Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget period and to 2050

Final report submitted for the project contract "Provision of services to review and update the UK agriculture MACC and to assess abatement potential for the 5th carbon budget period and to 2050"

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Abbreviations

AD	Anaerobic digestion
ALULUCF	Agriculture, land use and land use change
AP	Abatement potential
AR	Abatement rate
BSFP	British Survey of Fertiliser Practice
C	Carbon
CAD	Centralised Anaerobic Digester
CCC	The Committee on Climate Change
CE	Cost-effectiveness
CFP	Central feasible potential
CH_4	Methane
CI	Confidence interval
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CW	Carcass weight
ETS	Emissions Trading System
DA	Devolved Administration
Defra	Department for Environment, Food & Rural Affairs
DE%	Feed digestibility
DF	Douglas fir
DM	Dry matter
DMI	Dry matter intake
DR	Discount rate
E	England
EF_1	Emission factor for N_2O emissions from N inputs
EF_3	Emission factor for direct N_2O emissions from the manure management system
EF_4	Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces
EF_5	Emission factor for N_2O emissions from N leaching and runoff
EI	Emission intensity
FC	Forestry Commission
$Frac_{Leach}$	Fraction of all N added to/mineralised in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff
$Frac_{GASF}$	Fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x
$Frac_{GASM}$	Fraction of applied organic N fertiliser materials and of urine and dung N deposited by grazing animals that volatilises as NH_3 and NO_x
$Frac_{GasMS}$	Fraction of managed manure N that volatilises as NH_3 and NO_x in the manure management system

F_{SN}	Amount of synthetic fertiliser N applied to soils
GE	Gross energy intake
GHG	Greenhouse gas
GM	Genetic modification
GWP	Global warming potential
HFP	High feasible potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
LFA	Least Favourable Area
LFP	Low feasible potential
LW	Liveweight
MACC	Marginal abatement cost curve
MTP	Maximum technical potential
MCF	CH_4 conversion factor for manure management system
N	Nitrogen
N_2O	Nitrous oxide
N_{ex}	N excretion per head of livestock
NH_3	Ammonia
NI	Northern Ireland
NPV	Net present value
OFAD	On-farm Anaerobic Digester
OK	Oak
OSR	Oilseed rape
PF	Precision farming
PLF	Precision livestock farming
S	Scotland
SAB	Sycamore, ash, birch
UAA	Utilised agricultural area
VS	Volatile solid excreted by livestock
Y_m	Enteric CH_4 conversion factor, per cent of gross energy in feed converted to methane
W	Wales
WG	Weight gain of livestock

1 Executive summary

1.1 Background and objectives

Greenhouse gas (GHG) emissions from agriculture, land use and land use change (ALULUCF) are a significant percentage of UK emissions (9.0% in 2013, see Salisbury et al. (2015)). The UK Climate Change Act (2008) sets a target of achieving at least a 80% reduction in GHG emissions by 2050 relative to the 1990 baseline, and the Government has set carbon budgets for four five-year periods from 2008 to 2027, at levels recommended by the Committee on Climate Change (CCC). The CCC recommendations draw on the best available evidence, including the marginal abatement cost curves (MACCs) that have been developed for the ALULUCF sector.

The CCC needs to recommend the level of the 5th carbon budget covering the period 2028-32 by the end of 2015. In doing so, it is reviewing latest evidence on abatement potential and costs across sectors. The overall aim of this study was to develop an updated MACC for the UK ALULUCF sector. Specific objectives were to:

- Review the CCC's fourth carbon budget (2023-2027) ALULUCF abatement potential and costs in light of the latest evidence.
- Extend the analysis to cover the fifth carbon budget period.
- Provide a qualitative assessment of additional mitigation measures that could be available by 2050.

1.2 Identifying mitigation measures

This work builds on previous studies that have analysed the costs of mitigation within the UK (Eory 2015, MacLeod *et al.* 2010a, MacLeod *et al.* 2010b, Moran *et al.* 2008) and in other countries such as Ireland (Schulte *et al.* 2012) and France (Pellerin *et al.* 2013). There is a large number of potential ways of reducing emissions in the ALULUCF sector. A recent review identified 181 separate mitigation measures (MacLeod *et al.* 2015b). One of the first tasks for this project was to reduce this long list of potential mitigation measures to a subset of measures that can be analysed in more depth. In this project an initial list of 71 measures were reviewed by a group of experts using the following criteria:

- Likely abatement potential.
- Practical feasibility.
- Risk of negative co-effects.

