MW	219.34	11.43	6.990
AC	Crops-Soils-Drainage	1,741.02	14.44	8.731
EE	OFAD-BeefMedium	50.77	16.96	8.781
EB	OFAD-DairyMedium	44.12	24.10	8.826
AF	Crops-Soils-SpeciesIntro	365.98	174.22	9.192
BG	DairyAn-bST	132.31	224.10	9.324
AI	Crops-Soils-Nis	603.67	293.50	9.928
AH	Crops-Soils-ControlledRelFert	165.90	1,067.95	10.093
BH	DairyAn-Transgenics	504.29	1,691.28	10.598
AB	Crops-Soils-ReduceNFert	136.20	2,045.10	10.734
CA	BeefAn-Concentrates	80.96	2,704.54	10.815
AK	Crops-Soils-SystemsLessReliantOnInputs	10.05	4,434.34	10.825
AA	Crops-Soils-BiolFix	8.49	14,280.16	10.833

Table 7 2022 Abatement potential MTP

Code	Measure	First Year Gross Volume Abated [$ktCO_2e$]	Cost Effectiveness [£2006/tCO_2e]	Cumulative First Year Abatement [$MtCO_2e$]
CE	BeefAn-Ionophores	771.95	-1,747.79	0.772
CG	BeefAn-ImprovedGenetics	102.93	-3,602.93	0.875
AG	Crops-Soils-MineralNTiming	2,556.41	-103.38	3.431
AJ	Crops-Soils-OrganicNTiming	2,282.58	-68.48	5.714
AE	Crops-Soils-FullManure	1,016.13	-148.91	6.730
AN	Crops-Soils-ReducedTill	123.93	-1,052.63	6.854
BF	DairyAn-ImprovedProductivity	838.57	-0.07	7.693
BE	DairyAn-Ionophores	1,643.68	-48.59	9.336
BI	DairyAn-ImprovedFertility	769.48	-0.04	10.106
AL	Crops-Soils-ImprovedN-UsePlants	737.33	-76.10	10.843
BB	DairyAn-MaizeSilage	213.28	-262.63	11.056
AD	Crops-Soils-AvoidNExcess	613.48	-50.29	11.670
EI	Forestry-Afforestation	1,961.67	-7.12	13.631
EF	OFAD-PigsLarge	106.15	-2.44	13.738
AO	OFAD-BeefLarge	217.30	-1.12	13.955
AM	Crops-Soils-UsingComposts	174.47	0.00	14.129
DA	Crops-Soils-SlurryMineralNDelayed	104.83	0.00	14.234
EH	OFAD-PigsMedium	35.69	0.71	14.270
EC	OFAD-DairyLarge	557.35	3.47	14.827
EE	OFAD-BeefMedium	112.82	11.08	14.940
HT	CAD-Poultry-5MW	487.42	11.43	15.427
AC	Crops-Soils-Drainage	3,868.93	14.44	19.296
EB	OFAD-DairyMedium	98.05	17.11	19.394
AF	Crops-Soils-SpeciesIntro	813.29	174.22	20.208
BG	DairyAn-bST	294.01	224.10	20.502
AI	Crops-Soils-Nis	1,341.49	293.50	21.843
AH	Crops-Soils-ControlledRelFert	368.67	1,067.95	22.212
BH	DairyAn-Transgenics	1,120.64	1,691.28	23.333
AB	Crops-Soils-ReduceNFert	302.66	2,045.10	23.635
CA	BeefAn-Concentrates	179.90	2,704.54	23.815
AK	Crops-Soils-SystemsLessReliantOnInputs	22.33	4,434.34	23.837
AA	Crops-Soils-BiolFix	18.87	14,280.16	23.856

