# UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with Qualitative Analysis of Options to 2050

## Final Report to the Committee on Climate Change

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Dominic Moran[a], Michael MacLeod[a], Eileen Wall[a], Vera Eory[a], Guillaume Pajot[b], Robin Matthews[b], Alistair McVittie[a], Andrew Barnes[a], Bob Rees[a], Andrew Moxey[c], Adrian Williams[d], Pete Smith[e]

a. *Research and Development Division, SAC, West Mains Road, Edinburgh, EH9 3JG*
b. *MLURI, Craigiebuckler, Aberdeen*
c. *Pareto Consulting, Edinburgh*
d. *Cranfield University*
e. *Aberdeen University*

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# Executive summary

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

Government recognises the need to achieve emissions reductions in an economically efficient manner. In theory this means that some attempt should be made to equalise marginal abatement costs across different sectors. In other words, the cheapest units of greenhouse gas should be abated first. This suggests a requirement for information on abatement schedules or marginal abatement cost curves (MACC's), which show the relative cost of greenhouse gas mitigation by alternative mitigation methods and technologies. The CCC can then use these curves as a tool for setting carbon budgets. The MACCs can also be used by government to negotiate with emitting sectors and to develop a policy route map for affecting emissions reductions to meet proposed budgets.

This report describes the derivation of MACC's to depict abatement potential for (ALULUCF) in the UK. 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. This information provides a basis for identifying a sector's potential contribution to greenhouse gas budgets that is based on a cost-effectiveness analysis.

The methodology for deriving abatement potentials and the derivation of associated cost curves was supplied by the 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.

This project focussed predominantly on $CO_2$ abatement in forestry and non $CO_2$ gases, specifically, methane and nitrous oxide, which make up the main emissions from the land based sector. A range of sub sector specific abatement measures was identified from a variety of published and unpublished sources. Information on relevance and applicability to UK conditions was then derived from expert opinion, which was also used to estimate abatement potentials under UK conditions, and the extent to which measures would be additional to a business as usual baseline. Expert input was also sought for some of the relevant information on implementation costs. Cost information was augmented by modelling decision-making at the farm scale.

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 maximum technical potential (MTP) determined the absolute upper limit that might result from the highest technically feasible level of adoption or measure implementation in the sub sectors. Since this limit is not informed by the reality of non adoption or likely policy or social constraints, we also estimate high, central and low feasible potential (HFP/CFP/LFP) abatements, which are the levels thought most likely to emerge in the time scales and policy contexts under consideration.

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. Abatement potentials have also been estimated for the separate UK devolved administrations, i.e. England, Scotland, Wales and Northern Ireland.

The information was compiled in spreadsheets that allow transparency and flexibility in altering assumptions in several key data inputs.

Forestry potential contributes to the estimated total abatement in ALULUCF, which may be further enhanced by the extent to which wood products are assumed to displace carbon intensive construction materials and energy sources. We also estimate significant abatement potential in crop and soil measures and in livestock management. We do not identify any specific significant abatement opportunities in land-use change, but note that previous studies have, 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 CFP abatement 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 45.253$MtCO_2e$ 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 Table E.1 and 2, respectively, where the final column of cumulative abatement potential defines the MACC curve shown in Figure E.1and Figure E.2

For illustrative purposes, using the 2022 MACC this total central feasible potential can be divided between crop and soil measures 6.46[1] $MtCO_2e$, livestock measures 3.40 $MtCO_2e$, and forestry measures 0.98 $MtCO_2e$.

Table E.1 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 E1 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 7.85$MtCO_2e$ (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).

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[1] Where possible figures are reported to several decimal places for maximum transparency. Rounding to one significant figure would better reflect the uncertainties involved.

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 10.53 $MtCO_2e$ 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 annex to this report provides a 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. At this stage, the report only provides a qualitative assessment of the ancillary impacts (see Annex B). 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. Annex A provides 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 MtCO2e. 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 $MtCO_2e$.

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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.

There is clearly a need to clarify how measures qualify for inclusion in national inventory formats.

This report 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. As with other sectors, 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.

**Table E.1** **2022 Abatement potential CFP**

| Code | Measure | First Year Gross Volume Abated [ktCO$_2$e] | Cost Effectiveness [£2006/tCO$_2$e] | Cumulative First Year Abatement [MtCO$_2$e] |
|---|---|---|---|---|
| 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 |

Notes: (i) a more detailed explanation of the ordering of negative cost measures is provided in section 4.4.4 of this report.
(ii) Much of the discussion in this report refers to abatement potentials determined by considering an arbitrary cost-effectiveness cut off at approximately £100/tCO2e - i.e. in the above table up to and including the abatement delivered by implementing to measure EB.
(iii) For convenience in the corresponding MACC diagram below, measures offering abatement above £1000/tCO2e are not shown.

**Table E.2** **2022 Abatement potential MTP**

| Code | Measure | First Year Gross Volume Abated [ktCO$_2$e] | Cost Effectiveness [£2006/tCO$_2$e] | Cumulative First Year Abatement [MtCO$_2$e] |
|---|---|---|---|---|
| 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 |

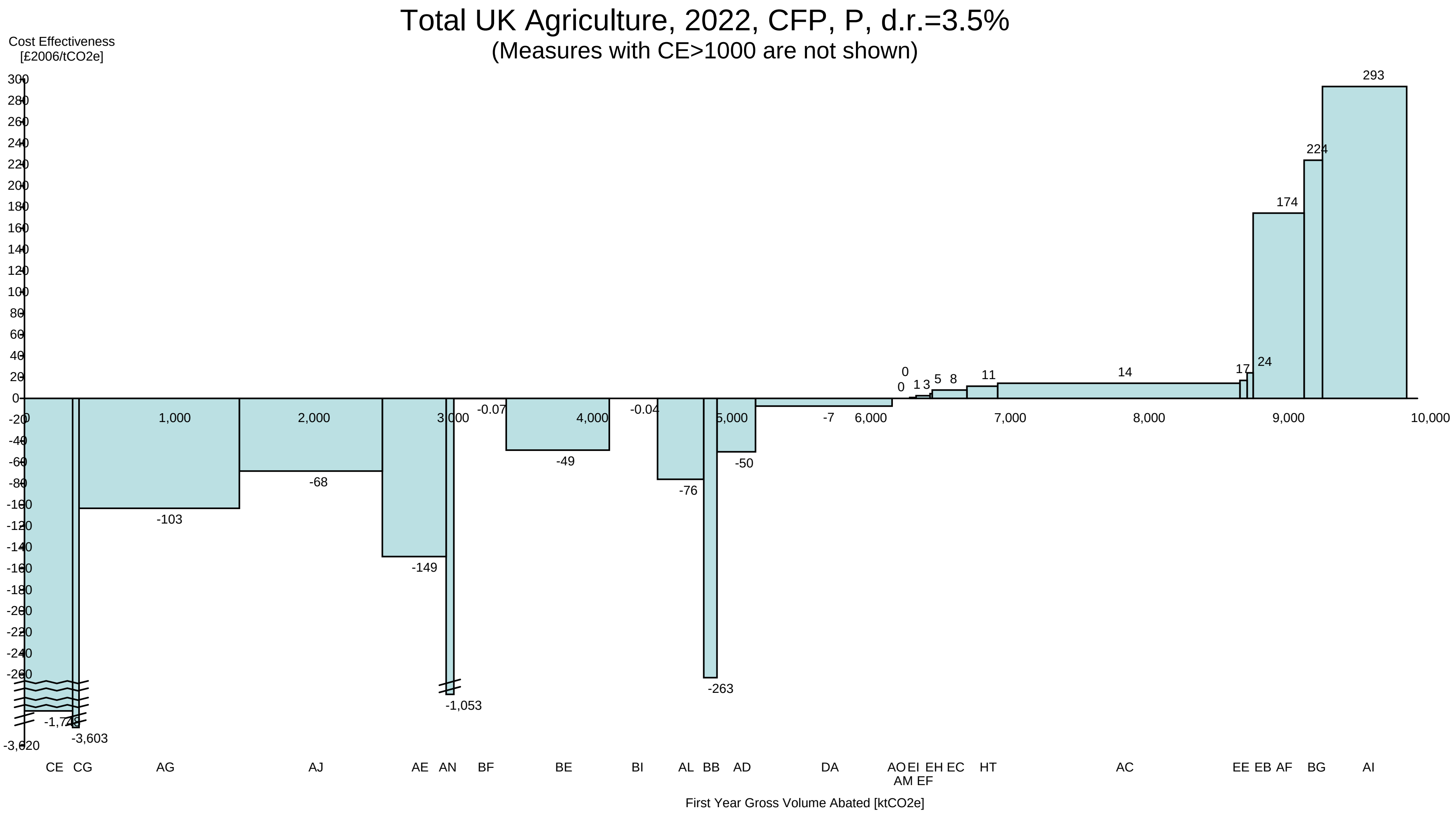

**Figure E.1** **MACC for UK agriculture 2022, CFP**

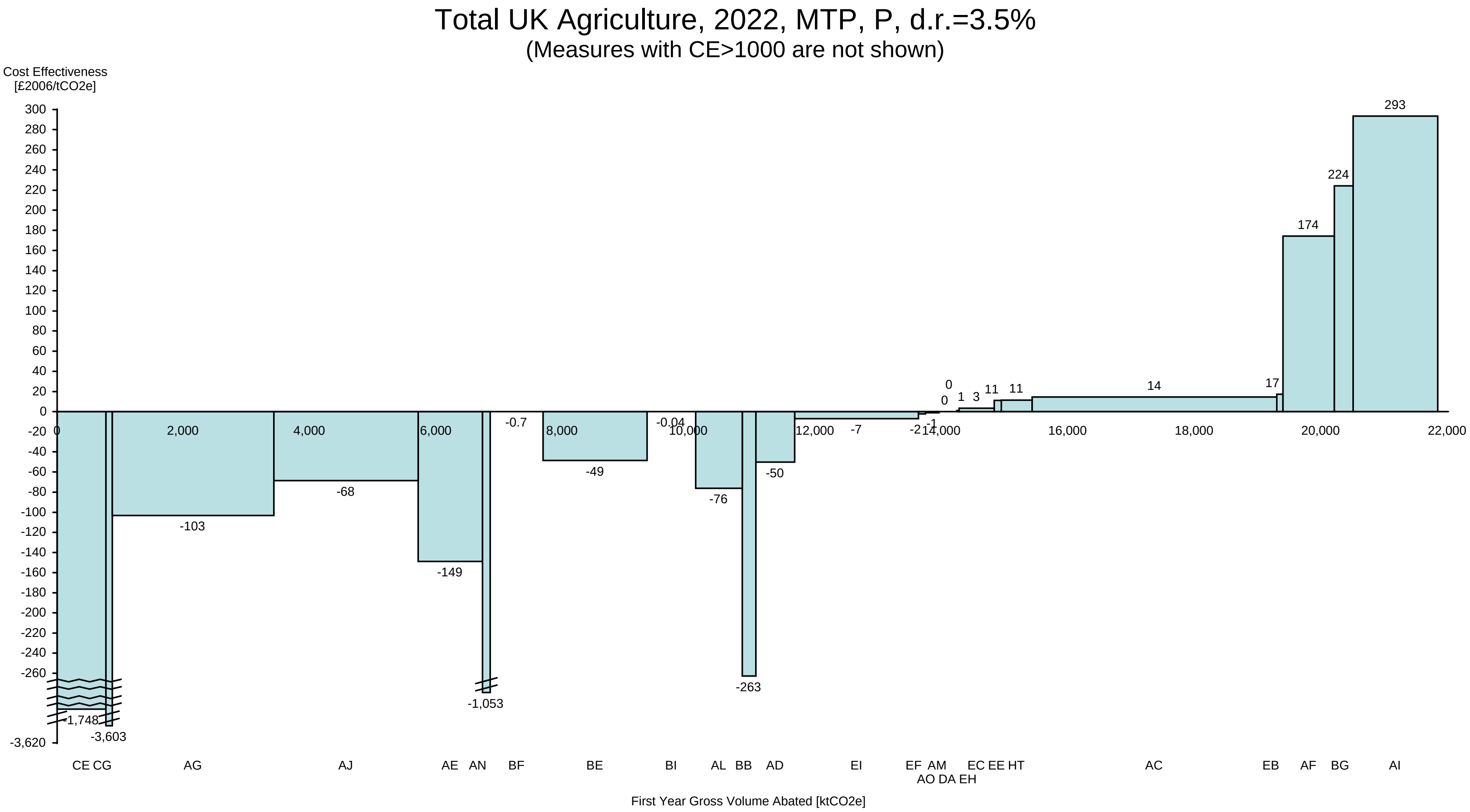

**Figure E.2 MACC for UK agriculture 2022, MTP**

# 1 Introduction

## 1.1 Background

The UK Committee on Climate Change is currently undertaking analysis with a view to deriving national carbon budgets that are part of an overall strategy of addressing emissions mitigation using cost-effectiveness analysis. Budgets will be set for 5-year periods up to 2012, 2017 and 2022. This report considers the potential scope for mitigation in the agriculture, land use, land use change and forestry sectors (ALULUCF). We consider emissions and abatement potential of all greenhouse gases expressed as carbon dioxide equivalents[3]. This information is combined with abatement cost information over the specified time horizons to derive a graphical representation of the cost of mitigation in the form of a marginal abatement cost curve (MACC).

A MACC ranks abatement measures in order of decreasing cost effectiveness. Measures to the left of the curve and below the x-axis indicate negative costs or savings to society from implementation. Measures to the right and above the x-axis illustrate costs to society from implementation. The MACC permits technologies and measures to be compared at the margin (i.e. the steps of the curve). The width of each provides information on the volume of abatement potential associated with a measure (see Figure 1.1). The graph provides a tool for cost-effectiveness or cost-benefit analysis. In the latter case, unit mitigation costs can be compared with the shadow price of carbon as the notional avoided damage costs.

Table 1.1 summarises the trends in aggregated direct greenhouse gas emissions covered by FCCC/CP/2002/8 by sector for the years 2000-2003. ALULUCF sectors are included largely under the headings agriculture and forestry. These figures show agricultural emissions to be around 44.733 $MtCO_2e$, excluding LUC (2003) or approximately 7% of UK emissions making the sector the second largest source of greenhouse gases. Agricultural emissions from this sector arise for both $CH_4$ and $N_2O$. Land-use change and forestry are a net sink in 2003. Emissions from this source occur for $CO_2$, $N_2O$ and $CH_4$.

Since 1990, emissions from this agricultural sector have declined by 14%, due to reduced emissions from enteric fermentation and agricultural waste disposal (related to lower livestock numbers) and from agricultural soils due to changes in agricultural practices and emissions from the use of synthetic fertiliser.

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 MACC approach, which enables a comparison of cost with the benefit of avoided carbon emission damages - the so-called shadow price of carbon (SPC). While the SPC is highlighted here as one potential avoided damages benchmark, we note that other potential benchmarks could be set using an implicitly higher shadow price. This report does not address this issue further and readers are referred to government guidance on

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[3] Converted based on the international convention of GWP100 as presented in the IPCC's Second Assessment Report.

the SPC[4] and to CCC's launch report. In the analysis presented in this report we also consider a notional benchmark of £100/t CO2e.

A broad range of mitigation options can be identified within the sector, but some systematic method needs to be employed to prioritise across measures differentiated by cost and mitigation potential. Marginal Abatement Cost curves (MACC) provide 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.

The development of MACC is a bottom-up process based on cost and abatement potential for individual technologies and measures identified across the ALULUCF sectors. For the purposes of the data collection and the compilation of data, we have separated the ALULUC and forestry sectors into discrete sub sectors and collections of measures.

**Table 1.1** **Aggregated emission trends per source category (Mt $CO_2$ equivalent)**

| Source Category | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|
| 1. Energy | 557.8 | 576.0 | 559.7 | 567.3 |
| 2. Industrial Processes | 29.8 | 27.9 | 25.7 | 26.8 |
| 3. Solvents and other product use[a] | - | - | - | - |
| 4. Agriculture | 49.1 | 46.1 | 46.4 | 45.8 |
| 5. Land-use Change and Forestry (emissions) | 15.1 | 14.9 | 14.5 | 14.7 |
| 5. Land-use Change and Forestry (removals) | -15.8 | -15.9 | -16.0 | -16.3 |
| 6. Waste | 14.8 | 13.4 | 11.9 | 11.1 |
| 7. Other | - | - | - | - |
| **Total** (emissions only) | **666.6** | **678.3** | **658.2** | **665.8** |
| **Total** (net $CO_2$ – sum of emissions and removals) | **650.8** | **662.5** | **642.2** | **649.6** |

Footnotes:

[a] Solvents and other product use emissions occur as NMVOC and so do not appear in this Table which covers direct greenhouse gases

http://www.ghgi.org.uk/documents/ES3_table_from_2005_NIR.pdf
UK Greenhouse Gas Inventory, 1990 to 2003
http://www.airquality.co.uk/archive/reports/cat07/0509161559_ukghgi_90-03_Issue_1.1.doc

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[4] Defra (2007) The Social Cost Of Carbon And The Shadow Price Of Carbon: What They Are, And How To Use Them In Economic Appraisal In The UK http://www.defra.gov.uk/environment/climatechange/research/carboncost/pdf/background.pdf

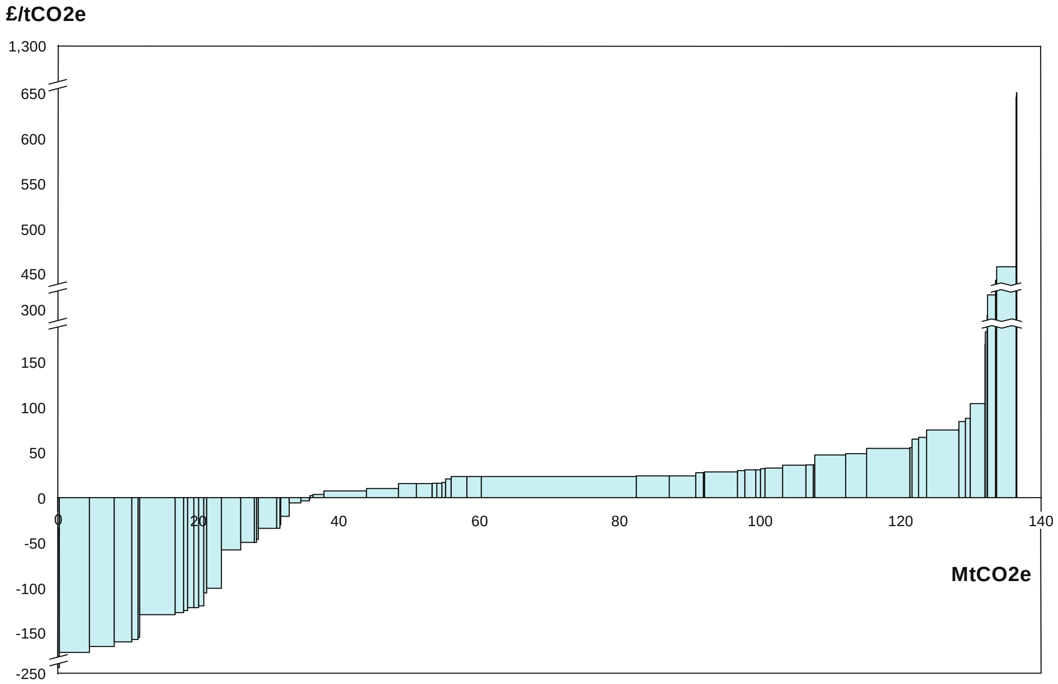

**Figure 1.1 Illustrative Marginal Abatement Cost Curve**

### 1.2 Objectives and Scope

The overall aim of this project is to set out the process and outcomes of a bottom up construction of MACC following recommended guidelines set out by the CCC. The scope includes the main greenhouse gases but excludes $CO_2$ emissions from energy use in on-farm heating or transportation. While the analysis considered the role of energy crops as an abatement option, a number of economic factors mitigate against this as a current cropping or land use decision. The analysis does not therefore contain a seperate section on energy crops.

The main objectives of this project were as follows:

- To identify all the potential GHG mitigation measures in the ALULUCF sectors;
- To review these measures and produce a short-list of feasible measures for detailed analysis;
- To calculate the stand alone abatement rates, abatement potentials and cost-effectiveness for each measure on the short-list;
- To calculate the combined abatement rates, abatement potentials and cost-effectiveness for each measure, taking into account the ways in which measures interact;
- To develop MACCs for ALULUCF (and the sub-sectors of crops/soils; livestock; forestry; land use change) for 2012, 2017 and 2022, for different combinations of discount rates and potential uptake/compliance scenarios.

The study was initiated with an ambitious terms of reference to derive MACC curves that included ancillary costs and benefits; i.e. non greenhouse gas costs and benefits from measure implementation. The extent or border of the costs and benefits was debated at length, since the life cycle costs of some measures such as reduced fertiliser use and the production of biofuels can clearly be measured to include their whole life costs and not those within the farm gate. Life Cycle Analysis (LCA) is clearly subject to much discussion and policy scrutiny. However, the data requirements for rigorous LCA were considered too onerous within the timeframe of this study. Accordingly, Annex 1 provides further background on the significance of LCA in the context of ALULUCF and details the relevant LCA implications of measures that are deemed relatively cost-effective by this study. While the MACC analysis clearly needs to reconcile some of the LCA costs, we do not consider the issue further in this report.

The main requirement for the study was a consideration of abatement potential in the sub sectors over and above any business as usual baseline. Thus there is a need to be specific about how much if any of the identified measures are already being implemented in our baseline as distinct from our uptake or 'increased abatement' scenarios. In these scenarios it is clearly possible for a wide variety of mitigation measures to be implemented across ALULUCF and for each measure to be implemented across a wide area. For example, it may be possible to convert large areas of arable crops and grassland to energy crops. While the abatement represented under this full technical potential is informative, it is likely to incur significant opportunity costs in terms of the displaced arable crops. It is unlikely therefore to be feasible in market or policy terms, and at best, it represents a notional upper bound below which policy can be fixed. While nevertheless identifying this full potential, our focus is more realistically on credible technological adoption within the timelines of interest and within the context of a likely policy environment. Credible adoption would also be determined by costs, which needed to be determined and broken down as far as possible into capital and recurrent expenditures (see below). These considerations would in turn lead to an abatement potential scenario that is considered to be a central technical potential from abatement options that are currently available. Looking into the future, the study was also asked to consider how existing constraints, might change over the reporting periods 2012, 2017, 2022. At the extreme within a time horizon of 2050, several technologies that are currently marginal in terms of their technical potential (i.e. in terms of cost) might nevertheless become less expensive to implement.

The assumptions of the MACC exercise were summarised in spreadsheet format to enable flexibility in model construction. Key inputs and outputs were:

- the range of mitigation measures across each sub sector
- Cost breakdown by measure; specifically capital and recurrent costs plus a qualitative assessment of ancillary (or external) costs and any potential life cycle implication
- Applicability of the measure - e.g. in terms of a baseline of land area, numbers of holdings or numbers of animals
- Unit abatement potential by measure
- Assumptions to define central feasible adoption ranges (i.e. upper and lower) below full technical potential
- Forecast input and output cost variables for future price changes over the relevant time horizons

The construction of the ALULUCF MACC was guided by a basic structure used by CCC for consistency across different sectors. This structure included a control panel of variables such as standard emissions factors, discount rates, and energy output prices.

The structure of this report is as follows. The next section outlines the source of several key parameters and assumptions used as MACC inputs. This information is common to subsequent chapters that detail the process and assumptions behind the construction of MACC curves for crop and soils, livestock and forestry sectors respectively. These chapters present MACC charts for 2022 Central Feasible Potential (CFP) alone. We also include the tables for: 2012 CFP and showing central, high and low feasible potential for 2017 and 2022. A penultimate chapter addresses the scope for abatement in residual land uses and land use changes. A final chapter presents the combined MACC's and offers caveats and suggestions for improving the analysis.

### 1.3 Key MAC Parameters

This section outlines the key stages of developing the MACC's and provides an overview of important assumptions made in relation to baselines, technical potentials and the derivation of cost information. These and other assumptions are subsequently revisited in the individual sub sector chapters, which also draw on scientific expert opinion to define some of the data requirements (e.g. the potential for measure interactions and resulting impacts on abatement potential). Figure 1.2 shows how the notional domestic carbon budget can be derived from the MACC.

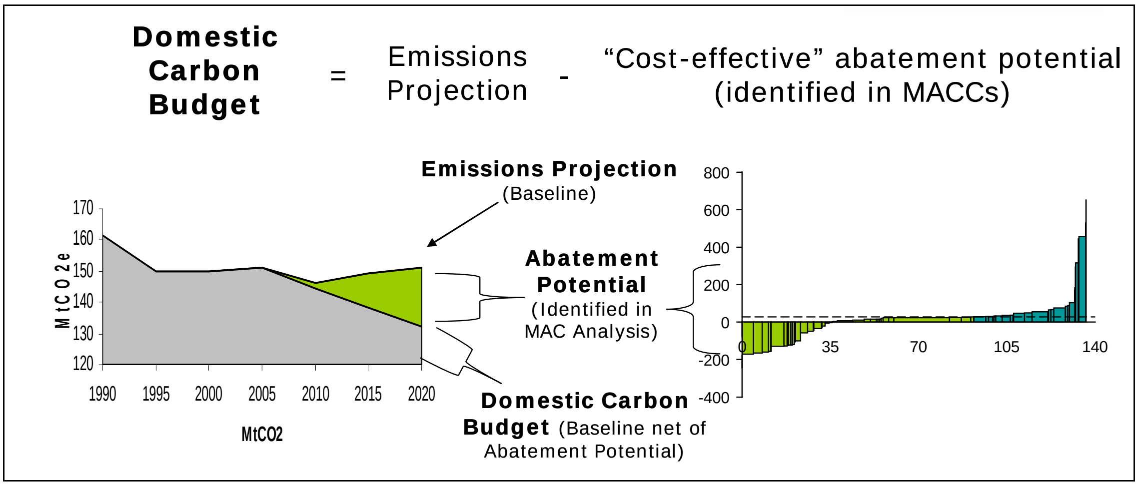

Figure 1.2 Deriving the domestic budget from a MACC

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 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 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 £/t$CO_2$e 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 discount rates from the control panel
    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[5] 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 1.3 below

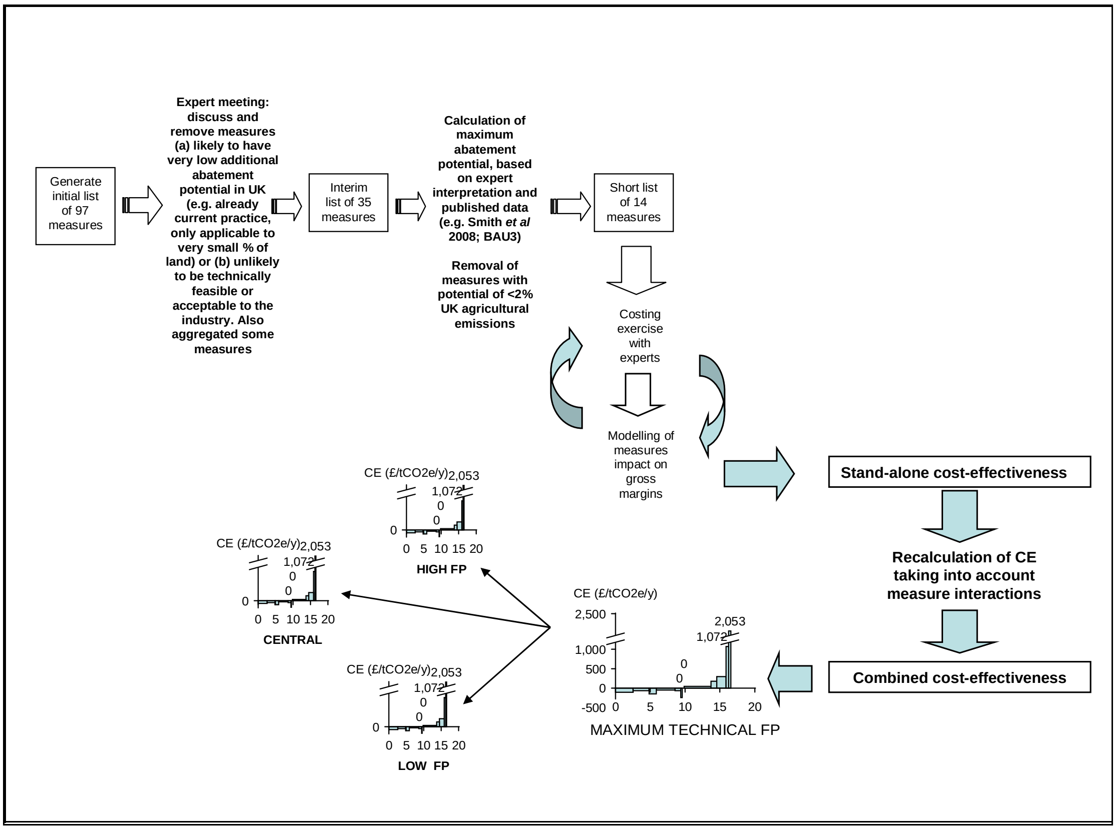

**Figure 1.3 MACC development process**

## 1.4 Baselines

In each ALULUCF 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.

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[5] 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.

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.

### 1.4.1 Agricultural Baselines

Recent and on-going structural change in UK agricultural production makes the determination of a reliable baseline particularly challenging. For this exercise the main source of baseline information is a recent exercise developing a UK Business as Usual projection (BAU3) (Defra SFF0601). The rest of this section gives details of this baseline (which was developed in previous projects, and used in this project).

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. The key assumptions are summarised below.

*CAP reform:*

- Includes anticipated responses to reform, as indicated by farmer surveys and expert opinion of the agricultural industry.

*Single Farm Payment:*

- Voluntary modulation of the Single Payment. The projections assumed that the Rural Development Plans for UK would go ahead as proposed with a deal on voluntary modulation. In the longer-term, we envisaged increased modulation, whether compulsory or voluntary, but anticipated some Single Farm Payment would remain, even until 2025.

*Response to existing Directives/legislation/conventions:*

- Water Framework Directive (WFD)
- Nitrates Directive
- Integrated Pollution Prevention and Control Directive
- Waste Framework Directive
- Kyoto
- Thematic Strategy on the Sustainable Use of Pesticides
- REACH

Most of these drivers would primarily affect management of land and inputs within agriculture, but may also influence choice of crops, livestock numbers and infrastructure change. Defra’s main response to the ‘agricultural element’ of the WFD has been to encourage a supportive approach in England. This is mirrored in the Devolved Administrations.

*Cross compliance:*

- This will ensure better adherence to existing regulations.

*Agri-environment schemes:*

- Planned targets for these schemes were assumed to be achieved.

*Set-aside:*

- Assumed set-aside phased out by 2015, but 50% of land would remain within agricultural production

*Milk quota:*

- Remains until 2015, will be removed by 2025.

*Social drivers:*

- Organic food – this would continue to expand on current trends.
- Hobby farming – the trend to more small, lifestyle and equine units was assumed to continue with little impact on commercial agriculture.
- Farmer demographics – average age of 56 (and rising) was assumed to be reflected in structural change with fewer farm businesses.
- Planning/development – need for more housing, interactions with land use/water resources, spatial considerations. Existing plans and trends were assumed to continue.

*Climate change*:

- There needed to be a consideration of potential longer-term impacts on choice of crops.

However, two specific responses also needed to be considered:

*Biofuel crops*:

- A move to renewable energy sources. This is an area of considerable uncertainty in the longer-term. Specific agreements already in place (e.g. Road Transport Fuel Obligations) taken into account.

*Water resources:*

- Increasing demand on water resources from agriculture and the population, which would vary regionally.

*Technical developments*:

- Increased efficiency of production, both of crops and livestock, so that yield per unit will increase. We assumed Genetic Modification (GM) would continue to be effectively blocked in Europe due to consumer pressure and the negative effect this has had in investment for crops adapted to our climates.

*Adoption of GM:*

- Assumed to continue elsewhere in the world.

*Global considerations:*

- International negotiations to liberalise world trade was assumed to continue with gradual success and the CAP was assumed to continue to be reformed to make it less trade distorting. Export Subsidies assumed to be removed by 2015.

These considerations were synthesised through a group of expert meetings and estimates, derived from a number of econometric based studies, were adjusted under discussion with commodity and policy experts.

*Policy not included within BAU3:-*

BAU3 did not include major new departures in policy making, for example complete abandonment of public funding for UK agriculture. It did not include potential drivers that are speculative at this stage.

In reality, some of the above drivers were taken into account more than the others, mainly because of lack of robust data for some elements. Consequently, it was major factors such as CAP reform (where work had previously been undertaken) that were the main considerations in developing projections on ‘infrastructure’. For changes in ‘management’, Defra project WQ0106 was able to inform this aspect and took into account many factors including NVZs, ECSFDI (and equivalents in devolved administrations), WFD and environmental stewardship schemes. Although this current project was undertaken during discussions on a revised NVZ Action Programme, some extension to NVZs was assumed. IPPC measures were assumed to impact mainly on gaseous emissions.

# 2 Mapping BAU3 onto the MACC Carbon Budget Years

BAU3 assumed a significant change in agricultural policy would occur in 2013. Hence the period of 2012 is unaffected as it changes linearly from the 2010 period, and the 2017 period accommodates, as did BAU3, its 2015 scenario of changes, such as CAP reform and the WFD. Similarly, 2020 and 2025 were produced with no future new policy implementations, hence the 2022 scenario can again be assumed to be a linear trend growth from 2020. Accordingly, a weighted linear average was used to adjust the BAU3 estimates to cover the carbon budget years, assuming no significant shifts in policies or market prices between the reference years and the forecasted years.

Whilst BAU3 provides the best estimates of agricultural land use in the next 20 years, there are some policy changes that have occurred since publication in 2006. Predominantly, these have been removal of set-aside and changes to English and Welsh Nitrate Vulnerable Zones regulations. The first is accounted for within the 2017 estimates as removal was expected to occur near the end of the 2006-2013 period. Nevertheless, an assumption was that 50% of land would return to production. It seems that this may have been a conservative estimate given the recent rises in wheat prices and the expectations of future cereal price growth. Thus, more land will be expected to return to agricultural activity and the figures provided here will underestimate the potential of technologies for abatement, as BAU3 is used to gross up on-farm effects. The Nitrate Vulnerable Zone regulations were included in the original projections and held constant over the projection periods. Recent changes have occurred to NVZ designated areas within England and, hence these recent change could not be accommodated for within the BAU3 projections. However, these impacts are minimal relative to wider policy measures to reduced inputs.

## 2.1 Baseline information for LULUCF

Non agricultural land use baseline information was mainly derived with reference to existing emissions inventory reporting produced by the Centre for Ecology and Hydrology (CEH). CEH data provide projections on afforestation rates and other land use transitions such as grassland conversion to alternative land uses. Some modifications to these projections were considered. For example, it is possible to conceive of higher afforestation projections than those considered by CEH.

## 2.2 Identifying additionality in abatement

Within agriculture it is important to determine the extent of additional abatement that is forecast relative to the BAU scenario. As shown in Figure 1.2 the notional carbon budget is measured relative to an emissions projection baseline. This raises specific challenges about the extent of likely direct and indirect abatement already taking place currently in BAU and accommodated within it. BAU abatement potential is based on largely static assumptions about abatement potential of key farm measures and fixed emissions factors (e.g. livestock numbers times emissions). As seen in the previous section, some allowance is also made for the indirect effects of a range of legislative changes that are included within BAU and its associated abatement potential. In terms of direct abatement measures considered in this report, it is important to be clear that we are restricted in our ability to predict how these evolving regulatory changes will lead to additional progressive uptake of abatement measures.

Figure 2.1 below sets out two trajectories defining the abatement potential under our central feasible potential (CFP) on uptake , the meaning of which is defined in the following section. The upper projection represents the interpolated BAU baseline relative to the estimated CFP trajectory. Our uncertainty about the BAU abatement means the gap between the two trajectories in Figure 2.1 below is likely to be smaller to the extent that the BAU (upper trend) will progressively include abatement potential ancillary to other policies. If we assume BAU to be represented by this interpolation it follows that the adoption rate assumptions made in deriving the relevant technical potentials (see next section) drive the extent of additionally. These adoption assumptions are made with the best guess of how the BAU may evolve given current knowledge and accounting for some other dynamic changes not accounted for in BAU; for example changing input and output prices.

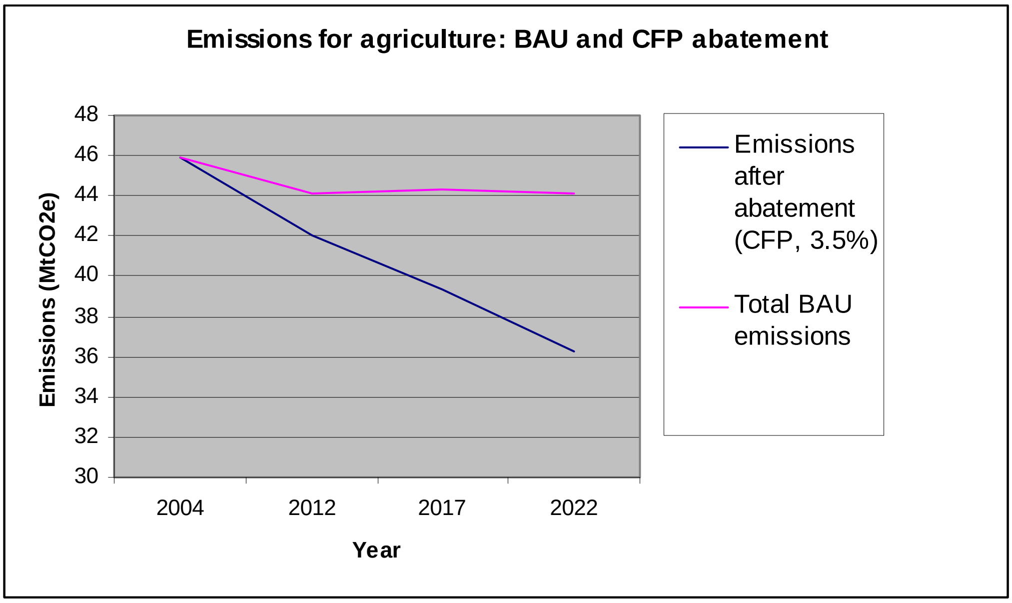

**Figure 2.1 Abatement potential measured against baseline**

## 2.3 Identifying technical potentials

The extent to which mitigation measures are adopted depends on the specifics of the measure and the policy framework; MAC curves can be constructed to reflect abatement potentials in terms of these different levels of adoption. This analysis distinguishes between four potential abatement scenarios: maximum technical; high feasible; central feasible; low feasible.

Maximum technical abatement potential is the amount by which it is possible to reduce GHG emissions by implementing a technology or practice that has already been demonstrated; i.e. the abatement that could be achieved if everyone who could adopt this measure did so as far as they could, regardless of cost. For a given measure this potential represents the upper limit on abatement, although it is unlikely to be realised. Instead, some lower level of adoption is likely, depending on the prevailing cost and policy environment.

These levels of adoption can be illustrated using a hypothetical example. ISuppose that a hypothetical government regulation mandates a form of technological improvement to say farm machinery that lowers emissions. The *maximum technical* would be defined by the percentage of machines that could technically fit the new add-on, which might be something under 100% since older machines may not be technically adaptable for the fix. Below this adoption rate we assume *a high feasible* level of adoption, which is the percentage of uptake if the government made them mandatory through regulation. Thus, we may see something below the full technical potential, the difference being non compliance by a small percentage of people who could technically retrofit the improvement..

We define the *central feasible* uptake as the likely percentage arising if there were a policy to subsidise the add-on or penalise emissions. This might result in compliance amongst 50% of those who are technically able to retrofit. Finally a *low feasible* adoption percentage is the level of uptake if the government has a voluntary retrofit scheme. We assume this may result in something below the central adoption level, e.g. as low as 10%.

### *High, Central and Low Potentials for Agriculture*

In practice, accurately forecasting the likely uptake of a policy requires modelling of farmer behaviour based on the specific incentives provided by each measure. While this is beyond the scope of the present project, it is possible to derive some estimates with reference to existing uptake/compliance rates and a few assumptions.