As a result of this exercise, the 24 measures in Table ES 1 were selected for further analysis. It should be noted that this list is inevitably based on a mixture of evidence and value judgments, and is not meant to be definitive. Other equally valid lists are possible, so non-inclusion of a measure in these MACCs should not be taken to imply a lack of abatement potential.

An additional 7 measures were selected for analysis of their longer term abatement potential (up to 2050), but not for inclusion in the MACC (Table ES 2).

Table ES 1 Measures for quantitative analysis

ID	Mitigation measure
MM1	Improving synthetic N use
MM2	Improving organic N planning
MM3	Low emission manure spreading
MM4	Shifting autumn manure application to spring
MM5	Catch and cover crops
MM6	Controlled release fertilisers
MM7	Plant varieties with improved N-use efficiency
MM8	Legumes in rotations
MM9	Legume-grass mixtures
MM10	Precision farming for crops
MM11	Loosening compacted soils and preventing soil compaction
MM12	Improving ruminant nutrition
MM13	Probiotics as feed additive
MM14	Nitrate as feed additive
MM15	High fat diet for ruminants
MM16	Improving cattle health
MM17	Improving sheep health
MM18	Selection for balanced breeding goals
MM19	Slurry acidification
MM20	Anaerobic digestion: cattle slurry with maize silage
MM21	Anaerobic digestion: pig/poultry manure with maize silage
MM22	Anaerobic digestion: maize silage only
MM23	Afforestation on agricultural land
MM24	Behavioural change in fuel efficiency of mobile machinery

Table ES 2 Measures for longer term abatement assessment

Mitigation measure
Nitrification inhibitors
Novel crops
Agroforestry (with low tree density)
Covering slurry stores

Mitigation measure
Precision livestock farming
GM livestock
Using sexed semen in dairy cattle reproduction

1.3 Quantifying the abatement potential and cost effectiveness of each measure

MACCs show the cost of reducing GHG emissions by one additional unit (cost-effectiveness) as a function of the cumulative GHG reduction achieved against a future reference scenario. The cost-effectiveness is the ratio of the net cost and the GHG abatement rate of the measure (expressed in this study in terms of £ per t of CO_2e reduction in emissions). The mitigation measures which have lower cost of abatement than the carbon price are defined as being cost-effective and economically efficient for society to implement. In the current analysis the carbon prices used in the UK public policy appraisal were applied: £78 t CO_2e^{-1} and £114 t CO_2e^{-1}, respectively, for 2030 and 2035.

Where possible, the mitigation calculations were aligned to the IPCC 2006 emission calculation methodology (IPCC 2006), and with relevant parameters sourced from the 2012 UK greenhouse gas inventory (Webb *et al.* 2014) and the 2013 UK greenhouse gas inventory which is under preparation (MacCarthy *et al.* 2014).

Abatement rates were estimated on an annual unitary basis (e.g. per area of land or per head of animal), then multiplied by the total number of units where the measure is applicable ('applicability') and the future additional uptake to estimate the annual abatement potential. For measures with lifetimes longer than a year and where the annual abatement is changing over time (e.g. *Afforestation on agricultural land*), the abatement expected in the relevant year is reported as an annual abatement potential. However, the discounted full lifetime abatement was used to calculate the cost-effectiveness of these measures.

The net costs of the measures were based on the estimated technical costs and benefits of the mitigation measures at the farm (both annual changes and capital investments). The scope of the study and lack of data prevented the inclusion of other costs, like time requirements of the implementation of the mitigation measures, on-farm transaction costs, public administration costs of mitigation policies, economic welfare effects, additional environmental impacts, human health effects or impacts on animal welfare. Furthermore, non-financial barriers were captured only in a limited way for some measures by reducing the maximum additional uptake of the measure. The absence of these cost elements should be borne in mind when interpreting the results.