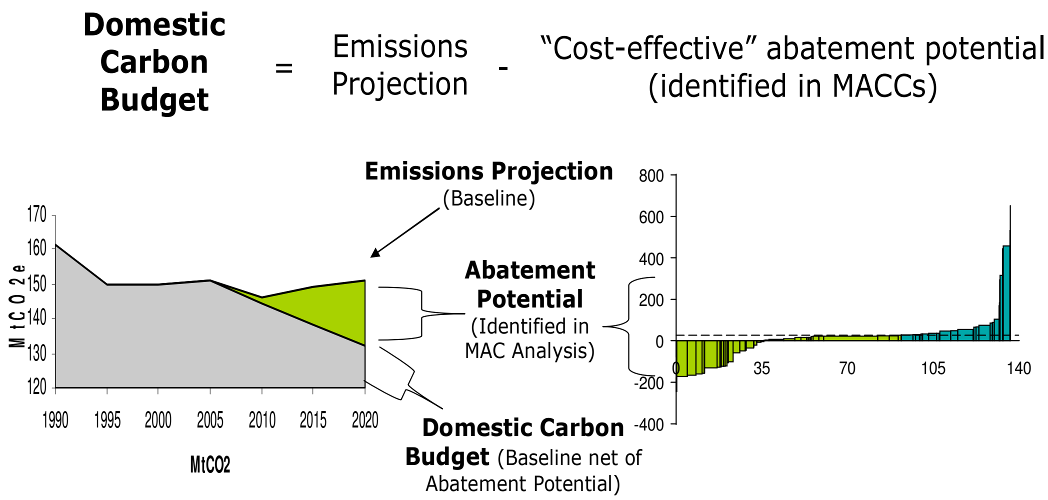

Figure 1 An illustrative MACC and its relationship to a carbon budget

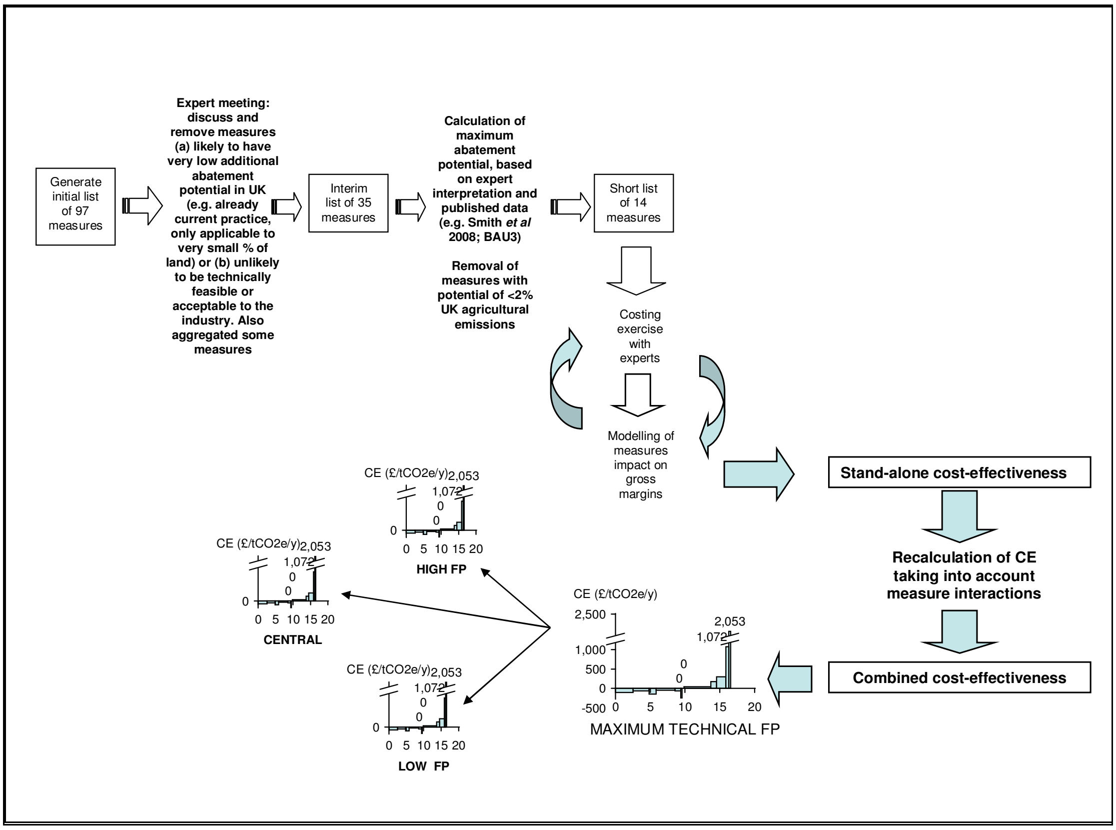

Figure 2 MACC development process