As will be seen in the sub sector chapters the definition of these potentials is made with reference to existing policy compliance rates. However, the sheets contain flexibility for these levels to be re set to test hypotheses on different rates

The definition of a low feasible scenario can be based on voluntary initiatives such as information dissemination and education. This is not enforceable and uptake will depend on the cost. Negative cost measures would be expected to have a higher uptake and positive cost measures would be assumed significantly lower.

A central feasible scenario can be based on incentive-based instruments, e.g. a cap and trade scheme or environmental stewardship, where action results in some form of financial compensation, such as direct payment, tax breaks or grants.

A high feasible scenario is most likely to be associated with forms of command and control regulation. Higher levels of compliance might be expected for measures that are more readily enforceable (e.g. measures that could be monitored as part of existing cross-compliance or quality assurance audits), with lower compliance for measures that are more difficult to monitor.

Table 2.1 to Table 2.3 outline the assumptions behind the uptake classification. In the first instance we distinguish four categories for measures in terms of their implementation cost and ease of enforcement:

- if the measure costs <=£0 and is easy to enforce, use the purple set of uptake%
- if the measure costs <=£0 and is difficult to enforce, use the blue set of uptake%
- if the measure costs >£0 and is easy to enforce, use the green set of uptake%
- if the measure costs >£0 and is difficult to enforce, use the yellow set of uptake%

**Table 2.1 Categorisation of potential depending on cost and ease of enforcement**

| Cost (£/ha) | Measure | Policy Type | Ease of Enforcement (see table 2) | Potential | Set of % |
|---|---|---|---|---|---|
| <=0 | A | H | E | H1 | SET ONE |
| | A | C | E | C | |
| | A | L | E | L1 | |
| | B | H | D | H2 | SET TWO |
| | B | C | D | C | |
| | B | L | D | L1 | |
| >0 | D | H | E | H1 | SET THREE |
| | D | C | E | C | |
| | D | L | E | L2 | |
| | E | H | D | H2 | SET FOUR |
| | E | C | D | C | |
| | E | L | D | L2 | |
| *Key*<br>H=High, i.e. Command and Control<br>C=Central, i.e. Incentive Based Measures<br>L=Low, i.e. Voluntary measures: education and information; self-regulation<br>E=Easy<br>D=Difficult | | | | | |

**Table 2.2 Uptake/compliance rates**

| *Potential* | *Meaning* | *Uptake/compliance* |
|---|---|---|
| L1 | Low potential for measures with –ve costs | 18% |
| L2 | Low potential for measures with +ve costs | 7% |
| C | Central, incentive-based measures | 45% |
| H1 | Easy to enforce (e.g. detectable as part of routine, e.g. cross-compliance, inspection) | 92% |
| H2 | Difficult to enforce (requires specific enforcement, random visits etc) | 85% |

*Rationale for Uptake/Compliance Rates*

L1. Voluntary uptake of measures in light of information/education**.** The figure is based on the ECSFDI uptake of 18% (see table below). (Note that some ECSFDI measures will have positive costs, however grants are available). Although this may seem low for measures with negative costs, it should be borne in mind that many farmers will already be aware of the measure and will have chosen not to implement for a variety of reasons. Also, providing information/ education can be expensive so the scheme is likely to be targeted on certain areas/sectors/farm types.

L2. Voluntary uptake of measures in light of information/education. Figure is based on participation rates in the LEAF scheme.

C. Central is the most difficult to predict, as there is a wide range of measures and incentive levels. However, 45% seems reasonable given that uptake of the Environmental Stewardship Entry Level Scheme (2007) was 48% in England and the Tir Cymen/Tir Gofal/Tir Cynnal (2007) was 41% in Wales.

H1. This was the average rate of compliance in 2006 for the Controlled Activities Regulations, the Pollution Prevention and Control Part A and Waste Management Licences in Scotland.

H2. This may seem high for a measure that is difficult to enforce, however the assumption is that greater effort is put into monitoring when enforcement is difficult and fines for non-compliance are raised to prevent mass non-compliance. 85% is at the lower end of estimates of farms passing their cross-compliance inspections.

Inevitably these assumptions are uncertain for any specific measure and a case can always be made for a higher/lower figure. It is hoped that in aggregate across the various cost-effective measures identified these assumptions are fit for purpose.

**Table 2.3 Uptake/Compliance with existing policies**

| *Measure* | *Uptake/Compliance* | |
|---|---|---|
| Nitrogen Vulnerable Zones (NVZs) | 97% of holdings in NVZs | Env Agency (2007) Spotlight on Business |
| Controlled Activities Regulations | 92% | SEPA Annual Report 2006-07 |
| Pollution Prevention and Control Part A. | 94% | SEPA Annual Report 2006-07 |
| Waste Management Licences | 89% | SEPA Annual Report 2006-07 |
| Cross compliance | 85% | Env Agency (2007) Spotlight on Business |
| | 90-97% compliance | Env Agency (2007, p22) Annual Report and Accounts 2006/07 |
| Pesticides Voluntary Initiative | 80% of UK arable area | |
| Environmental Stewardship Entry Level Scheme (2007) | 48.2% uptake of England ag area | Ag in the UK 2007, table 12.5 |
| Tir Cymen/Tir Gofal/Tir Cynnal (2007) | 41% of Wales ag area | Ag in the UK 2007, table 12.5 |
| Land Management Contract Scheme | 20% of holdings in Scotland | Scottish Government (2008) |
| England Catchment Sensitive Farming Delivery Initiative (ECSFDI) | ~18.4% of England's ag area (23% of area*80% of farmers said they'd take action) | http://www.defra.gov.uk/FARM/environment/water/csf/delivery-initiative.htm |
| LEAF Farming Scheme | 7% of UK ag area | Ag in the UK 2007, p136 |

## 2.4 Quantifying costs and the timing of benefits

Cost effectiveness analysis for the MACC requires a specific breakdown of private and social costs corresponding to the implementation profile for the measure and whether it incurs capital expenditure. Table 2.4 provides an example of the possible categorisation of costs and possible sources of data.

While it is possible to consider some measures as stand alone investments, for the most part agricultural measures need to be integrated into farm systems that operate under specific land labour and capital constraints. If the enterprise is considered to be operating at some notional efficiency frontier then an additional measure can displace other productive activities that are therefore an opportunity cost. The true cost of implementing the measure should therefore include an estimate of this opportunity cost, which can be derived by farm scale modelling.

**Table 2.4 Example: Precision farming**

| | *Costs and benefits to be included* | *Information required* | | | | | | | *Data sources* |
|---|---|---|---|---|---|---|---|---|---|
| | | *2012* | | | | | *2017* | *2022* | |
| | | Item | | Value (£) | Timing (year) | Lifetime (years) | … | … | |
| Net Private Cost | One-off costs | Capital costs, e.g. purchasing GPS equipment<br>Time spent learning how to use GPS | | 1000 | 0 | 10 | … | … | Market prices |
| | Recurring costs | O&M costs, e.g. extra labour related to management and maintenance, cost of repairs etc. | | 200/year | recurring | recurring | … | … | Market prices |
| | Opportunity cost | Foregone benefits of next best option | | 300 | 0 | 10 | … | … | Farm modelling |
| | Private (market) benefits | One-off | NA | - | - | - | … | … | |
| | | Recurring | Reduced N costs | 400/year | recurring | recurring | | | Market prices |
| Net Social Cost | Net private costs | See above[6] | | | | | … | … | |
| | External costs | None | | | | | … | … | NA |
| | External benefits (non-GHG) | Reduced aquatic N pollution | | £? Per kg of fertiliser saved | 5 years | recurring after 5 years | … | … | Existing valuations of N pollution mitigation e.g. Manuel's benefits work |
| Hybrid | Combination of private and social costs | | | | | | | | |

Costs based on LCA to be included where appropriate, e.g. changes in fertiliser application rates.

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[6] Under the social metric private costs are also annualised at a private (7%) rather than social (3.5%) discount rate. For simplicity taxes and subsidies are excluded from both measures.

### 2.5 Costs

The main data for costs were derived from the Farm Business Scheme Data (Defra, 2007). This covered the period 2005/06, which represents the latest reporting period for complete data. The FBS provides information on the physical and economic performance of farm businesses and is an annual survey commissioned by the government under which a range of management accounting information on all aspects of farmer's and grower's businesses is collected.

The survey uses a sample of farms that is representative of the national population of farms in terms of farm type, farm size and regional location. Hence, it provides a picture of the major variable and fixed costs across a number of activities for each farm type. The weakness of the FBS is that it does not directly relate variable costs to specific enterprises, but provides a farm level picture of costs. Accordingly, historically derived production relationships were used, from discussion with agricultural experts or published technical notes, which have been incorporated within the SAC farm level model.

# 3 Farm Level Modelling Approach

Mathematical programming allows us to capture the physical systems of the farm, the environment and the market place. In addition, the range of possible activities represented in the model are not only restricted to a situation of 'what is' but also to allow analysis of 'what could be possible'**.**

Modelling of the farming systems allows the researcher to establish quantified links between the inputs and outputs from the processes involved in the farming system. Indeed, the modelling process highlights areas which lack information, increases understanding of the systems as a whole and allows the static data and information to become dynamic and more enlightening.

Linear programming (LP) is the foundation of a set of practical optimising techniques known as mathematical programming methods. Farm level models have been developed which can directly answer questions of how farmers would react to changes in policy or market conditions. The output of this work allows us to understand the changes in the mix of activities on a farm and the impacts on finance.

The dual (or shadow) price can be calculated on changes to these activities, and manipulation of various constraints within the model enables the calculation of these cost effects at farm level. At its most straight-forward this would be a greater restriction on nitrogen applied, which, when solved, is evidenced in activity changes, i.e. reduction in cereals grown.

The model used is the SAC Farm Level Model, which has been developed and applied to policy analysis for the last ten years. The recent application includes an analysis of Energy Crops (Renwick et al., 2006)[7]. The model is based on a central matrix of activities and constraints. The base model (pre-parameterised for farm types) has 194 activities and 205 constraints. Activities range from hectares of cropping activity to numbers of animals of various categories, e.g. heifers in calf etc., born, bought and sold. Constraints range over the main variable and fixed costs that are present on most UK farming systems, e.g. land area, N, P and K applications etc. The objective function is to maximise gross margins, hence it provides a response for the optimal allocation of resources. The model is based within MS Excel and has a central control panel to change the key values for these constraints. This allows each farming type, e.g. cereal, mixed etc., to be typified and described within the model. Critically, it also allows options for changing activity mixes on the farm or constraints to accommodate particular abatement technologies.

The process of modelling within this project followed a number of linked steps to apply abatement scenarios to the farm level model for this research project. These are namely:-

## 3.1 Define Farm Types

A number of farm types could be used to model abatement options, however due to time and resource constraints only three farm types have been used, namely an

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[7] Defra (2005) Farm level economic impacts of energy crop production, Cambridge University and SAC

average size cereal farm, a mixed farm and dairy farm. These are defined by agricultural census data (Defra, 2006[8]) to provide an indicator of baseline activities and constraints, such as land area and type.

The need to characterise costs through this limited farm characterisation can inevitably affect results that would ideally be based on a wider range of farm types in and account for regional differences. However, this choice allows the modelling effort to be kept to a minimum to fit within the timescale of this project.

## 3.2 Identify Financial Profiles

Farm business survey data (as discussed above) were used to typify the main costs per farm type and to relate the implicit system constraints from implementation of the range of crop and livestock measures

However, as this research covers four time periods, prices and costs have to be adjusted to account for changes in prices from the base period to 2012, 2017 and 2022. Hence, major output and input prices for agricultural products were obtained from the Agriculture in the UK publication (Defra, 2007[9]). This provided data on prices from the early 1990s. However, only the period 2000 to 2006 was used to define the trend in prices and project them forward until 2022. A weighted average of costs and prices from 2000 to 2006 was used, which covers a number of significant policy and economic impacts, in particular significant shifts in the agricultural policy support system, a number of animal health scares and price increases in cereals. Consequently, an average of these prices are deemed robust enough to capture any future price shocks up to 2022. In addition, an assumption regarding technological growth was included within the future farm models and imputed through a 2% per annum growth in yield for each of the 3 future periods.

## 3.3 Running Scenarios

The farms defined in step (i) were optimised under the assumption of maximising gross margins within the LP model for each period, 2006, 2012, 2017 and 2022. This gave the baseline scenario on which to compare the impact of abatement scenarios. Hence the scenarios adopted and their translation into a modelling problem and the change in Gross Margin were recorded between the baseline scenario and the modelled output.

## 3.4 Aggregation of Changes to Costs

These changes in gross margins were defined as the cost or benefits of adopting a particular abatement strategy. The differential was then calculated on a per ha (cereal/mixed farms) or a per animal (dairy farms) basis. However, a weakness in this approach is that farm decisions are measured at their optimal efficiency levels, as the implicit assumption of an LP model, is to optimise resources. Consequently, some account had to made of the spread of efficiencies throughout the industry to

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[8] Defra (2006) June Agricultural Census. Accessible at:
http://www.defra.gov.uk/esg/work_htm/publications/cs/farmstats_web/default.htm

[9] Defra (2007) Agriculture in the UK. Accesible at
https://statistics.defra.gov.uk/esg/publications/auk/

accommodate these differences. Hadley (2006)[10] provided an analysis of the efficiency distribution of farms within England, examining major sectors. The efficiency distributions for dairy, cereal and mixed farms were applied to the results. Notably, few farmers were recorded as operating at 100% efficiency but, on average, the majority had efficiency scores of around 80 to 90%.

Consequently, the first step to aggregation was to adjust the differences in gross margins by a weight, which represents the efficiency distribution within the system. The approach adopted was to simply multiply the cost by a weight representing the bands of inefficiency, namely 90% (0.9); 80% (0.8); 70% (0.7); >70% (0.6). This is not ideal, but a more rigorous approach would require further imposition of constraints upon the LP model and, increase program solving time. Hence, this approach was felt able to capture the inefficiencies within each sector without losing too much accuracy in estimation. Each value was then multiplied by the weight of each efficiency category within that industry.

Once adjusted for the efficiency factor, costs could be aggregated upwards. For the dairy sector this was simply a matter of multiplying the cost per animal by the number of dairy animals estimated to exist from the BAU3 estimates of the four time periods. For crops, our experts provided an expected spread of adoption by land type, e.g. grassland, cereals and oilseeds, etc. and the cost per ha could be aggregated up by multiplying across these four categories. A final constraint was added to account for the level of adoption throughout the industry. This process is best illustrated in Box 3.1 below.

**Box 3.1 Formula and example used.**

a. Estimate gross margin for abatement option, e.g. £-3/ha

b. Multiply the gross margin by the efficiency weighting, e.g. 90% efficiency, and then multiply by the percentage of farms reported to have this level of efficiency, e.g. 23%, to weight up the estimates across the whole population of UK farmers.

c. This is then multiplied by either : i) Number of UK dairy animals (for dairy industry); or ii) Number of hectares per land type that the technology is estimated to effect

d. This is then multiplied by the adoption rate across the sector over the three periods.

### 3.5 Discounting costs

The calculation of abatement costs delivered by some measures requires the consideration of cost profiles that stretch over a number of years. A consistent treatment of alternative cost streams involves time discounting and the treatment of discount rates can make significant differences to the cost effectiveness of

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[10] Hadley, D. 'Patterns in technical efficiency and technical change at the farm-level in England and Wales, 1982-2002'. *Journal of Agricultural Economics,* Vol. 57, (2006) pp. 81-100.

abatement options. The question posed is then essentially ‘which discount rate should we use - a social discount rate to reflect society’s preference for benefits now/costs later or the much higher private discount rates?

In this analysis unless otherwise stated we present all results using a social discount rate of 3.5%. The rate is consistent with the objective of considering mitigation investments from a public perspective. The spreadsheet model can be adjusted to reflect a private rate of time preference (e.g. 7%), which may be more important where any capital expenditures should consider a private opportunity cost of capital.

### 3.6 Measure Interactions

Abatement measures are rarely likely to be undertaken on a stand alone basis and the order of implementation may have significant influence on the incremental levels of abatement, and therefore cost effectiveness accruing to successive measures. The extent to which order effects are relevant varies over crop and livestock measures and many measures are clearly mutually exclusive.

This project used scientific expertise to develop a systematic approach to the evaluation of interactions. The method is described in the crop and soil section below. The presence of interactions explains any apparent discrepancy (i.e. missing measures) between stand alone abatement and the final MACC tables.

While considering interactions between measures within subsectors, there is also a need to consider interactions between subsectors, (e.g. between crop and livestock measures). These interactions have not been evaluated in this project.

Measures may also interact in terms of their cost as well as in terms of how much GHG they abate. For example, it is possible that the capital investment or training undertaken to implement a measure may mean that similar investment is not required for another measure, thereby reducing the costs of the measures when applied together. Alternatively, implementing two measures together may lead to competing demands for resources and require expenditure that would not be necessary when the measures are applied independently. Predicting such interactions is complex and beyond the scope of this study.

### 3.7 Reconciliation with National Inventory

The UK’s national inventory of GHG emissions accounts for emissions in accordance with guidelines produced by the IPCC (IPCC 2006). These guidelines take account of GHG production and removal by using empirically based emission factors. Within these calculations, the $CO_2$ emissions from land use and land use change are heavily based upon the amount of change between given land uses within a defined period. Thus the changes in land use assumed by BAU3 would be reflected in the emissions projections. Emissions of $N_2O$ from soils use emission factors to calculate direct and indirect emissions from fertiliser and manure applications. These estimates would not directly include many of the mitigation measures considered in this report. However, they would be expected to influence the inventory indirectly since measures such as the use of improved timing of fertiliser applications could be expected to reduce overall fertiliser inputs and therefore reported $N_2O$ emissions. Conversely other measures such as nitrification inhibitors might be expected to reduce $N_2O$ emissions, but might not also lead to reductions in fertiliser applications.

In these circumstances, the application of this mitigation option would not be represented in inventory reports (as currently defined).

Annex C of this report provides an assessment of our understanding of which mitigation options would be included in the inventory. Clearly there is a distinction to be made between direct an indirect measures and the extent to which measures not currently counted may nevertheless impact upon direct measures.   This report does not attempt to clarify this distinction further although we note that on going inventory refinement may alter the abatement potentials estimate here.

# 4 Mitigation options in Crops and Soils

## 4.1 Key Findings

*Total abatement potential ($MtCO_2e/y$) at a cost of <=£15/$tCO_{2e}$, 3.5%*

| *Potential* | *2012* | *2017* | *2022* |
|---|---|---|---|
| *High feasible* | | | 10.100 |
| *Central feasible* | 1.426 | 3.354 | 5.165 |
| *Low feasible* | | | 1.614 |

The feasible potentials in 2022 were estimated to range from 1.614 - 10.100$MtCO_2e$, i.e. an annual abatement of approximately 1.614 - 10.100$MtCO_2e$ could be achieved in the crops/soils sub-sector at a cost of <=£15/t by 2022. The measures needed to achieve this abatement are:

- Improved timing of mineral fertiliser N application
- Improved timing of slurry and poultry manure application
- Full allowance of manure N supply
- Plant varieties with improved N-use efficiency
- Reduced tillage
- Avoiding N excess
- Use composts, straw-based manures in preference to slurry
- Separate slurry applications from fertiliser applications by several days
- Improved drainage

The central feasible potential of 5.165 $MtCO_2e$ represents 11.4% of the 2005 UK agricultural GHG emissions and 20.1% of emissions from agricultural soils (the NAEI reported these as 45.253 $MtCO_2e$ and 25.110 MtCO2e respectively, excluding LUC). All of this abatement would be directly realised in the agricultural sector, although much of it would not be picked up by the current Inventory methodology (we estimate just 0.155 MtCO2e would be).

The selected options need not displace emissions overseas since they are expected to either have no or a slightly positive impact on yields. They may also generate some ancillary benefits in reducing life cycle GHG emissions related to fertiliser production and in other environmental areas, particularly water pollution.

Measures with positive costs are eighth or ninth best option, and therefore have significantly reduced abatement rates, due to interaction with other measures. This means they tend not to be cost-effective, leaving a gap between measures costing £0/t $CO_{2e}$ and the remaining options, the costs of which rise rapidly.

Interest rate makes little difference due to the fact that only one measure (reduced tillage) with one-off costs had negative costs for any of the years/discount rates.

These findings need to be treated with some caution as the results are contingent on a series of assumptions.

## 4.2 General

### 4.2.1 Overview of sector

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.

Nitrous oxide is a powerful greenhouse gas with a global warming potential of 310 times greater than that of $CO_2$ (Solomon et al. 2007). Most $N_2O$ is released from soils, and the use of nitrogen based fertilisers increases losses significantly. Nitrogen is applied in fertilisers and manures in order to promote plant growth. However, the nutrient requirements of the crop and the nutrient content of the soils are not always balanced. If N is in excess supply, soil microbes can convert the excess to $N_20$. Better nutrient management can therefore reduce direct $N_20$ emissions, and the indirect $CO_2$ emissions associated with fertiliser manufacture and distribution. Emissions of $N_20$ can be reduced through nutrient management by, for example: reducing the excess application of N; making full use of manure N; timing the application of fertiliser so that they are applied when required by the plants; using slow release fertilisers or nitrification inhibitors; using biological fixation (e.g. from clover or legumes) to provide N.

Methane uptake and release from agricultural soils is a relatively minor component of greenhouse gas exchange (although release from ruminant animals and manures is important).

### 4.2.2 What's covered in crops and soils category

Grasslands (including rough grazing land) occupy 12.5 Mha or 52% of the land area of the UK, while croplands occupy 4.6 M ha or 19% of the land area (http://www.defra.gov.uk/environment/statistics/land/). These areas remain relatively constant, although any changes in land use (including changes that occur as a consequence of changes within a rotation) can contribute significantly to changes in greenhouse gas exchange and are accounted for in the reporting procedures used by the IPCC (IPCC 2006). Emissions of greenhouse gases from agriculture occur as a direct consequence of management (e.g. $N_2O$ loss from soils that receive fertiliser N), and indirect processes (such as $N_2O$ loss from N that has leached into rivers). Both processes are accounted for in the IPCC methodology and mitigation referred to in this report includes both direct and indirect emissions. The IPCC does however acknowledge that there is considerable uncertainty in many of the emissions associated with indirect processes.

### 4.2.3 Crops and soils emissions: how much and trends

While croplands and grasslands are recognised as important sources and sinks for greenhouse gases, considerable uncertainties exist regarding their magnitude, and spatial and temporal variability (Janssens *et al.* 2003; Soussana *et al.* 2007). It has been estimated that improved management of the UK's agricultural land (improved tillage, fertiliser and manure management, soil management and extensification) could result in a C mitigation potential of 6.1 $Mty^{-1}$ (Smith et al. 2000). Mitigation of greenhouse gas emissions needs to take account of emissions of the collective emissions of $CO_2$, $N_2O$ and $CH_4$, since mitigation measures taken to reduce emissions of one greenhouse gas can sometimes result in corresponding increases in emissions of non target gases. The approach taken is therefore to measure changes the global warming potential of a system (which integrates the warming potential of $CO_2$, $N_2O$ and $CH_4$ in a single measurement and expresses them as C equivalents). Such approaches have been successfully used to assess mitigation potential of changes to management that can involve complex interactions (Soussana *et al.* 2007; Sutton *et al.* 2007).

### 4.2.4 Main modelling complexities

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.

### 4.2.5 Criteria/rationale and brief description for screening measures in each sector

The measures were screened using the approach outlined in Figure 4.1. 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 (see Annex A4). The long list was discussed at an expert meeting (see Annex I4 for details of the Crops/Soils Expert Group)[11], 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 (see 4.4.3) so that measures with small abatement potential could be identified. The interim list was reduced to a short list of 15 using a range of criteria (see Annex B4). Several measures with small (<2%) abatement measures were included in the short list, in particular some measures between 1 and 2% likely to have negative costs were included.

The abatement potentials in Annex B4, C4 and E4 are stand alone; the actual abatement for most measures will be reduced when actually applied in combination with other measures. For example, once the excess application of fertiliser has been reduced, there is less inefficiency for other measures to improve on (see section on interactions of measures). Therefore any measure with a small stand alone

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[11] Expert judgement involved an assessment by relevant subject experts of the published data on mitigation options overlaid with a judgement of the effectiveness of these different options at a national scale. It should be noted that individual mitigation options are often reported in the literature on a site specific basis (i.e. they are based on experiments at a limited number of sites). In order to upscale to a national level experts that are familiar with UK conditions have made a prediction of the likely national contribution. Although this approach lacks the rigorous objective standards that would normally be applied by upscaling of GHG inventories, it is the only practical option short of a full scale modelling approach (which was not possible in the timescale available).

abatement potential will have to be at the front of the queue (i.e. have negative costs) to have a significant abatement potential when implemented in combination. Even though measures between 1 and 2% are likely to have very small abatement potential, those with negative costs were included as they are win-win and may be of importance for some farm types or regions.

### 4.3 Selection and Description of Mitigation Measures

Annex A and Annex B list the measures in the long list and short list, and reasons why measures were removed. Annex C gives brief descriptions of each of the measures on the short list and their abatement rates. More detail on each of the measures is given below.

*Using biological fixation to provide N inputs (clover)*
Using legumes to biologically fix nitrogen reduces the requirement for N fertiliser to a minimum. It is assumed that use of biological fixation means that there will be less N in the system, and therefore a reduction in $N_2O$ emissions. However, it should be noted that legumes can also be a source of $N_2O$ emissions (Rochette and Janzen, 2005), and there is uncertainty regarding the extent to which biological fixation will reduce emissions. It has been assumed that this measure will reduce yield by 30%.

*Species introduction (including legumes)*
The species that are introduced are either legumes (see comment regarding biological fixation above) or they are taking up N from the system more efficiently and there is therefore less available for $N_2O$ emissions. This measure differs from biological fixation in that the species introduced are varieties that are not commonly used in the UK at present. It has been assumed that an extra sowing will be required, which will increase machine and labour costs by 5%, and that yields will be reduced by 7%. These costs are partially offset by a reduction in the amount of N fertiliser used – it is assumed that N purchase costs will be down by 10%.

*Reduce N fertiliser*
An across the board reduction in the rate at which fertiliser is applied will reduce the amount of N in the system and the associated $N_2O$ emissions. For example, if N is applied twice instead of three time a year, the N purchase costs will be reduced by approximately 30%, labour /machine costs will be reduced by 5% and a reduction in $N_2O$ in the order of 0.5tCO2e/ha/y achieved. As the reduction is not targeted at areas where N is applied in excess, it is assumed that there will be a reduction in yield of 20%.

*Avoiding N excess*
Reducing N application in areas where it is applied in excess reduces N in the system and therefore reduces $N_2O$ emissions. There are various schemes and advisory activities to help farmers apply N at optimum recommended rates, for example: Defra's RB209 guidance (http://www.defra.gov.uk/farm/environment/land-manage/nutrient/fert/rb209/index.htm); Sinclair (2002). Unlike simply reducing N fertiliser application rates, avoiding N excess should not lead to reductions in yield. It is assumed that the N fertiliser purchase costs will be reduced by 10%.

*Full allowance of manure N supply*
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. In addition, the manure N is more likely to be applied when the crop is going

to make use of the N, and therefore $N_2O$ emissions will be reduced. This measure should reduce N fertiliser inputs by about 15%.

*Improved timing of mineral fertiliser N application*
*Improved timing of slurry and poultry manure application*
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. This can be achieved by avoiding time delays between the application of N and its uptake by the plants, i.e. by avoiding applying fertiliser when the crop is not growing, or when there is no crop. Both these measures are essentially best practice and should not entail any additional costs (providing adequate storage is available). In fact, improving timing should result in small (3-5%) increases in yield through more efficient use of the nutrients.

*Separate slurry applications from fertiliser applications by several days*
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. It is assumed that weather conditions allow separation of the applications, that slurry can be stored before spreading or is available for spreading at the appropriate time. There should be no significant costs associated with this measure.

*Use composts, straw-based manures in preference to slurry*
Composts provide a more steady release of N than slurries which increase soil moisture content and provide a source of easily degradable products, which in turn increases microbial demand. Both these increase anaerobic conditions and thereby loss of nitrous oxide which is avoided by use of composts. Composts also have a higher C:N ratio so that released N is more likely to be immobilised temporarily and thereby reduce $N_2O$ emissions. It is assumed that composts contain enough N to provide fertiliser, and that the composts will not immobilise soil or fertiliser N and reduce crop productivity. There should be no significant costs associated with this measure.

*Controlled release fertilisers*
Controlled release fertilisers supply N, usually in the urea form, at a progressive rate over 2- 6months, more slowly than conventional fertilisers. This progressive, slow release of mineral N ensures that microbial conversion of the mineral N in soil to nitrous oxide and ammonia is reduced. It is assumed that the fertiliser releases N at the promised rate, and that the rate of release does not go up due to unusual circumstances such as heavy rain, warm weather, or trampling by animals. It is assumed that these fertilisers are considerably (50%) more expensive than conventional fertilisers. These costs will be partly offset by the reduced number of applications required.

*Nitrification inhibitors*
Nitrification inhibitors slow the rate of conversion of fertiliser ammonium to nitrate. This means that the rate of reduction of nitrate to nitrous oxide (or dinitrogen) is decreased and emissions of nitrous oxide decrease. Nitrification inhibitors are used in New Zealand, however Pollok (2008, p22) has noted that “They are expensive and significant reductions in mineral fertilizer requirements would be needed to make them cost-effective… there appears to be a need to measure effectiveness under UK systems”. It is assumed that the inhibitor makes good contact with the fertiliser or urine patch to be effective, and that the inhibitor will be applied at the right time and to the right fertiliser type. It is assumed that inhibitors lead to significant cost

increases (equivalent to a 50% increase in fertiliser costs). These costs will be slightly offset by the reduced labour/machine costs.

*Adopting systems less reliant on inputs (nutrients, pesticides etc)*
Moving to less intensive systems that use less input can reduce the overall greenhouse gas emissions. For the purposes of this study, it has been assumed that the change is akin to moving from conventional production system to a LEAF farm type of system, with reduced input of pesticides, nutrients etc. It is estimated that this change would result in a reduction in yield of 10%, however this would be offset by the reduced N fertiliser bill (estimated to be reduced by 25%).

*Plant varieties with improved N-use efficiency*
Different plant species utilise N with different levels of efficiency. There should therefore be scope for selectively breeding plants that utilise N more efficiently. Adopting new plant varieties that can produce the same yields using less N would reduce the amount of fertiliser required and the associated emissions. However, as Pollok (2008, p22) notes, improving N use efficiency “without adverse effects on other important agronomic characteristics will be difficult and will take many years to come to market”. For this study, it has been assumed that new varieties will be able to produce current yields with 30% less N fertiliser.

*Reduced tillage / No-till*
No tillage, and to a lesser extent, minimum (shallow) tillage reduces release of stored carbon in soils because of decreased rates of oxidation. The lack of disturbance by tillage can also increase the rate of oxidation of methane from the atmosphere. It is assumed that nitrous oxide emissions are not increased due to concentration of microbial activity and nitrogen fertiliser near the surface and due to increase soil wetness associated with the greater compactness of the soil, and that crop growth and hence net primary productivity is not reduced by use of these techniques. This measure requires specialist machinery and therefore has significant one-off costs; Beaton *et al* reported the cost of a power harrow to be £20,000. This cost is offset by reductions in overall cultivation costs of around 16%.

*Improving land drainage*
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. Improving land drainage has significant one-off costs and recurring costs. It has been reported that drainage has a one-off cost of £1850/ha to build then £250/ha every five years to maintain (Beaton *et al* 2007). These costs are likely to be offset by increases in yield; it is estimated that improving drainage will increase yields by 10%.

## 4.4 Data and Measurement

### 4.4.1 Baselines and Additionality

The crops/soils abatement potential is measured relative to a business-as-usual (BAU) scenario based on the following assumptions:

- the land use projections from the BAU3 project, these are summarised in Table 4.1. See section 2 for further details on the construction of the baseline.
- costs of measures are calculated using an LP model which uses forecasts of input and output prices, see section 3.
- the abatement rates of individual measures are constant over time

- emissions factors for different land types are constant over time - i.e. we have assumed no uptake of abatement in the BAU

**Table 4.1 BAU3 land use projections**

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

### 4.4.2 Costs

Secondary data about costs was 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 (for example, effects on yields, input purchase costs, labour and machinery costs, capital purchases), The model was then used to calculate each measures' impact on the gross margins of a representative (a) cereal and (b) mixed farm. The model and the assumptions underpinning it are described in detail in section 3. The assumptions made in calculating the cost of the measures are given in Annex D4.

The results from the model were used to calculate the weighted mean cost of each measure by multiplying the cost/ha for different farm types by the amount of land in the UK that the measure could be applied to (see Annex D4). The stand alone cost-effectiveness was then obtained by dividing the cost (£/ha/y) by the abatement rate ($tCO_{2e}$/ha/y).

### 4.4.3 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 (see section 2.3). 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*. 2008) was combined with an expert's judgement to derive estimates of the abatement rates of each of the measures on the interim list. These rates were reviewed independently by another two experts, who ranked the uncertainty of the estimated abatement rate and their agreement with it (see Annex C). 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.

*What is included and excluded*
The abatement rate is for on farm direct emissions, averaged across all sectors. It doesn't include wider life cycle impacts, for example $CO_2$ emitted during the manufacture of fertiliser, but does include indirect $N_20$ emissions (see 4.2.2). For further discussion of the wider impacts, see Annex A and B at the end of the report.

### 4.4.4 Cost-effectiveness (CE)

*CE of combinations of 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) (see Annex E). 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):

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

For example, measures AB have an IF of 0.55, that is to say, that abatement rate of measure B ("reducing N fertiliser") is multiplied by 0.55 when applied after measure A. Each time a measure is implemented, the abatement rates of ALL of the remaining measures are recalculated by multiplying them by the appropriate IF, i.e. if measure A is implemented first, than all the remaining measures are multiplied by the IF in row A (see Table 4.2). Therefore, after each measure is implemented, the abatement rates and CE of each remaining measure has to be recalculated, and the "next best" measure (in terms of CE) selected. In order to perform this repeated calculation, the routine "Get Ranking" was written in PERL (see annex H).

The IFs for the measures were discussed and estimated by a group of experts (see Annex F). Due to time constraints and the complexity of estimating the IFs, it had to be assumed that the IF's are symmetric, i.e. that IF(AB) = IF (BA). In reality, in some cases this will not be true. The analysis undertaken in this study was restricted to looking at 2-way interactions. Multiple interactions are likely to occur in practice, but the affect of these could only adequately be assessed using more complex process based models. For the purposes of this study multiple interactions are captured as the product of cumulative two-way interaction factors. Further analysis was beyond the scope of the present study.

**Table 4.2** **Calculating the abatement rate of combinations of measures**

| Measure implemented | Measure | Stand alone abatement rate t $CO_2$e/ha/y | Abatement rate when interaction is taken into account (IFs underlined) |
|---|---|---|---|
| First | A: bio fix | 1 | 1 |
| Second | D: avoid excess N | 0.4 | 0.4*0.55= 0.22 |
| Third | E: species intro | 0.5 | 0.5*0.9*0.9=0.405 |
| Fourth | H: cont release | 0.3 | 0.3*0.55*0.75*0.6=0.074 |
| Etc | | | |

A further complication is uncertainty regarding the extent to which measures overlap. The way measures interact depends on how they abate (which is represented by their interaction factor) *and* the extent to which they are applied on overlapping areas of land. For example, in Table 4.3, if we have two measures C and D and the abatement rate of D is reduced by 30% when applied after C (i.e. the interaction factor (CD) is 0.7). Again, due to time constraints, it was simply assumed that the measures would have 50% overlap.

**Table 4.3** **Effect of overlap on abatement**

| Measure | Stand alone abatement rate ($tCO_2$e/ha/y) | % of grassland measure could be applied to | Interaction factor | Abatement per 100ha assuming 100% overlap | Abatement per 100ha assuming 50% overlap |
|---|---|---|---|---|---|
| C | 1 | 60 | na | 60%*100=**60** | **60** |
| D | 1 | 60 | 0.7 | 60%*100*0.7 =**42** | (60*100*0.5)+ (60*100*0.5*0.7) =30+21=**51** |

*Reason for ordering measures below the x-axis according to saving rather than cost-effectiveness.*

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.

In a model MAC, 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), while those to the right have lowest 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 to those with positive costs. The interaction factor 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, i.e. less expensive and therefore more CE. The costs of the measures with positive costs increase as we move from left to right and the effect of the interaction factors (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 > the increase between bars). However, for measures with negative costs the bars shorten as we move from left to right, BUT the IF lengthen the bars, which means that the bars will not necessarily get shorter (i.e. CE will not decrease)[12]. For example, in Table 4.4 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, i.e. the (negative) cost per ha multiplied by the area the measure could be applied to. This approach has the advantages that (a) the potential savings are unaffected by the effects of measures interacting, and (b) it is consistent with profit-maximising behaviour.

**Table 4.4 Example showing the effects of measure interaction on 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 |
| **So combined CE of X,Y and Z** | **-7** | **-8.6** | **-7.9** |

### 4.4.5 Uncertainties

It has been assumed that all measures are somehow on the menu, i.e. all measures are substitutable, which means that we apply the most cost-effective measure (A) to all the land it can be applied to, then apply the next most cost-effective measure (B) etc. In reality, a farm (e.g. that has no cereals), may not be able to implement measure B, and will therefore go from A to C. Or a farm converting to organic production may choose to use biological fixation along with a package of other measures that make sense as a whole. In other words, many individual farms will not apply each of the measures in order of cost-effectiveness as the MACC assumes, as some options will not be open to them and others will appear more attractive than their cost-effectiveness suggests due to ancillary costs and benefits. While it was necessary to assume that all measures were substitutable and are applied in order of cost-effectiveness in order to generate the MAC for the crops and soils sub-sector, the limitations of this approach need to recognised. The most important limitation is that the cost of measures with moderate or high stand alone costs are exaggerated and appear higher than they would be in reality. This is because it is assumed that they will be applied after all the measures with negative costs and low positive costs. Future refinement would be to generate specific MAC curves for farm types.

High levels of uncertainty are associated with some of the mitigation measures proposed as recognised by the IPCC (IPCC 2006). In particular, indirect emissions of $N_2O$ resulting from emissions from drainage water and ammonia deposition are poorly understood and are excluded at this point. There is also a high level of uncertainty associated with emissions of $N_2O$ derived from N inputs by biological fixation. Biological fixation can reduce emissions in two ways; by a reduction in the fossil fuel input required to manufacture the fertiliser, and through a reduction of losses of $N_2O$ from the soil following fixation. Recent research has indicated that

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[12] For simplicity we assume that the IFs affect each measure's abatement potential, and hence cost effectiveness, but not the cost per hectare

$N_2O$ released from biologically fixed N is significantly lower than that from inorganic fertilisers (Carter & Ambus 2006). It has therefore been proposed that future revisions to IPCC guidelines should not include emissions from biologically fixed N (Rochette & Janzen 2005).

There is much interest in reduced and zero tillage as a means of reducing GHG emissions. Again there is considerable uncertainly regarding the magnitude of emissions savings that can be achieved by these techniques. It is agrued widely that reduced tillage can help to increase C sequestration in soils (Liebig *et al.* 2005; Martens *et al.* 2005). It is argued by (Blanco-Canqui & Lal 2008) that storage of additional carbon only occurs in surface layers under no-tillage (NT) management and doesn't therefore result in an overall increase in C storage. However, it seems likely that NT also contributes to lower losses of C from respiration (Paustian *et al.* 1997), and would therefore deliver increases in C sequestration even if these were not measurable in the short term (<5 years) For these reasons we have assumed that tillage can contribute to reduced GHG emissions but have reduced the abatement rate from 0.3 $tCO_{2e}$/ha/y proposed by (Smith *et al.* 2008) to 0.15 $tCO_{2e}$/ha/y.

It is often argued that systems level changes such as those between conventional and low input or organic farming can lead to reductions in overall greenhouse gas emissions. It is likely that current inventory calculations would not fully account for the changes in emissions, since the inventory is calculated as a result of emissions factors associated with individual management practices. Where there is a change in the whole farming system it is possible that interactions occur that would not be identified. Further more individual practices may be poorly represented, such as biological fixation (see above) or not represented at all (such as improved timing of manure applications to increase N uptake efficiency). Such system changes may therefore represent more significant reductions in greenhouse gas emissions than is currently allowed for in the inventory.