The data sources and calculation methods depended on the specific measure and are detailed in section 3 of the report. Once initial estimates of the cost-effectiveness and abatement potential had been made, a workshop was held at which key assumptions were discussed by a group of experts. The findings of the workshop were used to refine the calculations.

The analysis aimed at exploring the average potential abatement and cost-effectiveness of mitigation measures in the UK and in the four DAs, therefore the results should be used at the country level only. The abatement potential and cost-effectiveness results of the measures are likely to vary significantly between farms.

When two or more measures are implemented on-farm they can interact, either enhancing or, more often, reducing each other's efficacy. If these interactions are not taken into account, then there is a risk that the total abatement will be overestimated. An approach similar to that employed in the 2008 UK agricultural MACC (Moran *et al.* 2008) and the 2010 update (MacLeod *et al.* 2010c) was used to take into account the effect of interactions. Thus the "without interactions" results are assuming no interactions, and the "with interactions" results include interactions between measures. The financial interactions were considered to be marginal and thus interaction factors were not developed for the net costs.

1.4 Abatement scenarios

The abatement potential of a measure is a function of the abatement rate and the uptake of the measure. We considered four scenarios representing different levels of uptake of the measures: a maximum feasible potential and three scenarios reflecting different levels of policy intervention designed to incentivise take-up. This follows the approach developed in the UK agricultural MACC analysis in 2008 (Moran *et al.* 2008). These are shown in Table ES 3. The values reflect the maximum uptake achieved in 2035 under the different scnearios; uptake in previous years is considered to be a proportion of it, assuming linear additional uptake from 2015 to 2035.

Table ES 3 Uptake scenarios used

Uptake scenario	Policy assumption		Uptake
Low feasible potential (LFP)	Information/education policies	Measures with positive technical costs	7%
		Measures with negative technical costs	18%
Central feasible potential (CFP)	Financial incentives for uptake (or disincentives for emissions)	All measures	45%
High feasible potential (HFP)	More stringent policy framework, e.g. regulation	Measures which are difficult to monitor and enforce	85%

Uptake scenario	Policy assumption		Uptake
		Measures which are easy to monitor and enforce	92%
Maximum technical potential (MTP)	Theoretical maximum abatement if the measure is applied wherever it is agronomically possible	All measures	100%

1.5 Key results

1.5.1 Summary results

The analysis demonstrates that in the UK, implementing the cost-effective measures (i.e. those with cost-effectiveness below the carbon (C) price), could reduce emissions by between 0.53 and 6.99 Mt CO_2e in 2030 depending on the policy scenario (see Table ES 4). By 2035 the cost-effective abatement potential increases to between 1.26 and 13.48 Mt $CO_2e\ y^{-1}$. The order of the measures on the MACCs does not change substantially between the years or with discount rate 3.5% and 7%, and all but one measure stay either cost-effective or not cost-effective across the scenarios.

Table ES 4 Cost-effective and total abatement potential in 2030 and 2035 in the UK, with four different uptake scenarios (Mt $CO_2e\ y^{-1}$, d.r. 3.5%)

		Low feasible potential	Central feasible potential	High feasible potential	Maximum technical potential
Cost-effective abatement[1]	2030	0.53	2.87	6.31	6.99
Cost-effective abatement	2035	1.26	6.01	12.36	13.48
Total abatement[2]	2030	0.75	4.13	8.77	9.69
Total abatement	2035	1.43	7.10	14.25	15.57

Notes:
[1] Abatement that could be achieved by implementing measures with CE under the C price (C price in 2030: £78 t CO_2e^{-1}, C price in 2035: £114 t CO_2e^{-1})
[2] Abatement that could be achieved by implementing all measures, regardless of the C price

The contribution of the devolved administrations to the UK 2030 cost-effective abatement potential is 51%, 14%, 30% and 5% by England, Wales, Scotland an Northern Ireland in central feasible potential (Table ES 5). The abatement potential is dominated by forestry in all four DAs, with livestock and cropping related mitigation measures adding to the abatement at varying degree (Figure ES 1).