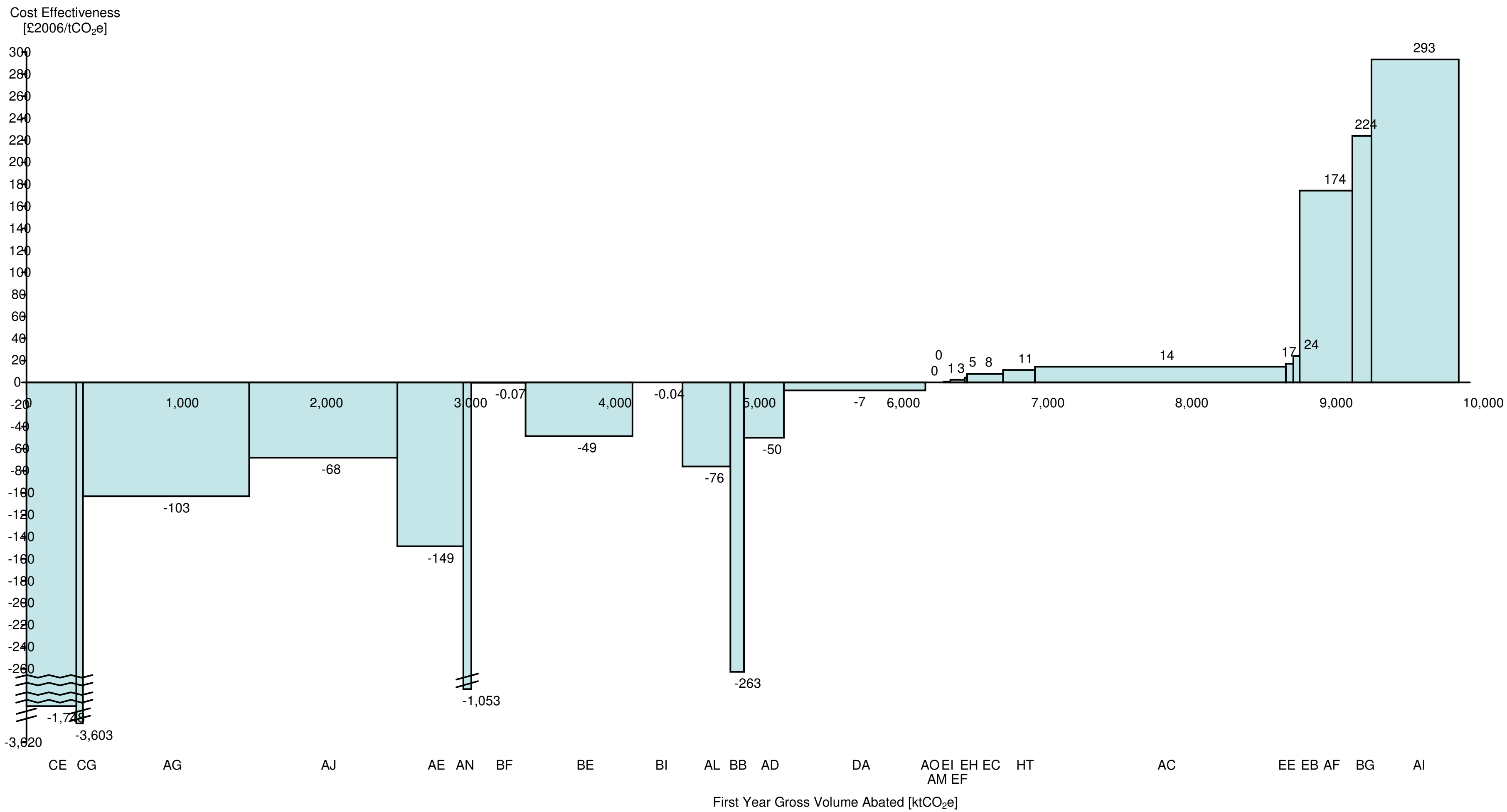

Figure 3 Total UK ALULUCF abatement Central Feasible Potential 2022 (d.r.=3.5% Measures with CE>1000 are not shown)