## 4.5 Results and conclusions

*Overall abatement potentials and costs*

The feasible potentials in 2022 were estimated to range from 1.614 - 10.100MtCO2e, i.e. an annual abatement of approximately 1.614 - 10.100Mt$CO_2$e could be achieved in the crops/soils sub-sector at a cost of <=£100/t by 2022 (Table 4.5). The measures needed to achieve this abatement are:

- Improved timing of mineral fertiliser N application
- Improved timing of slurry and poultry manure application
- Full allowance of manure N supply
- Plant varieties with improved N-use efficiency
- Reduced tillage
- Avoiding N excess
- Use composts, straw-based manures in preference to slurry
- Separate slurry applications from fertiliser applications by several days
- Improved drainage

**Table 4.5 Total abatement potential ($MtCO_2e/y$) at a cost of <=£100/$tCO_2e$, and discount rate 3.5%**

| *Potential* | *2012* | *2017* | *2022* |
|---|---|---|---|
| *High feasible* | | | 10.100 |
| *Central feasible* | 1.426 | 3.354 | 5.165 |
| *Low feasible* | | | 1.614 |

The central feasible potential of 5.165 MtCO2e represents 11.4% of the 2005 UK agricultural GHG emissions and 20.1% of emissions from agricultural soils (the NAEI reported these as 45.253 MtCO2e and 25.110 MtCO2e respectively, excluding LUC). Pollock (2008, p23) concluded that "overall reductions using currently viable approaches are likely to be modest (maximally some 10-15% of current emissions assuming similar levels of production)". While these results are similar, direct comparison is difficult as it is not clear what % of the 10-15% is accounted for by crops/soils measures, what time scale the 10-15% is to be achieved over or what cost of measure was used in measuring viable levels of uptake.

IGER (2001) concluded that "$N_2O$ emissions could be reduced by 32.5% (maximum feasible reduction) at a cost of £97 billion. Cost effective reduction potential, determined by the point at which the cost curve becomes exponential, is approximately 18%, with total on farm savings of £916 million. However, a reduction of 20% could also be achieved at a negligible net cost." CLA/AIC/NFU (2007) reached a similar conclusion, and suggested that "combined improvements in livestock and crop nitrogen efficiencies could mitigate ($N_20$) emissions by up to 20%". These results appear consistent with our estimate for high feasible potential, which is 22.7% reduction. However, once again comparison is difficult without greater scrutiny of the assumptions and metrics used in arriving at these estimates.

*Displacement of production and emissions*
If UK emissions are reduced by simply reducing levels of production, then there is a danger of displacing production to other countries. This would harm the farming industry without providing any benefit in terms of reducing global GHG emissions. It is therefore important to highlight any measures that could lead to displacement.

There are four measures that can lead to reduced yields and five that can lead to increase yields (see Annex D for further details):

*Reduced yields*
Using biological fixation to provide N inputs (clover)
Reduce N fertiliser
Species introduction (including legumes)
Adopting systems less reliant on inputs (nutrients, pesticides etc)

*Increased yields*
Improved drainage

*Negligible yield increase*
Controlled release fertilisers
Nitrification inhibitors
Improved timing of mineral fertiliser N application
Improved timing of slurry and poultry manure application

With the exception of improved drainage and improved timing of applications, none of these measures appear cost-effective, and it is therefore unlikely that there will be significant changes in production levels associated with the crops/soils mitigation.

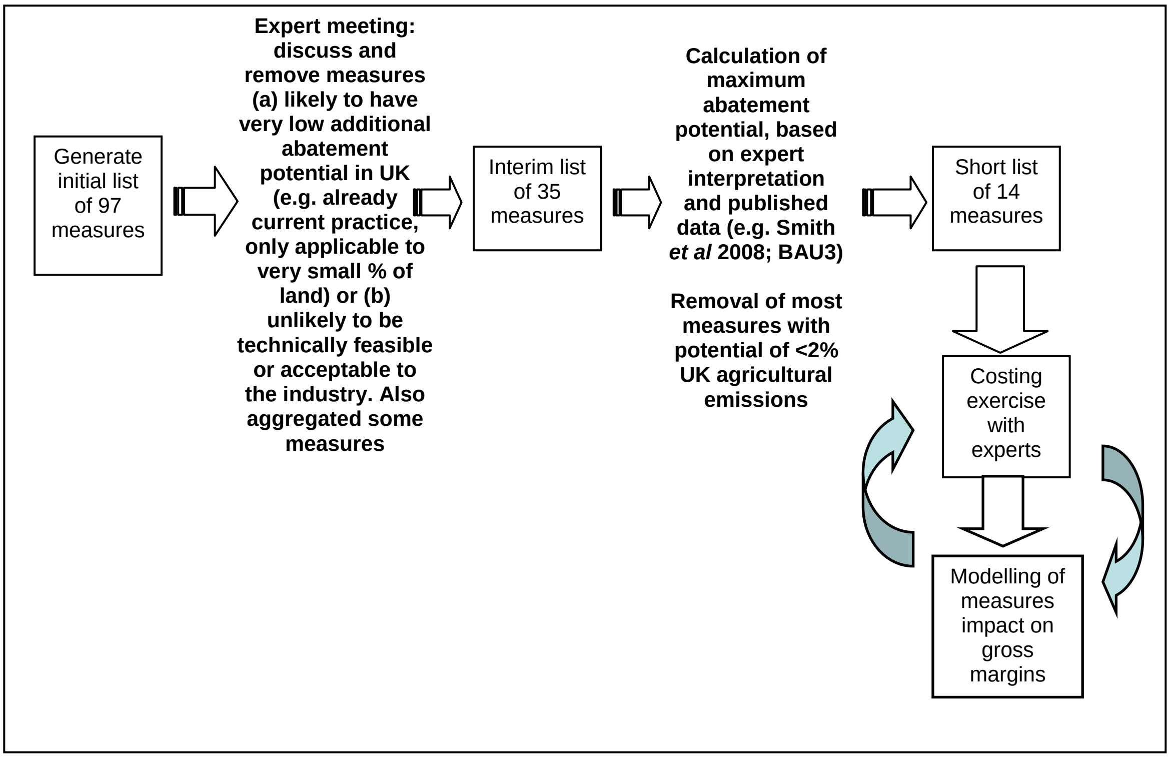

**Figure 4.1** **Approach to screening measures**

## Annex A4 Full list of measures and reasons for omission from interim list

| ID | Category | Sub-category | Measure | Include in interim list? | Reason for omission |
|---|---|---|---|---|---|
| 1 | Cropland management | Agronomy | Improved crop varieties | y | |
| 2 | Cropland management | Agronomy | Extending the perennial phase of rotations | y | |
| 3 | Cropland management | Agronomy | Reducing bare fallow | y | |
| 4 | Cropland management | Agronomy | Adding nutrients when deficient | n | small % of land deficient |
| 5 | Cropland management | Agronomy | Adopting systems less reliant on inputs (nutrients, pesticides etc) | y | |
| 6 | Cropland management | Agronomy | Catch/cover crops | y | |
| 7 | Cropland management | Agronomy | Maintain crop cover over winter | y | |
| 8 | Cropland management | Agronomy | Keep pH at an optimum for plant growth | n | current practice |
| 9 | Cropland management | Agronomy | Changing from winter to spring cultivars | y | |
| 10 | Cropland management | Nutrient management | Precision farming | y | |
| 11 | Cropland management | Nutrient management | Avoiding N excess | y | |
| 12 | Cropland management | Nutrient management | Full allowance of manure N supply | y | |
| 13 | Cropland management | Nutrient management | Improved timing of mineral fertiliser N application | y | |
| 14 | Cropland management | Nutrient management | Split fertilisation (baseline amount of N fertilizer but divided into three smaller increments) | y | |
| 15 | Cropland management | Nutrient management | Wheat | n | Grouped under 14 split fertilisation |
| 16 | Cropland management | Nutrient management | irrigated wheat | n | Grouped under 14 split fertilisation |
| 17 | Cropland management | Nutrient management | Maize | n | Grouped under 14 split fertilisation |
| 18 | Cropland management | Nutrient management | irrigated maize | n | Grouped under 14 split fertilisation |
| 19 | Cropland management | Nutrient management | Use the right form of mineral N fertiliser | y | |
| 20 | Cropland management | Nutrient management | Improved timing of slurry and poultry manure application | y | |
| 21 | Cropland management | Nutrient management | Separate slurry applications from fertiliser applications by several days | y | |
| 22 | Cropland management | Nutrient management | Use composts, straw-based manures in preference to slurry | y | |
| 23 | Cropland management | Nutrient management | Mix nitrogen rich crop residues with other residues of higher C:N ratio | y | |
| 24 | Cropland management | Nutrient management | Placing N precisely in soil | y | |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 25 | Cropland management | Nutrient management | Trailing hose | n | Grouped under 24 placing N precisely |
| 26 | Cropland management | Nutrient management | Trailing shoe | n | Grouped under 24 placing N precisely |
| 27 | Cropland management | Nutrient management | Injection | n | Grouped under 24 placing N precisely |
| 28 | Cropland management | Nutrient management | Increasing rate of infiltration into soil (dilution of manure, app. of water after spreading) | n | Potential risk of denitrification |
| 29 | Cropland management | Nutrient management | Controlled release fertilisers | y |  |
| 30 | Cropland management | Nutrient management | Nitrification inhibitors | y |  |
| 31 | Cropland management | Nutrient management | Wheat | n | Grouped under 30 nitrification inhibitors |
| 32 | Cropland management | Nutrient management | irrigated wheat | n | Grouped under 30 nitrification inhibitors |
| 33 | Cropland management | Nutrient management | Maize | n | Grouped under 30 nitrification inhibitors |
| 34 | Cropland management | Nutrient management | irrigated maize | n | Grouped under 30 nitrification inhibitors |
| 35 | Cropland management | Nutrient management | Production of natural nitrification inhibitors by plants | n | unlikely |
| 36 | Cropland management | Nutrient management | Application of urease inhibitor | y |  |
| 37 | Cropland management | Nutrient management | Plant varieties with improved N-use efficiency | y |  |
| 38 | Cropland management | Nutrient management | Using biological fixation to provide N inputs (clover) | y |  |
| 39 | Cropland management | Nutrient management | Reduce N fertiliser (wheat, barley, oilseed rape) | y |  |
| 40 | Cropland management | Nutrient management | Fertilisation reduction by 30% | n | Grouped under 39 reduce N fertiliser |
| 41 | Cropland management | Nutrient management | Wheat | n | Grouped under 39 reduce N fertiliser |
| 42 | Cropland management | Nutrient management | irrigated wheat | n | Grouped under 39 reduce N fertiliser |
| 43 | Cropland management | Nutrient management | Maize | n | Grouped under 39 reduce N fertiliser |
| 44 | Cropland management | Nutrient management | irrigated maize | n | Grouped under 39 reduce N fertiliser |
| 45 | Cropland management | Nutrient management | Fertilisation reduction by 20% | n | Grouped under 39 reduce N fertiliser |
| 46 | Cropland management | Nutrient management | Wheat | n | Grouped under 39 reduce N fertiliser |
| 47 | Cropland management | Nutrient management | irrigated wheat | n | Grouped under 39 reduce N fertiliser |
| 48 | Cropland management | Nutrient management | Maize | n | Grouped under 39 reduce N fertiliser |
| 49 | Cropland management | Nutrient management | irrigated maize | n | Grouped under 39 reduce N fertiliser |
| 50 | Cropland management | Nutrient management | Fertilisation reduction by 10% | n | Grouped under 39 reduce N fertiliser |
| 51 | Cropland management | Nutrient management | Wheat | n | Grouped under 39 reduce N fertiliser |
| 52 | Cropland management | Nutrient management | irrigated wheat | n | Grouped under 39 reduce N fertiliser |
| 53 | Cropland management | Nutrient management | Maize | n | Grouped under 39 reduce N fertiliser |
| 54 | Cropland management | Nutrient management | irrigated maize | n | Grouped under 39 reduce N fertiliser |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 55 | Cropland management | Nutrient management | Applying organic input on cropland instead of on grassland | n | Grouped under 39 reduce N fertiliser |
| 56 | Cropland management | Longer term structural and management changes | Tightening the N cycles (regionally optimised plant and animal production) | y |  |
| 57 | Cropland management | Tillage/residue management | Reduced tillage | y |  |
| 58 | Cropland management | Tillage/residue management | Reduced tillage - CO2 sequestration | n | Grouped with 57 reduced tillage |
| 59 | Cropland management | Tillage/residue management | Retain crop residues | y |  |
| 60 | Cropland management | Tillage/residue management | No-till | n | Grouped with 57 reduced tillage |
| 61 | Cropland management | Tillage/residue management | Wheat | n | Grouped with 57 reduced tillage |
| 62 | Cropland management | Tillage/residue management | irrigated wheat | n | Grouped with 57 reduced tillage |
| 63 | Cropland management | Tillage/residue management | Maize | n | Grouped with 57 reduced tillage |
| 64 | Cropland management | Tillage/residue management | irrigated maize | n | Grouped with 57 reduced tillage |
| 65 | Cropland management | Tillage/residue management | Avoid no-tillage, consider occasional deep ploughing | n | Current practice |
| 66 | Cropland management | Tillage/residue management | Plough in early spring, spread crop residues evenly and control compaction | n | Current practice |
| 67 | Cropland management | Tillage/residue management | Avoid burning of residues | n | Current practice - burning unlikely to become legal again |
| 68 | Cropland management | Water and soil management | Improved irrigation | y |  |
| 69 | Cropland management | Water and soil management | Land drainage | y |  |
| 70 | Cropland management | Water and soil management | Loosen compacted soils / Prevent soil compaction | y |  |
| 71 | Cropland management | Rice management | NA | n | No rice in UK |
| 73 | Grazing land management/ pasture improvement | Grazing intensity and timing | Intensive grazing (cattle are frequently rotated between pastures) - beef | n | Current practice |
| 74 | Grazing land management/ pasture improvement | Grazing intensity and timing | Intensive grazing (cattle are frequently rotated between pastures) - dairy | n | Current practice |
| 75 | Grazing land management/ pasture improvement | Take stock off from wet ground |  | n | Current practice |
| 76 | Grazing land management/ pasture improvement | Increased productivity | Fertilization | n | -ve abatement potential |
| 77 | Grazing land management/ pasture improvement | Increased productivity | Pasture renovation | n | Current practice |
| 78 | Grazing land management/ pasture improvement | Increased productivity | Species introduction (including legumes) | y |  |

| | | | | | |
|---|---|---|---|---|---|
| 79 | Grazing land management/ pasture improvement | Increased productivity | Introducing /enhancing high sugar content plants (e.g. "high sugar" ryegrass) | y | |
| 80 | Grazing land management/ pasture improvement | Increased productivity | New forage plant varieties for improved nutritional characteristics | y | |
| 81 | Grazing land management/ pasture improvement | Nutrient management | SEE AT CROPLAND MGTM - NUTRIENT MGMT | n | See crops |
| 82 | Grazing land management/ pasture improvement | Fire management | | n | Small abatement potential |
| 83 | Grazing land management/ pasture improvement | Water and soil management | Adjust pH to more than 5 by liming | n | Current practice |
| 84 | Grazing land management/ pasture improvement | Water and soil management | Land drainage - SEE AT CROPLAND MGMT | n | See crops |
| 85 | Grazing land management/ pasture improvement | Water and soil management | Prevent soil compaction | y | |
| 86 | Management of organic soils | Avoid drainage of wetlands | | y | |
| 87 | Management of organic soils | Avoiding row crops and tubers | | n | Unlikely due to high value of land |
| 88 | Management of organic soils | Avoiding deep ploughing | | n | Small abatement potential |
| 89 | Management of organic soils | Maintaining a shallower water table | Peat | y | |
| 90 | Management of organic soils | Maintaining a shallower water table | Arable | n | Unlikely |
| 91 | Restoration of degraded lands | Erosion control | | n | Small amount of degraded land so small potential |
| 92 | Restoration of degraded lands | Revegetation | | n | Small amount of degraded land so small potential |
| 93 | Restoration of degraded lands | Nutrient amendments | | n | Small amount of degraded land so small potential |
| 94 | Restoration of degraded lands | Organic amendments (manures, biosolids, composts, etc.) | | n | Small amount of degraded land so small potential |
| 95 | Restoration of degraded lands | Reducing tillage | | n | Small amount of degraded land so small potential |
| 96 | Restoration of degraded lands | Retaining crop-residues | | n | Small amount of degraded land so small potential |
| 97 | Restoration of degraded lands | Conserving water | | n | Small amount of degraded land so small potential |

## **Annex B4 Interim list of measures and estimated abatement rates**

| | | | Estimated maximum % additional area of each land category that each measure could be applied to in the UK by 2022 | | | | | Abatement rates | Abatement potential (stand alone) by 2022 | | Include in MACC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Category | Sub-category | Measure | Grassland (LFA + non-LFA) *not* including rough grazing | Cereals and oil seeds | Root crops | Other crops | Total area (ha) | t CO2e/ ha/y | Mt CO2e/ year | % of UK agri emissions (2005) | |
| Cropland management | Nutrient management | Using biological fixation to provide N inputs (clover) | 80 | 20 | 20 | 20 | 6,378,847 | 0.5 | 6.378847 | 14.3% | Y |
| Cropland management | Nutrient management | Reduce N fertiliser | 90 | 90 | 90 | 90 | 9,918,926 | 0.5 | 4.959463 | 11.1% | Y |
| Cropland management | Water and soil management | Improved land drainage | 40 | 30 | 20 | 20 | 4,002,082 | 1 | 4.002082 | 8.9% | Y |
| Cropland management | Nutrient management | Avoiding N excess | 20 | 20 | 20 | 20 | 8,816,823 | 0.4 | 3.526729 | 7.9% | Y |
| Cropland management | Nutrient management | Full allowance of manure N supply | 80 | 50 | 20 | 10 | 7,597,835 | 0.4 | 3.039134 | 6.8% | Y |
| Grazing land management/pasture improvement | Increased productivity | Species introduction (including legumes) | 60 | 40 | 30 | 30 | 5,799,959 | 0.5 | 2.899979 | 6.5% | Y |
| Cropland management | Nutrient management | Improved timing of mineral fertiliser N application | 70 | 80 | 70 | 50 | 8,121,050 | 0.3 | 2.436315 | 5.4% | Y |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cropland management | Nutrient management | Controlled release fertilisers | 70 | 80 | 80 | 80 | 8,121,050 | 0.3 | 2.436315 | 5.4% | Y |
| Cropland management | Nutrient management | Nitrification inhibitors | 70 | 80 | 80 | 80 | 8,121,050 | 0.3 | 2.436315 | 5.4% | Y |
| Cropland management | Longer term structural and management changes | Tightening the N cycles (regionally optimised plant and animal production) | 70 | 70 | 60 | 60 | 7,714,720 | 0.3 | 2.314416 | 5.2% | N - high level of uncertainty |
| Cropland management | Nutrient management | Improved timing of slurry and poultry manure application | 70 | 60 | 50 | 40 | 7,308,391 | 0.3 | 2.192517 | 4.9% | Y |
| Management of organic soils | Avoid drainage of wetlands | | 10 | 5 | 0 | 0 | 898,938 | 2 | 1.797877 | 4.0% | N - high level of uncertainty, also likely to displace significant amounts of production and emissions |
| Cropland management | Nutrient management | Application of urease inhibitor | 70 | 60 | 50 | 50 | 7,308,391 | 0.2 | 1.461678 | 3.3% | N - N$_2$0 reduction small and offset by indirect N$_2$0 emissions |
| Cropland management | Agronomy | Adopting systems less reliant on inputs (nutrients, pesticides etc) | 60 | 40 | 30 | 30 | 5,799,959 | 0.2 | 1.159992 | 2.6% | Y |
| Cropland management | Nutrient management | Plant varieties with improved N-use efficiency | 20 | 60 | 40 | 40 | 3,829,523 | 0.2 | 0.765905 | 1.7% | Y |
| Cropland management | Nutrient management | Mix nitrogen rich crop residues with other residues of higher C:N ratio | 30 | 40 | 30 | 20 | 3,712,638 | 0.2 | 0.742528 | 1.7% | N - marginal, too localised |
| Cropland management | Nutrient management | Separate slurry applications from fertiliser applications by several days | 70 | 60 | 50 | 40 | 7,308,391 | 0.1 | 0.730839 | 1.6% | Y |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cropland management | Tillage/residue management | Reduced tillage / No-till | 0 | 50 | 10 | 10 | 2,031,647 | 0.15 | 0.609494 | 1.4% | Y |
| Cropland management | Nutrient management | Use composts, straw-based manures in preference to slurry | 50 | 50 | 40 | 30 | 5,510,515 | 0.1 | 0.551051 | 1.2% | Y |
| Cropland management | Nutrient management | Precision farming | 20 | 25 | 40 | 30 | 2,407,370 | 0.2 | 0.481474 | 1.1% | N - small potential |
| Cropland management | Agronomy | Improved crop varieties | 5 | 50 | 25 | 25 | 2,379,533 | 0.2 | 0.475907 | 1.1% | N - small potential, see plant varieties with improved N |
| Grazing land management/pasture improvement | Water and soil management | Prevent soil compaction | 50 | 40 | 30 | 30 | 5,104,185 | 0.05 | 0.255209 | 0.6% | N - small potential |
| Grazing land management/pasture improvement | Increased productivity | New forage plant varieties for improved nutritional characteristics | 60 | 20 | 20 | 10 | 4,987,300 | 0.05 | 0.249365 | 0.6% | N - small potential |
| Cropland management | Tillage/residue management | Retain crop residues | 0 | 30 | 40 | 40 | 1,218,988 | 0.2 | 0.243798 | 0.5% | N - small potential |
| Cropland management | Water and soil management | Loosen compacted soils / Prevent soil compaction | 40 | 40 | 30 | 30 | 4,408,412 | 0.05 | 0.220421 | 0.5% | N - small potential |
| Cropland management | Agronomy | Catch/cover crops | 0 | 50 | 30 | 30 | 2,031,647 | 0.1 | 0.203165 | 0.5% | N - small potential |
| Cropland management | Water and soil management | Improved irrigation | 0 | 5 | 10 | 10 | 203,165 | 1 | 0.203165 | 0.5% | N - small potential |
| Grazing land management/pasture improvement | Increased productivity | Introducing /enhancing high sugar content plants (e.g. "high sugar" ryegrass) | 40 | 30 | 20 | 20 | 4,002,082 | 0.05 | 0.200104 | 0.4% | N - small potential |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cropland management | Nutrient management | Split fertilisation (baseline amount of N fertilizer but divided into three smaller increments) | 30 | 40 | 30 | 20 | 3,712,638 | 0.05 | 0.185632 | 0.4% | N - small potential |
| Cropland management | Nutrient management | Use the right form of mineral N fertiliser | 30 | 30 | 30 | 30 | 3,306,309 | 0.05 | 0.165315 | 0.4% | N - small potential |
| Cropland management | Nutrient management | Placing N precisely in soil | 10 | 40 | 40 | 40 | 2,321,091 | 0.05 | 0.116055 | 0.3% | N - small potential |
| Cropland management | Agronomy | Maintain crop cover over winter | 0 | 50 | 30 | 30 | 2,031,647 | 0.05 | 0.101582 | 0.2% | N - small potential |
| Cropland management | Agronomy | Extending the perennial phase of rotations | 0 | 20 | 20 | 20 | 812,659 | 0.1 | 0.081266 | 0.2% | N - small potential |
| Cropland management | Agronomy | Reducing bare fallow | 0 | 20 | 10 | 10 | 812,659 | 0.1 | 0.081266 | 0.2% | N - small potential |
| Cropland management | Agronomy | Changing from winter to spring cultivars | 0 | 40 | 5 | 0 | 1,625,317 | 0.05 | 0.081266 | 0.2% | N - small potential |
| Management of organic soils | Maintaining a shallower water table | peat | 5 | 0 | 0 | 0 | 347,887 | | 0 | 0.0% | N - small potential |

## Annex C4 Description of the measures on the short list

| *Measure* | *Description of the measure* | *Estimate of measures abatement rate t CO2e/ha/y*[1] | *Experts agreement with the estimated abatement rate*[2] | *Experts ranking of the uncertainty regarding the abatement rate*[3] |
|---|---|---|---|---|
| Using biological fixation to provide N inputs (clover) | Using legumes to biologically fix nitrogen reduces the requirement for N fertiliser to a minimum. Less N in the system, and therefore reduce $N_20$ emissions. It may also reduce yield. | 0.5 | h | m |
| Reduce N fertiliser | Reduces N in the system and therefore reduces $N_2O$ emissions. It may also reduce yield | 0.5 | h | l |
| Improving land drainage | Improving drainage reduces $N_2O$ emissions because the soil is drier. The yield may be improved and thus more uptake of N from the system. | 1 | m | m |
| Avoiding N excess | Reducing N application in areas where is applied in excess reduces N in the system and therefore reduces $N_2O$ emissions. | 0.4 | h | m |
| Full allowance of manure N supply | 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. In addition, the manure N is more likely to be applied when the crop is going to make use of the N, and therefore $N_2O$ emissions will be reduced. We have assumed that most of the species introduced would be legumes or possibly use N more efficiently | 0.4 | h | h |
| Species introduction (including legumes) | The species are either legumes (see comment regarding biological fixation for measure 38) or they are taking up more N from the system and therefore less available for $N_2O$ emissions | 0.5 | h | h |
| Improved timing of mineral fertiliser N application | Matching the timing of application with the time the crop will make most use of the fertiliser. Hence reduced the likelihood of $N_2O$ emissions. | 0.3 | h | m |

| | | | | |
|---|---|---|---|---|
| Controlled release fertilisers | Controlled release fertilisers supply N, usually in the urea form, at a progressive rate over 2-6months, more slowly than conventional fertilisers. This progressive, slow release of mineral N ensures that microbial conversion of the mineral N in soil to nitrous oxide and ammonia is reduced. It is assumed that the fertiliser releases N at the promised rate, and that the rate of release does not go up due to unusual circumstances such as heavy rain, warm weather, trampling by animals | 0.3 | h | m |
| Nitrification inhibitors | Nitrification inhibitors slow the rate of conversion of fertiliser ammonium to nitrate. This means that the rate of reduction of nitrate to nitrous oxide (or dinitrogen) is decreased and emissions of nitrous oxide decrease. It is assumed that the inhibitor makes good contact with the fertiliser or urine patch to be effective, and that the inhibitor will be applied at the right time and to the right fertiliser type. | 0.3 | h | l |
| Improved timing of slurry and poultry manure application | Applying the N when and where the crop requires it. Reduces the likelihood of $N_2O$ emissions as there is a better match of supply and demand | 0.3 | h | h |
| Adopting systems less reliant on inputs (nutrients, pesticides etc) | This is akin to moving from conventional production system, to a LEAF farm type of system, with reduced input of pesticides, nutrients etc) | 0.2 | m | h |
| Plant varieties with improved N-use efficiency | Adopting new plant varieties that can produce the same yields using less N | 0.2 | h | m |
| Separate slurry applications from fertiliser applications by several days | Applying slurry and fertiliser together because easily degradable compounds in the slurry and increased water contents can greatly increase the denitrification of available N and thereby the emission of nitrous oxide. It is assumed that weather conditions allow separation of the applications, that slurry can be stored before spreading or is available for spreading at the appropriate time. | 0.1 | h | l |

| | | | | |
|---|---|---|---|---|
| Reduced tillage / No-till | Not tillage, and to a lesser extent, minimum (shallow) tillage store carbon in soils because of decrease rates of oxidation. The lack of disturbance by tillage can also increase the rate of oxidation of methane from the atmosphere. It is assumed that nitrous oxide emissions are not increased due to concentration of microbial activity and nitrogen fertiliser near the surface and due to increase soil wetness associated with the greater compactness of the soil, and that crop growth and hence net primary productivity is not reduced by use of these techniques. | 0.15 | h | m |
| Use composts, straw-based manures in preference to slurry | Composts provide a more steady release of N than slurries which increase soil moisture content and provide a source of easily degradable products which increase microbial demand. Both these increase anaerobic conditions and thereby loss of nitrous oxide which is avoided by use of composts. Composts also have a higher C:N ratio so that released N is more likely to be immobilised temporarily and thereby reduce $N_2O$ emissions. It is assumed that composts contain enough N to provide fertiliser, and that the composts will not immobilise soil or fertiliser N and reduce crop productivity. | 0.1 | h | m |
| *Notes*<br>1. This value is averaged across all sectors. C mitigation is restricted to on farm reduction without accounting for C input to fertiliser manufacture etc.<br>2. Mode of the experts ranking of their agreement with the estimate of the measures abatement rate (high, medium, low, don't know)<br>3.Mode of the experts ranking of the uncertainty regarding the abatement rate of this measure (high, medium, low, don't know) | | | | |

## Annex D4 Assumptions used in calculating the costs of measures

| | | Private costs | | Private benefits | | | | |
|---|---|---|---|---|---|---|---|---|
| **Measure** | **Lifetime of measure** | **One off** | **Recurring** | **One off** | **Recurring** | **Timing of GHG abatement** | **Durability** | **Description of ancillary costs/benefits** |
| Using biological fixation to provide N inputs (clover) | Annual | 0 | Yield reduced by 30% | 0 | N purchase cost reduced by 60%; labour and machine costs reduced by 5% | immediate | permanent | |
| Reduce N fertiliser | Annual | 0 | Yield reduced by 20% | 0 | N purchase costs reduced by 30%; labour and machine costs reduced by 5% | immediate | permanent | Reduced N loss |
| Improving land drainage | 20 years | From Beaton *et al* (2007): £1850/ha to build, then £250/ha every 5 years to clean | 0 - maintenance costs low | 0 | Increased yield of 10% | immediate | 20 years | Improved plant growth, reduces denitrification |
| Avoiding N excess | Annual | 0 | no yield reduction | 0 | N purchase costs reduced by 10%, N limit reduced by 10% | immediate | permanent | Reduced N loss |
| Full allowance of manure N supply | Annual | 0 | 0 | 0 | Reduce N purchase costs by 15% | immediate | permanent | |
| Species introduction (including legumes) | Annual | 0 | Possibly an extra sowing so mech and labour costs increased by 5%; yields reduced by 7% | 0 | reduction in N purchase costs by 10% | immediate | permanent | improved soil condition |
| Controlled release fertilisers | annual | 0 | Fertiliser purchase costs increased by 50% | 0 | Yield increase 2% (Ball *et al*. 2004); half the number of applications - so machine and labour | immediate | permanent | reduces nitrate leaching |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | reduced by 5% |  |  |  |
| Nitrification inhibitors | Annual | 0 | Fertiliser purchase costs increased by 50% | 0 | Yield increase of 2%; machine and labour reduced by 5% | immediate | permanent |  |
| Improved timing of mineral fertiliser N application | Annual | 0 | 0 | 0 | Small yield increase (~5%); no N reductions | immediate | permanent |  |
| Improved timing of slurry and poultry manure application | Annual | 0 | 0 | 0 | Small yield increase (~3%); no N reductions | immediate | permanent |  |
| Adopting systems less reliant on inputs (nutrients, pesticides etc) | Annual | 0? | Yield down by 10% | 0 | N purchase costs reduced by 25% | immediate | permanent | Like becoming a LEAF farm - various effects |
| Plant varieties with improved N-use efficiency | Annual | 0 | Yield unaffected | 0 | N purchase costs down 30% | immediate | permanent | Risk of loss of grain quality |
| Separate slurry applications from fertiliser applications by several days | Annual | 0 | Yield unaffected | 0 | 0 | immediate | permanent |  |
| Reduced tillage / No-till | 20 | £20,000 for a power harrow, lifespan 20 years (Beaton *et al* 2007, p252) | 0 | 0 | Overall cultivation costs (spraying, ploughing, drilling, harvesting etc) reduced by 16% (Ball 1985, p40) | immediate | permanent |  |
| Use composts, straw-based manures in preference to slurry | Annual | 0 | 0 | 0 | 0 | immediate | permanent |  |
| *Note the yield effects estimates are rough averages across grassland and cropland.* |  |  |  |  |  |  |  |  |

## Annex E4 Cost and stand-alone cost-effectiveness

| | | Weighted mean cost (£/ha/y) | | | Stand alone CE (£/tCO2e) | | |
|---|---|---|---|---|---|---|---|
| **Measure** | Estimated abatement rate t CO2e/ha/y | 2012 | 2017 | 2022 | 2012 | 2017 | 2022 |
| Using biological fixation to provide N inputs (clover) | 0.5 | 16.42 | 40.71 | 43.27 | 16.42 | 40.71 | 43.27 |
| Reduce N fertiliser | 0.5 | 42.43 | 54.97 | 61.52 | 84.86 | 109.95 | 123.04 |
| Improved land drainage 3.5% | 1 | 37.57 | 32.78 | 14.12 | 37.57 | 32.78 | 14.12 |
| Improved land drainage 7% | 1 | 67.82 | 62.60 | 45.37 | 67.82 | 62.60 | 45.37 |
| Improved land drainage 7.5% | 1 | 72.23 | 66.62 | 47.72 | 72.23 | 66.62 | 47.72 |
| Avoiding N excess | 0.4 | -7.39 | -10.40 | -13.80 | -18.48 | -26.01 | -34.50 |
| Full allowance of manure N supply | 0.4 | -52.27 | -39.35 | -20.55 | -130.68 | -98.38 | -51.38 |
| Species introduction (including legumes) | 0.5 | 18.54 | 24.51 | 24.69 | 37.09 | 49.03 | 49.39 |
| Improved timing of mineral fertiliser N application | 0.3 | -17.76 | -23.32 | -32.43 | -59.21 | -77.74 | -108.08 |
| Controlled release fertilisers | 0.3 | 25.00 | 30.12 | 47.56 | 83.33 | 100.40 | 158.54 |
| Nitrification inhibitors | 0.3 | 25.00 | 30.12 | 47.56 | 83.33 | 100.40 | 158.54 |
| Improved timing of slurry and poultry manure application | 0.3 | -8.40 | -15.71 | -21.48 | -28.00 | -52.35 | -71.59 |
| Adopting systems less reliant on inputs (nutrients, pesticides etc) | 0.2 | 18.38 | 18.80 | 17.26 | 91.92 | 94.00 | 86.28 |
| Plant varieties with improved N-use efficiency | 0.2 | -6.35 | -10.66 | -14.32 | -31.75 | -53.31 | -71.60 |
| Separate slurry applications from fertiliser applications by several days | 0.1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Reduced tillage / No-till 3% | 0.15 | 71.00 | -13.00 | -65.00 | 236.67 | -43.33 | -216.67 |
| Reduced tillage / No-till 7% | 0.15 | 111.00 | 28.00 | -24.00 | 370.00 | 93.33 | -80.00 |
| Reduced tillage / No-till 7.5% | 0.15 | 117.00 | 34.00 | -18.00 | 390.00 | 113.33 | -60.00 |
| Use composts, straw-based manures in preference to slurry | 0.1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

## **Annex F4** **Table of interaction factors, assuming 50% overlap**

| **Measures interaction factors** | | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Using biological fixation to provide N inputs (clover) | a | 1 | 0.55 | 0.7 | 0.55 | 0.9 | 0.5 | 0.55 | 0.55 | 0.62 | 0.9 | 0.65 | 1 | 0.55 | 1 | 1 |
| Reduce N fertiliser | b | 0.55 | 1 | 0.7 | 0.55 | 0.9 | 0.5 | 0.9 | 0.75 | 0.75 | 0.9 | 0.65 | 1 | 0.9 | 0.9 | 0.9 |
| Improving land drainage 3.5% | c | 0.7 | 0.7 | 1 | 0.9 | 0.9 | 1.05 | 1 | 1 | 1.05 | 1.05 | 1 | 1 | 1 | 1.1 | 1 |
| Avoiding N excess | d | 0.55 | 0.55 | 0.9 | 1 | 0.9 | 0.5 | 0.9 | 0.75 | 0.75 | 0.9 | 0.65 | 1 | 0.9 | 0.9 | 0.9 |
| Full allowance of manure N supply | e | 0.9 | 0.9 | 0.9 | 0.9 | 1 | 0.75 | 0.6 | 0.6 | 1 | 0.55 | 0.55 | 1 | 0.6 | 0.75 | 1 |
| Species introduction (including legumes) | f | 0.5 | 0.5 | 1.05 | 0.5 | 0.75 | 1 | 0.9 | 0.9 | 0.9 | 0.9 | 0.75 | 0.85 | 1 | 1 | 1 |
| Improved timing of mineral fertiliser N application | g | 0.55 | 0.9 | 1 | 0.9 | 0.6 | 0.9 | 1 | 0.95 | 1 | 1 | 0.9 | 1 | 0.6 | 1.05 | 1 |
| Controlled release fertilisers | h | 0.55 | 0.75 | 1 | 0.75 | 0.6 | 0.9 | 0.95 | 1 | 0.75 | 0.9 | 0.75 | 0.9 | 0.75 | 0.9 | 0.9 |
| Nitrification inhibitors | I | 0.62 | 0.75 | 1.05 | 0.75 | 1 | 0.9 | 1 | 0.75 | 1 | 0.9 | 0.75 | 1 | 1 | 0.9 | 0.9 |
| Improved timing of slurry and poultry manure application | j | 0.9 | 0.9 | 1.05 | 0.9 | 0.55 | 0.9 | 1 | 0.9 | 0.9 | 1 | 0.75 | 1 | 0.6 | 0.5 | 0.75 |
| Adopting systems less reliant on inputs (nutrients, pesticides etc) | k | 0.65 | 0.65 | 1 | 0.65 | 0.55 | 0.75 | 0.9 | 0.75 | 0.75 | 0.75 | 1 | 1 | 0.75 | 0.5 | 0.75 |
| Plant varieties with improved N-use efficiency | l | 1 | 1 | 1 | 1 | 1 | 0.85 | 1 | 0.9 | 1 | 1 | 1 | 1 | 0.9 | 0.9 | 0.9 |
| Separate slurry applications from fertiliser applications by several days | m | 0.55 | 0.9 | 1 | 0.9 | 0.6 | 1 | 0.6 | 0.75 | 1 | 0.6 | 0.75 | 0.9 | 1 | 1.05 | 0.75 |
| Reduced tillage / No-till 3% | n | 1 | 0.9 | 1.1 | 0.9 | 0.75 | 1 | 1.05 | 0.9 | 0.9 | 0.5 | 0.5 | 0.9 | 1.05 | 1 | 0.5 |
| Use composts, straw-based manures in preference to slurry | o | 1 | 0.9 | 1 | 0.9 | 1 | 1 | 1 | 0.9 | 0.9 | 0.75 | 0.75 | 0.9 | 0.75 | 0.5 | 1 |

## Annex G4 Results

### Table 4.6 Crops and Soils Measures Central Feasible Potential, 2012, 3.5% discount rate

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| AE | Crops-Soils-FullManure | 388.53 | -124.99 | 0.389 |
| AG | Crops-Soils-MineralNTiming | 192.50 | -94.38 | 0.581 |
| AJ | Crops-Soils-OrganicNTiming | 158.01 | -48.70 | 0.739 |
| AL | Crops-Soils-ImprovedN-UsePlants | 101.76 | -30.37 | 0.841 |
| AD | Crops-Soils-AvoidNExcess | 85.68 | -24.24 | 0.926 |
| AO | Crops-Soils-UsingComposts | 43.85 | 0.00 | 0.970 |
| AM | Crops-Soils-SlurryMineralNDelayed | 12.57 | 0.00 | 0.983 |
| AC | Crops-Soils-Drainage | 443.17 | 42.25 | 1.426 |
| AI | Crops-Soils-Nis | 207.90 | 124.96 | 1.634 |
| AF | Crops-Soils-SpeciesIntro | 92.33 | 145.36 | 1.726 |
| AH | Crops-Soils-ControlledRelFert | 51.42 | 505.20 | 1.778 |
| AB | Crops-Soils-ReduceNFert | 42.27 | 1,269.44 | 1.820 |
| AK | Crops-Soils-SystemsLessReliantOnInputs | 5.63 | 2,361.94 | 1.826 |
| AA | Crops-Soils-BiolFix | 2.40 | 5,419.00 | 1.828 |
| AN | Crops-Soils-ReducedTill | 2.58 | 6,743.54 | 1.831 |