Table ES 5 Cost-effective abatement potential by DA (Mt $CO_2e\ y^{-1}$, 2030, CFP, d.r. 3.5%)

	AP
UK	2.87
England	1.46
Wales	0.40
Scotland	0.88
Northern Ireland	0.14

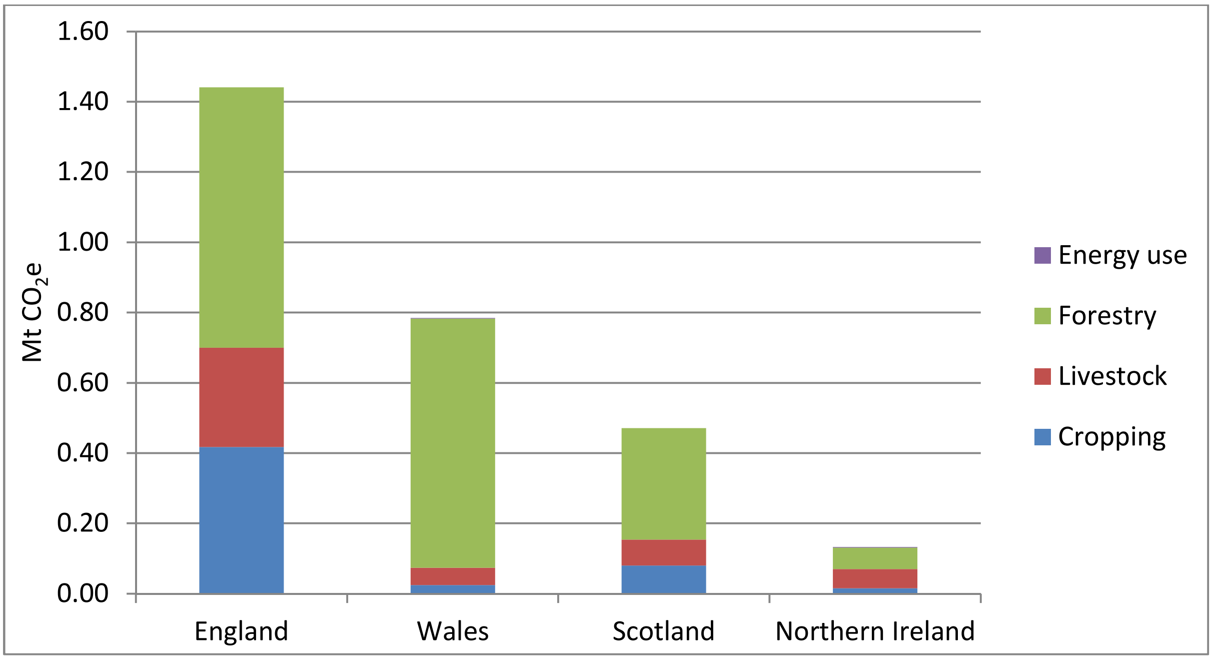

Figure ES 1 Contribution of cropping, livestock, forestry and energy use related mitigation measures to the cost-effective abatement by DA (2030, CFP, d.r. 3.5%)

1.5.2 Marginal abatement cost curves

The MACC for the UK, 2030 (CFP, d.r. 3.5%) is presented on Figure ES 2 and Table ES 6. Results for other scenarios can be found in Section 5.1 and Appendix D.

The largest contributor (>50%) to the cost-effective abatement potential in all four countries and in every year and scenario was

- *Afforestation on agricultural land.*

Six other mitigation measures made up 50-60% of the remaining mitigation under the C price:

- *Improving cattle health,*
- *Precision farming for crops,*
- *Loosening compacted soils and preventing soil compaction,*
- *Improving sheep health,*
- *Anaerobic digestion: pig/poultry manure with maize silage,*
- *Anaerobic digestion: maize silage only.*

Further abatement could be achieved with more expensive measures (with CE > the carbon price), particularly:

- *Nitrate as feed additive,*
- *Legumes in rotations,*
- *High fat diet for ruminants.*
- *Slurry acidification,*
- *Controlled release fertilisers,*
- *Anaerobic digestion: cattle slurry with maize silage.*

However, it should be noted that some of the measures that are not cost-effective with interactions are cost-effective when considered in isolation, therefore they could become cost-effective depending on which other measures are also implemented.