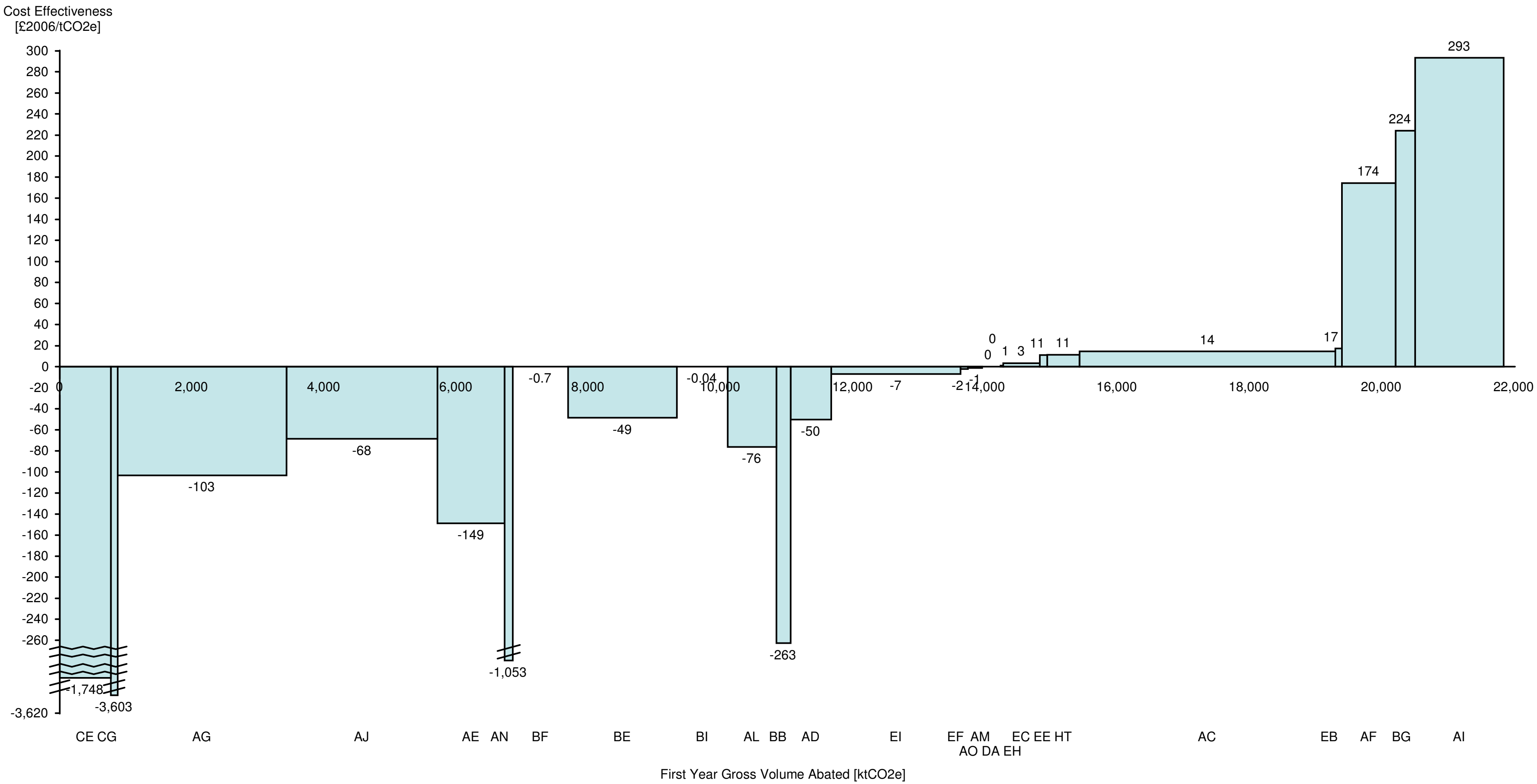

Figure 4 Total UK ALULUCF abatement Maximum Technical Potential 2022 (d.r.=3.5% Measures with CE>1000 are not shown)