**Table 4.7 Crops and Soils Measures Central Feasible Potential 2017, 3.5% discount rate**

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---:|---:|---:|
| AE | Crops-Soils-FullManure | 892.77 | -94.09 | 0.893 |
| AG | Crops-Soils-MineralNTiming | 445.29 | -123.93 | 1.338 |
| AJ | Crops-Soils-OrganicNTiming | 364.20 | -91.05 | 1.702 |
| AL | Crops-Soils-ImprovedN-UsePlants | 238.36 | -50.99 | 1.941 |
| AN | Crops-Soils-ReducedTill | 32.59 | -233.92 | 1.973 |
| AD | Crops-Soils-AvoidNExcess | 178.00 | -37.90 | 2.151 |
| AO | Crops-Soils-UsingComposts | 50.63 | 0.00 | 2.202 |
| AM | Crops-Soils-SlurryMineralNDelayed | 30.41 | 0.00 | 2.232 |
| AC | Crops-Soils-Drainage | 1,121.99 | 33.51 | 3.354 |
| AI | Crops-Soils-Nis | 432.61 | 167.28 | 3.787 |
| AF | Crops-Soils-SpeciesIntro | 212.21 | 192.17 | 3.999 |
| AH | Crops-Soils-ControlledRelFert | 107.00 | 676.32 | 4.106 |
| AB | Crops-Soils-ReduceNFert | 87.82 | 1,827.36 | 4.194 |
| AK | Crops-Soils-SystemsLessReliantOnInputs | 6.47 | 4,831.12 | 4.200 |
| AA | Crops-Soils-BiolFix | 5.46 | 13,435.29 | 4.206 |

**Table 4.8 Crops and Soils Measures Central Feasible Potential 2022, 3.5% discount rate**

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| AG | Crops-Soils-MineralNTiming | 1,150.39 | -103.38 | 1.150 |
| AJ | Crops-Soils-OrganicNTiming | 1,027.16 | -68.48 | 2.178 |
| AE | Crops-Soils-FullManure | 457.26 | -148.91 | 2.635 |
| AN | Crops-Soils-ReducedTill | 55.77 | -1,052.63 | 2.691 |
| AL | Crops-Soils-ImprovedN-UsePlants | 331.80 | -76.10 | 3.022 |
| AD | Crops-Soils-AvoidNExcess | 276.06 | -50.29 | 3.298 |
| AO | Crops-Soils-UsingComposts | 78.51 | 0.00 | 3.377 |
| AM | Crops-Soils-SlurryMineralNDelayed | 47.17 | 0.00 | 3.424 |
| AC | Crops-Soils-Drainage | 1,741.02 | 14.44 | 5.165 |
| AF | Crops-Soils-SpeciesIntro | 365.98 | 174.22 | 5.531 |
| AI | Crops-Soils-Nis | 603.67 | 293.50 | 6.135 |
| AH | Crops-Soils-ControlledRelFert | 165.90 | 1,067.95 | 6.301 |
| AB | Crops-Soils-ReduceNFert | 136.20 | 2,045.10 | 6.437 |
| AK | Crops-Soils-SystemsLessReliantOnInputs | 10.05 | 4,434.34 | 6.447 |
| AA | Crops-Soils-BiolFix | 8.49 | 14,280.16 | 6.455 |

**Table 4.9 Crops and Soils Measures High Feasible Potential 2022, 3.5% discount rate**

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| AG | Crops-Soils-MineralNTiming | 2,172.95 | -103.38 | 2.173 |
| AJ | Crops-Soils-OrganicNTiming | 1,940.19 | -68.48 | 4.113 |
| AE | Crops-Soils-FullManure | 863.71 | -148.91 | 4.977 |
| AN | Crops-Soils-ReducedTill | 114.02 | -1,052.63 | 5.091 |
| AL | Crops-Soils-ImprovedN-UsePlants | 678.34 | -76.10 | 5.769 |
| AD | Crops-Soils-AvoidNExcess | 521.45 | -50.29 | 6.291 |
| AO | Crops-Soils-UsingComposts | 160.52 | 0.00 | 6.451 |
| AM | Crops-Soils-SlurryMineralNDelayed | 89.11 | 0.00 | 6.540 |
| AC | Crops-Soils-Drainage | 3,559.42 | 14.44 | 10.100 |
| AF | Crops-Soils-SpeciesIntro | 748.23 | 174.22 | 10.848 |
| AI | Crops-Soils-Nis | 1,140.27 | 293.50 | 11.988 |
| AH | Crops-Soils-ControlledRelFert | 313.37 | 1,067.95 | 12.302 |
| AB | Crops-Soils-ReduceNFert | 257.26 | 2,045.10 | 12.559 |
| AK | Crops-Soils-SystemsLessReliantOnInputs | 20.55 | 4,434.34 | 12.579 |
| AA | Crops-Soils-BiolFix | 17.36 | 14,280.16 | 12.597 |

**Table 4.10 Crops and Soils Measures Low Feasible Potential 2022, 3.5% discount rate**

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| AG | Crops-Soils-MineralNTiming | 460.15 | -103.38 | 0.460 |
| AJ | Crops-Soils-OrganicNTiming | 410.86 | -68.48 | 0.871 |
| AE | Crops-Soils-FullManure | 182.90 | -148.91 | 1.054 |
| AN | Crops-Soils-ReducedTill | 15.49 | -1,052.63 | 1.069 |
| AL | Crops-Soils-ImprovedN-UsePlants | 132.72 | -76.10 | 1.202 |
| AD | Crops-Soils-AvoidNExcess | 110.43 | -50.29 | 1.313 |
| AO | Crops-Soils-UsingComposts | 12.21 | 0.00 | 1.325 |
| AM | Crops-Soils-SlurryMineralNDelayed | 18.87 | 0.00 | 1.344 |
| AC | Crops-Soils-Drainage | 270.83 | 14.44 | 1.614 |
| AF | Crops-Soils-SpeciesIntro | 56.93 | 174.22 | 1.671 |
| AI | Crops-Soils-Nis | 93.90 | 293.50 | 1.765 |
| AH | Crops-Soils-ControlledRelFert | 25.81 | 1,067.95 | 1.791 |
| AB | Crops-Soils-ReduceNFert | 21.19 | 2,045.10 | 1.812 |
| AK | Crops-Soils-SystemsLessReliantOnInputs | 1.56 | 4,434.34 | 1.814 |
| AA | Crops-Soils-BiolFix | 1.32 | 14,280.16 | 1.815 |

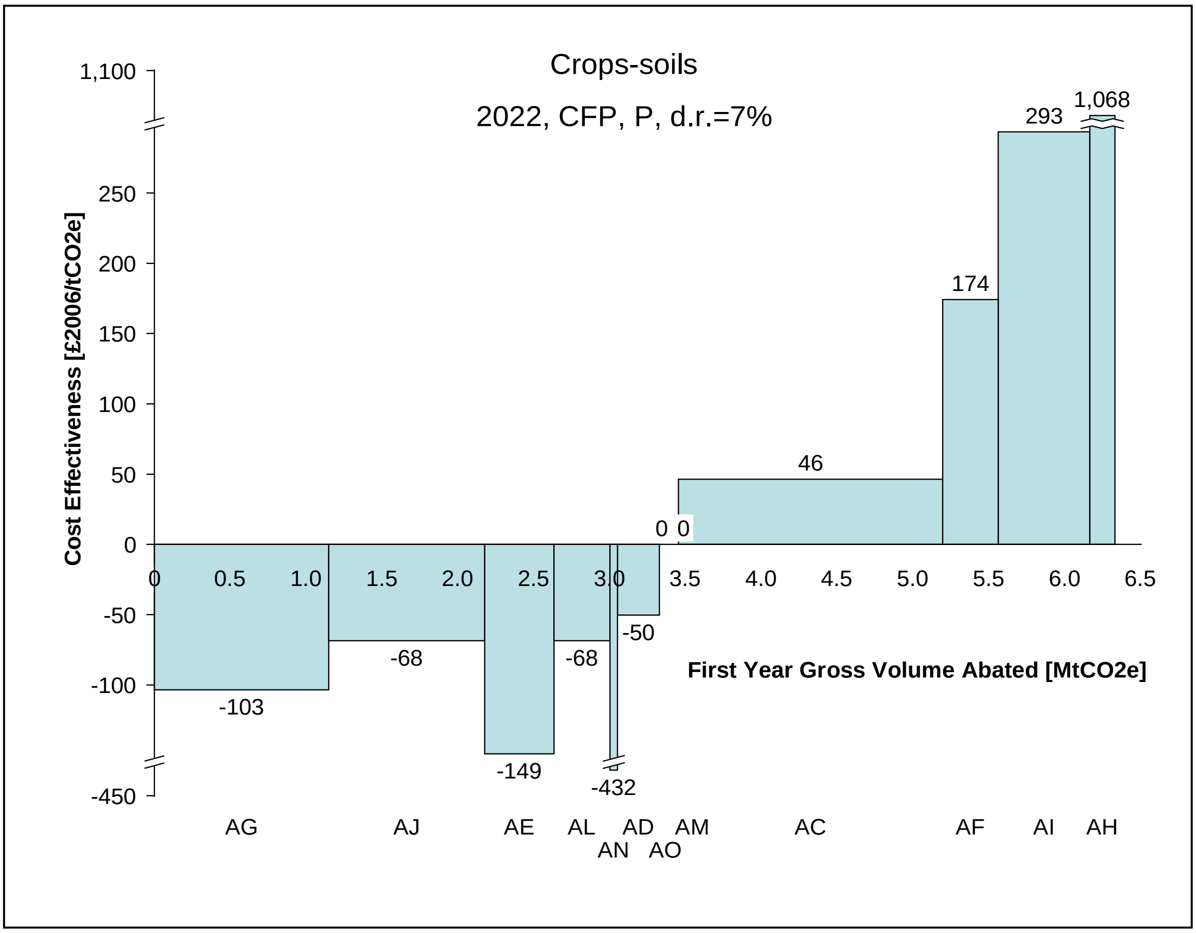

**Figure 4.2 Crops and soils MACC, Central Feasible Potential 2022, private discount rate**

Measures with CE>£2000/tCO$_2$e - i.e. AB, AK, AA - not included in the curve

Key

AA: Using biological fixation to provide N inputs (clover)
AB: Reduce N fertiliser
AC: Improved land drainage 3.5%
AD: Avoiding N excess
AE: Full allowance of manure N supply
AF: Species introduction (including legumes)
AG: Improved timing of mineral fertiliser N application
AH: Controlled release fertilisers
AI: Nitrification inhibitors
AJ: Improved timing of slurry and poultry manure application
AK: Adopting systems less reliant on inputs (nutrients, pesticides etc)
AL: Plant varieties with improved N-use efficiency
AM: Separate slurry applications from fertiliser applications by several days
AN: Reduced tillage / No-till
AO: Use composts, straw-based manures in preference to slurry

## Annex H4 "Get Ranking"

Factors.txt: measure interaction factors; the matrix should be symmetric

Parameters.txt:

'Abatement': /unit averaged annual lifetime AP (tCO2e/unit/y) OR /unit total lifetime AP (tCO2e/unit)
'Volume': total averaged annual lifetime AP (tCO2e/y) OR total lifetime AP (tCO2e) - needed to calculate the number of units
'Cost': /unit averaged annual lifetime NPV (£2006/unit/y) OR /unit lifetime NPV (£2006/unit); negative values mean cost, positive ones savings - ? Surely should be other way round?

*What does the program do?*
1 calculates the number of units, total cost and cost effectiveness values
2 identifies those with negative costs (=savings)
3 ranks negative ones
3a chooses that one with smallest total cost (largest absolute value of total cost, i.e. highest total savings)
3b multiplies all the rest's abatement potentials (including positive ones) with the factors, recalculates cost-effectiveness (multiplying the APs of all the remaining ones by the relevant interaction factors, to get a (generally) reduced AP)
3c chooses the second highest saving
3d multiplies all the rest's APs with the factors, recalculates cost-effectiveness
3e etc - for negatives
4 ranks positive (and zero) ones
4a chooses the one wih smallest cost effectiveness (cheapest option)
4b multiplies all the rest's APs with the factors, recalculates cost-effectiveness
4c chooses the second lowest cost-effectiveness
4d multiplies all the rest's APs with the factors, recalculates cost-effectiveness
5 creates output table

## Annex I4 Crops/Soils Measures Expert Group

Dr Bob Rees
Senior Soil Scientist
Crops and Soils Group
SAC

Dr Kairsty Topp
Agricultural Systems Modeller
Land Economy and Environment Group
SAC

Dr Bruce Ball
Senior Researcher (Soil Science)
Crops and Soils Group
SAC

Dr Steve Hoad
Researcher (Cereals)
Crops and Soils Group
SAC

# 5 Mitigation options from livestock

## 5.1 Key Findings

*Total abatement potential ($MtCO_2e/y$) at a cost of <=£100/$tCO_{2e}$, 3.5%, social metric*

| *Potential* | *2012* | *2017* | *2022* |
|---|---|---|---|
| *High feasible* | | | 5.02 |
| *Central feasible* | 0.635 | 1.594 | 2.68 |
| *Low feasible* | | | 1.266 |

The feasible potentials in 2022 were estimated to range from 1.266 - 5.02$MtCO_2e$, i.e. an annual abatement of approximately 1.266 - 5.02$MtCO_2e$ could be achieved in the livestock sub-sector at a cost of <=£25/t by 2022. The measures needed to achieve this abatement are the same in each case, they are:

- Beef Animal-Ionophores
- BeefAn-Improved Genetics
- DairyAn-Improved Productivity
- DairyAn-Ionophores
- DairyAn-Improved Fertility
- DairyAn-Maize Silage
- On farm anaerobic digestion (OFAD)-PigsLarge
- OFAD-BeefLarge
- OFAD-PigsMedium
- Central anaerobic digestion (CAD)-Poultry-5MW
- OFAD-DairyLarge
- OFAD-BeefMedium
- OFAD-DairyMedium

The central feasible potential of 2.68 $MtCO_2e$ represents around 5 % of the 2005 UK agricultural GHG emissions. The NAEI reported the 2005 GHG emissions from agriculture as 44.733 $MtCO_2e$ (excluding LUC) of which approximately 44% were due to enteric fermentation in ruminants and manure management). It should be noted that the NAEI figures are based on the national inventory reporting of GHG emissions. Due to the nature of inventory reporting, not all of the abatement potential reported in this study would be reflected in the current inventory mechanisms. Although proportion reflected in the current inventory reporting framework varies across options, approximately 50% of the reported abatement potential would be reflected in national inventory reporting.

As in the case of crop and soil abatement potential interactions can reduce the abatement potential of some succeeding measures, many livestock options are cancelled out due to incompatibility. These findings need to be treated with some caution as the results are contingent on a series of assumptions that are outlined in this section.

This chapter focuses on applying options within the livestock sector with the aim of reducing emissions from livestock production in the UK. Some of the options includes options that may rely on using arable land to support livestock feed requirements. Therefore there is a risk of displacing some emissions, given competition with arable land for feed options, but that yield from livestock if anything may be increased

Bio (anaerobic) digestion have been considered in this sector, in that managing the manure of animals in this manner reduces the GHG emissions associated with the usual manner of storing manure. There could be further benefit on these types of measures as power is generated and therefore displaces some of the emissions in wider power generation.

Although not considered in the economic appraisal of the efficiency of mitigation options from livestock some of the options that show a favourable effect on GHG emissions and are shown to be cost effective may also have ancillary impacts (positive and negative) that need to be considered, particularly regarding animal welfare.

## 5.2 Background

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 digestion in slurry storage. 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.

## 5.3 Prioritisation of abatement options examined

A review of the literature highlighted a vast array of abatement options from the livestock industry (Annex A5), 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 5.1 and detailed below.

**Table 5.1 List of applicable livestock abatement options studied in this report**

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

## 5.4 Methodology for estimating the abatement potential and cost-effectiveness of mitigation options from livestock

Information on the abatement potential of each option studied was reviewed. There have been many studies examining various abatement options, examining different aspects of their application, efficacy and/or cost effectiveness. Some of the abatement options studied herein have used some base assumptions as quoted in the IGER study on cost curve assessments of mitigation options (IGER, 2001). A wider literature review was also conducted to ensure that the estimates fell within other studies and on the whole they were. However, with many of these options there will be differences in the reported effects due to differences in experimental protocol, site effects, dose effects, animal variation, which means that the range can be far wider than for more established and widely applied methods.

The input information required for each abatement option included the efficiency of the abatement options (i.e., reduction on $CH_4$ per animal), the applicability (the maximum percentage of animals to which the abatement options could be applied), the effect on productivity, if any (i.e., percentage dis/improvement in production with the application of the abatement options), and/or the effect on feed intake. Other input data were adoption rates and animal numbers from BAU3, IPCC emission factors, manure storage capacities and proportions of manure handled in different systems, efficiency data for anaerobic digestion plants, lifetimes of each measure and relevant cost data.

A productivity effect was applied when dealing with dairy animal abatement options, in that it was assumed an improvement in dairy yield would result in a reduction in the total number of animals under a quota scenario. The converse was also true such that if an abatement option reduced production (mode of action was directly on reducing methane emissions) then the number of dairy cows would increase to obtain the previous level of milk output. This was only applied in the dairy scenario.

For beef it was assumed that producers would increase production output if output were improved with a particular abatement option. The calculation of abatement potential and associated costs was detailed in the spreadsheet to ensure that changes to the expected impact of an option would update results automatically. A brief summary of the assumptions in the livestock animal measures is given in Table 5.6 and of manure management options in Table 5.7.

**Table 5.2 Description of the "direct" and "indirect" costs associated with dairy animal abatement measures**

| | Direct | Indirect | Notes |
|---|---|---|---|
| Concentrate | Switching to higher concentrate content in the diet | Fewer animals to maintain through the year | Concentrate cost linked to cereal price forecast |
| Maize silage | Switching maize for grass silage | “” | |
| Propionate | Annual admin cost | “” | |
| Probiotics | Annual admin cost | “” | |
| Ionophores | Annual admin cost | “” | |
| Bovine Somatatrophin | Annual admin cost | “” | |
| Genetic improvement in production traits | Free | “” | |
| Genetic improvement in fertility traits | Free | “” | |
| Transgenic offspring | Estimated cost offspring of transgenic parents | “” | Capital cost with lifetime of 5 years |

**Table 5.3 Description of the "direct" and "indirect" costs associated with beef animal abatement measures**

| | Direct | Indirect | Notes |
|---|---|---|---|
| Concentrate | Switching to higher conc content diet | Increase income from increased yield | Concentrate cost linked to cereal price forecast |
| Propionate | Annual admin cost | “” | |
| Probiotics | Annual admin cost | “” | |
| Ionophores | Annual admin cost | “” | |
| bSt | Annual admin cost | “” | |
| Gen imp – prod$^n$ | Free | “” | |
| Transgenic offsp | Est. cost offspring of transgenic parents | “” | Cap. cost with lifetime of 5 yrs |

The cost of implementing each animal management abatement option was estimated using the annual cost of administering the abatement option per treated animal 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. For dairy cattle, the cost-effectiveness also accounted for the reduction in overall annual costs by reducing the cow herd size at a fixed level of output if the abatement option improved productivity. The animal numbers for current and the future time points were taken from mapped BAU3 livestock numbers described earlier. The baseline annual $CH_4$ emissions (enteric fermentation and manure) from a particular livestock industry were calculated using IPCC Tier 1 methodologies. For beef cattle the cost of implementing an abatement option considered the direct costs of application of the options as well as any indirect benefit that may accrue from increased production output through increased volume of meat sales. Costs were considered at 2006 prices (adjusted from reported values). A description of the costs assumed are given in Table 5.2 for dairy, Table 5.3 for beef and Table 5.7 for manure management options with the actual costs assumed in the three budget periods in Annex B5.

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 livestock options were developed in line with those for other agricultural sectors. This included the use of the BAU3 estimates of livestock numbers such that each measure was applied to the number of livestock in 2012, 2017 and 2022. The assumed technical potential and feasibility levels for livestock and manure management options also follow the values earlier in this report based on uptake and compliance rates. The uptake/compliance rates were applied based on costs for each abatement option (i.e., positive or negative) and if the measure was assumed to be difficult or easy to enforce (see earlier section for further details). Some of the livestock measures may never be applicable in all livestock systems (e.g., use of feed additives is unlikely to become allowable in organic herds). This is not reflected in the uptake/compliance rates per say but it was assumed that these abatement options were only applicable to a proportion of the livestock population (e.g., 90% applicability of bovine somatatrophin in dairy). Uptake levels for anaerobic digestion options are set for central, high and low feasible potentials for 2022 at 45%, 75% and 30%, respectively. For 2008 0% uptake was assumed, and for the years in between the same linear adoption function was set up to calculate the uptake rates as was used for other livestock options.

Each of the abatement potentials and their cost-effectiveness was first studied on a stand alone basis. However, it is unlikely that all measures studied will work effectively together (e.g., there is no way of applying a manure management strategy such as covering tanks if central or on farm anaerobic digestion is taking place). On the other hand some of the abatement options may be complementary and can be applied simultaneously (e.g., genetic improvement and dietary modifications). There has been little work done on the effects of combined measures in livestock systems. Therefore in this study interactions between livestock measures were assumed to be either 0 or 1, such that 0 meant that the pair wise combination of measures could not be applied simultaneously and 1 meant that measures could be applied simultaneously and the effects could be additive. Taking interactions into consideration resulted in a much shorter list of options than the original, stand alone list.

## 5.5 Modifications to the diet and dietary supplementation

Methane emissions from ruminant species can be reduced by replacing the roughage proportion of the diet with concentrates (e.g., Blaxter and Claperton, 1965). A higher concentrate diet may increase the methane produced by an individual animal but will, however, reduce the amount of methane produced per unit of product. Animals fed a concentrate based diet tend to produce more (e.g., higher milk yields in dairy cattle) and/or reach final weight faster (i.e., meat sheep and cattle reach slaughter weight at a younger age). Overall, the impact of this is that fewer animals are required and meat animals are kept for a shorter period thereby reducing emissions at a fixed output level.

It is important to note that ruminant species can convert plant products unusable by humans into a usable protein source. There will be an increasing conflict between using cereals and the arable land for feeding animals with food for humans and or the production of fuel crops. There is also the side effect that production of industrial concentrates is energy-intensive and could lead to increased emissions of $CO_2$ and $N_2O$ from increased fertiliser production and application throughout the entire production chain.

*Option 1: Increase the proportion of high starch concentrates in the diet*

Estimates of the impact on production for dairy of using high starch feeds in the diet were obtained from the IGER study (IGER, 2001). The IGER study (2001) extrapolated the impact of methane emissions and milk yield when standard concentrate ration in the diet was replaced with a high starch concentrate and when the amount of concentrate was doubled at the expense of silage using simulation models (Mills *et al*., 2001). The outcome of the model estimated that milk yield would increase by 14% while $CH_4$ emissions decrease by 7% (Table 5.4). These values were used to estimate the abatement potential of increasing starch content of diary diet.

**Table 5.4 Effect of increasing starch content of the diet in dairy cattle (IGER, 2001)**

| | Standard diet | High starch diet | Diff | % Diff |
|---|---|---|---|---|
| Intake (dry matter) | 15 | 15 | | |
| Milk yield (kg) | 21.76 | 24.71 | 2.95 | 13.56 |
| $CH_4$ (kg) | 16.84 | 15.73 | -1.11 | -6.59 |

The costs of changing the diet were also taken from the IGER study but adjusted to 2006 prices and then recalculated at each of the time points to account for increases in cereal prices (IGER, 2001). These were derived based on a fixed indoor feeding period of 205 days and the cost of changing the proportions of concentrates: grass silage: maize silage in the diet per animal per annum. Concentrate price was linked to the cereal forecast price assumed in the farm level modelling while grass and maize silage price was assumed at the 2006 level.

It is important to note with this option, that there may be competition for resources for components of a dairy/beef concentrate diet into the future, in that grain may be required for human diets, for monogastric feed and potentially for fuel. It should also be noted that there could be some life cycle emissions not considered by examining the direct effect of this option on animal emissions only (e.g., energy required for production of concentrates, management of crops for diets). This option was studied for beef and dairy cattle.

*Option 2 Increase the proportion of maize silage in the diet*

Estimates of the impact on production for dairy of using high starch feeds in the diet were obtained from the IGER study (IGER, 2001). The study examined the impact of production and methane emissions if the proportion of grass: maize silage in the diet was changed from 3:1 to 1:3. The outcome of the model estimated a 7% increase in milk yield and a 2% increase in $CH_4$ production (Table 5.5). These values were used to estimate the abatement potential of increasing the proportion of maize silage in a typical dairy diet. The costs of switching to higher proportion of maize silage in the diet were estimated in a similar manner to Option 1. This option was studied for beef and dairy cattle.

**Table 5.5 Effect of increasing proportion of maize silage in the diet (IGER, 2001)**

| | Standard diet | High starch diet | Diff | % Diff |
|---|---|---|---|---|
| Intake (dry matter) | 15 | 15 | | |
| Milk yield (kg) | 21.76 | 23.23 | 1.47 | 6.75 |
| $CH_4$ (kg) | 16.84 | 17.14 | 0.3 | 1.78 |

*Option 3 Propionate precursors*

Hydrogen produced in the rumen through fermentation can react to produce either $CH_4$ or propionate. By adding propionate precursors (e.g., fumarate) to animal feed, more hydrogen is used to produce propionate and less $CH_4$ is produced. The effect of administering propionate precursors to animals (daily) on methane production is shown in Figure 5.1 (IGER, 2001). Reading from Figure x.1, increasing the percentage of propionate at the expense of acetate by 25% results in a 22.3% reduction in $CH_4$. These results are in line other quoted experimental studies (e.g., Ungerfield *et al.,* 2007) There is also a favourable effect on milk yield (15%). This option was studied for beef and dairy cattle. The costs assumed for this option are given in Annex B5 and are based on the feeding of propionate precursors to animals.

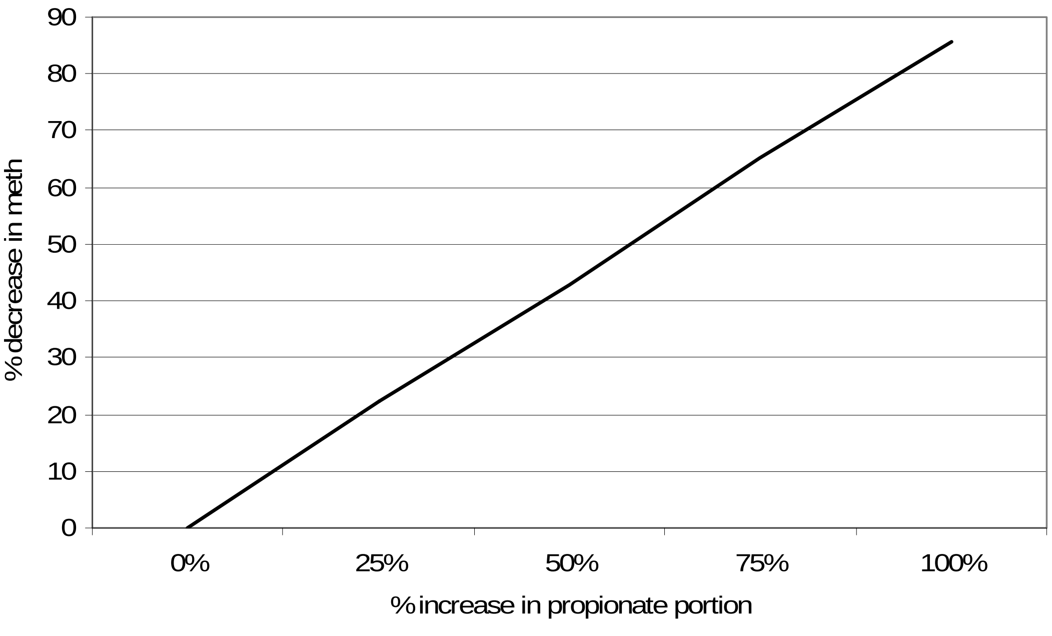

**Figure 5.1 Impact of increasing the proportion of propionate in the rumen on methane output (IGER, 2001).**

*Option 4 The use of probiotics*

Probiotics (have also been referred to as directly fed microbials, examples being *Saccheromyces cerevisiae* and *Aspergillus oryzae*) are used to divert hydrogen from methanogenesis towards acetogenesis in the rumen. This means that acetate: methane levels in the rumen are altered resulting in a reduction in the overall methane produced by enteric fermentation. There is an added benefit in that acetate is a source of energy for the animal and therefore can improve overall productivity of the animal. These additives can be used in diets with high grain content. There is variation in the extent to which probiotic additives reduce methane emission (van Nevel & Demeyer, 1995; Moss et al, 2000). The use of probiotics as an abatement option is estimated to reduce $CH_4$ production by 7.5% and improve production by 10%. This option was studied for beef and dairy cattle. The costs assumed for this option are given in Annex B5 and are based on the feeding probiotics to animals.

*Option 5 The use of ionophores*

Ionophore antimicrobials (e.g., monensin) are used to improve efficiency of animal production by decreasing the dry matter intake (DMI) and increasing performance and decreasing $CH_4$ production. It should be noted that the use of these additives are forbidden in the EU but they have been routinely used as a growth promoter in some non-EU countries. The effect of these types of feed additives on production and/or $CH_4$ output varies from study to study. The values used in this study are a 25% reduction in $CH_4$ production coupled with a 25% improvement in production (van Nevel & Demeyer, 1995). This option was studied for beef and dairy cattle. There have been some reports of potential unfavourable side-effects with the application of this treatment with an increase in metabolic disorders in the animal (McGuffey et al., 2001; Duffield et al., 2008). This option was studied for beef and dairy cattle. The costs assumed for this option are given in Annex B5 and are based on the feeding ionophores to animals

*Option 6. Bovine somatotrophin (bST)*

Administering bST to dairy cattle has been shown to increase milk production and has been used previously in various countries. This has also been shown to reduce $CH_4$ emissions (Bauman et al., 1985). In many cases, this option increases $CH_4$ emissions per animal but typically increases milk production sufficiently to lower emissions per unit of milk. The use of bST is widely unacceptable to European consumers. In this study it was assumed that bST would improve milk production by 17.5% and increase $CH_4$ production by 10%. This option was studied for beef and dairy cattle. The costs assumed for this option are given in Annex B5 and are based on treating animals with bSt.

### 5.6 Breeding for improved efficiency

Generally, selection for efficiency of production in livestock species will help to reduce emissions. In many cases this can be achieved simply through selection on production traits and traits related to the efficiency of the entire production system (e.g., fertility and longevity traits). The impact of selection on these traits is two fold

- Reducing the number of animals required to produce a fixed level of output: There has been an overall reduction of annual methane emissions (28% from

- Increasing the efficiency of production will help reduce the finishing period for meat animals, therefore reducing emissions per unit output. Hyslop (2003) demonstrated that efficiency of the beef production system was paramount in reducing the GHG emissions/unit output showing that intensive concentrate based systems produce the lowest emissions (note: this study did not consider the externalities of the system such as the carbon cost of producing concentrate diets). Further analyses of the data showed that there was also a significant breed difference suggesting that bigger continental breeds of cattle produced less emissions/unit output than the smaller British type breeds (Hyslop, 2003). This opportunity for switching breeds is not considered in this analysis, but may offer abatement potential. However, genetic improvement of beef animals is examined in this study and shows some of the abatement potential of improving the types of animals in a system on overall economic and environmental efficiency.

A recently completed Defra funded project (AC0204) modelled the effect of genetic improvement on emissions from UK livestock systems using Life Cycle Analysis. This study showed that historic genetic improvement in UK livestock species has had a favourable effect on the overall productivity of livestock species. It has also had a favourable associated effect on the reduction of emissions from many livestock species via improvements in efficiency of the production system. Improvement in livestock species has resulted in a 0.8-1.2% per annum decrease in emissions from species that readily adopt genetic improvements throughout the population (i.e., pigs, poultry and dairy cattle). However the impact of genetic improvement in beef cattle and sheep has a far lower penetration rate and the best genetics do not disseminate through all strata of the livestock population.

### *Option 7 Genetic improvement*

Genetic improvement was considered for beef and dairy animals. For dairy, 2 options were considered. First, current conventional genetic improvement was considered whereby milk production is expected to improve at a rate of 1.5% per annum (Simm, 1998). As genetic improvement, if carried out consistently, will lead to permanent and cumulative change in the population, it was assumed that production would continue to improve at a rate of 1.5% per annum. There was no associated effect on $CH_4$ emissions modelled, even though report to Defra (AC0204) that used life cycle analysis, assumed a favourable effect in the reduction of greenhouse gases of approximately 1% per annum. The method applied in the overall framework of examining abatement potential from dairy, accounts for a reduction in animal numbers with an improvement in milk production per cow. This will partly take account of some of the wider life cycle issues with examining the potential of genetic improvement. A second option for genetic improvement in dairy was considered, this time considering a shift in the emphasis of the national breeding goal from dairy cows to select animals with improved fertility. The study of Garnsworthy (2004) showed that if fertility was returned its level in 1995 enteric methane emissions from the milking herd would be reduced 11%. Using the results of Wall *et al* (2007) an index that would bring about this improvement in fertility over a 10 year period would result in a halving of the improvement in milk production. The impact of such a change of selection emphasis in UK dairy cattle was modelled.

As discussed earlier, the recently completed Defra funded project (AC0204) showed the potential impact of genetic improvement on overall GHG emissions within the sections of the national beef herd that adopts genetic improvement on data recording. The potential of the beef industry to reach this reduction is limited by the low uptake and use of genetic indices and data recording across the population. The impact of increasing the use of genetic improvement across a wider proportion of the beef herd was modelled by examining the difference between current low rates of uptake (10%) to a higher rate of uptake (50%). These values were simplified, with expert guidance, from the study of Amer et al. (2007).

The costs for use of genetic improvement tools was deemed to be zero as these tools are currently developed and calculated routinely for dairy and beef animals as part of the levy contribution and other supported funds. The effect of genetic improvement on $CH_4$ reduction and production improvement was cumulative over the time period studied such that an annual reduction potential of 1% would become 2% after two years. This cumulative effect would continue for as long at this measure was applied.

### *Option 8. Use of transgenic offspring*

Taking a longer term view of potential abatement options, it is possible to envisage that genetically modified livestock may be developed with desirable trait characteristics, one of which may include increased feed efficiency and therefore reduced greenhouse gas emissions. This scenario is highly speculative. It was assumed that directly genetically modified animals would not be used routinely in production of livestock products (meat and milk). However, the offspring of genetically modified/transgenic animals, via the use of semen and/or embryos of genetically modified animals, may have some potential applicability to the production of livestock products. It was assumed that the offspring of animal(s) genetically modified would be more efficient and would produce 20% less $CH_4$ and 10% more milk. The cost of administration was estimated based on the current value of a high genetic merit dairy animal. This option was examined for dairy only. This is assumed to be an expensive option as the cost of a high genetic merit animal is high as the production potential of the animal is high relative to an average animal. It is hard to estimate the cost of the a transgenic animal as it is mainly an experimental process. However this may change with time and maybe a mitigation option in the medium to long term.

**Table 5.6 Summary of the abatement potential assumptions for animal management options of dairy cows.***

| | Production improvement (%) | $CH_4$ reduction (%) | Notes |
|---|---|---|---|
| Concentrate | 14 | 7 | |
| Maize silage | 7 | -2 | |
| Propionate precursors | 15 | 22 | |
| Probiotics | 10 | 7.5 | |
| Ionophores | 25 | 25 | |
| Bovine somatatrophin | 17.5 | 10 | |
| Genetic improvement – production | 7.5-22.5 | 0 | Cumulative effect over years |
| Genetic improvement - fertility | 3.25-11.25 | 2.5-7.5 | Cumulative effect over years |
| Transgenic offspring | 10 | 20 | |

***** This table summarises the assumptions used for the dairy animal management options giving the values assumed in the spreadsheet for the effect of each abatement option on production and reduction in methane output.

### 5.7 Manure management options

The manure management options, excluding anaerobic digestion, which will be discussed later, were developed to be driven by the livestock number projections of BAU3. Assumptions on manure output per livestock category were taken from Prevention of Environmental Pollution from Agricultural Activity (PEPFAA, 2005). Greenhouse gases from manure were calculated based on volume produced from different livestock categories as described by the UK national inventory reporting (Choudrie et al., 2008). Distributions of storage type were combined from various reports (IGER, 2001; UK Choudrie et al., 2008; Smith et al., 2000 & 2001). The rate of reduction of $CH_4$ and potential increase in $CO_2$ as a result and costs were taken from IGER (2001) and are shown in Table 5.7. Options included the covering of slurry tanks and lagoons and the aerating of slurry and manure while being stored. These options were applied to beef and dairy cattle and pigs.

**Table 5.7 Summary of the abatement potential and cost assumptions for livestock manure management abatement options***

| | $CH_4$ reduction (%) | $CO_2$ produced | Capital cost (20 yrs) | Running cost |
|---|---|---|---|---|
| Covering slurry tanks/lagoons | 20 | 0 | Cover costs | 0 |
| Aerobic tanks/lagoons | 20 | 5-7 t/yr | Equipment | annual |

***** This table summarises the assumptions used for the manure management options giving the values assumed in the spreadsheet for the effect of each abatement option on reduction in methane output and the overall carbon dioxide produced in applying that measure.

## 5.8 Anaerobic digestion

### 5.8.1 On Farm Anaerobic Digestion (OFAD)

Three livestock types are considered to be suitable for OFAD: dairy cattle, other cattle and fattening pigs (Mistry and Misselbrook, 2005). For each livestock type three holding size categories are considered: small, medium and large. These are as defined in Agriculture in the UK (Defra, various years)

**Table 5.8 Livestock holding sizes assumed for estimating abatement potential via anaerobic digestion.**

| | Small | Medium | Large |
|---|---|---|---|
| Dairy cattle | 1 to 49 | 50 to 99 | Over 100 |
| Other cattle | 1 to 19 | 20 to 49 | Over 50 |
| Fattening pigs | 1 to 199 | 200 to 999 | Over 1000 |
| Laying hens (CAD only) | 1 to 9,999 | 10,000 to 99,999 | Over 100,000 |

The livestock and holdings number projections (see note below) are used to determine the average herd size for holdings in each size category. These were used as the basis of the $CH_4$ emissions, and AD cost and income streams. IPCC emissions factors were used for each livestock type and the typical proportion of year (or herd) housed (from Mistry and Misselbrook, 2005) were used to determine proportion of slurry/manure that can be collected for digestion.

Following adjustment for leakage (3%) energy potential from AD is calculated (converted from GJ to kWh then kW). The required generator capacity is determined by rounding up output energy (kW) to: 1 - 10 in increments of 1 kW, then 15, 20, 25, 30, then increments of 10 kW.

High, low and central capital costs are estimated using formulae reported in FEC Services Ltd (2003) based on costs quoted in AD literature. Any capital costs can be selected for remaining calculations. Note that no assumption has been made regarding minimum capital costs; these would certainly apply to smaller farms. Interest payments on borrowed capital are not currently included in the model (although can be endogenous to the choice of discount rate used). Annual running costs are set as 2% of capital costs (as per Mistry and Misselbrook, 2005).

Electricity generation was estimated to be 35% efficient, and 20% of output is assumed to be used on AD plant (as per Mistry and Misselbrook, 2005). The value of electricity and ROCs are linked to price forecasts defined by CCC in their Control Panel. Grid connection costs have not been included in capital costs. Combined income from electricity and ROCs can be assumed to approximate avoided cost of purchased electricity to account for power used on-farm if not exported.

Heat output is included in the model, with 50% generated assumed to be available for use on farm. Currently no assumption has been made regarding the source of energy that this use of heat has displaced, and therefore the degree of $CO_2e$ emission offset from elsewhere. The value of the heat used is again linked to price forecasts defined by CCC in their Control Panel.

Methane abatement is calculated as tonnes $CO_2e$. These are net of $CO_2$ avoided from electricity generation (based on typical 0.43 kg $CO_2$/kWhe), $CO_2$ emissions from digester (40% of biogas, based on 1 $tCO_2$ = 556.2 $m^3$) and $CO_2$ emissions from methane combustion (based on 0.23 kg $CO_2$/kWh). Cost per tonne $CO_2$e avoided over project lifetime is calculated as net emission saving divided by net project cost for each farm size band.

### 5.8.2 Central Anaerobic Digestion (CAD)

The calculation of CAD potential takes a different starting point to that used for OFAD. The OFAD calculations were built up from the average herd size for each holding size category (small, medium or large) based on projected livestock and holdings numbers. IPCC emissions factors were then used to determine the $CH_4$ emissions for the average holding and from that the potential AD generating potential was determined. Costs, incomes and abatement potentials were then calculated for the average holding.

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 due to the reduction in per unit capital costs for larger plants. For each generator size the required volume of $CH_4$ was calculated and IPCC emissions 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.

Capital and running costs were then determined on a per plant basis using the same assumptions as for OFAD. A further cost element that arises with CAD is the transport costs of slurry/manure. Transport costs[13] were based on Freight Transport Association data[14] on costs per mile (converted to per kilometre) and cost per tonne transported for a 17 tonne truck (with a payload of 11 tonnes). Average distances from holding to CAD plant for each livestock category were based on the same assumptions of 15km for cattle and pigs and 60km for poultry used by Mistry and Misselbrook (2005). The quantity of slurry/manure produced by each holding was then used to determine the number of trips required per annum to supply each CAD plant.

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.

### 5.8.3 Use of digestate

Neither the OFAD nor CAD calculations currently make any assumptions regarding the use of the digestate resulting from the AD process. In both cases the digestate is classed as waste. However in the case of OFAD, farmers can apply for a licence to spread the waste on land. For cattle farms this would allow the digestate to be used as a nutrient source for pasture in the same manner as slurry and manure.

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[13] Private transport costs only were considered, i.e. emissions and other social costs are excluded. Transport related emissions are not expected to be large relative to the emissions abated by CAD

[14] http://www.fta.co.uk/about/about-the-industry/delivering-economy.pdf

With respect to CAD this situation becomes more complex as slurry/manure may be mixed with other feedstocks such as municipal waste. This together with the mixing of slurry/manure form several holdings creates a more complex regulatory environment and also raises issues of biosecurity if spread on agricultural land. Consequently, alternative sources of fertiliser may be required to compensate for the nutrients present in the slurry/manure sent to CAD.

Fully considering the consequences of this situation within the AD calculations would add a considerable layer of complexity. Although slurry/manure is a valuable source of nutrients for pasture land, the extent to which adoption of CAD would result in nutrient deficiencies would depend on the nutrient budgets of individual holdings and the extent to which adequate application occurs during periods when livestock are not housed. It could be the case, particularly in areas designated as Nitrate Vulnerable Zones, where excess slurry/manure was being produced. In such situations CAD would provide an important disposal route for surplus nutrients.

### 5.8.4 Livestock and holdings projections

Livestock numbers were projected for 2012, 2017 and 2022 from estimates produced for BAUIII (for 2010, 2015, 2020 and 2025) using linear changes for each year. Holding numbers were calculated from projected trend lines from historical holdings numbers between 1993 and 2005 published in Agriculture in the UK (various years). The functional form chosen for these trends depended on which form gave the most conservative projected trend. The future livestock numbers and projected holding numbers then needed to be reconciled.

For fattening pigs and laying hens it was assumed that the structure of the industry would not change from present observations. That is the percentage of total livestock numbers would remain constant across each holding size category. For dairy and other cattle it was assumed that average herd size for both small and medium holdings would not change over time. However the numbers of both these types of holdings was projected to decline over time. Consequently there was additional livestock leaving these sized categories. Furthermore the number of large cattle holdings declines at a relatively low rate. It was consequently assumed that there would be a consolidation of these animals into large holdings, where average herd sizes will increase over time.

A further complication arises with respect to dairy and other cattle because herd sizes are typically only expressed in terms of breeding females (“dairy cows and heifers” and “beef cows and heifers”). However, over 6 million cattle of other classifications are not accounted for in these figures. The percentages of these additional animals that are present on either dairy or beef farms were calculated for the BAU3 projection (the percentages were found to be stable over time). The animals were then apportioned to either dairy or beef sectors on this basis. IPCC emissions factors for each type of animal were then used to express these animals in terms of either dairy cow or beef cow equivalents.

### 5.9 Results

Table 5.9 sets out the relevant potentials.

**Table 5.9 Total abatement potential ($MtCO_2e/y$) at a cost of <=£100/$tCO_2e$, 3.5%, social metric**

| *Potential* | *2012* | *2017* | *2022* |
|---|---|---|---|
| *High feasible* | | | 5.02 |
| *Central feasible* | 0.635 | 1.594 | 2.68 |
| *Low feasible* | | | 1.266 |

The feasible potentials in 2022 were estimated to range from 1.266 - 5.02$MtCO_2e$, i.e. an annual abatement of approximately 1.266 - 5.02$MtCO_2e$ could be achieved in the livestock sub-sector at a cost of <=£100/t by 2022. The measures needed to achieve this abatement are:

- BeefAn-Ionophores
- BeefAn-ImprovedGenetics
- DairyAn-ImprovedProductivity
- DairyAn-Ionophores
- DairyAn-ImprovedFertility
- DairyAn-MaizeSilage
- On farm anaerobic digestion (OFAD)-PigsLarge
- OFAD-BeefLarge
- OFAD-PigsMedium
- Central anaerobic digestion (CAD )-Poultry-5MW
- OFAD-DairyLarge
- OFAD-BeefMedium
- OFAD-DairyMedium

The central feasible potential of 2.68 $MtCO_2e$ represents around 5 % of the 2005 UK agricultural GHG emissions (the NAEI reported these as 44.733 $MtCO_2e$, excluding LUC).

The results for livestock show that a range of options, both animal and manure management options, show high potential for the abatement of GHG from livestock systems. However, it should be noted that some options are currently prohibited by EU law such as the use of ionophores as a feed additive in livestock rations. The addition of ionophores in the diets of livestock is not prohibited else where in the world (e.g., USA) and these systems see an increase in the efficiency of production. In the future it could become an option in the EU, particularly if proven to be an effective abatement tool. It should also be noted that reported effects, particularly in the long term, of the use of ionophores can vary. To ensure the effects of ionophores are consistent in UK livestock systems it would be necessary to study their effect in practice and in actual livestock systems over the longer term.

Some of the top abatement options that proved cost effective were in the beef sector. This can be expected given the range of efficiencies in UK beef systems ranging from low input extensive grazing based systems with animals reaching final slaughter weight at 2 years or more to high input grain based systems with systems with animals reaching final slaughter weight at 1 year or less. Also, in beef sector, as described earlier, the use of recording and genetic selection tools means the productivity improvements experienced in the systems that utilise these tools is not as widespread as in other livestock sectors (e.g., dairy, pig, poultry). The uptake of such tools and increasing the efficiency of production in some beef systems will have a large impact on overall GHG emissions but will also have an impact on the overall farm profit and sustainability.

Other dietary options that could play a role in the abatement of GHG emissions include changes to the diet that decrease the roughage content of the diet for livestock. This could lead to potential land use resource conflict in that the land suitable for growing cereal/maize for livestock diets is limited in the UK and therefore there is a potential conflict with using the land for growing feed for livestock or food for humans or fuel for biofuel production. The alternative option, if land is not available in the UK, is to source these livestock diet components from outside the UK and therefore run the risk of displacing emissions to elsewhere outside the UK. It is also important to note that ruminants are particularly useful in that they convert a diet indigestible by human (e.g, grass) in to product that can feed humans (meat and milk). It is likely, that with climate change that the UK will be one of the places in the world with favourable grass growth conditions and therefore may be able to utilise this resource to produce animal products with other parts of the world utilising land for the production of cereal etc for human food and fuel consumption. The balance between these conflicts needs to be studied in far more detail considering the wider world issues that will influence them.

Although not considered in the economic appraisal of the efficiency of mitigation options from livestock some of the options that show a favourable effect on GHG emissions and are shown to be cost effective may also have ancillary impacts (positive and negative) that need to be considered, particularly regarding animal welfare. For example, some of the options involve the administration of additives/ injections that increase the efficiency growth/production in the animal such that they produce more product in a shorter space of time. These options can have adverse effects on the animals as this maybe “pushing” the animals too much and negatively affect other biological functions such as fertility. However, the example of selecting animals for breeding based on information on production potential and their fertility and “fitness” traits potential (broader and balanced breeding goals) could have favourable effects for animal welfare such that the “fitness” traits are improved as well as production traits, just in a more balanced manner.

The results highlight the role of anaerobic digestion (AD) in abating GHG emissions from livestock systems, both on farm and in a central location. However, the on-farm options tend to be only effective in larger scale farms. The potential to use central AD to abate GHG emissions will be related to the spatial distributions of farms supplying it around the central facility. It should be noted that the use of central or on-farm AD could be supplemented and the overall efficiency and cost-effectiveness improved if other waste sources mixed into the AD. This would require tying together some aspects of the "waste" sector with the AD examples for the "agriculture" sector. considering AD across the industry sectors could also play an important role as power is generated and therefore displaces some of the emissions in wider power generation.

## Annex A5 Review and ranking of potential mitigation options from livestock

Extent to which the measure is likely to be a technically feasible and industry-acceptable means of abatement by the given year ranked from 1-5, where: 1=will almost certainly be feasible and acceptable; 2=will probably be feasible and acceptable; 3=will possibly be feasible and acceptable; 4= will probably be unfeasible or unacceptable; 5= will almost certainly be unfeasible and /or acceptable

|  |  |  | Ranking |  |  | **Effects** (+ denotes emission reduction or enhanced removal) |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **Sub-category** | **Measure** | 2012 | 2017 | 2022 | $CO_2$ | $CH_4$ | $N_2O$ | $NH_3$ | $NO_3$- |
| Livestock mgmt | Increased nutrient use efficiency and improved feeding practices | Feeding more concentrates (replacing forages) |  |  |  | ? | + | ? |  |  |
|  |  | Increased concentrate in diet - dairy | 2 | 2 | 2 |  |  |  |  |  |
|  |  | Increased concentrate in diet - beef | 2 | 2 | 2 |  |  |  |  |  |
|  |  | Increased concentrate in diet - beef | 2 | 2 | 2 |  |  |  |  |  |
|  |  | Analysis of forage and fodder | 3 | 3 | 2 |  | + | + |  |  |
|  |  | Target specific livestock nutrient requirements | 3 | 3 | 2 |  |  |  |  |  |
|  |  | Balance diet for energy and protein (e.g. reducing protein, increasing carbohydrates, increasing condensed tannins) |  |  |  |  | +/- | + | + |  |
|  |  | High fat diet - dairy | 2 | 2 | 2 |  | + |  |  |  |
|  |  | High starch diet (maize) - dairy | 2 | 2 | 2 |  |  |  | + | -? |
|  |  | High starch diet (maize) - beef | 2 | 2 | 2 |  |  |  |  |  |
|  |  | High starch diet (maize) - beef | 2 | 2 | 2 |  |  |  | + | -? |
|  |  | Increase protein quality (balanced essential AA comp.) | 3 | 2 | 2 |  |  | + | + |  |
|  |  | Increased milking frequency | 3 | 2 | 2 |  |  |  |  |  |
|  |  | Use of hormones |  |  |  |  |  |  |  |  |
|  |  | Steroids | 5 | 4 | 4 |  |  |  |  |  |
|  |  | Bovine somatotropin | 5 | 4 | 4 |  |  |  |  |  |
|  |  | bST - dairy | 5 | 4 | 4 |  |  |  |  |  |
|  |  | Estimating potential CH4 production from feeds | 4 | 3 | 3 |  |  |  |  |  |
|  |  | Mechanical treatment of feed | 3 | 3 | 2 | - | + |  |  |  |
|  |  | Chemical treatment of low quality feedstuffs | 4 | 3 | 3 |  | + |  |  |  |
|  |  | (Multi)Phase feeding | 3 | 3 | 3 |  |  | + | + |  |
|  |  | Improved feed conversion (increasing energy content and digestibility) - beef | 2 | 2 | 2 |  |  |  |  |  |
|  |  | Improved feed conversion (increasing energy content and digestibility) - dairy | 2 | 2 | 2 |  |  |  |  |  |

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | Use of antibiotics - beef | 4 | 4 | 3 |  |  |  |  |  |
|  | Continuing conventional dietary improvement | 2 | 2 | 2 |  |  |  |  |  |
|  | Improved diets for pigs | 2 | 2 | 2 |  |  |  |  |  |
| Specific agents and dietary additives to suppress methanogenesis | In general |  |  |  |  | + |  |  |  |
|  | Adding certain oils to the diet | 3 | 3 | 2 |  | + |  |  |  |
|  | Ionophores and natural extracts to modify rumen microbial fermentation | 3 | 3 | 3 |  | + |  |  |  |
|  | Ionophores - dairy | 3 | 3 | 3 |  | + |  |  |  |
|  | Antibiotics | 4 | 4 | 4 |  | + |  |  |  |
|  | Propionate precursors |  |  |  |  | + |  |  |  |
|  | beef | 4 | 4 | 3 |  | + |  |  |  |
|  | beef | 4 | 4 | 3 |  |  |  |  |  |
|  | dairy | 4 | 4 | 3 |  |  |  |  |  |
|  | Hexose partitioning | 4 | 4 | 3 |  | + |  |  |  |
|  | Probiotics (e.g. yeast products) | 4 | 3 | 3 |  | +? |  |  |  |
|  | Alternative hydrogen acceptors (e.g. unsaturated fatty acids) | 5 | 5 | 4 |  | + |  |  |  |
|  | Promoting acetogens |  |  |  |  | + |  |  |  |
|  | Genetic modification of rumen microflora | 5 | 5 | 4 |  | + |  |  |  |
|  | Immunogenic approaches to eliminate methanogens | 5 | 5 | 4 |  | + |  |  |  |
|  | Halogenated methane analogues | 5 | 5 | 4 |  | + |  |  |  |
|  | Organic acids | 4 | 4 | 4 |  | + |  |  |  |
|  | Defaunating agents | 5 | 5 | 5 |  | + |  |  |  |
|  | Naturally ocurring plant compounds (new species/GM) | 5 | 4 | 3 |  | + |  |  |  |
|  | Directly fed microbes (acetogens, methane oxidisers) | 5 | 4 | 3 |  | + |  |  |  |
|  | Adding certain enzymes to the diet | 4 | 3 | 2 |  | + |  |  |  |
|  | Antimethanogens | 5 | 4 | 4 |  |  |  |  |  |
| Vaccination against methanogens | In general |  |  |  |  |  |  |  |  |
|  | beef | 5 | 5 | 4 |  |  |  |  |  |
|  | sheep | 5 | 5 | 4 |  |  |  |  |  |
|  | beef | 5 | 5 | 4 |  |  |  |  |  |
|  | dairy | 5 | 5 | 4 |  |  |  |  |  |
|  | sheep and goats | 5 | 5 | 4 |  |  |  |  |  |
| Structural and management changes | Reduction in the number of replacement heifers / Improved fertility management | 2 | 1 | 1 |  | + | + | + | + |
|  | Multi use of cows (milk, calves and meat) | 3 | 2 | 1 | ? | ? | ? |  |  |
|  | More feed production on farm scale or local level | 2 | 2 | 1 | + |  | + |  |  |
|  | Organic farming | 3 | 3 | 3 |  |  |  |  |  |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Organic farming - dairy | 3 | 3 | 3 | | | | | |
| | | Winter management of cattle (collected and re-utilised excreta) | 3 | 2 | 2 | | | + | | + |
| | | Increase of grazing in comparison to housing | 3 | 3 | 3 | | | -? | + | |
| | | Increase of housing in comparison to grazing | 3 | 3 | 3 | | | | | |
| | | Reduce stocking rates | | | | | | | | |
| | | 25% - dairy | 3 | 3 | 3 | | | | | |
| | | 25% - beef | 3 | 3 | 3 | | | | | |
| | | 25% - sheep | 3 | 3 | 3 | | | | | |
| | | 10% - dairy | 2 | 2 | 2 | | | | | |
| | | 10% - beef | 2 | 2 | 2 | | | | | |
| | Animal breeding and genetics | Selection for reduced methane production | 5 | 4 | 3 | | + | | | |
| | | Selection for longevity , fertility, and other non-productive traits | 2 | 1 | 1 | | | | | |
| | | Selection for higher yield | 2 | 1 | 1 | | | | | |
| | | Improved milk yield by 30% - dairy | 4 | 3 | 2 | | | | + | + |
| | | Cloning | 5 | 5 | 5 | | | | | |
| | | GM livestock | 5 | 5 | 5 | | | | | |
| | | Artificial insemination | 1 | 1 | 1 | + | + | + | | |
| | | Planned selection of male/female at insemination (embryo and sperm sexing) | 2 | 2 | 2 | + | + | + | | |
| | | Twinning | 3 | 3 | 3 | + | + | + | | |
| | | Transgenic manipulation - dairy | 5 | 5 | 4 | | | | | |
| | | Transgenic manipulation - beef | 5 | 5 | 4 | | | | | |
| | | Improved genetic potential - dairy | 1 | 1 | 1 | | | | | |
| Manure/ biosolid mgmt | Housing | New low-emission livestock and poultry housing systems | 3 | 3 | 3 | ? | ? | ? | + | |
| | | Natural ventilation | 3 | 2 | 2 | + | | + | + | |
| | | Decreasing of air velocity above manure | 2 | 2 | 2 | | | | + | |
| | | Cooling the manure covered surfaces | 4 | 3 | 3 | | + | + | + | |
| | | Filtration of animal house emissions | 4 | 3 | 3 | | | - | + | |
| | | Tied systems instead of loose-housing systems | ? | ? | ? | | | | + | |
| | | Slurry-based systems - dairy | | | | | | | | |
| | | Straw-based systems - dairy | | | | | | | | |
| | | Loose-housing, deep litter stalls - dairy | | | | | | | | |
| | | Cages and aviaries instead of floor systems for layer hens | ? | ? | ? | | | + | +/- | |
| | | Keeping surfaces, manure and animals dry | 2 | 2 | 2 | | + | | + | |
| | | Improved drinking systems | 2 | 2 | 2 | | | | + | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Drying of manure (esp. poultry) | 4 | 4 | 4 | | + | | + |
| | | Absorption of urine / Use of bedding material | 2 | 2 | 2 | | | -? | + |
| | | Straw-based systems | 2 | 2 | 2 | | | - | + |
| | | Deep litter systems | 2 | 2 | 2 | | -? | - | ? |
| | | Deep litter systems - pigs | 2 | 2 | 2 | | | | |
| | | Slurry-based systems / Deep dung channels | 3 | 3 | 3 | | | + | + |
| | | Partly or fully slatted floors | 2 | 2 | 2 | | + | + | + |
| | | Frequent manure removal - dairy | 2 | 2 | 2 | | | | + |
| | | Frequent manure removal - beef | 2 | 2 | 2 | | | | + |
| | | Frequent manure removal - pigs | 2 | 2 | 2 | | | | + |
| | Improved storage and handling | Cooling | 4 | 3 | 3 | | + | + | + |
| | | Decreasing the airflow across slurry and FYM | 4 | 3 | 3 | | | | + |
| | | Covering manure heaps | 2 | 2 | 2 | | + | -? | - |
| | | Lowering the filling level of slurry storage | 2 | 2 | 2 | | | + | |
| | | Covering slurry | 2 | 2 | 2 | | | | + |
| | | Low technology covering: floating oil | 3 | 3 | 3 | | - | | + |
| | | Allowing the build-up of and protecting the natural crust on cattle slurry | 2 | 2 | 2 | | + | -? | + |
| | | Low technology covering: straw, peat and bark - dairy | 2 | 2 | 2 | | -/+? | -? | + |
| | | Low technology covering: granulates - dairy | 2 | 2 | 2 | | | + | + |
| | | Flexible plastic cover - dairy | 3 | 3 | 3 | | | | + |
| | | Rigid covers and roofs - dairy | 3 | 3 | 3 | | + | | + |
| | | Low technology covering: straw, peat and bark - beef | 2 | 2 | 2 | | -/+? | -? | + |
| | | Low technology covering: granulates - beef | 2 | 2 | 2 | | | + | + |
| | | Flexible plastic cover - beef | 3 | 3 | 3 | | | | + |
| | | Rigid covers and roofs - beef | 3 | 3 | 3 | | + | | + |
| | | Developing a natural crust on pig slurry | 2 | 2 | 2 | | | | |
| | | Low technology covering: straw, peat and bark - pigs | 2 | 2 | 2 | | -/+? | -? | + |
| | | Low technology covering: granulates - pigs | 2 | 2 | 2 | | | + | + |
| | | Flexible plastic cover - pigs | 2 | 2 | 2 | | | | + |
| | | Rigid covers and roofs - pigs | 2 | 2 | 2 | | + | | + |
| | | Separating solids from slurry | 4 | 4 | 3 | | + | | |
| | | Rapid separation of faeces and urine | 5 | 4 | 4 | | | - | + |
| | | Handling manures in solid (aerobic) form (e.g., composting) | 4 | 3 | 3 | | + | +/- | + |
| | | Switch from anaerobic to aerobic facilities - all pigs | 3 | 3 | 3 | | | | |
| | | Controlled aeration during slurry storage | 3 | 3 | 2 | | + | -? | -? |
| | | Change from solid manure to slurry (anaerobic) system | 3 | 2 | 2 | - | - | + | |

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Minimising of stirring slurry | 3 | 2 | 2 | ? | ? | + |  |
|  |  | Switch solid manure to slurry storage | 3 | 2 | 2 | -? | + | -cows<br>+pigs | - |
|  |  | Reducing the pH of manure | 4 | 3 | 3 | + | + | + |  |
|  |  | Reducing the surface per unit volume of slurry or FYM (e.g tanks instead of lagoons) | 3 | 2 | 2 | 0 | +? | + |  |
|  |  | Combustion of poultry litter | 4 | 4 | 3 |  |  |  |  |
|  |  | Controlled denitrification processes in slurry | 4 | 4 | 3 |  | +/- |  |  |
|  |  | Increasing the carbon content of the manure (adding straw) | 3 | 2 | 2 | +? | + |  |  |
|  |  | Compaction of FYM | 4 | 4 | 2 | - | - | + |  |
|  |  | Comminution of FYM | ? | ? | ? |  | + |  |  |
|  |  | Increased frequency of slurry spreading - all pigs | 2 | 2 | 2 |  |  |  |  |
|  |  | Increased frequency of slurry spreading - beef | 2 | 2 | 2 |  |  |  |  |
|  |  | Increased frequency of slurry spreading - dairy | 2 | 2 | 2 |  |  |  |  |
|  | Anaerobic digestion and CH4 capture | In general | 3 | 3 | 3 | + | + | -/+? | -? |
|  |  | Centralised | 3 | 2 | 2 |  |  |  |  |
|  |  | On-farm - dairy | 4 | 3 | 3 |  |  |  |  |
|  |  | On-farm - dairy | 4 | 3 | 3 |  |  |  |  |
|  |  | High-tech digesters - dairy | 4 | 4 | 4 |  |  |  |  |
|  |  | Low-tech digester - dairy | 4 | 3 | 3 |  |  |  |  |
|  |  | Complete-mix digester with engine - dairy | 4 | 4 | 3 |  |  |  |  |
|  |  | Plug-flow digester with engine - dairy | 4 | 4 | 3 |  |  |  |  |
|  |  | Fixed-film digester with engine - dairy | 4 | 4 | 3 |  |  |  |  |
|  |  | Complete-mix digester without engine - dairy | 4 | 4 | 3 |  |  |  |  |
|  |  | Plug-flow digester without engine - dairy | 4 | 4 | 3 |  |  |  |  |
|  |  | Fixed-film digester without engine - dairy | 4 | 4 | 3 |  |  |  |  |
|  |  | Covered slurry tanks - dairy | 3 | 2 | 2 |  |  | + |  |
|  |  | Covered lagoons - dairy | 3 | 2 | 2 |  |  | + |  |
|  |  | Covered lagoon without engine - dairy | 3 | 2 | 2 |  |  |  |  |
|  |  | Covered lagoon with engine - dairy | 3 | 3 | 2 |  |  |  |  |
|  |  | On-farm - beef | 4 | 4 | 4 |  |  |  |  |
|  |  | On-farm - beef | 4 | 4 | 4 |  |  |  |  |
|  |  | High-tech digesters - beef | 5 | 5 | 4 |  |  |  |  |
|  |  | Low-tech digester - beef | 4 | 4 | 4 |  |  |  |  |
|  |  | Covered lagoons - beef | 3 | 3 | 3 |  |  | + |  |
|  |  | Covered slurry tanks - beef | 3 | 3 | 3 |  |  | + |  |
|  |  | On-farm - pig | 3 | 3 | 3 |  |  |  |  |
|  |  | High-tech digesters - fatteners | 4 | 4 | 4 |  |  |  |  |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Low-tech digester - fatteners | 3 | 3 | 3 | | | | | |
| | | High-tech digesters - sows and boars | 4 | 4 | 4 | | | | | |
| | | Low-tech digester - sows and boars | 3 | 3 | 3 | | | | | |
| | | Complete-mix digester with engine - hogs | 4 | 4 | 4 | | | | | |
| | | Fixed-film digester with engine - hogs | 4 | 4 | 4 | | | | | |
| | | Complete-mix digester without engine - hogs | 4 | 4 | 4 | | | | | |
| | | Fixed-film digester without engine - hogs | 4 | 4 | 4 | | | | | |
| | | Covered slurry tanks - all pigs | 2 | 2 | 2 | | | | + | |
| | | Covered lagoons - all pigs | 2 | 2 | 2 | | | | + | |
| | | Covered lagoon with engine - hogs | 3 | 3 | 3 | | | | | |
| | | Covered lagoon without engine - hogs | 2 | 2 | 2 | | | | | |
| | | On-farm - poultry | 3 | 3 | 3 | | | | | |

## Annex B5 Summary of costing assumptions for livestock animal and livestock manure management options excluding anaerobic digestion.

| Abatement option | Applied | 2008 | 2012 | 2017 | 2022 | Notes |
|---|---|---|---|---|---|---|
| Increased high starch concentrates in diet (cost of diet switch [£(2008)/hd/y]) | Dairy, beef | 123.8567 | 136.6189 | 154.0611 | 173.3187 | 2001 IGER values inflated to 2008 values. Concentrate price varied following cereal forecast |
| Increased maize silage in diet | | | | | | |
| Increased maize silage in diet (cost of diet switch [£(2008)/hd/y]) | Dairy, beef | -6.18679 | -6.18679 | -6.18679 | -6.18679 | 2001 IGER values inflated to 2008 values and then held constant |
| Propionate precursors (cost of feed additive [£(2008)/hd/y]) | Dairy, beef | 22.95881 | 22.95881 | 22.95881 | 22.95881 | 2001 IGER values inflated to 2008 values and then held constant |
| Probiotics (cost of feed additive [£(2008)/hd/y]) | Dairy, beef | 13.70278 | 13.70278 | 13.70278 | 13.70278 | 2001 IGER values inflated to 2008 values and then held constant |
| Ionophores (cost of feed additive [£(2008)/hd/y]) | Dairy, beef | 6.621803 | 6.621803 | 6.621803 | 6.621803 | 2001 IGER values inflated to 2008 values and then held constant |
| Bovine somatotropin (cost of bST [£(2008)/hd/y]) | Dairy, beef | 80.67 | 80.67 | 80.67 | 80.67 | 2001 IGER values inflated to 2008 values and then held constant |
| Improved genetic potential for dairy cows – productivity | Dairy | 0 | 0 | 0 | 0 | |
| Improved genetic potential for dairy cows – fertility | Dairy | 0 | 0 | 0 | 0 | |
| Improved genetic potential for beef cattle | Beef | 0 | 0 | 0 | 0 | |
| Transgenic manipulation of ruminants (cost of transgenic offspring [£(2008)/hd/y]) | Dairy | 5000 | 5000 | 5000 | 5000 | Estimated based on the value of a high genetic merit animal |
| | | | | | | |
| <u>General costs of dairy herds</u> | | | | | | |
| Variable cost of upkeep (VC) [£(2008)/hd/y] | | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Dairy cows (cubicles) | 114.794 | 114.794 | 114.794 | 114.794 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy cows (litter) | 151.0448 | 151.0448 | 151.0448 | 151.0448 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy heifers (cubicles) | 99.08538 | 99.08538 | 99.08538 | 99.08538 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy heifers (litter) | 135.3361 | 135.3361 | 135.3361 | 135.3361 | 2001 IGER values inflated to 2008 values and then held constant |
| Herd depreciation (HD) [£(2008)/hd/y] | | | | | |
| Dairy cows (cubicles) | 118.1533 | 118.1533 | 118.1533 | 118.1533 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy cows (litter) | 118.1533 | 118.1533 | 118.1533 | 118.1533 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy heifers (cubicles) | 0 | 0 | 0 | 0 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy heifers (litter) | 0 | 0 | 0 | 0 | 2001 IGER values inflated to 2008 values and then held constant |
| Feeding [£(2008)/hd/y] | | | | | |
| Dairy cows (cubicles) | 363.2446 | 363.2446 | 363.2446 | 363.2446 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy cows (litter) | 363.2446 | 363.2446 | 363.2446 | 363.2446 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy heifers (cubicles) | 246.1184 | 246.1184 | 246.1184 | 246.1184 | 2001 IGER values inflated to 2008 values and then held constant |
| Dairy heifers (litter) | 246.1184 | 246.1184 | 246.1184 | 246.1184 | 2001 IGER values inflated to 2008 values and then held constant |
| Beef price [£2008/liveweight kg] | 1.57 | 1.71838 | 1.923727 | 2.153614 | www.fwi.co.uk, (10/07/08, Total Cat: Avg Price) for 2008 value, and then annual growth based on forecasts used in farm-scale modelling |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Covering lagoons |  |  |  |  |  |
| Annual running cost [£(2008)/hd/y] | 0 | 0 | 0 | 0 | 2001 IGER values inflated to 2008 values and then held constant |
| One-off cost [£(2008)/hd/y] | 13710.03 | 13710.03 | 13710.03 | 13710.03 | 2001 IGER values inflated to 2008 values and then held constant |
| Covering slurry tanks |  |  |  |  |  |
| Annual running cost [£(2008)/hd/y] | 0 | 0 | 0 | 0 | 2001 IGER values inflated to 2008 values and then held constant |
| One-off cost [£(2008)/hd/y] | 20171.73 | 20171.73 | 20171.73 | 20171.73 | 2001 IGER values inflated to 2008 values and then held constant |
| Switch from anaerobic to aerobic storage - slurry tanks |  |  |  |  |  |
| Annual running cost [£(2008)/hd/y] | 1812.537 | 1812.537 | 1812.537 | 1812.537 | 2001 IGER values inflated to 2008 values and then held constant |
| One-off cost [£(2008)/hd/y] | 8458.508 | 8458.508 | 8458.508 | 8458.508 | 2001 IGER values inflated to 2008 values and then held constant |
| Switch from anaerobic to aerobic storage - lagoons |  |  |  |  |  |
| Annual running cost [£(2008)/hd/y] | 2416.717 | 2416.717 | 2416.717 | 2416.717 | 2001 IGER values inflated to 2008 values and then held constant |
| One-off cost [£(2008)/hd/y] | 12083.58 | 12083.58 | 12083.58 | 12083.58 | 2001 IGER values inflated to 2008 values and then held constant |
| Switch from anaerobic to aerobic storage - concrete pads |  |  |  |  |  |
| Annual running cost [£(2008)/hd/y] | 725.015 | 725.015 | 725.015 | 725.015 | 2001 IGER values inflated to 2008 values and then held constant |
| One-off cost [£(2008)/hd/y] | 3625.075 | 3625.075 | 3625.075 | 3625.075 | 2001 IGER values inflated to 2008 values and then held constant |

## Annex C5 Livestock measures results

### Table 5.10 Livestock Measures Central Feasible Potential, 2012

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| CE | BeefAn-Ionophores | 103.39 | -1,384.37 | 0.103 |
| CG | BeefAn-ImprovedGenetics | 4.60 | -2,873.75 | 0.108 |
| BE | DairyAn-Ionophores | 215.77 | -49.99 | 0.324 |
| BB | DairyAn-MaizeSilage | 27.99 | -270.22 | 0.352 |
| BF | DairyAn-ImprovedProductivity | 41.82 | -0.07 | 0.394 |
| BI | DairyAn-ImprovedFertility | 33.38 | -0.04 | 0.427 |
| EF | OFAD-BeefLarge | 27.47 | 3.36 | 0.454 |
| EI | OFAD-PigsLarge | 14.18 | 6.63 | 0.469 |
| HT | CAD-Poultry-5MW | 61.36 | 9.43 | 0.530 |
| EH | OFAD-PigsMedium | 4.77 | 11.67 | 0.535 |
| EC | OFAD-DairyLarge | 64.19 | 13.63 | 0.599 |
| EE | OFAD-BeefMedium | 15.56 | 18.33 | 0.614 |
| EB | OFAD-DairyMedium | 20.76 | 26.12 | 0.635 |
| BG | DairyAn-bST | 38.60 | 230.48 | 0.674 |
| BH | DairyAn-Transgenics | 147.13 | 1,739.62 | 0.821 |
| CA | BeefAn-Concentrates | 24.12 | 2,110.15 | 0.845 |

### Table 5.11 Livestock Measures Central Feasible Potential 2017

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| CE | BeefAn-Ionophores | 227.68 | -1,556.29 | 0.228 |
| CG | BeefAn-ImprovedGenetics | 20.26 | -3,217.28 | 0.248 |
| BF | DairyAn-ImprovedProductivity | 174.13 | -0.07 | 0.422 |
| BE | DairyAn-Ionophores | 480.61 | -49.28 | 0.903 |
| BB | DairyAn-MaizeSilage | 62.39 | -266.23 | 0.965 |
| BI | DairyAn-ImprovedFertility | 160.70 | -0.04 | 1.126 |
| EF | OFAD-BeefLarge | 62.35 | 3.33 | 1.188 |
| EI | OFAD-PigsLarge | 31.45 | 3.82 | 1.220 |
| EH | OFAD-PigsMedium | 10.58 | 8.14 | 1.230 |
| EC | OFAD-DairyLarge | 154.53 | 10.60 | 1.385 |
| HT | CAD-Poultry-5MW | 139.15 | 10.80 | 1.524 |
| EE | OFAD-BeefMedium | 33.80 | 18.07 | 1.558 |
| EB | OFAD-DairyMedium | 36.40 | 25.53 | 1.594 |
| BG | DairyAn-bST | 86.00 | 227.17 | 1.680 |
| BH | DairyAn-Transgenics | 327.68 | 1,715.14 | 2.008 |
| CA | BeefAn-Concentrates | 53.11 | 2,394.58 | 2.061 |

### Table 5.12 Livestock Measures Central Feasible Potential 2022

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| CE | BeefAn-Ionophores | 347.38 | -1,747.79 | 0.347 |
| CG | BeefAn-ImprovedGenetics | 46.32 | -3,602.93 | 0.394 |
| BF | DairyAn-ImprovedProductivity | 377.36 | -0.07 | 0.771 |
| BE | DairyAn-Ionophores | 739.66 | -48.59 | 1.511 |
| BI | DairyAn-ImprovedFertility | 346.26 | -0.04 | 1.857 |
| BB | DairyAn-MaizeSilage | 95.98 | -262.63 | 1.953 |
| EI | OFAD-PigsLarge | 47.77 | 0.96 | 2.001 |
| EF | OFAD-BeefLarge | 97.79 | 2.52 | 2.099 |
| EH | OFAD-PigsMedium | 16.06 | 4.69 | 2.115 |
| EC | OFAD-DairyLarge | 250.81 | 7.96 | 2.365 |
| HT | CAD-Poultry-5MW | 219.34 | 11.43 | 2.585 |
| EE | OFAD-BeefMedium | 50.77 | 16.96 | 2.635 |
| EB | OFAD-DairyMedium | 44.12 | 24.10 | 2.680 |
| BG | DairyAn-bST | 132.31 | 224.10 | 2.812 |
| BH | DairyAn-Transgenics | 504.29 | 1,691.28 | 3.316 |
| CA | BeefAn-Concentrates | 80.96 | 2,704.54 | 3.397 |

### Table 5.13 Livestock Measures High Feasible Potential 2022

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| CE | BeefAn-Ionophores | 656.16 | -1,747.79 | 0.656 |
| CG | BeefAn-ImprovedGenetics | 94.69 | -3,602.93 | 0.751 |
| BF | DairyAn-ImprovedProductivity | 771.49 | -0.07 | 1.522 |
| BE | DairyAn-Ionophores | 1,397.13 | -48.59 | 2.919 |
| BI | DairyAn-ImprovedFertility | 707.92 | -0.04 | 3.627 |
| BB | DairyAn-MaizeSilage | 181.29 | -262.63 | 3.809 |
| EI | OFAD-PigsLarge | 79.61 | -0.89 | 3.888 |
| EF | OFAD-BeefLarge | 162.98 | 0.53 | 4.051 |
| EH | OFAD-PigsMedium | 26.77 | 2.52 | 4.078 |
| EC | OFAD-DairyLarge | 418.01 | 5.51 | 4.496 |
| HT | CAD-Poultry-5MW | 365.57 | 11.43 | 4.862 |
| EE | OFAD-BeefMedium | 84.61 | 13.75 | 4.946 |
| EB | OFAD-DairyMedium | 73.54 | 20.29 | 5.020 |
| BG | DairyAn-bST | 270.49 | 224.10 | 5.290 |
| BH | DairyAn-Transgenics | 1,030.99 | 1,691.28 | 6.321 |
| CA | BeefAn-Concentrates | 152.92 | 2,704.54 | 6.474 |

**Table 5.14 Livestock Measures Low Feasible Potential 2022**

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| CE | BeefAn-Ionophores | 138.95 | -1,747.79 | 0.139 |
| CG | BeefAn-ImprovedGenetics | 18.53 | -3,602.93 | 0.157 |
| BF | DairyAn-ImprovedProductivity | 150.94 | -0.07 | 0.308 |
| BE | DairyAn-Ionophores | 295.86 | -48.59 | 0.604 |
| BI | DairyAn-ImprovedFertility | 138.51 | -0.04 | 0.743 |
| BB | DairyAn-MaizeSilage | 38.39 | -262.63 | 0.781 |
| EI | OFAD-PigsLarge | 31.84 | 1.89 | 0.813 |
| EF | OFAD-BeefLarge | 65.19 | 3.52 | 0.878 |
| EH | OFAD-PigsMedium | 10.71 | 5.78 | 0.889 |
| EC | OFAD-DairyLarge | 167.20 | 9.18 | 1.056 |
| HT | CAD-Poultry-5MW | 146.23 | 11.43 | 1.202 |
| EE | OFAD-BeefMedium | 33.85 | 18.57 | 1.236 |
| EB | OFAD-DairyMedium | 29.42 | 26.01 | 1.266 |
| BG | DairyAn-bST | 20.58 | 224.10 | 1.286 |
| BH | DairyAn-Transgenics | 78.44 | 1,691.28 | 1.365 |
| CA | BeefAn-Concentrates | 12.59 | 2,704.54 | 1.377 |

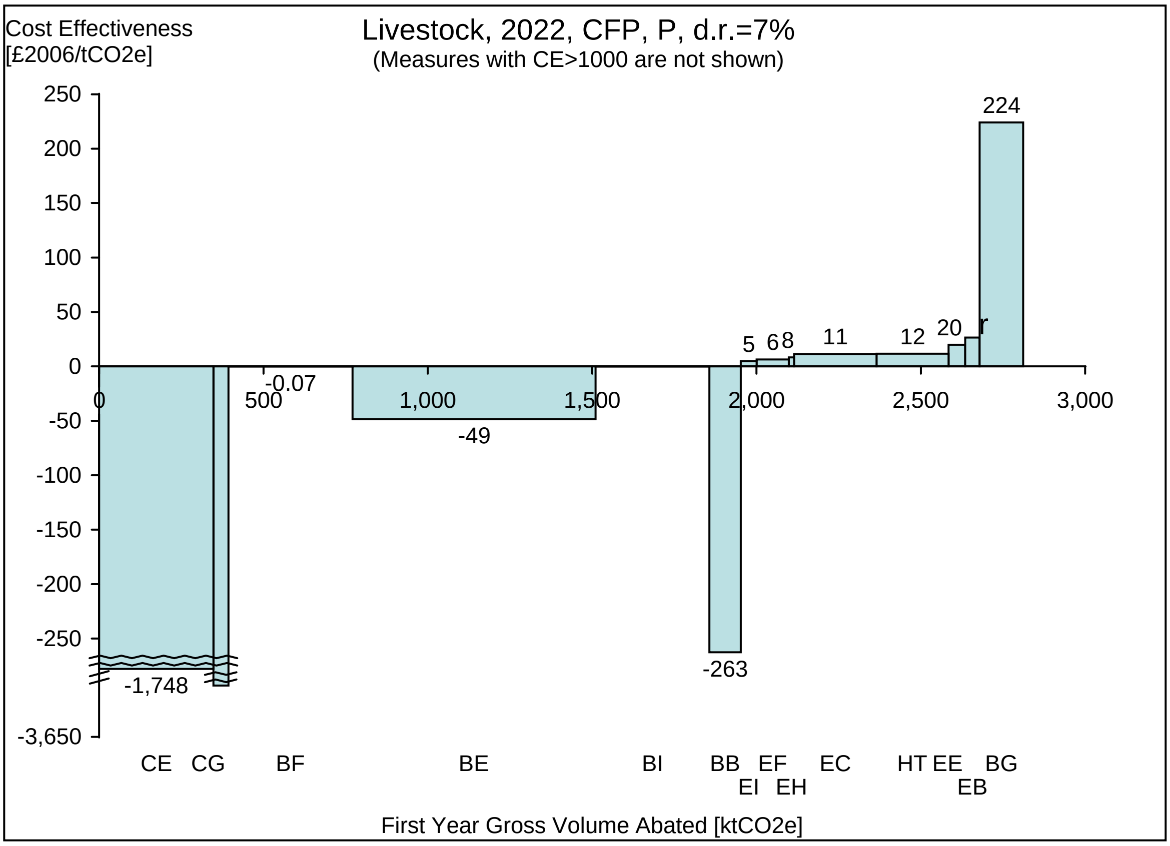

**Figure 5.2 Livestock MACC with interactions for the central feasible in 2022 with a discount rate = 7%**

# 6 Mitigation options in forestry

## 6.1 Key Findings

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.

We distinguish between abatement potential through *sequestration* and through *substitution*. The former offers direct abatement in the forestry sector and may be considered fairly reliable. Current estimates of the latter are based on incomplete data and assumed savings may not accrue to the UK inventory.

*Total* sequestration *abatement potential ($MtCO_2e/y$) at a cost of <=£100/$tCO_{2e}$, 3.5%, social metric*

| *Potential* | *2012* | *2017* | *2022* |
|---|---|---|---|
| *High feasible* | -0.03 | 0.54 | 1.67 |
| *Central feasible* | -0.02 | 0.32 | 0.98 |
| *Low feasible* | -0.003 | 0.06 | 0.20 |

The feasible potentials in 2022 were estimated to range from 0.20 – 1.67 $MtCO_2e$, i.e. this annual abatement could be achieved in the forestry sub-sector at a cost of <=£100/t by 2022. Actual cost-effectiveness is a saving of £7.12/$tCO_2e$ (£2006).

This abatement is achieved by afforestation – increasing the planting rate to up to 30,000 ha/year from 2009 without any additional substitution of harvested timber. It is also possible to consider afforestation with an additional element of substitution abatement provided by wood products that can then be used to displace emissions in energy generation and/or other sectors, though this will not accrue until beyond the budget periods.

Substitution abatement potential is more obviously relevant to a measure of shorter rotation lengths specifically aimed at increasing the amount of wood harvested. This substitution potential offsets the likely increase in emissions resulting from the shorter rotations themselves (e.g. from increased soils disturbance). Where harvested wood substitutes for fossil fuels in power generation, abatement potential from *substitution* from shorter rotations is 0.79 $MtCO_2e$ in 2022 (central feasible potential). This rises to 10.53 $MtCO_2e$ when the wood is used directly to substitute for carbon intense materials (steel and cement) in other sectors. This comes at a cost of £12.07/$tCO_2e$ (£2006) or £0.52/$tCO_2e$ (£2006), respectively.

These figures demonstrate the significant role that increased biomass resource may be able to play in substituting for carbon-intensive end uses. However, we expect the true abatement may be lower and the true cost higher as:

- Forest biomass may be used overseas, or displace imported products, with no impact on UK emissions
- Any resources shifted from steel/concrete production may move into other emitting activities
- Downstream costs in biomass use are not considered
- Future energy systems are likely to be less carbon intensive
- There is a risk that carbon saving potentials are also reflected in projected biomass/timber prices

Our illustrative abatement potential is derived from scenarios involving coniferous species. The potential ancillary benefits offered by broadleaf forests are likely to be an important policy determinant of the true species mix. But this afforestation trajectory (and thus the likelier true potentials) is currently difficult to specify.

## 6.2 Overview of the sector

The process of photosynthesis combines atmospheric carbon dioxide with water, subsequently releasing oxygen into the atmosphere and incorporating the carbon atoms into the cells of plants. Additionally, forest soils capture carbon. Trees are long-lived plants that develop a large biomass, thereby capturing large amounts of carbon over decades. A young forest, when growing rapidly, can sequester relatively large volumes of additional carbon roughly proportional to the forest's growth in biomass. An old-growth forest acts as a reservoir, holding large volumes of carbon, even if it is not experiencing net growth. Managed forests offer the opportunity for influencing forest growth rates and providing for full stocking, both of which allow for more carbon sequestration. It has to be emphasised that wood products represent significant carbon stores. More importantly, wood products substitute to $CO_2$ intensive products as:

- fossil fuels in the energy generation sector;
- concrete or steel in the construction sector.

In broad terms two forms of abatement potential are inherent in longer term afforestation and stand management, versus shorter term rotations aimed at increasing product substitution potential. We term these *sequestration* potential and *substitution* potential, and it is important to consider them separately, as the next section identifies.

Forestry is significant land use in the UK, occupying 11.6% of the total land area (Smith & Gilbert, 2003). Brainard *et a*l (2003) show that the UK's forests contain 163 million tonnes of carbon. Existing data show that forestry has the potential to remove significant amounts of $CO_2$ through tree plantations and forest management.

## 6.3 Mitigation measures

IPCC (2007) identifies several measures likely to increase the forestry abatement potential. For European countries, measures that could be implemented are:

- afforestation of agricultural lands;
- forest management to increase carbon density at the stand/landscape level (maintaining forest cover, minimising forest carbon soils losses, increasing rotation lengths, increasing growth and managing drainage, low thinning regime);
- storing carbon in wood products.

The initial focus was on measures aimed at increasing carbon storage in the forest stand. Four measures described in IPCC (2007) were selected: afforestation and low thinning regimes for conifers forests and longer rotations for both broadleaf and conifer forests. These measures were selected more for their illustrative technical potential than for their likelihood of adoption across the whole forest stock (including wood products).

However, data limitations in relation to broadleaf plantings and the importance of abatement potential in product substitution was emphasised by the project steering group. Specifically, it was suggested that focusing on forest carbon storage with low harvest rates ignores the fact that wood products are substitutes to $CO_2$ intensive products. There is an argument for accrediting these displaced emissions potential to the cost-effectiveness of appropriate harvesting regimes. Clearly this potential can be increased depending on the assumed harvest rates and life cycle of harvested forest products.

We therefore consider two measures both of which include benefits estimates of the impact of wood products on substitution issues:

- afforestation
- implementation of shorter rotations (increasing average timber harvests providing more wood products, and so more substitution possibilities).

*Sequestration and Substitution*

There are important reasons to distinguish between *sequestration* abatement potential that derives from removing carbon from the atmosphere by increasing the carbon contained in the forest stock and *substitution* abatement potential that displaces fossil fuel use in other sectors by substituting biomass produced in the forestry sector.

- *Sequestration* abatement directly affects the emissions attributed to the LULUCF sector in the UK emissions Inventory. *Substitution* abatement will accrue in other sectors.
- *Sequestration* abatement is a one-off opportunity. Once a forest reaches its full size it will no longer sequester significant carbon from the atmosphere. Converting land to forest therefore can only be done once, offering abatement for the years whilst the forest is growing (49 years in our assumptions), but then little more. In contrast biomass may be produced year after year, offering ongoing opportunities to reduce emissions.
- *Substitution* abatement may not be reflected in the UK Inventory at all. For example, timber products may substitute for imported steel (or timber), meaning emissions savings would be captured in another country's emissions inventory. Alternatively, timber or biomass may be exported and used overseas, without affecting UK emissions.
- Even if timber substitutes for UK produced steel, the UK steel industry may maintain output by increasing exports. Even if output is reduced the released resources could be deployed in other carbon-emitting industry.
- It is beyond the scope of this analysis to consider the best use of produced biomass, e.g. whether it should be co-fired with coal in power stations, or used for off-gas-grid heating. There will be different costs associated with these different uses, which will in part be determined by the carbon price in the EU ETS and by the UK's renewable energy strategy. A full analysis requires a full assessment of the costs of the use of the biomass (which is likely to entail higher costs than conventional fossil fuel use) as well as its production.
- The precise use chosen will affect the cost-effectiveness of the biomass production and we must be wary of double-counting the benefits where the price paid for biomass may reflect the EU ETS and hence the value of any carbon saving. Any estimate of cost-effectiveness must therefore be interpreted with considerable caution.

- There are however, clear benefits of increasing the UK's production of biomass as a low-carbon renewable fuel. We therefore make indicative estimates of how much carbon saving could result from increased biomass production for our two chosen measures. However, we do not present these savings in the headline results given the key issues outlined but that are not fully addressed in this report.

*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). In this report we assume that all trees planted will be harvested (and then replanted) after 49 years. We assume 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.

*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.

## 6.4 Data, measurement and assumptions

### 6.4.1 Baselines, rotation lengths, carbon sequestration and substitution benefits

*Afforestation measure*

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).

For afforestation, CEH use three scenarios for forestry (see **Error! Reference source not found.**). 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.

**Table 6.1 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

From the assumed baseline (the mid emissions scenario), the difference in removals to the low emissions scenario gives the full technical abatement potential at 100% adoption. These effectively assume higher planting rates occur for every year from 2006, whereas of course the earliest increased planting could begin is 2009. To control for this we simply move the abatement potential back 3 years, so 2019 in table 6.1 forms the basis for the 2022 MAC curve, which therefore has 1.96MtCO$_2$e[15] full technical potential.

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[15] This is calculated as 8750.5 ktCO$_2$e (for the low emissions scenario in 2019) minus 6788.8 ktCO$_2$e (in the baseline)

High, central and low feasible potentials were defined at 85%, 50% and 10% adoption, respectively.

The lifetime of the afforestation measure is set to 49 years, corresponding to the economic optimum rotation length for conifer management. This does not affect abatement potential in the period to 2022 as none of the newly planted trees are harvested; its relevance is in calculating cost effectiveness.

*Shorter rotation length measure*

CEH assumes a rotation length of 59 years for the conifer forests, which means that every year the harvested area corresponds to the area planted 59 years earlier. The assumption made here is that shorter rotation length of 49 years will be introduced. 49 years tends to be closer to the economic optimum. At this age, trees are also old enough to provide good quality timber; which is likely to substitute to $CO_2$ intensive products.

Since these two options (baseline and shorter rotations) have to be compared regarding their lifetime greenhouse gas emissions/savings and costs/benefits, it has been decided to use a longer lifetime (100 years) for this measure. This means that we assume that for the next 100 years forests will be harvested at 49 years of age rather than 59, meaning on average more biomass is produced each year. Data from the most recent forest inventory (Smith & Gilbert, 2003), as well as carbon storage models (Bateman & Lovet, 2000) have been used to simulate carbon storage per age class.

High, central and low feasible potentials were defined in a similar way as for the afforestation measure, i.e. as 85%, 50% and 10% of full potential respectively. For the full technical potential we assume that the shorter rotations mean that an additional 14,200 ha is harvested each year up to 2012 (21,700 ha rather than 7,500 ha in the baseline), and then an extra 8,400 ha each year up to 2022, (30,100 ha rather than 21,700). These rates are not sustainable in the long-term of course, as moving from a 59 year rotation to a 49 year rotation can ultimately only increase harvesting rates on average by a sixth (10/59) on a given harvested area (this implies average increases in harvest rates of no more than 3,000-4,000 ha in the long term). Some of the identified abatement is therefore likely to be offset by future lower harvesting rates.

*Additional assumptions*

- It is assumed that all new conifer plantations have the same growth characteristics as Sitka spruce (*Picea sitchensis* (Bong.) Carr.) under an intermediate thinning management regime. Sitka spruce is the most common species in UK forests, being about 50% by area of all conifer forest. Milne *et al.* (1998, quoted by Thomson & Van Oijen, 2007;
- the carbon sequestration rate for the new plantations is averaged over the length of the rotation and is 3.6 tons of carbon per hectare (sitka spruce, YC 16, estimated from Bateman & Lovet,2003; in the range of other estimates; see Broadmeadow & Matthews, 2003);
- we assume an additional storage capacity of one and a half tonnes/ha/yr to take into account carbon storage in soils and dead organic matter. The equilibrium carbon density after the transition from grassland to forestland is 47 kg per m2 (average UK, from Thomson &Van Oijen, 2007). It is considered that this transition occurs over an intermediate time scale (300 years).
- as in the projections, it is assumed that the forests planted before 1920 are neutral in terms of their contribution to carbon storage (822,000 hectares);

- Substitution benefits have been estimated with numbers provided by the Forest Research (taken as given for this indicative analysis). Previous work undertaken by FC has shown that every forest management operation generates some avoided emissions in the energy sector and in other sectors. Some high and low estimates are given for thinning operations and clear cutting. Conservative estimates have been used for the purpose of this study. However, the assumptions are based on current production practices in energy, steel and concrete production, which are likely to become less carbon intense in future, implying the assumptions will become less conservative for later years. The assumptions are:
    - 0.25669 ktCO2/ha for substituting fossil fuels in the energy sector
    - 2.576 ktCO2/ha for substituting energy-intense products, and they are non-additive.

### 6.4.2 Costs and incomes

*Afforestation measure*

New forest plantations involve two types of costs: planting costs and the value of land used for planting

- Planting costs are estimated at £1250 per hectare (FC, 2006).;
- Land values are driven by the opportunity costs using different land types.

Uncultivated land
Low yielding cultivated land
Marginal land
Existing forest

Ultimately the assumption made here is that woodlands will displace uncultivated land with a low agricultural potential: rough grazing areas. BAU3 predictions show 5.5 million ha of this land type. Therefore the value of the next best land use, derived from the Farm Management Handbook (Beaton *et a*l., 2007), is £141/ha sheep grazing area. This assumption can be altered in the spreadsheet developed for the measure

Forest management generates some incomes (thinning and clear cutting operations). These are based on timber prices (**Error! Reference source not found.**) showing the standing sales timber prices for conifers provided by the Forestry Commission (2008), and income generated from each harvest **Error! Reference source not found.**(thinnings and clear cut).

**Table 6.2 Timber prices: sales contracts for standing coniferous timber from forest enterprise areas**

| ***Average volume per tree in cubic metres*** | ***Average price £/m3*** | ***Volume m3*** | ***Total price £*** |
|---:|---:|---:|---:|
| ***0.074*** | £2.94 | 3,103 | £9,118 |
| ***0.124*** | £5.23 | 58,958 | £308,260 |
| ***0.174*** | £6.91 | 104,474 | £721,487 |
| ***0.224*** | £5.21 | 316,050 | £1,646,409 |
| ***0.274*** | £7.99 | 309,413 | £2,470,974 |
| ***0.424*** | £7.34 | 738,329 | £5,422,152 |
| ***0.499*** | £11.22 | 251,245 | £2,819,917 |
| ***0.599*** | £6.18 | 195,075 | £1,206,248 |
| ***0.699*** | £7.22 | 113,592 | £819,842 |
| ***0.799*** | £11.35 | 127,778 | £1,450,644 |
| ***0.899*** | £16.70 | 29,288 | £489,014 |
| ***0.999*** | £9.67 | 33,801 | £326,848 |
| ***1*** | £15.09 | 68,075 | £1,027,212 |
| | | 2,348,781 | |

Source: Forestry Commission website
http://www.forestry.gov.uk/pdf/SSPI_Ave_Prices_Mar08.pdf/$FILE/SSPI_Ave_Prices_Mar08.pdf

**Table 6.3 Income generated from harvest (thinnings and clear cut)**

| | Age | Volume per tree [$m^3$] | Volume harvested [$m^3$] | Timber prices [£(2008)/$m^3$] | Income [£(2008)/harvest] |
|---|---:|---:|---:|---:|---:|
| 1st thinning | 25 | 0.29 | 40 | 7.99 | 319.6 |
| 2nd thinning | 30 | 0.474 | 40 | 7.34 | 293.6 |
| 3rd thinning | 35 | 0.728 | 40 | 7.22 | 288.8 |
| 4th thinning | 40 | 1.036 | 40 | 15.089 | 603.56 |
| Clear cut | 49 | 1.2 | 495 | 15.089 | 7469.055 |
| Clear cut | 59 | 1.2 | 552.66 | 15.089 | 8339.0867 |

Projections of future timber prices are needed to get a picture of how the curves should evolve through time. Increasing demand from processors, new developments and increased usage of wood fibre in power generation create the conditions for rising prices. International shortages are also contributing to rising prices. Discussions with the Forestry Commission led us to assume a constant real rate of increase (2.5% per year).

*Shorter rotation measure*

The rotation length option generates a change in the forest value, since harvesting occurs earlier, but provides a lower income per hectare.

The additional cost involved in this option again is planting cost. It is estimated at £1250 per hectare (FC, 2006). Incomes are generated from thinnings and harvesting. These values are based again on the timber prices shown in the previous section, and estimated to be the same as in the case of afforestation, with the only difference is that income from harvesting a 59 year old forest generates higher income than harvesting a 49 year old forest.

## 6.5 Results

### 6.5.1 Abatement potential

*Afforestation measure*

**Error! Reference source not found.** gives the abatement potentials for the afforestation measure at 50% adoption (central feasible potential), with increased planting rates beginning from 2009. The first year abatement potential is negative as it is likely that soils disturbances due to forest operations before planting will constitute a source of CO$_2$. This is offset in the later years, resulting in a high annual average abatement potential through the lifetime, and positive abatement from 2013 onwards.

The higher planting rate for this measure will also generate more biomass resource, which in theory may offer further indirect benefits. However, the first year abatement potential for wood products is nil; harvest occurs only at the end of the rotation. This means assumptions on substitution would be particularly speculative as the energy sector is likely to be significantly decarbonised when products are harvested, so that the Forest Research assumptions on substitution benefits are unlikely to apply. We therefore do not attempt to quantify potential savings but note the co-benefit of increased biomass production.

**Table 6.4 Sequestration abatement potential for afforestation, central feasible potential**

| | | AP [kt CO$_2$] |
|---|---|---|
| **Sequestration AP - Direct benefits (biomass + soils C sequestration)** | 2012 | -17 |
| | 2017 | 315 |
| | 2022 | 981 |

*Shorter rotation length measure*

Table 6.5 presents the abatement potentials for the short rotation option, including both (small negative) sequestration and (larger) substitution impacts. Most of the results (the annual variations are important) are due to the age structure of the forest, i.e. the area that would be harvested in each year under baseline and under the option differ greatly due to different planting rates 49 and 59 years before the harvest. Considering the direct effects alone, this option would cause a small amount of net CO$_2$ emissions over the lifetime and in the first year. Direct effects are completely offset by the greenhouse gas benefits in the energy sector and especially by benefits in product substitution. First years abatement potentials from wood products and energy are positive as more areas are harvested under the 49 years assumption (as outlined in section 6.4.1). Lifetime abatement however cannot sustain these rates – as noted above the measure implies on average up to a one sixth increase in the amount of wood harvested, whilst these figures represent a 50% increase for 2017 and 2022 (and 200% increase in 2012).

**Table 6.5 Abatement potential for shorter rotations, central feasible potential**

| | | First yr AP [kt $CO_2$] |
|---|---|---|
| AP - Direct benefits (biomass + soils C sequestration) | 2012 | -466 |
| | 2017 | -437 |
| | 2022 | -287 |
| AP - Indirect benefits - energy end use | 2012 | 521 |
| | 2017 | 693 |
| | 2022 | 1,078 |
| AP - Indirect benefits - product substitution | 2012 | 5,226 |
| | 2017 | 6,955 |
| | 2022 | 10,819 |

### 6.5.2 Cost effectiveness

Both measures are expected to broadly break-even over their lifetimes, and hence imply a cost per tonne close to zero.

**Table 6.6 Cost effectiveness of the forestry measures, 2022, CFP, social metric**

| Measure | Cost Effectiveness [£2006/$tCO_2e$] |
|---|---|
| Afforestation, sequestration only | -7.12 |
| Afforestation, substitution in energy sector | -5.54 |
| Afforestation, substitution in other sectors | -1.82 |
| Rota length, substitution in energy sector | 12.07 |
| Rota length, substitution in other sectors | 0.52 |

### 6.5.3 Discussion

The range of assumptions used in this analysis means that our estimated potentials are indicative and sensitivity analysis should be undertaken to determine the impact of a range of domestic and international factors. The absence of ancillary benefits is a key weakness in the analysis, since the provision of public good benefits from a broader species mix may potentially influence the abatement cost effectiveness. A full analysis would require a much more involved model and set of assumptions than we have used here.

In addition to the assumptions made here significant further uncertainties relate to:

- The extent to which product substitution will be driven by changes in relative prices between wood and traditional construction material and fossil fuel energy sources
- how growth patterns will alter under climate change scenarios. Some effects could be positive (more $CO_2$ and $N_2O$ in the atmosphere could improve growth) whereas other factors (rainfall changes, extreme events) could have a negative impact;
- how international oil price increases could lead to a major switch to wood energy generation; which could have a greater impact on wood prices (compared to the rate of increase we assumed);
- however, these assumptions on wood prices are also a function of investments in timber processing

# 7 Mitigation options in Land Use and Land Use Change (LULUC)

## 7.1 Key findings

This section does 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. The key measures considered are:

- Peatland restoration
- Halting liming of organic soils
- land use transitions between grassland transitions and other agricultural uses

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.

## 7.2 Background

By affecting the flux of carbon to and from soils, land use changes have the potential to aid mitigation efforts. That is, protecting existing carbon stores and enhancing the sequestration of carbon can be achieved through encouraging some land use changes, including conversion of agricultural land to forestry and transitions between different forms of agricultural use. The former are reported separately elsewhere in this report, but changes of use within agriculture are considered here. Although there are some data and modelling issues, the analysis presented suggests that aggregate emission savings from changes between agricultural land uses may be fairly modest and that unit costs per tonne of $CO_2$e are relatively high due to the value forgone in reduced farm output. The unit costs are sensitive to valuation of agricultural output which is highly dependent on both global commodity prices and support payments. Given structural changes in global demand for commodities, there are few reasons to suppose that these costs might be lower between now and 2022. We can speculate that increased adoption of biotechnology may provide options for alternative land use over a longer time horizon (i.e. to 2050).

Limited evidence on the extent of potential peatland restoration in Scotland suggests that the marginal cost of emissions reduction may be as low as £27/t $CO_2$e. This accords with US-EPA studies that suggest that wetland restoration was generally worthwhile. While such restoration may only account for a small proportion (0.9%) of LULUCF emission and a small fraction of the total national target, it is probably worth doing, although not in isolation from other measures.

## 7.3 Overview of sector

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.

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 (Thomson & van Oijen, 2008)).

## 7.4 Main modelling complexities

### 7.4.1 Criteria/rationale and brief description for screening measures in each sector

Since land management change within agriculture is considered in the crop and soils measures and transitions to and from forestry fall are considered in that section, this section considers the significance of a range of land use transitions outside the forestry sector.

Potential land use transitions were examined according to the area of land undergoing a given transition and the size of the emission / sink caused by the transition. Land use transitions that are very infrequent or that occur on only very small areas of land were not considered further since even high per-area emissions / sinks would have little impact upon overall GHG emissions at the national level. The other criteria considered were cost effectiveness. If mitigation of an emission or creation of a sink by a given transition relies upon prohibitively expensive technology / methods, it was not considered further. The land use transitions considered are discussed below.

## 7.5 Mitigation measures

This section details the potential abatement measures considered.

### 7.5.1 Conversion from arable to grassland

The abatement potential and costs of transitions from various crops to different grassland uses were calculated for the four regions, England, Scotland, Wales and Northern Ireland. It is important to consider this from not only from the point of view of the effect of the transition on changes in soil carbon, but also to include the uses to which the cropland and grassland are put before and after the transition, to estimate the opportunity costs and overall abatement potential.

The following crops were considered: wheat, winter barley, spring barley, oats, other cereals, oil-seed rape, and potatoes, while set-aside, sheep, beef and dairy were considered as uses of grassland. Transitions from the seven crops to the three grassland uses gave a total of 28 potential abatement options.

### 7.5.2 Reduced ploughing of grassland

About 40% of the impacts of agriculture in Scotland are through $CO_2$ released from ploughing of grassland (e.g. Moxey, 2008). According to the land use transition matrix used in the UK Greenhouse Gas Inventory, 1990 to 2006 (Choudrie et al., 2008), some 95,948 ha of grassland are converted annually to cropland. However, it is unclear whether this is a real transfer, and not just grassland that regularly goes between cropland and grassland, rather than conversion to permanent cropland. In any case, grassland can arguably only be maintained with adequate livestock numbers (which are declining), encouraging more livestock would have negative GHG consequences (Smith et al., 2008)- so overall a reduction in ploughed grassland area is not considered to be a viable option.

### 7.5.3 Peat restoration

A functioning peat-bog should sequester in the order of 200 kgC $ha^{-1}$ $y^{-1}$, while a degraded one could lose up to 200 kgC $ha^{-1}$ $y^{-1}$. Hence restoration could, in time, result in a net gain of 400 kgC $ha^{-1}$ $y^{-1}$. Restoration could typically involve a one-off cost of £400-1000 per ha, although there might be smaller recurrent costs depending upon the degree of success (S. Chapman, pers. comm.). There is some variation in this cost however with Natural England (2008) citing a median project cost from a review of restoration projects of £1600/ha, which includes the cost of land purchase. However, assuming the lower cost is spread over 10 years, this would be a unit cost of £27-68 $tCO_2e^{-1}$.

In Scotland, the area of degraded 'basin peat' is cited as 12,000 ha, but this is an underestimate. The area of 'eroded blanket peat' is about 150,000 ha, but only about 6% of this is actually eroded, giving 9,000 ha (S. Chapman, pers. comm.). Using these figures, the technical abatement potential for restoration of basin peat in Scotland is 24,000 × 400 = 9.6 kt C $y^{-1}$, and for blanket peat, if erosion can be stopped, 3.6 kt C $y^{-1}$. This gives a total for Scotland of 13.2 kt C $y^{-1}$, ignoring any methane emission reinstated to the restored peatland. Assuming a similar picture for England & Wales, (actually more basin peat, less blanket peat but more eroded) the UK total might be 26 kt C $y^{-1}$ (or 0.026 Mt C $y^{-1}$) (S. Chapman, pers. comm.).

Assuming these figures are correct, the 13.2 kt C $y^{-1}$ (~0.05 $MtCO_2$ $y^{-1}$) saved through peat restoration in Scotland represents about 0.09% of the country's total emissions of about 55 $MtCO_2$ $y^{-1}$ (2003), or about 0.9% of its LUCF emissions of 5.2 $MtCO_2$ $yr^{-1}$ (2003), if all of the peat is restored. A more recent estimate from Natural England (2008) suggests a combined saving as high as 1.47 $MtCO_2e$/year might be available from restoration in England. However, the same document notes a range of scientific uncertainties that could reduce this figure and we therefore do not consider it further.

### 7.5.4 Halting liming of organic soils

Rangel-Castro *et al*. (2004) estimate that liming of organic soils in Scotland causes the loss of about 1400-2800 tC $y^{-1}$ (0.005-0.010 $MtCO_2$ $y^{-1}$) of soil carbon, which represents between 0.01% and 0.02% of total GHG emissions in Scotland, or about

0.1% to 0.2% of LUC emissions. Assuming that this percentage will be similar across the UK (it will likely be substantially less for England and Wales, due to the lower proportion of organic soils present), the cessation of liming of organic soils as an abatement option has not been included in this analysis.

## 7.6 Data and Measurement

### 7.6.1 Land use transition matrices

Land use transition matrices are used within the LULUCF inventory. Methods are detailed in the LULUCF inventory and were summarised by Amanda Thomson (CEH) as follows for the ECOSSE final report. The land use transition matrices and are based on three national datasets on land use change covering the period 1950 to the present.

- The Monitoring Landscape Change (MLC) project (Hunting Technical Services Ltd, 1986) which assessed land use change in England and Wales between 1947, 1969 and 1980 using aerial photography.
- The National Countryside Monitoring Scheme (NCMS) (Mackey *et al.*, 1998) which assessed land cover change in Scotland between 1947, 1973 and 1988 using aerial photography.
- The Countryside Surveys (Barr *et al.*, 1993; Firbank, 2003), which are national (GB) field surveys managed by the Centre for Ecology and Hydrology. These are available for 1984, 1990 and 1999.

Each of these data sources uses a different land classification system, so the original classes are grouped into the land use categories used for the GHGI to allow comparison between datasets and over time.

To date, only country-level (England, Scotland, Wales and Northern Ireland) land use change matrices for the GHGI have been developed but recently Amanda Thomson and colleagues have begun developing matrices at 20km x 20km, as this is the scale found to achieve an acceptable balance between detail and accuracy in other components of the GHGI. However, it is the country-level land use transition matrices that are used for the GHGI and in this study.

Amanda Thomson notes in the ECOSSE final report “For Scotland and Wales (England also) measured land area and change data are available from surveys taken in 1947, 1969/1973, 1980 (England and Wales only), 1984, 1990 and 1998. Measured land use change data over the different periods were used to estimate annual changes by assuming that these were uniform across the measurement period, e.g. the period 1980-84 was filled using data from the Countryside Survey (CS) assuming the same annual rate of change as seen for 1984-90. The period 1999-2003 was extrapolated forward from the CS assuming the same annual rate of change as seen for 1990-98. Another CS is planned for 2007-2008, which will allow the land use change estimates to be updated in the future.”

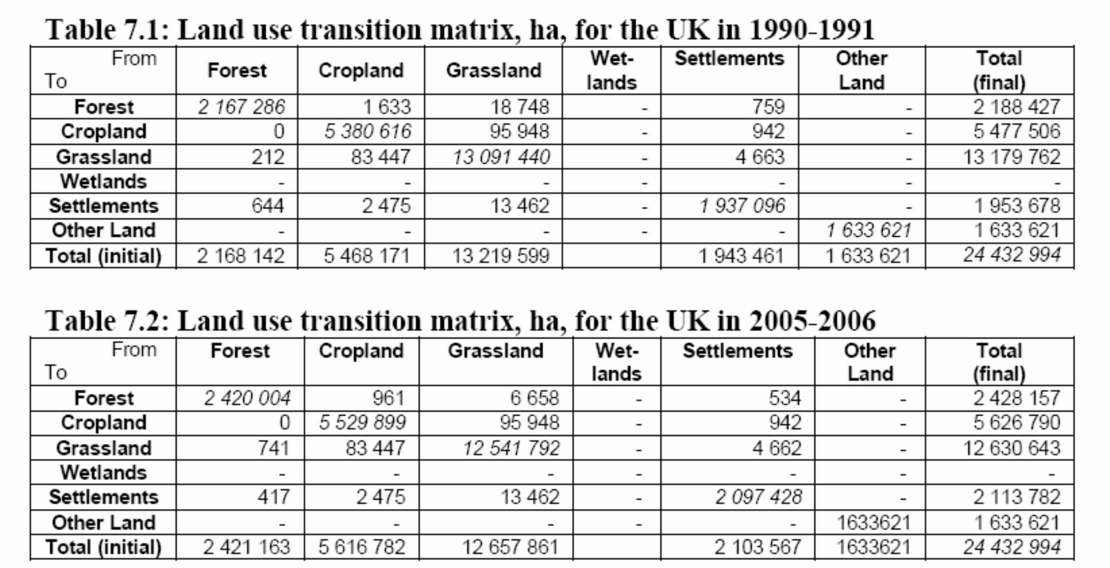

**Table 7.1: Land use transition matrix, ha, for the UK in 1990-1991**

| From<br>To | Forest | Cropland | Grassland | Wet-lands | Settlements | Other Land | Total (final) |
|---|---|---|---|---|---|---|---|
| **Forest** | *2 167 286* | 1 633 | 18 748 | - | 759 | - | 2 188 427 |
| **Cropland** | 0 | *5 380 616* | 95 948 | - | 942 | - | 5 477 506 |
| **Grassland** | 212 | 83 447 | *13 091 440* | - | 4 663 | - | 13 179 762 |
| **Wetlands** | - | - | - | - | - | - | - |
| **Settlements** | 644 | 2 475 | 13 462 | - | *1 937 096* | - | 1 953 678 |
| **Other Land** | - | - | - | - | - | *1 633 621* | 1 633 621 |
| **Total (initial)** | 2 168 142 | 5 468 171 | 13 219 599 | | 1 943 461 | 1 633 621 | *24 432 994* |

**Table 7.2: Land use transition matrix, ha, for the UK in 2005-2006**

| From<br>To | Forest | Cropland | Grassland | Wet-lands | Settlements | Other Land | Total (final) |
|---|---|---|---|---|---|---|---|
| **Forest** | *2 420 004* | 961 | 6 658 | - | 534 | - | 2 428 157 |
| **Cropland** | 0 | *5 529 899* | 95 948 | - | 942 | - | 5 626 790 |
| **Grassland** | 741 | 83 447 | *12 541 792* | - | 4 662 | - | 12 630 643 |
| **Wetlands** | - | - | - | - | - | - | - |
| **Settlements** | 417 | 2 475 | 13 462 | - | *2 097 428* | - | 2 113 782 |
| **Other Land** | - | - | - | - | - | 1633621 | 1 633 621 |
| **Total (initial)** | 2 421 163 | 5 616 782 | 12 657 861 | | 2 103 567 | 1633621 | *24 432 994* |

**Figure 7.1 Land use transition matrices calculated in the UK Greenhouse Gas Inventory, 1990 to 2006 (Choudrie *et al.*, 2008). The 1990-91 areas were estimated from the Countryside Survey data, translated into IPCC land use categories and adjusted to take account of other data sources.**

### 7.6.2 Baselines

In the Annual Report 2007 (Thomson & van Oijen, 2008, Chapter 4), projections of the emissions for years from 2006 to 2020 were made for each activity for the UK and for each of the Devolved Administration areas, England, Scotland, Wales, and Northern Ireland. For each, three scenarios were developed – 'low', 'mid' and 'high', based on particular assumptions. For the Land Use Change (Soils) activity, the annual rates of change in land use area for 1990 to 2005 were used as a basis to project forward for the period 2006-2020, but this was modified for each of the three scenarios in the following way. A Monte Carlo approach was used to vary the inputs of the equation calculating the changes in soil carbon for each year following a change in land use – i.e. the rate of change ($k$), the area activity data ($A_T$), and the values for soil carbon equilibrium under initial and final land use ($C_f - C_0$). The model was run 1000 times using values for these inputs selected from within a range. The minimum value of these simulations was used for the 'low' scenario, the mean value for the 'mid' scenario, and the maximum value for the 'high' scenario. Results were presented as the net flux of $CO_2$ for four of the land use categories (forest land, cropland, grassland, and settlements) for each of the regions.

For the purposes of the present analysis, it was not possible to obtain the land use change trajectories used for the CEH projections. Similarly, there were uncertainties with the land use transition matrices above, particularly for the cropland to grassland transition which we are interested in, which are discussed in more detail below. Thus, we employed BAU3 estimates which assumed a small increase in the area of grassland from 2004 to 2025 equivalent to a 3% change in England, 2% change in Scotland, no change in Wales, and 2% change in Northern Ireland, which were obtained after balancing land after growth in crops and also predicted changes in livestock numbers, and also assuming 50% of set-aside which remained in the system under other cropping activities. On an annual basis, this equated to a 0.15%, 0.10%, 0.0% and 0.10% increase respectively. Aggregated to the whole of the UK, this gave an annual increase in grassland area of around 7500 ha per year.

## 7.7 Costs

### 7.7.1 Sources of data

The gross margins (GM, £ ha$^{-1}$) for the various enterprises, typical fertiliser inputs for the crops, and liming rates for grassland, were obtained from Beaton *et al*. (2007), and are shown in Table 7.1. For the purposes of the analysis, it was assumed that lime was applied *pro rata* annually, although in reality, it is more likely that it would be applied every five years. Stocking densities were obtained from Beaton *et al*. (2007). In the absence of more detailed information, the same values were used in each of the four regions.

**Table 7.1 Input data for the various enterprises used in the analysis. Gross margins , fertiliser and lime data from Beaton *et al*. (2007).**

| Enterprise | Area (ha) | GM (£ ha$^{-1}$) | N fertiliser (kg N ha$^{-1}$) | Lime (kg ha$^{-1}$) | Stocking rate (head ha$^{-1}$) |
|---|---|---|---|---|---|
| Wheat | 1748400 | 738 | 200 | | |
| W Barley | 321300 | 688 | 180 | | |
| S Barley | 274200 | 490 | 110 | | |
| Oats | 65500 | 783 | 120 | | |
| Other cereals | 19900 | 482 | 180 | | |
| OSR | 480000 | 436 | 210 | | |
| Potatoes | 102400 | 1311 | 220 | | |
| Vegetables | 108700 | 2432 | 100 | | |
| | | | | | |
| Beef | | 198 | 175 | 1000 | 0.5 |
| Sheep | | 141 | 0 | 1000 | 5.5 |
| Dairy | | 751 | 250 | 1000 | 2.9 |
| Set aside | | 0 | 0 | 0 | 0.0 |

### 7.7.2 Costs

The cost of the abatement option was calculated as the opportunity cost foregone of the cropping system being converted subtracted from the return from the new land use (i.e. set-aside, dairy, beef, sheep). Opportunity costs foregone were calculated as the gross margin values for each crop. Returns from the new land use were calculated as follows. For the ‘set-aside’ option, it was assumed that returns were zero – our understanding is that, although compulsory set-aside remains in existence, it has a 0% value for this year. For the other land uses involving livestock, returns were calculated as the gross margin values from Beaton (2007).

We have not explicitly included the costs of labour of conversion of cropland into grassland. We have not currently included any changes in input (fertilisers, lime, etc.) over time.

### 7.7.3 Other assumptions

We have assumed that the gross margin data from Beaton (2007) are the same for all four of the Devolved Regions. We recognise that this is not realistic, but in the absence of more detailed data, we believe that it is a fair assumption.

### 7.7.4 Farm scale model description

Results for each of the regions are shown in Table 7.2, Table 7.3, Table 7.4 and Table 7.5 respectively, and for the whole of the UK in Table 7.6, ordered by unit cost (£ tCO2e). In each region, a switch from arable to dairy resulted in a net increase in GHG emissions, so these data are not shown. In some transitions, there is an extremely high unit cost (e.g. £132275 tCO2e in the case of oats-to-beef in England, Table 7.2) – this was generally due to a high opportunity cost involved in the transition, and very small reductions in GHG emissions.

**Table 7.2 Unit costs (£ $tCO_2e^{-1}$) and technical abatement potential ($MtCO_2e$) of various land use transitions from arable to grassland for England.**

| From | To | Unit Cost (£ $tCO_2e^{-1}$) | Technical abatement potential ($MtCO_2e$) |
|---|---|---|---|
| OSR | Setaside | 170 | 1.230 |
| Other cereals | Setaside | 203 | 0.047 |
| OSR | Sheep | 246 | 0.575 |
| S Barley | Setaside | 251 | 0.536 |
| W Barley | Setaside | 289 | 0.765 |
| Wheat | Setaside | 295 | 4.373 |
| Other cereals | Sheep | 336 | 0.020 |
| Oats | Setaside | 389 | 0.132 |
| OSR | Beef | 431 | 0.265 |
| Potatoes | Setaside | 500 | 0.269 |
| Wheat | Sheep | 525 | 1.988 |
| W Barley | Sheep | 539 | 0.326 |
| S Barley | Sheep | 592 | 0.162 |
| Other cereals | Beef | 768 | 0.007 |
| Potatoes | Sheep | 929 | 0.129 |
| Oats | Sheep | 988 | 0.043 |
| Wheat | Beef | 1099 | 0.859 |
| W Barley | Beef | 1325 | 0.119 |
| Potatoes | Beef | 1815 | 0.063 |
| Oats | Beef | 132275 | 0.000 |

Only those transitions with a positive technical abatement potential (i.e. GHG emission reductions) are shown.

**Table 7.3 Unit costs (£ $tCO_2e^{-1}$) and technical abatement potential ($MtCO_2e$) of various land use transitions from arable to grassland for Scotland. Only those transitions with a positive technical abatement potential (i.e. GHG emission reductions) are shown.**

| From | To | Unit Cost (£ $tCO_2e^{-1}$) | Technical abatement potential ($MtCO_2e$) |
|---|---|---|---|
| OSR | Setaside | 170 | 0.091 |
| Other cereals | Setaside | 203 | 0.004 |
| OSR | Sheep | 229 | 0.046 |
| S Barley | Setaside | 251 | 0.475 |
| W Barley | Setaside | 289 | 0.122 |
| Wheat | Setaside | 295 | 0.239 |
| Other cereals | Sheep | 308 | 0.002 |
| OSR | Beef | 369 | 0.023 |
| Oats | Setaside | 389 | 0.040 |
| Wheat | Sheep | 486 | 0.117 |
| W Barley | Sheep | 494 | 0.057 |
| Potatoes | Setaside | 500 | 0.002 |
| S Barley | Sheep | 513 | 0.166 |
| Other cereals | Beef | 615 | 0.001 |
| Oats | Sheep | 866 | 0.015 |
| Potatoes | Sheep | 866 | 0.001 |
| Wheat | Beef | 926 | 0.056 |
| W Barley | Beef | 1062 | 0.024 |
| Potatoes | Beef | 1579 | 0.001 |
| Oats | Beef | 6088 | 0.002 |
| S Barley | Beef | 8296 | 0.009 |

Only those transitions with a positive technical abatement potential (i.e. GHG emission reductions) are shown.

**Table 7.4 Unit costs (£ $tCO_2e^{-1}$) and technical abatement potential ($MtCO_2e$) of various land use transitions from arable to grassland for Wales. Only those transitions with a positive technical abatement potential (i.e. GHG emission reductions) are shown.**

| From | To | Unit Cost (£ $tCO_2e^{-1}$) | Technical abatement potential ($MtCO_2e$) |
|---|---|---|---|
| OSR | Setaside | 170 | 0.008 |
| Other cereals | Setaside | 203 | 0.005 |
| S Barley | Setaside | 251 | 0.028 |
| OSR | Sheep | 276 | 0.003 |
| W Barley | Setaside | 289 | 0.018 |
| Wheat | Setaside | 295 | 0.037 |
| Other cereals | Sheep | 384 | 0.002 |
| Oats | Setaside | 389 | 0.006 |
| Potatoes | Setaside | 500 | 0.006 |
| OSR | Beef | 561 | 0.001 |
| Wheat | Sheep | 592 | 0.015 |
| W Barley | Sheep | 617 | 0.007 |
| S Barley | Sheep | 757 | 0.007 |
| Potatoes | Sheep | 1035 | 0.002 |
| Other cereals | Beef | 1176 | 0.000 |
| Oats | Sheep | 1231 | 0.002 |
| Wheat | Beef | 1487 | 0.005 |
| W Barley | Beef | 2029 | 0.002 |
| Potatoes | Beef | 2295 | 0.001 |

Only those transitions with a positive technical abatement potential (i.e. GHG emission reductions) are shown.

**Table 7.5 Unit costs (£ $tCO_2e^{-1}$) and technical abatement potential ($MtCO_2e$) of various land use transitions from arable to grassland for Northern Ireland.**

| From | To | Unit Cost (£ $tCO_2e^{-1}$) | Technical abatement potential ($MtCO_2e$) |
|---|---|---|---|
| OSR | Setaside | 170 | 0.001 |
| Other cereals | Setaside | 203 | 0.001 |
| OSR | Sheep | 238 | 0.000 |
| S Barley | Setaside | 251 | 0.042 |
| W Barley | Setaside | 289 | 0.010 |
| Wheat | Setaside | 295 | 0.021 |
| Other cereals | Sheep | 322 | 0.000 |
| Oats | Setaside | 389 | 0.004 |
| OSR | Beef | 400 | 0.000 |
| Potatoes | Setaside | 500 | 0.012 |
| Wheat | Sheep | 506 | 0.010 |
| W Barley | Sheep | 517 | 0.004 |
| S Barley | Sheep | 552 | 0.014 |
| Other cereals | Beef | 688 | 0.000 |
| Potatoes | Sheep | 899 | 0.006 |
| Oats | Sheep | 927 | 0.001 |
| Wheat | Beef | 1011 | 0.004 |
| W Barley | Beef | 1188 | 0.002 |
| Potatoes | Beef | 1696 | 0.003 |
| Oats | Beef | 12394 | 0.000 |

Only those transitions with a positive technical abatement potential (i.e. GHG emission reductions) are shown.

**Table 7.6 Unit costs (£ $tCO_2e^{-1}$) and technical abatement potential ($MtCO_2e$) of various land use transitions from arable to grassland for the whole of the United Kingdom.**

| From | To | Unit Cost (£ $tCO_2e^{-1}$) | Technical abatement potential ($MtCO_2e$) |
|---|---|---|---|
| OSR | Setaside | 170 | 1.329 |
| Other cereals | Setaside | 203 | 0.057 |
| OSR | Sheep | 244 | 0.628 |
| S Barley | Setaside | 251 | 1.081 |
| W Barley | Setaside | 289 | 0.914 |
| Wheat | Setaside | 295 | 4.670 |
| Other cereals | Sheep | 332 | 0.025 |
| Oats | Setaside | 389 | 0.182 |
| OSR | Beef | 421 | 0.293 |
| Potatoes | Setaside | 500 | 0.289 |
| Wheat | Sheep | 519 | 2.148 |
| W Barley | Sheep | 532 | 0.395 |
| S Barley | Sheep | 580 | 0.333 |
| Other cereals | Beef | 742 | 0.009 |
| Potatoes | Sheep | 920 | 0.140 |
| Oats | Sheep | 968 | 0.060 |
| Wheat | Beef | 1070 | 0.942 |
| W Barley | Beef | 1280 | 0.147 |
| Potatoes | Beef | 1777 | 0.069 |
| Oats | Beef | 33553 | 0.002 |

Only those transitions with a positive technical abatement potential (i.e. GHG emission reductions) are shown.

A point to notice is that the unit costs of each transition are relatively high – the lowest transition giving a positive reduction in GHG emissions in each region is £170 tCO2e in the case of OSR→set-aside, with other transitions to set-aside ranging up to £500 tCO2e in the case of potatoes. For the transition from oats to beef, a unit cost of £33553 tCO2e was calculated, a combination of the high opportunity cost involved in the transition and relatively small reductions in GHG emissions.

## 7.8 Abatement potential

### 7.8.1 Sources of data

For the various enterprises, typical fertiliser inputs for the crops, and liming rates for grassland, were obtained from Beaton et al. (2007), and are shown in Table 7.1. Total area under each crop for each of the devolved regions were obtained from Welsh Assembly Government, Dept. of Environment 2005 data. Rates of carbon sequestration in the soil were calculated from the equilibrium soil carbon density figures presented in Tables 1-19 to 1-22 in Choudrie (2008). IPCC emission factors were used to calculate the GHG emissions from fertiliser inputs, liming, and stock numbers, and are shown in Table 7.1. Emissions of non-CO2 GHGs were converted to CO2-equivalents using the IPCC values (1 CH4 = 21 CO2e; 1 N2O = 310 CO2e).

Technical abatement potential was calculated as the product of the reductions in net emission rates per ha and the total area under each crop.

### 7.8.2 Modelling abatement potential

The abatement potential of conversion of cropland to grassland was calculated as the difference between the GHG emissions from the cropping system being converted from and the emissions from the new land use (i.e. set-aside, dairy, beef, sheep), plus the carbon sequestered as a result of the transition from cropland to grassland. GHG emissions from each crop were calculated as the amount of fertiliser multiplied by the fertiliser emission factor then converted to CO2 equivalents, and from the livestock by multiplying the head per hectare by the per head emission factors. Rates of C accumulation under grassland were calculated from the differences in the equilibrium soil carbon densities under each land use presented in Tables 1-19 to 1-22 in Choudrie (2008), and assuming times to reach equilibrium of 100, 300, 100, and 300 years for England, Scotland, Wales and Northern Ireland, respectively (Choudrie et al., 2008, Tables 1-23 and 1-24). C accumulation was assumed to be linear over this time. This gave values of 0.35, 0.375, 0.315, and 0.36 t C ha-1 y-1 for England, Scotland, Wales and Northern Ireland, respectively.

For the projections out to 2020, only the changes in soil carbon were considered. The uptake of the abatement option of converting cropland to grassland was modelled according to the actual conversion to set-aside in the early 1990s (Figure 7.2). This started in 1990 and by 1994 has reached an area of 728,000 throughout the whole of the UK, or about 12% of the 6 million ha total arable land at that time. This was assumed to represent 100% uptake; we also considered 90% (maximum technical abatement potential), 85% (high feasible abatement potential), 50% (central feasible abatement potential) and 10% uptake (low feasible abatement potential).

### 7.8.3 What is included and excluded

Biomass changes between land uses were not considered, as it was assumed that the differences between biomass contained on cropland and grassland were negligible in comparison to changes in soil carbon and other GHG emissions. We have also not included the GHG emissions from machinery used in cultivating the cropping system, or any GHG emissions associated with livestock production other than the emissions on a per head basis from the livestock themselves.

We have not assumed that any of the input parameters have changed over time. We have assumed that the fertiliser and stocking rate data from Beaton (2007) are the same for all four of the Devolved Regions. We recognise that this is not realistic, but in the absence of more detailed data, we believe that it is a fair assumption.

### 7.8.4 Uncertainties

The CEH Annual Inventory report (Choudrie et al., 2008) (Table 7.1 & 7.2) gives values of 83,447 ha y-1 cropland-to-grassland, and 95,948 ha y-1 from grassland-to-cropland (i.e. a net change of -12,501 ha y-1) for both 1990-01 and 2005-06. The description indicates that the 1990-01 data have come from the Countryside Survey data and the 2005-06 by rolling these forward, and for the crop/grass transitions are assumed to be the same for each year. It is not clear if these 1990-01 data include conversion of arable to set-aside. According to the Defra agricultural statistics data, land converted to set-aside in 1990 was 72,000 ha (Figure 7.2), very similar to the 83,447 ha y-1 figure above (indeed, the average of the 1990-1991 set-aside figures is 84,500 ha y-1), but conversion to set-aside varies considerably between 1990 and 2006, with a gradual decline of about 60,000 ha y-1 from about 2001 onwards (Figure 7.2).

Indeed, a check with CEH Edinburgh indicated that although set-aside was recorded separately from grassland in the Countryside Survey, it was lumped in with grassland for the Inventory. If this is the case, then the assumption that the figure for cropland-to-grassland conversion is constant from 1990-01 to 2005-06 would be incorrect, and inappropriate to use as a baseline for future conversions. Further difficulties will arise from distinctions between short-term, rotational and long-term set-aside too, not to mention its use for non-food crops. Thus, we must acknowledge that the Inventory was not designed for the uses to which we are now trying to put it. In principle, annual data from IACS (as was, but perhaps not now) and the Agricultural Census would be better - but the former is difficult to access and the latter lacks spatial precision, although can be used to estimate Markov transition matrices.

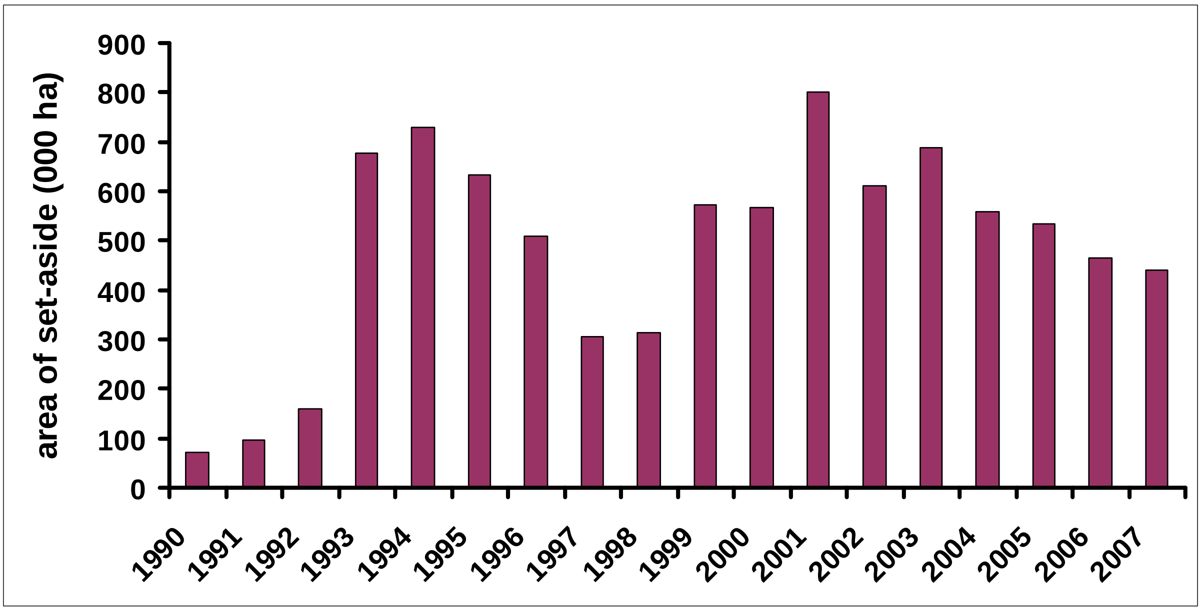

**Figure 7.2** Areas of set-aside in the United Kingdom 1990-2007. Source: Defra Agricultural Land Use; United Kingdom (Table 3.1).

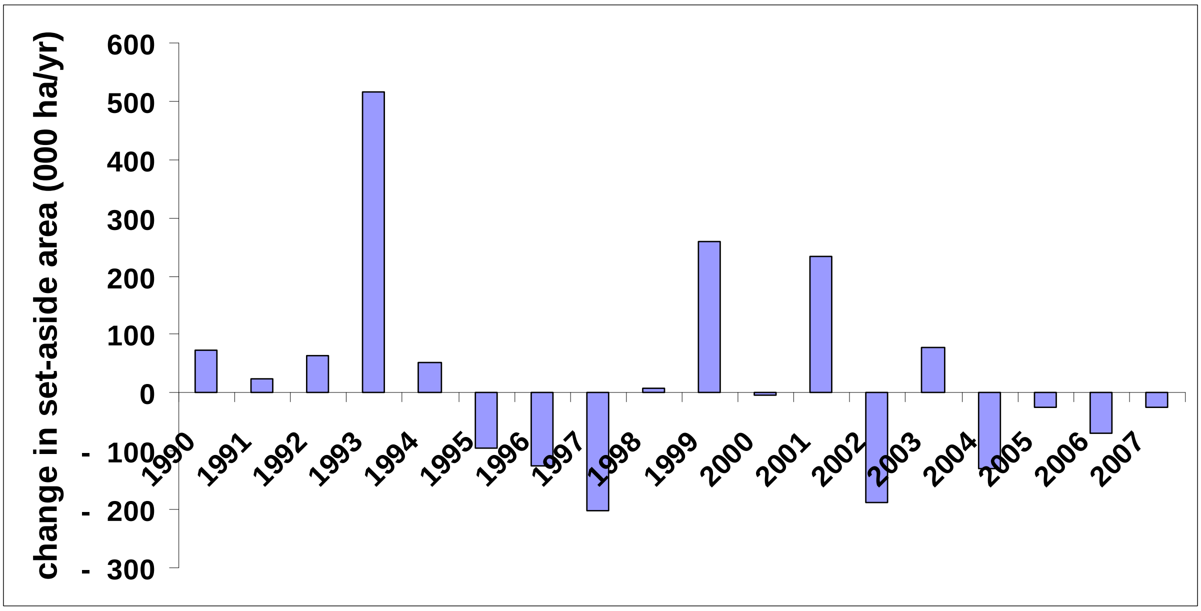

**Figure 7.3** Annual changes in set-side in the United Kingdom 1990-2007. Source: Defra Agricultural Land Use; United Kingdom (Table 3.1).

## 7.9 Results

Results showed that, apart from transitions to set-aside, the technical abatement potentials are relatively low. Looking at the values for the whole of the UK (Table 7.6) the highest abatement potential is for converting all arable land to set-aside at 8.52 MtCO2e reduction (

Figure 7.4), which is 1.3% of the UK's total GHG emissions of 654 MtCO2e (2005). Other transitions from arable to grassland are significantly less than this, with dairy even representing a large increase in GHG emissions.

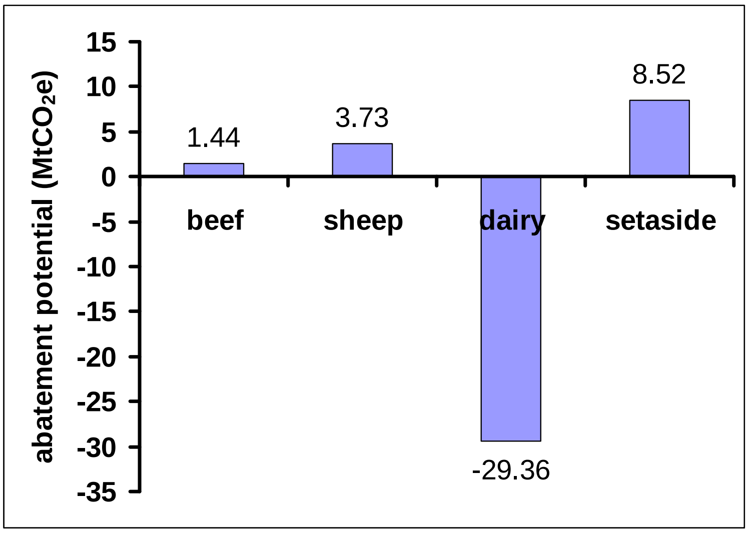

**Figure 7.4 Technical abatement potential ($MtCO_2e$) of converting all arable land in the UK into grassland with different uses (beef, sheep, dairy, no livestock).**

This combination of high unit costs and low technical abatement potentials would seem to suggest that, apart from set-aside, land use changes from arable-to-grassland will not be a significant option for achieving overall national GHG emission reductions. Moreover, this analysis takes no account of whether it is feasible in terms of soils, distance to markets, etc. that may further constrain these potential land use transitions.

# 8 Discussion

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. The combined total MTP abatement estimates for 2012, 2017 and 2022 (social discount rate) are 5.83 MtCO2e, 14.91 MtCO2e and 23.86 MtCO2e respectively.

For demonstration purposes, using the 2022 central feasible potential MACC (Table 8.1 and Figure 8.1) this total central feasible potential is divided between crop and soil measures 6.46 $MtCO_2e$, livestock measures 3.40 $MtCO_2e$, and forestry measures 0.98 $MtCO_2e$.

The 2022 MACC 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 E1 and associated MACC, costs then rise progressively. After measure AC (crop-soils drainage) there is a steep rise in the abatement cost per tonne.

The overall abatement potential is highly influenced by forestry potential, which we stress is subject to a range of potential caveats. For agriculture alone, the central feasible potential of 7.85$MtCO_2e$ (at <£100/t) represents 17.3% of the 2005 UK agricultural GHG emissions (which the NAEI reported to be 45.253MtCO2e in 2005 – not including emissions from agricultural machinery). Although there are no similar benchmark studies, the results presented here partly corroborate conclusions on abatement potential identified in IGER (2001), which concluded that:

"Cost effective ($CH_4$) reduction potential, determined by the point at which the cost curve becomes exponential, is approximately 12% with total on farm savings of £128 million. However, a 15% reduction in emissions can be achieved with negligible net costs. Cost-effective ($N_2O$) reduction potential is approximately 18%, with total on farm savings of £916 million. However, a reduction of 20% could also be achieved at a negligible net cost."

CLA/AIC/NFU (2007) reached similar conclusions about $N_2O$, and suggested that "combined improvements in livestock and crop nitrogen efficiencies could mitigate ($N_20$) emissions by up to 20%". Finally, Pollock (2008, p23) concluded that "overall reductions using currently viable approaches are likely to be modest (maximally some 10-15% of current emissions assuming similar levels of production)".

While these results have reached similar conclusions (i.e. that the mitigation potential is of the order of 15%+/- 5%), some caution should be exercised in making direct comparison as they are based on different methodologies and assumptions.

Table 8.1 also shows how the 2022 potential can be broken down over the UK devolved administrations. Each administration abatement potential was allocated based on the proportion of land area and animal numbers in each administration. At this point we have not allocated projected abatement from forestry or bio digestion plant to any of the administrations. Thus the current DA figures do not show a country split for this overall potential. For forestry, we could use CEH assumptions about the relative planting for the budget time periods, but have not at this point.

In the case of anaerobic digestion, our ability to split the overall potential is hampered by uneven data availability across the administrations. For example, country level data for farm sizes in Wales and Northern Ireland were not available.

Table 8.2 presents the 2022 CFP for a higher discount rate of 7.0%. This rate has the effect of re ordering some crop measures and has negligible overall impact on the cumulative abatement potential.

A number of caveats need to be stressed regarding the results presented in this report. 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. Some ancillary impacts will be significant, and they ideally need to be quantified and added to the cost estimates. At this stage, the report only provides a qualitative assessment of the ancillary impacts (see Annex 1). Work is currently underway to include estimates of these largely non -market impacts

A similar caveat applies to the need to extend the consideration of costs to the life cycle impact of some measures. Annex 2 provides 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.

It should also be noted that projections of emission savings are also highly dependent on assumed rates of adoption given appropriate incentive or regulatory frameworks. For example, ADAS et al. (2007) project emission savings of around 6% in the near future on the basis of the uptake of best practice. Yet prior experience would perhaps suggest that best practice is not necessarily adopted rapidly nor universally - due to, for example, risk aversion or capital constraints (Kurkalova et al., 2006; Engler-Palma & Hoag, 2007; Smith et al., 2007c).

Indeed, recent studies of UK farmer attitudes and behaviour towards (especially) agri-environmental schemes and regulations imply that much remains to be done. Key areas for further consideration include the provision of information and advice, but also understanding motivations and constraints in relation to responses to policy signals (Allman et al., 2006; Garforth et al., 2006; Barnes et al., 2007; Burton et al., 2007; Smith et al., 2007c). This may be of particular importance given on-going changes to (other) aspects of agricultural policy and to commodity market trends. This suggests that further attention to communication and knowledge transfer (KT) activities should accompany R&D efforts directed at identifying and costing mitigation options.

As with other sectors, the effectiveness of measures is influenced by interactions between measures and their environment. We have tried to reduce this uncertainty by explicit consideration of how interactions can change the order and effectiveness of measure implementation. These interaction effects were considered within the sub sectors (i.e. crops/soils and livestock), but we note that there are potential interactions between these sub sectors that we have been unable to address in this report.

This report raises a number of further 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 set of relatively well-understood abatement technologies. In contrast agriculture and land use are more atomistic, heterogeneous and regionally diverse.

These factors can alter the abatement cost-effectiveness outlined here, and we stress there is inherent uncertainty in trying to extrapolate field scale results on emissions to a national scale and vice versa. 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.

The time profile of abatement potential can evidently be altered by technological and regulatory change that can alter the feasibility and cost of rolling out some options. Some changes are potentially more imminent (e.g. regulatory reforms on controlled wastes), while others are more uncertain or dependent on societal attitudes. Looking out to 2050 is speculative, but Annex D details a list of potential changes that could enhance abatement potentials we have identified. In addition to technology and societal acceptance, an increasing carbon price is also likely to induce innovation and adoption.

Taking the baseline of 1990 emissions of approximately 56MtCO2e (1990)[16] this exercise suggests that around 9MtCO2e (around 16%) may be reduced under a reasonable cost threshold (i.e £100/tCO2e) by 2022. This is in addition to the 12 MtCO2e reduction in emissions from 1990 to 2006, giving an overall reduction of 21 MtCO2e (38%). Beyond this, various scenarios can be painted for further reductions involving

- Increased penetration of the existing measures
- Penetration by horizon technologies
- A combination of both with demand side measures

In crops the current list of measures shows considerable potential to reduce N use. It is not theoretically possible to reduce N2O to zero whilst maintaining yield, but a range of precision technologies and genetic modification may offer substantial further efficiency savings. In livestock, the prospect of lower demand for livestock products (through changing diets) offers further potential for reducing methane emissions. A combination of increasing prices and changing tastes are likely to further reduce domestic consumption of red meat products, but more explicit modelling is required to determine the extent to which this will reduce emissions.

Afforestation offers modest savings (e.g. 2MtCO2e) through increased sequestration, but we note that these savings cannot go on for ever as they rely on *increasing* the amount of forest (which is limited by the availability of land). Substitution benefits from biofuels are likely to diminish as currently carbon intense sectors (like power generation) decarbonise – although biomass could have a potentially important role in facilitating such decarbonisation in other sectors of the economy.

As annex D shows, there is a broad range of potential technological developments that could contribute to increasing the sector abatement potential. While there is little evidence of the adoption potential and considerable scientific uncertainty about the efficacy of some technologies, it would not seem implausible for abatement to rise from projected BAU of 18% to between 50 and 70% of 1990 emissions. A reasonable though cautious assessment is that the high feasible abatement potential identified in the full MAC curves (17MtCO2e) could be achieved by 2050. This would imply emissions from agriculture in 2050 of around 50% below 1990 levels (with 12MtCO2e AP in crops/soils at <£300/tCO2e in 2020 and 6MtCO2e from livestock and manure management). Accepting that the MACC's are not exhaustive and that looking forward to 2050 new (currently unanticipated) technologies may develop and diets may change away from emissions intensive foods (like beef) an ambitious

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[16] http://www.ghgi.org.uk/documents/ES3_table_from_2005_NIR.pdf

scenario could see emissions reduced as low as 20MtCO2e (63% below 1990) or even less. But clearly any outlook to 2050 is unavoidably speculative.

**Table 8.1 MACC, central feasible potential 2022, social metric**

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | England [ktCO2e] | NI [ktCO2e] | Scotland [ktCO2e] | Wales [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Total Cost [£2006, Millions] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|---|---|---|---|---|
| CE | BeefAn-Ionophores | 347.38 | 167.12 | 54.78 | 83.69 | 41.78 | -1,747.79 | -607.157 | 0.347 |
| CG | BeefAn-ImprovedGenetics | 46.32 | 22.28 | 7.30 | 11.16 | 5.57 | -3,602.93 | -166.880 | 0.394 |
| AG | Crops-Soils-MineralNTiming | 1,150.39 | 777.34 | 83.63 | 176.58 | 112.83 | -103.38 | -118.928 | 1.544 |
| AJ | Crops-Soils-OrganicNTiming | 1,027.16 | 672.24 | 82.29 | 161.66 | 110.97 | -68.48 | -70.336 | 2.571 |
| AE | Crops-Soils-FullManure | 457.26 | 287.22 | 40.74 | 74.42 | 54.87 | -148.91 | -68.089 | 3.029 |
| AN | Crops-Soils-ReducedTill | 55.77 | 47.64 | 0.59 | 6.75 | 0.79 | -1,052.63 | -58.705 | 3.084 |
| BF | DairyAn-ImprovedProductivity | 377.36 | 245.95 | 51.09 | 38.08 | 42.24 | -0.07 | -54.210 | 3.462 |
| BE | DairyAn-Ionophores | 739.66 | 482.08 | 100.15 | 74.64 | 82.78 | -48.59 | -35.939 | 4.201 |
| BI | DairyAn-ImprovedFertility | 346.26 | 225.68 | 46.88 | 34.94 | 38.76 | -0.04 | -29.846 | 4.548 |
| AL | Crops-Soils-ImprovedN-UsePlants | 331.80 | 248.49 | 15.75 | 46.26 | 21.30 | -76.10 | -25.249 | 4.879 |
| BB | DairyAn-MaizeSilage | 95.98 | 62.55 | 12.99 | 9.69 | 10.74 | -262.63 | -25.213 | 4.975 |
| AD | Crops-Soils-AvoidNExcess | 276.06 | 184.71 | 20.76 | 42.56 | 28.03 | -50.29 | -13.885 | 5.251 |
| DA | Forestry-Afforestation | 980.84 | + | + | + | + | -7.12 | -284.9068 | 6.232 |
| AO | Crops-Soils-UsingComposts | 78.51 | 52.22 | 6.00 | 12.21 | 8.09 | 0.00 | 0.000 | 6.311 |
| AM | Crops-Soils-SlurryMineralNDelayed | 47.17 | 30.87 | 3.78 | 7.42 | 5.10 | 0.00 | 0.000 | 6.358 |
| EI | OFAD-PigsLarge | 47.77 | * | * | * | * | 0.96 | 0.920 | 6.406 |
| EF | OFAD-BeefLarge | 97.79 | * | * | * | * | 2.52 | 4.933 | 6.503 |
| EH | OFAD-PigsMedium | 16.06 | * | * | * | * | 4.69 | 1.508 | 6.520 |
| EC | OFAD-DairyLarge | 250.81 | * | * | * | * | 7.96 | 39.908 | 6.770 |
| HT | CAD-Poultry-5MW | 219.34 | * | * | * | * | 11.43 | 50.136 | 6.990 |
| AC | Crops-Soils-Drainage | 1,741.02 | 1,121.94 | 145.62 | 277.16 | 196.30 | 14.44 | 25.138 | 8.731 |
| EE | OFAD-BeefMedium | 50.77 | * | * | * | * | 16.96 | 17.224 | 8.781 |
| EB | OFAD-DairyMedium | 44.12 | * | * | * | * | 24.10 | 21.270 | 8.826 |
| AF | Crops-Soils-SpeciesIntro | 365.98 | 233.25 | 31.52 | 58.73 | 42.49 | 174.22 | 63.762 | 9.192 |
| BG | DairyAn-bST | 132.31 | 86.23 | 17.91 | 13.47 | 14.70 | 224.10 | 29.659 | 9.324 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| AI | Crops-Soils-Nis | 603.67 | 410.08 | 43.27 | 91.88 | 58.44 | 293.50 | 177.174 | 9.928 |
| AH | Crops-Soils-ControlledRelFert | 165.90 | 112.70 | 11.89 | 25.25 | 16.06 | 1,067.95 | 177.174 | 10.093 |
| BH | DairyAn-Transgenics | 504.29 | 328.68 | 68.28 | 50.89 | 56.44 | 1,691.28 | 4,264.463 | 10.598 |
| AB | Crops-Soils-ReduceNFert | 136.20 | 91.13 | 10.24 | 21.00 | 13.83 | 2,045.10 | 278.539 | 10.734 |
| CA | BeefAn-Concentrates | 80.96 | 38.95 | 12.77 | 19.50 | 9.74 | 2,704.54 | 219.221 | 10.815 |
| AK | Crops-Soils-SystemsLessReliantOnInputs | 10.05 | 6.41 | 0.87 | 1.61 | 1.17 | 4,434.34 | 44.565 | 10.825 |
| AA | Crops-Soils-BiolFix | 8.49 | 4.99 | 0.88 | 1.44 | 1.18 | 14,280.16 | 121.284 | 10.833 |

* It has not been possible to disaggregate the savings from anaerobic digestion due to limitations in available data
+ In theory the forestry abatement potential can be split based on the CEH figures for England, Scotland, Wales and Northern Ireland, but we have not undertaken such an analysis here

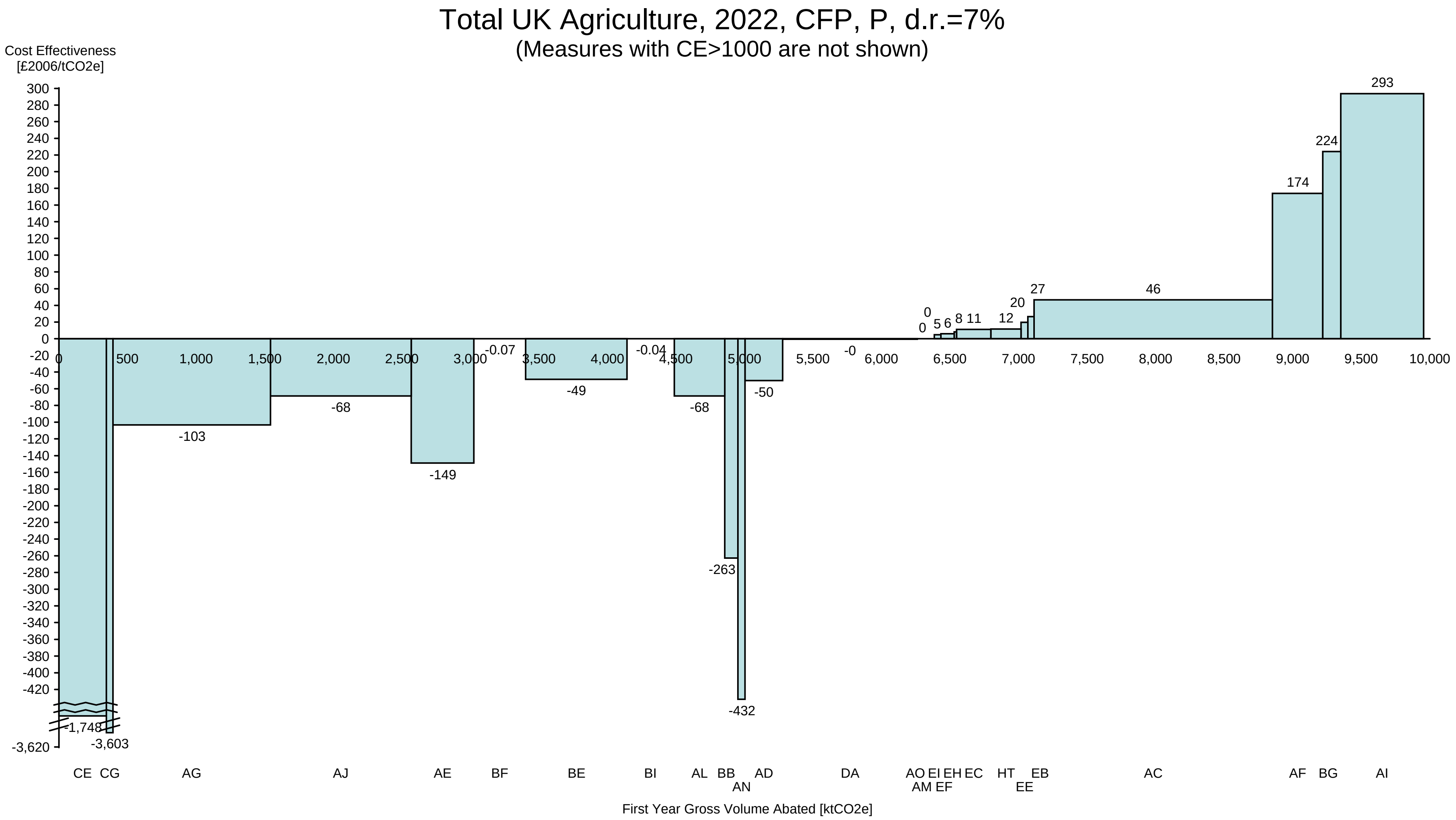

**Figure 8.1** **MACC, central feasible potential 2022, private discount rate**

**Table 8.2 Central Feasible Potential 2022 using a 7.0% discount rate**

| Code | Measure | First Year Gross Volume Abated [ktCO2e] | Cost Effectiveness [£2006/tCO2e] | Cumulative First Year Abatement [MtCO2e] |
|---|---|---|---|---|
| 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 |
| BF | DairyAn-ImprovedProductivity | 377.36 | -0.07 | 3.406 |
| BE | DairyAn-Ionophores | 739.66 | -48.59 | 4.146 |
| BI | DairyAn-ImprovedFertility | 346.26 | -0.04 | 4.492 |
| AL | Crops-Soils-ImprovedN-UsePlants | 368.67 | -68.49 | 4.860 |
| BB | DairyAn-MaizeSilage | 95.98 | -262.63 | 4.956 |
| AN | Crops-Soils-ReducedTill | 50.19 | -431.85 | 5.007 |
| AD | Crops-Soils-AvoidNExcess | 276.06 | -50.29 | 5.283 |
| DA | Forestry-Afforestation | 980.84 | -0.43 | 6.264 |
| AO | Crops-Soils-UsingComposts | 78.51 | 0.00 | 6.342 |
| AM | Crops-Soils-SlurryMineralNDelayed | 47.17 | 0.00 | 6.389 |
| EI | OFAD-PigsLarge | 47.77 | 4.64 | 6.437 |
| EF | OFAD-BeefLarge | 97.79 | 6.11 | 6.535 |
| EH | OFAD-PigsMedium | 16.06 | 8.17 | 6.551 |
| EC | OFAD-DairyLarge | 250.81 | 11.26 | 6.802 |
| HT | CAD-Poultry-5MW | 219.34 | 11.56 | 7.021 |
| EE | OFAD-BeefMedium | 50.77 | 19.80 | 7.072 |
| EB | OFAD-DairyMedium | 44.12 | 26.57 | 7.116 |
| AC | Crops-Soils-Drainage | 1,741.02 | 46.38 | 8.857 |
| AF | Crops-Soils-SpeciesIntro | 365.98 | 174.22 | 9.223 |
| BG | DairyAn-bST | 132.31 | 224.10 | 9.355 |
| AI | Crops-Soils-Nis | 603.67 | 293.50 | 9.959 |
| AH | Crops-Soils-ControlledRelFert | 165.90 | 1,067.95 | 10.125 |
| BH | DairyAn-Transgenics | 504.29 | 1,691.90 | 10.629 |
| AB | Crops-Soils-ReduceNFert | 136.20 | 2,045.10 | 10.765 |
| CA | BeefAn-Concentrates | 80.96 | 2,704.54 | 10.846 |
| AK | Crops-Soils-SystemsLessReliantOnInputs | 10.05 | 4,434.34 | 10.856 |
| AA | Crops-Soils-BiolFix | 8.49 | 14,280.16 | 10.865 |

## 8.1 Exclusions

This section provides a summary of the main exclusions from the report estimates, followed by recommendations for further work.

*General*

- Life cycle costs
- Ancillary costs and benefits
- Demand-side measures, e.g. management through taxation of GHG-intensive products such as common CO2e tax on all consumption, or specific taxes on GHG-intensive food (i.e. meat)
- The study does not explicitly model demand and output reductions as a result of measure implementation
- CO2 emissions from heating for farm buildings are excluded

*Crops/soils specific*

Measures excluded during the scoping:

- Those judged likely to be technically unfeasible or unacceptable to the industry in the time period
- Measures likely to have very low additional abatement potential in UK (e.g. already current practice, only applicable to very small % of land). However, several measures with small (<2% of UK agricultural emissions) abatement measures were included in the short list, in particular measures likely to have negative costs.

*Livestock specific*

Measures excluded during the score

- All abatement measures for sheep were excluded due to the difficulty in applying animal or manure management options in many sheep systems
- Very few poultry animal or manure management (apart from anaerobic digestion options) showed much abatement potential and were therefore not considered
- Many of the nutritional management options (e.g., feed additives) are likely not to be allowable on organic (or equivalent) certified production systems and therefore it was assumed that these would not be applied on these types of systems in dairy or beef
- Any option that may lead to displacement of livestock production from UK to elsewhere (i.e., reducing national herd/flock size with no pro rata increase in production to maintain current levels of output) were not considered in this study

*Forestry specific*

- Increased afforestation area scenarios on a range of land classes
- Afforestation scenarios using mixed broad leaf and coniferous species
- Other non market benefits related to forest types

*Land use and land use change specific*

- Improved data on peatland restoration potential

### 8.2 Recommendations for further work

Time constraints meant that quantitative estimates of relevant ancillary costs and benefits were not possible under the project. Similarly, the project was unable to calculate the full life cycle costs and benefits of some measures. There was also some concern that the forestry MAC required further work to develop a central feasible storyline. This observation is however related to the development of policy scenarios. In addition, the lack of specific curves for different farm types is a weakness in the context of this project. Specific recommendations are:

1. Improving forest policy scenarios in the current MAC;
2. Reviewing and improving the interactions matrix for measures developed in the initial project;
3. Further inclusion of ancillary costs and benefits data;
4. Further inclusion of LCA data;
5. Development of MACs for different farm types. This would provide more farm-specific detail as a basis for targeted policy implementation than can be offered by the current level of aggregation.
6. Complete and full partitioning of effects into those measurable in the national inventory and those not, along with recommendations on improvements to inventory to estimate complete emissions from agriculture

Improvement of the forestry MAC requires a continuation of current work with further input on policy scenarios from Forest Research. The main issue with the current forestry MAC relates to the depiction of realistic policy scenarios.

The estimation of ancillary costs and benefits and the LCA are more significant pieces of work that require more inputs than the improvement to the forestry MAC. In the case of the ancillary costs and benefits, SAC already has access to a considerable data base of non market benefit (transfer) estimates that can be used to improve our estimates of the further ancillary impacts of abatement at farm level. The aim here would be to merge these data with existing spreadsheet model.

The incorporation of LCA is more problematic in terms of the data requirement for some measures, however significant LCA impacts should be quantified and included in the MAC “bars”.

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# Annex A Systems LCA Perspectives on Measures Proposed to Reduce GHG emissions from Agriculture

Agricultural abatement measures can be considered in isolation, but in reality, most measures cause interactions with other aspects of farming operations or crop-soil processes (systems effect). This report has attempted to develop an interactions matrix to account for some of these processes in so far as they are currently understood in UK systems.

But some measures also have implications for other GHG emissions that would be considered in an environmental Life Cycle Assessment (LCA) in which all the abiotic resource use and GHG emissions associated with a unit output of production are quantified. Several agricultural measures have complex LCA stories associated with their use. The message that comes out is that livestock measures are more complex and than arable measures and that some measures have greater potential LCA impacts than others. Any recalculation of cost effectiveness should perhaps prioritise the high impact measures.

There are also time dependent effects, e.g. reducing the N fertiliser for one year only will give a lower reduction in yield and than if the same measure is applied year on year, because the soil N pool.

In the timeframe of this report, it has not been possible to pursue the full LCA costs as adjustments to the MACC analysis. In this section we highlight the relevance of these costs and suggest how LCA might influence the estimated cost-effectiveness.

*A simple arable example*

Controlled release fertilisers supply N, usually in the urea form, at a progressive rate over 2-6 months, more slowly than conventional fertilisers and leads to lower losses of $N_2O$ and $NH_3$ and hence improves N utilisation efficiency (NUE). In theory, we thus need less N per ha to maintain yield or apply the same N per ha and increase yield.

The systems consequences include the potential for fewer fertiliser applications (hence less fuel used and so less fossil $CO_2$ emitted) and reduced nitrate leaching (hence a reduction in secondary $N_2O$ emissions). If yields per ha a re increased for the same N supply, then the cultivation and harvesting energies per tonne are reduced.

From the LCA perspective, urea takes more fossil energy (hence $CO_2$ release) to produce 1 kg synthetic N than $NH_4NO_3$. Other materials must be used to control the N release rate and prevent the higher field losses of $NH_3$ that are common from urea and these manufacturing costs must also be accounted for.

From a long term perspective, the measure will have variable performance depending on factors like the weather, e.g. heavy rain or unseasonably warm weather. If long term performance does not match initial expectations (e.g. yield vs N input) farmers may over-supply this form of N in some years (another systems effect). There should be relatively little interaction with other crops or implication for land use change.

The true overall, long-term effects are thus the balance between higher manufacturing costs against the benefits of reduced application costs (both number of applications and the amounts of N used and associated field emissions), based on the long term N rates that allow for variable performance.

*A complex "arable" example*

Replacing synthetic N fertilisers with N from biological fixation by legumes can have considerable savings in manufacturing fertiliser as well as field emissions of $N_2O$ and $N_2O$ emissions during manufacturing and less fuel for fertiliser application. Also, $N_2O$ is not emitted during fixation (according to IPCC 2006) unlike applied N (whether as synthetic, manure or arable residues).

This has, however, major implications, because arable yields will be lower per hectare. In addition, land is needed for legumes such as clover-grass leys. With lower yields per ha, more energy is needed per t for crop cultivation and harvesting (apart from what is attributable to the clover-grass ley). The inclusion of leys may also require more inversion tillage in primary cultivation after the ley and potentially increase cultivation energies over what may have been possible using direct drilling or reduced input tillage. If a non-organic system, herbicide use may still allow reduced tillage methods to be used.

The move to arable with leys will increase average soil C content per ha over a rotation (although not by as much as if the leys were permanent), so contributing to increased soil C storage. It will change N leaching and hence secondary $N_2O$ emissions, but cultivating leys does cause leaching and elimination cannot be expected.

The change in land use is profound and raises questions about what will the land be used for. It is a proposal that will be much more applicable to the drier east, especially in England. Introducing grass-clover leys suggests either they are dedicated to N fixation and little offtake is expected or that the leys become stocked with ruminants in order to use the leys *in situ*. A third option is to export conserved forage to the west. The former will clearly increase land requirements and could induce more arable cropping in the wetter west, presumably cultivating formerly grassed areas. In that case, soil C in those areas will be lost. If stocked, there will be a need for new infrastructure (buildings, fences, forage stores, manure stores), with associated resource use for construction (and economic cost). There is also a question of whether animal production in the west is expected to fall to balance increase production in the East and whether functioning facilities become redundant. If so and if grassland is taken out of production in the West, soil C loses there will partly offset the gains in the East.

The overall effects are thus complex and depend on many interacting changes in farming systems at local and National levels. Although nominally an arable measure, the systems effects clearly interact with the arable sector.

*A simple animal example*

In the finishing stage of beef production bovine somatotropin can increase productivity and increase overall resource use efficiency, so leading to reduced enteric emissions and emissions associated with each t feed needed. This has little effect of systems, but the fossil energy (hence $CO_2$ emissions) in manufacture must be accounted for.

*A more complex animal example*

Increasing maize silage, instead of grass silage, in the diet can increase productivity per cow and hence lead to reduced GHG emissions per litre milk. Maize silage contains less protein than grass silage so that the concentrates for dairy cows contain more protein. The proportions of crops used for the concentrates thus differ (and the LCA inventory of crop nutrition, cultivation and harvesting for their production is thus different). There also limits on the location of land that is suitable for maize (mainly latitude) and the relative ease of growing grass or maize differ between soil types and location. Furthermore, in the Cranfield LCA, we assume that milk production requires calves, so all burdens of calf deliveries are debited to milk and the spare calves available for beef finishing enter beef systems “free of breeding overheads”. If a cow produces more milk, we need fewer to derive the same national yield (assuming longevity and fertility remain unchanged). Thus, fewer spare calves would be available to be finished as beef. To maintain the national beef supply with fewer dairy calves thus requires more single suckle beef, which emits more GHG per unit output because of its high breeding overheads.

*Manure management –an example that embraces arable and animal production*

The use of composts or straw-based manures in preference to slurry has been costed for arable production with the rationale of reducing $N_2O$ emissions at the time of application and N uptake by crops. This omits other factors that should be accounted for. This proposed measure has both systems and LCA interactions.

First, emissions during animal housing and subsequent manure storage and land application must be accounted for, including direct emissions of GHG ($N_2O$ and $CH_4$) and N losses as $N_2$ and $NH_3$). Active composting tends to create more emissions than passive storage. The overall N losses determine how much excreta is needed ultimately to supply the N to crops to obtain a set yield response. This in turn determines how much feed is needed to supply that manure. The energies needed for manure management must also be considered, in housing, storage (plus more if actively composting) and land application. If changing from slurry to straw based systems, many housing types will need modification, e.g. straw blocks slurry channels, so that extensive modification or renewal may be required. Running costs for straw systems tend to be higher, e.g. slurry channels can be emptied by gravity, while FYM must be dug or pushed out. Straw is not universally available. In the wetter west, some must be transported from drier areas, so adding to fossil $CO_2$ emissions, with proportion imported depending on local conditions. This will also relocate C and N to animal areas from arable ones where the straw could otherwise have been incorporated into soil, with consequences for soil C balances.

So, what starts as a simple single-approach method actually has major systems effects together with large LCA implications.

In following tables we attempt to provide a qualitative LCA caveat to some of the measures identified in the MACC cost-effectiveness hierarchy A ranking scale of 0 – 4 (0 = no impact; 4 = high impact) indicates the LCA-systems potential or implication for that measure. The rankings are applied for each measure independently rather than a universal global scale. The overall effect is thus proportional to the apparent impact of the measure combined with the ranking. Most animal measures have complex effects, e.g. changed cropping requirements and or effects on beef if the measure is applied to dairy. Most manure practices also have complex interactions.

| ***Measure*** | ***Description of the measure*** | ***LCA-Systems Observation*** | ***LCA-Systems Ranking 0-4 **** | ***CE results (2022, CFP, S)*** |
|---|---|---|---|---|
| **Animal management** | | | | |
| Increased high starch concentrate in diet | | Reduces enteric $CH_4$, but land use changes (more arable per unit output), possible loss of soil C if more grassland cultivated. [#] Potential reduction of “free” beef calf supply through higher productivity (PRBC). | 4 | CE>100 |
| Increased maize silage in diet | | Needs higher protein concentrates for dairy. Limits on land suitability for maize. PRBC. | 3 | CE<0 |
| Propionate precursors | | Need to allow for fossil energy ($CO_2$ emissions) in manufacture. PRBC. | 3 | CE<0 |
| Probiotics | | Need to allow for fossil energy ($CO_2$ emissions) in manufacture. PRBC. | 3 | CE<0 |
| Ionophores | | Need to allow for fossil energy ($CO_2$ emissions) in manufacture. PRBC. | 3 | CE<0 |
| Bovine somatotropin | | Need to allow for fossil energy ($CO_2$ emissions) in manufacture. PRBC. | 3 | CE>100 |
| Improved genetic potential for dairy cows – productivity | | Potential benefits of smaller cows with capacity to digest more forage. PRBC. Extra benefit if male dairy calves have enhanced beef potential. | 4 | CE<0 |
| Improved genetic potential for dairy cows – fertility. | | Reduced overheads. PRBC. | 3 | CE<0 |
| Improved genetics for beef cattle | | Little effect if the improvement is only better nutrient utilisation, if higher performance requires a dietary change, someMISSING land use is | 1 | CE<0 |

| ***Measure*** | ***Description of the measure*** | ***LCA-Systems Observation*** | ***LCA-Systems Ranking 0-4 **** | ***CE results (2022, CFP, S)*** |
|---|---|---|---|---|
| | | implied | | |
| Transgenic manipulation of ruminants | | PRBC | 3 | CE>100 |
| | | | | |
| **Manure management** | | | | |
| Covering lagoons | | N losses as $NH_3$, $N_2$ and $N_2O$ reduced, so potential fertiliser N savings, but require low loss applicators. Water management can save money in wet areas, but cost more in drier. Must include fossil energy of cover. | 4 | 0<CE<100 |
| Covering slurry tanks | | As above | 4 | 0<CE<100 |
| Switch from anaerobic to aerobic storage – tanks | | $CH_4$ emissions reduced, but $N_2O$ emissions increase and must allow for fossil $CO_2$ from electricity. More N lost as $NH_3$, so less synthetic N fertiliser replacement is possible and secondary $N_2O$ emissions occur. Side benefits of odour control. | 3 | Dairy, Pigs : CE>100<br>Beef : 0<CE<100 |
| Switch from anaerobic to aerobic storage – lagoons | | As above | 3 | D, B: 0<CE<100<br>P: CE>100 |
| Anaerobic digestion | | Variable depending on whether other wastes are imported and on the on-farm use of generated electricity and heat. A side benefit of the Holsworthy operation was much better manure management by participating farmers because each load of digestate had | 4 | CE variable (-6 <CE<113) |

| ***Measure*** | ***Description of the measure*** | ***LCA-Systems Observation*** | ***LCA-Systems Ranking 0-4 **** | ***CE results (2022, CFP, S)*** |
|---|---|---|---|---|
| | | an analysis certificate for NPK and was easier to spread than raw manure. | | |

[#] Potential reduction of "free" beef calf supply through higher productivity (PRBC). In LCA, dairying requires calves so all burdens of calf rearing are debited to milk and the spare calves available for beef finishing enter beef systems free of overheads. To maintain the beef supply if fewer dairy calves are available requires more single suckle beef with its high overheads.

- The rankings are applied for each measure independently rather than a universal global scale. The overall effect is thus proportional to the apparent impact of the measure combined with the ranking.

| ***Crop/soil measures*** | ***Description of the measure*** | ***LCA-Systems Observation*** | ***LCA-Systems Ranking 0-4 **** | ***MACC rank (2022, CFP, S)*** |
|---|---|---|---|---|
| Using biological fixation to provide N inputs (clover) | Using legumes to biologically fix nitrogen reduces the requirement for N fertiliser to a minimum. Less N in the system, and therefore reduce $N_20$ emissions. It may also reduce yield. | Reduced yields of crops, *massive effects on land use*, possible relocation of livestock nationally. | 4 | 15 (CE>100) |
| Reduce N fertiliser | Reduces N in the system and therefore reduces $N_2O$ emissions. It may also reduce yield | Long term yield reductions expected (increases cultivation energy per t), particular problems with bread wheat quality and N supply. | 3 | 13 (CE>100) |
| Improving land drainage | Improving drainage reduces $N_2O$ emissions because the soil is drier. The yield may be improved and thus more uptake of N from the system. | Good as long as yield up for same N in, expect more P and K as offtake increases. | 2 | 9 (0<CE<100) |
| Avoiding N excess | Reducing N application in areas where is applied in excess reduces N in the system and therefore reduces $N_2O$ emissions. | Good rational use of resources, but how widespread these days? | 1 | 6 (CE<0) |
| Full allowance of manure N supply | 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. In addition, the manure N is more likely to be applied when the crop is going to make use of the N, and therefore $N_2O$ emissions will be reduced. We have assumed that most of the species introduced would be legumes or possibly use N more efficiently | Excellent rational use of resources and will provide positive benefits. The practical challenge is in implementation because manures, especially solid, have variable chemical properties. | 1 | 3 (CE<0) |
| Species introduction (including legumes) | The species are either legumes (see comment regarding biological fixation for measure 38) or they are taking up more N from the system and therefore less available for $N_2O$ emissions | Increasing N utilisation efficiency must be good, secondary effects may be larger. | 2 | 10 (CE>100) |
| Improved timing of | Matching the timing of application with the time the crop will make most use of the fertiliser. Hence | Secondary effect may be in more N applications, so more fuels, but | 1 | 1 (CE<0) |

| *Crop/soil measures* | *Description of the measure* | *LCA-Systems Observation* | *LCA-Systems Ranking 0-4 ** | *MACC rank (2022, CFP, S)* |
|---|---|---|---|---|
| synthetic fertiliser N application | reduced the likelihood of $N_2O$ emissions. | expect $2^{nd}$ order. | | |
| Controlled release fertilisers | Controlled release fertilisers supply N, usually in the urea form, at a progressive rate over 2- 6 months, more slowly than conventional fertilisers. This progressive, slow release of mineral N ensures that microbial conversion of the mineral N in soil to nitrous oxide and ammonia is reduced. It is assumed that the fertiliser releases N at the promised rate, and that the rate of release does not go up due to unusual circumstances such as heavy rain, warm weather, trampling by animals | Urea takes more fossil energy (i.e. $CO_2$ release) to produce 1 kg N than $NH_4NO_3$. What are these ones? $NH_3$ field losses from urea tend to be higher than. Need to allow for sub-optimal performance. Great potential if all benefits fully realisable. | 3 | 12 (CE>100) |
| Nitrification inhibitors | Nitrification inhibitors slow the rate of conversion of fertiliser ammonium to nitrate. This means that the rate of reduction of nitrate to nitrous oxide (or dinitrogen) is decreased and emissions of nitrous oxide decrease. It is assumed that the inhibitor makes good contact with the fertiliser or urine patch to be effective, and that the inhibitor will be applied at the right time and to the right fertiliser type. | Must allow for manufacturing energy costs and $CO_2$ emissions and possible extra field applications. | 2 | 11 (CE>100) |
| Improved timing of slurry and poultry manure application | Applying the N when and where the crop requires it. Reduces the likelihood of $N_2O$ emissions as there is a better match of supply and demand | Good rational use of resources. Can be practical conflict in timing field operations, sometimes causing cropping changes, e.g. winter to spring. | 2 | 2 (CE<0) |
| Adopting systems less reliant on inputs | This is akin to moving from conventional production system, to a LEAF farm type of system, with reduced input of pesticides, nutrients etc) | Expect land use changes; must allow for long term effects of yield of reductions in inputs. | 3 | 14 (CE>100) |

| ***Crop/soil measures*** | ***Description of the measure*** | ***LCA-Systems Observation*** | ***LCA-Systems Ranking 0-4 **** | ***MACC rank (2022, CFP, S)*** |
|---|---|---|---|---|
| Plant varieties with improved N-use efficiency | Adopting new plant varieties that can produce the same yields using less N | Excellent, secondary effects of more P and K with more off take | 1 | 4 (CE<0) |
| Separate slurry applications from fertiliser applications by several days | Applying slurry and fertiliser together because easily degradable compounds in the slurry and increased water contents can greatly increase the denitrification of available N and thereby the emission of nitrous oxide. It is assumed that weather conditions allow separation of the applications, that slurry can be stored before spreading or is available for spreading at the appropriate time. | May need extra slurry storage, may be conflict in field operation timing causing secondary effects.<br>*Q: Is the current practice that common anyway*? | 1 | 8 (CE=0) |
| Reduced tillage / No-till | No tillage, and to a lesser extent, minimum (shallow) tillage store carbon in soils because of decrease rates of oxidation. The lack of disturbance by tillage can also increase the rate of oxidation of methane from the atmosphere. It is assumed that nitrous oxide emissions are not increased due to concentration of microbial activity and nitrogen fertiliser near the surface and due to increase soil wetness associated with the greater compactness of the soil, and that crop growth and hence net primary productivity is not reduced by use of these techniques. | Also affects cultivation energy, hence reduced fossil $CO_2$, more herbicides needed, not always possible to maintain indefinitely, hence soil C storage potential reduced, not for all crops (e.g. potatoes). | 3 | 5 (CE<0) |
| Use composts, straw-based manures in preference to slurry | Composts provide a more steady release of N than slurries which increase soil moisture content and provide a source of easily degradable products which increase microbial demand. Both these increase anaerobic conditions and thereby loss of nitrous oxide which is avoided by use of composts. | Must allow for emissions in housing and manure storage (both direct GHG and N as $NH_3$), changes in housing systems from slurry to straw (both capital and higher running fossil energy costs), transport of straw to | 4 | 7 (CE=0) |

| ***Crop/soil measures*** | ***Description of the measure*** | ***LCA-Systems Observation*** | ***LCA-Systems Ranking 0-4 **** | ***MACC rank (2022, CFP, S)*** |
|---|---|---|---|---|
|  | Composts also have a higher C:N ratio so that released N is more likely to be immobilised temporarily and thereby reduce $N_2O$ emissions. It is assumed that composts contain enough N to provide fertiliser, and that the composts will not immobilise soil or fertiliser N and reduce crop productivity. | areas where not currently grown and effects on land where straw was once incorporated in soil. |  |  |

- The rankings are applied for each measure independently rather than a universal global scale.  The overall effect is thus proportional to the apparent impact of the measure combined with the ranking.

# Annex B Qualitative assessment of ancillary costs and benefits of measures

The MACC curves include direct economic costs and benefits to producers of each measure to determine their cost effectiveness. However, it is likely that further ancillary or external costs and benefits could arise that do not directly affect producers. These cost or benefits could either accrue to other sectors (where they could take the form of increased GHG emissions) or society as a whole. In the case of increased GHG emissions arising in other sectors these should properly be assessed as part of a LCA of each measure.

Ancillary benefits are likely to be particularly significant in the case of forestry measures, and an existing body of non market valuation studies demonstrates values for recreation, biodiversity and landscape, which are all relevant to the choice of species and the location of new planting. Indeed, forestry policy appears to be trying to deliver on a range of non market outputs that may not be based on optimising on greenhouse gas abatement at all.

An initial scoping of ancillary costs and benefits is presented in the table below for arable and livestock measures. Full assessment of these ancillary costs and benefits would require quantification of the both the physical effect and the application of economic values to provide a common metric across a range of impacts. These economic values can be derived from existing valuation data such as those contained in the Environmental Accounts for Agriculture[17] or valuation databases such as EVRI[18]. Some of the less tangible effects such as the public acceptance of livestock measures such as transgenic manipulation may not have existing valuation data. However, these values may in practice be revealed in changes in demand for products where such measures have been applied. This is a potentially important market effect that could present a barrier to uptake of some measures.

*An arable example – "Adopting systems less reliant on inputs"*
In this measure the reduced use of inputs is likely to lead to local water quality improvements due to a reduction in puts with a consequent improvement in ecological status. Lower inputs of pesticides might also result in improved biodiversity on farms adopting this measure. However, if the measure is accompanied by a reduction in yield then more land will need to enter production either in the UK or abroad to maintain production levels. Consequently the ancillary benefits may be offset be costs elsewhere.

*A livestock example – "Anaerobic digestion"*
The ancillary costs that arise from anaerobic digestion are associated with central anaerobic digestion. Primarily these relate to the additional road transport required to move slurries and manures from farms to AD plants, specifically: congestion, accident costs, noise and infrastructure depreciation. The removal of a nutrient source from some farms may also result in an increase in the use of mineral N with associated manufacturing externalities (this should be included in LCA). There may also be further externalities arising from disposal of digestate (land fill or incineration) unless this is allowed to be applied to land as a nutrient.

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[17] https://statistics.defra.gov.uk/esg/reports/envacc/SFS0601%20EnvAccForAgriculture_FULL.pdf

[18] http://www.evri.ca/english/default.htm

AD also offers potential for improvements in water quality due to reduced run-off and has been considered for this purpose in Scotland[19].

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[19] http://www.scotland.gov.uk/Topics/Environment/Water/bathingwaters/Biogasandcomposting

| ***Measure*** | ***Description of the measure*** | ***Potential ancillary cost/benefits*** | ***MACC rank (2022, CFP, S)*** |
|---|---|---|---|
| Using biological fixation to provide N inputs (clover) | Using legumes to biologically fix nitrogen reduces the requirement for N fertiliser to a minimum. Less N in the system, and therefore reduce $N_20$ emissions. It may also reduce yield. | • Water quality improvement due to reduced run-off<br>• Lower externalities from N production/transport<br>• Improved biodiversity<br>• Greater land take for arable to counteract reduced yield | 15 (CE>100) |
| Reduce N fertiliser | Reduces N in the system and therefore reduces $N_2O$ emissions. It may also reduce yield | • Water quality improvement due to reduced run-off<br>• Lower externalities from N production/transport<br>• Greater land take for arable to counteract reduced yield | 13 (CE>100) |
| Improving land drainage | Improving drainage reduces $N_2O$ emissions because the soil is drier. The yield may be improved and thus more uptake of N from the system. | • Water quality improvement due to reduced run-off | 9 (0<CE<100) |
| Avoiding N excess | Reducing N application in areas where is applied in excess reduces N in the system and therefore reduces $N_2O$ emissions. | • Water quality improvement due to reduced run-off<br>• Lower externalities from N production/transport | 6 (CE<0) |
| Full allowance of manure N supply | 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. In addition, the manure N is more likely to be applied when the crop is going to make use of the N, and therefore $N_2O$ emissions will be reduced. | • Lower externalities from N production/transport<br>• Increased road transport externalities (congestion, noise, accidents, infrastructure, fuel use) from manure transport<br>• Potentially higher land take for arable to counteract reduced yield due to nutrient variability | 3 (CE<0) |
| Species introduction (including legumes) | The species are either legumes (see comment regarding biological fixation for measure 38) or they are taking up more N from the system and therefore less available for $N_2O$ emissions. We have | • Water quality improvement due to reduced run-off<br>• Lower externalities from N production/transport | 10 (CE>100) |

| ***Measure*** | ***Description of the measure*** | ***Potential ancillary cost/benefits*** | ***MACC rank (2022, CFP, S)*** |
|---|---|---|---|
| | assumed that most of the species introduced would be legumes or possibly use N more efficiently | | |
| Improved timing of synthetic fertiliser N application | Matching the timing of application with the time the crop will make most use of the fertiliser. Hence reduced the likelihood of $N_2O$ emissions. | • Water quality improvement due to reduced run-off | 1 (CE<0) |
| Controlled release fertilisers | Controlled release fertilisers supply N, usually in the urea form, at a progressive rate over 2- 6 months, more slowly than conventional fertilisers. This progressive, slow release of mineral N ensures that microbial conversion of the mineral N in soil to nitrous oxide and ammonia is reduced. It is assumed that the fertiliser releases N at the promised rate, and that the rate of release does not go up due to unusual circumstances such as heavy rain, warm weather, trampling by animals | • Higher externalities from N (urea) production<br>• Increased run-off if N release assumptions not realised | 12 (CE>100) |
| Nitrification inhibitors | Nitrification inhibitors slow the rate of conversion of fertiliser ammonium to nitrate. This means that the rate of reduction of nitrate to nitrous oxide (or dinitrogen) is decreased and emissions of nitrous oxide decrease. It is assumed that the inhibitor makes good contact with the fertiliser or urine patch to be effective, and that the inhibitor will be applied at the right time and to the right fertiliser type. | • Higher externalities from manufacturing | 11 (CE>100) |

| ***Measure*** | ***Description of the measure*** | ***Potential ancillary cost/benefits*** | ***MACC rank (2022, CFP, S)*** |
|---|---|---|---|
| Improved timing of slurry and poultry manure application | Applying the N when and where the crop requires it. Reduces the likelihood of $N_2O$ emissions as there is a better match of supply and demand | • Water quality improvement due to reduced run-off | 2 (CE<0) |
| Adopting systems less reliant on inputs | This is akin to moving from conventional production system, to a LEAF farm type of system, with reduced input of pesticides, nutrients etc) | • Water quality improvement due to reduced run-off<br>• Biodiversity improvement (on-farm)<br>• Potentially higher land take for arable to counteract reduced yield | 14 (CE>100) |
| Plant varieties with improved N-use efficiency | Adopting new plant varieties that can produce the same yields using less N | • Water quality improvement due to reduced run-off | 4 (CE<0) |
| Separate slurry applications from fertiliser applications by several days | Applying slurry and fertiliser together because easily degradable compounds in the slurry and increased water contents can greatly increase the denitrification of available N and thereby the emission of nitrous oxide. It is assumed that weather conditions allow separation of the applications, that slurry can be stored before spreading or is available for spreading at the appropriate time. | • Water quality improvement due to reduced run-off | 8 (CE=0) |
| Reduced tillage / No-till | No tillage, and to a lesser extent, minimum (shallow) tillage store carbon in soils because of decrease rates of oxidation. The lack of disturbance by tillage can also increase the rate of oxidation of methane from the atmosphere. It is assumed that nitrous | • Reduced soil erosion<br>• Water quality improvement | 5 (CE<0) |

| ***Measure*** | ***Description of the measure*** | ***Potential ancillary cost/benefits*** | ***MACC rank (2022, CFP, S)*** |
|---|---|---|---|
| | oxide emissions are not increased due to concentration of microbial activity and nitrogen fertiliser near the surface and due to increase soil wetness associated with the greater compactness of the soil, and that crop growth and hence net primary productivity is not reduced by use of these techniques. | | |
| Use composts, straw-based manures in preference to slurry | Composts provide a more steady release of N than slurries which increase soil moisture content and provide a source of easily degradable products which increase microbial demand. Both these increase anaerobic conditions and thereby loss of nitrous oxide which is avoided by use of composts. Composts also have a higher C:N ratio so that released N is more likely to be immobilised temporarily and thereby reduce $N_2O$ emissions. It is assumed that composts contain enough N to provide fertiliser, and that the composts will not immobilise soil or fertiliser N and reduce crop productivity. | • Lower emissions from N production/transport<br>• Higher emissions from manure storage<br>• Increased road transport externalities (congestion, noise, accidents, infrastructure, fuel use) from straw transport | 7 (CE=0) |

| ***Measure*** | ***Potential ancillary cost/benefits*** | ***CE results (2022, CFP, S)*** |
|---|---|---|
| **Animal management** | | |
| Increased high starch concentrate in diet | • Increased arable production impacts | CE>100 |
| Increased maize silage in diet | • Increased arable production impacts | CE<0 |
| Propionate precursors | • Manufacturing externalities<br>• Public/consumer acceptance | CE<0 |
| Probiotics | • Manufacturing externalities<br>• Public/consumer acceptance | CE<0 |
| Ionophores | • Manufacturing externalities<br>• Public/consumer acceptance | CE<0 |
| Bovine somatotropin | • Manufacturing externalities<br>• Public/consumer acceptance | CE>100 |
| Improved genetic potential for dairy cows – productivity | • Public/consumer acceptance<br>• Animal health/welfare | CE<0 |
| Improved genetic potential for dairy cows – fertility. | • Public/consumer acceptance<br>• Animal health/welfare | CE<0 |
| Improved genetic potential for beef cattle | • Public/consumer acceptance<br>• Animal health/welfare | CE<0 |
| Transgenic manipulation of ruminants | • Public/consumer acceptance<br>• Animal health/welfare | CE>100 |

| ***Measure*** | ***Potential ancillary cost/benefits*** | ***CE results (2022, CFP, P)*** |
|---|---|---|
| **Manure management** | | |
| Covering lagoons | • Potential air quality (ammonia) impacts<br>• Water quality improvement | 0<CE<100 |
| Covering slurry tanks | • Potential air quality (ammonia) impacts<br>• Water quality improvement | 0<CE<100 |
| Switch from anaerobic to aerobic storage – tanks | • Potential air quality (ammonia) impacts<br>• Water quality improvement | Dairy, Pigs : CE>100<br>Beef : 0<CE<100 |
| Switch from anaerobic to aerobic storage – lagoons | • Potential air quality (ammonia) impacts<br>• Water quality improvement | D, B: 0<CE<100<br>P: CE>100 |
| Anaerobic digestion | • Water quality improvement<br>• CAD: Increased road transport externalities (congestion, noise, accidents, infrastructure, fuel use)<br>• CAD: Higher emissions from N production/transport to replace digestate nutrients<br>• CAD: Externalities associated with digestate disposal if not utilised for N | CE variable (-6 <CE<113) |

# Annex C Interaction of MACC measures and GHG Inventory

| Code: | Subsector: | Measure: | In the inventory? | Direct | Indirect |
|---|---|---|---|---|---|
| AA | Crops-Soils | Using biological fixation to provide N inputs (clover) | Y | X | |
| AB | Crops-Soils | Reduce N fertiliser | Y | X | |
| AC | Crops-Soils | Land drainage | Y | | X |
| AD | Crops-Soils | Avoiding N excess | Y | | X |
| AE | Crops-Soils | Full allowance of manure N supply | Y | | X |
| AF | Crops-Soils | Species introduction (including legumes) | Y | | X |
| AG | Crops-Soils | Improved timing of mineral feritiser N application | Y | | X |
| AH | Crops-Soils | Controlled release fertilisers | N | | |
| AI | Crops-Soils | Nitrification inhibitors | N | | |
| AJ | Crops-Soils | Improved timing of slurry and poultry manure application | N | | |
| AK | Crops-Soils | Adopting systems less reliant on inputs | Y | X | |
| AL | Crops-Soils | Plant varieties with improved N-use efficiency | N | | |
| AM | Crops-Soils | Separate slurry applications from fertiliser applications by several days | N | | |
| AN | Crops-Soils | Reduced tillage / No-till | N | | |
| AO | Crops-Soils | Use composts, straw-based manures in preference to slurry | Y | | X |
| BA | DairyAn | Increased high starch concentrate in diet | in part | X | X |
| BB | DairyAn | Increased maize silage in diet | in part | X | X |
| BC | DairyAn | Propionate precursors | in part | X | X |
| BD | DairyAn | Probiotics | in part | X | X |
| BE | DairyAn | Ionophores | in part | X | X |
| BF | DairyAn | Improved genetic potential for dairy cows – productivity | Y | X | |
| BG | DairyAn | Bovine somatotropin | in part | X | X |
| BH | DairyAn | Transgenic manipulation of ruminants | in part | X | X |
| BI | DairyAn | Improved genetic potential for dairy cows - fertility | in part | X | X |
| CA | BeefAn | Increased high starch concentrate in diet | N | | X |
| CC | BeefAn | Propionate precursors | N | | X |
| CD | BeefAn | Probiotics | N | | X |
| CE | BeefAn | Ionophores | N | | X |
| CG | BeefAn | Improved genetic potential for beef cattle | N | | X |
| DA | Forestry | Afforestation | Y | X | |
| DB | Forestry | Rotation length | Y | X | |
| EB | OFAD | Dairy cattle - medium farms | Y | X | |
| FA | DairyManure | Covering lagoons | Y | X | |
| FB | DairyManure | Covering slurry tanks | Y | X | |
| FC | DairyManure | Switch from anaerobic to aerobic storage - slurry tanks | Y | X | |
| FD | DairyManure | Switch from anaerobic to aerobic storage - lagoons | Y | X | |
| GA | BeefManure | Covering lagoons | Y | X | |
| GB | BeefManure | Covering slurry tanks | Y | X | |
| GC | BeefManure | Switch from anaerobic to aerobic storage - slurry tanks | Y | X | |
| GD | BeefManure | Switch from anaerobic to aerobic storage - lagoons | Y | X | |
| HA | CAD | Dairy-1MW | N | | X |
| IA | PigsManure | Covering lagoons | Y | X | |
| IB | PigsManure | Covering slurry tanks | Y | X | |
| IC | PigsManure | Switch from anaerobic to aerobic storage - slurry tanks | Y | X | |
| ID | PigsManure | Switch from anaerobic to aerobic storage - lagoons | Y | X | |

The above table (Annex C) highlights if the abatement potential as calculated in this study would be included in the UK national inventory of GHGs. In general, only a proportion of the options would be considered and measured in the current UK inventory. However, for some of the measures a proportion of the abatement potential would be reflected in the inventory as currently practiced. For example, in the crops and soils option, when a mitigation measure indirectly affects the inventory value, about 20% of the emission abatement would be recognised in the inventory. Thus for example if a farmer were to split the timing of fertiliser applications or to use improved crop varieties, it would make more N available for for growth and should therefore allow a slight lowering of overall N application. This would in turn be translated into a lower $N_2O$ emission being reported in the inventory given that reported emissions are proportional to overall N applications. The magnitude of these effects is uncertain, but some estimates of reflected abatement potential are listed in Table AC1. Some measures such as improved drainage are unlikely to have any net effect on reported emissions since overall fertiliser applications may not change despite a reduction in $N_2O$ emission.

**Table AC1** Percentage of the abatement potential in 2022 that would be reflected in the UK GHG inventory as currently estimated for crops

| | 2022 | 2017 | 2012 |
|---|---|---|---|
| Improved Mineral N Timing | 20 | 20 | 20 |
| Improved Organic N Timing | 20 | 20 | 20 |
| Full accounting for Manure | 20 | 20 | 20 |
| Reduced Tillage | 0 | 0 | 0 |
| Improved N-Use by Plants | 10 | 10 | 10 |
| Avoiding N Excess | 100 | 100 | 100 |
| Using Composts | 20 | 20 | 20 |
| Slurry Mineral N Delayed | 0 | 0 | 0 |
| Improved drainage | 0 | 0 | 0 |
| New Species Introduction | 0 | 0 | 0 |
| NIs | 0 | 0 | 0 |

Only a proportion of the livestock abatement options would be reflected in the UK inventory as it is currently estimated. The category of “DairyAn” examined the abatement potential of various animal management interventions in dairy systems. These included nutritional and genetic improvement interventions to reduce GHG emissions. The assumptions in estimating the abatement potential from dairy systems assumed that milk quotas would still be operational into the future and therefore if an abatement measure improved production then the number of animals required to meet the national quota would reduce. These measures would be reflected, in part in the national GHG inventory. However, many of the “DairyAn” options have an additional GHG reducing effect, in that they reduce overall $CH_4$ output and this effect would not be accounted for the UK inventory.

**Table AC2** Percentage of the abatement potential in 2022 that would be reflected in the UK GHG inventory as currently estimated.for animals

| Code: | Subsector: | Measure: | %age reflected in Inventory |
|---|---|---|---|
| BA | DairyAn | Increased high starch concentrate in diet | 65 |
| BB | DairyAn | Increased maize silage in diet | 140 |
| BC | DairyAn | Propionate precursors | 41 |
| BD | DairyAn | Probiotics | 59 |
| BE | DairyAn | Ionophores | 50 |
| BF | DairyAn | Improved genetic potential for dairy cows - productivity | 100 |
| BG | DairyAn | Bovine somatotropin | 208 |
| BH | DairyAn | Transgenic manipulation of ruminants | 33 |
| BI | DairyAn | Improved genetic potential for dairy cows - fertility | 60 |

Table AC2 describes the proportion of the “DairyAn” abatement options that would be accounted for in the UK GHG inventory based on a reduction of animal numbers only. It can be seen for two of the options (maize silage and bSt) that the abatement as measured by the inventory would be higher that the abatement potential estimated by this study. For these two abatement options there is an unfavourable effect on $CH_4$ production, in that output per animal increases. However, this increase is outweighed by the production increase and the knock-on effect of reducing animal numbers. All “BeefAn”, manure and anaerobic digester options do not reduce animal numbers and therefore will not be affected the same way as options the “DairyAn” abatement options.

# Annex D 2050 potentials

Looking out to 2050, a range of technological and regulatory barriers need to be overcome. The latter are conditioned by public acceptance of the application of some potential scientific solutions for low emissions production. This annex details a few of the suggested options. It is not a comprehensive audit of technologies.

The most obvious technological progression will probably involve the increasing penetration of genetic modification in plant and animal production. More ambitious technologies include nano biotechnologies the increased use of artificial intelligence in computational systems biology to develop low emissions solutions - e.g. to waste management.

Ambitious technologies for farm, food and waste management include:

- Use of mobile mapping, sensing and analysis to identify and solve problems in situ.
- Use of sentinel plants that have a reporter gene to indicate if stressed e.g. water or disease or are in need of nutrients.
- Robotics for crop monitoring and precision spraying: intelligent machines to walk fields and spot treat problems or call up other machines (i.e. multi-robotics) to spray large or small areas, to remove weeds, to scare off pests, including insects, to select and harvest individual plants or parts of field when ready.
- Digitisation of all land, fields, crops in conjunction with data platforms to collate records of inputs, records of outputs, product distribution and markets.
- Exponential growth in speed and miniaturisation of computing power/processing to provide real-time data on status of every field, crop and plant.

More conservative suggestions include:

- More diversity in crop species and cropping systems to offset pest and disease problems i.e. pesticides have an energy and environmental cost.
- Use of more diversified plant breeding populations e.g. cereals for improving local adaptation to soil type and nutrient availability.
- More mixed farming or more diverse production systems e.g. livestock & arable or agroforestry to help closing the nutrient cycle i.e. less inorganic fertiliser costs, less transport costs.
- Increasing synchrony between nutrient supply and demand as a means by which nitrogen use efficiency could be improved
- developmental modifications: e.g. chilling and vernalisation requirement modifications, flowering time modifications
- new or changed pest and pathogen challenges: breeding and crop protection cost implications
- water use efficiency: water acquisition and efficiency of use – changes in crop agronomy-cultivar cost effectiveness, investment in infrastructure such as irrigation etc
- nutrient use efficiency: breeding for acquisition and subsequent efficiency of use improvement

- interaction with agronomy changes
- cropping changes: new crops and their implications for the economy
- biomass crops: prospects for current and next generation
- carbon sequestration: agronomy-crop interactions, tillage and rotation implications

Livestock

- Developing breeding goals that help mitigate UK emissions. This should take account of the system of production. Work is required to develop techniques/tools to measure emissions on a per animal and per field/farm basis. Then incentives will need to be put in place to ensure uptake (maybe farmers will take part under a labelling type scheme "Green Milk").

- Matching plant genetics and animal genetics: Plant and animal breeders developing schemes that work together. For example, plant breeding develop sward and animal breeding ensures that animals can utilise and thrive on the sward (and vice versa)

- Genetic modification of plant and/or animals. As with breeding options these should be developed in tandem and ensuring that they work in practice in real farming systems. EU and consumer issues with respect to GM will need to be overcome

- Development of low emissions animals by traditional breeding and/or GM

- Development of integrated farming systems and precision farming systems

- Plant and tree breeding to aid in C sequestration

- Manure management. Improve efficiency of bio digestion and integrate with other waste management options (e.g., household waste).

- Developing improved technologies to maximise nutrient availability to plant/soil when using manure as an organic fertiliser (e.g., next stage direct injection methods)
- Develop routine manure quality testing and consider when using for spreading
  Manure additives

- Developing consumer "friendly" animal feed additives (complementary crops etc)