The next section (Section 1.6) provides a brief discussion of the results and key aspects of each measure.

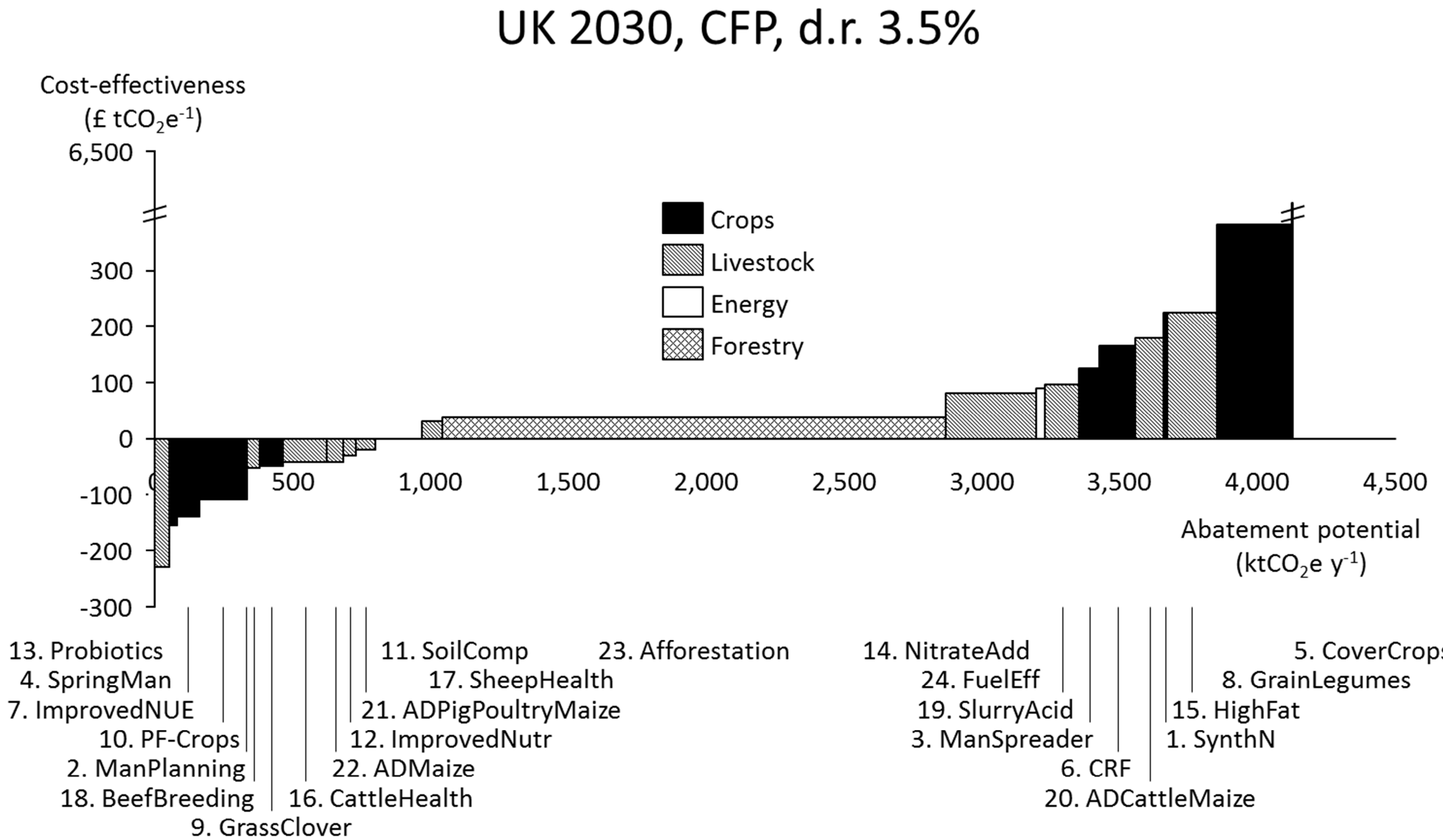

Figure ES 2 Marginal abatement cost curve (with interactions, 2030, UK, CFP, d.r. 3.5%), note that the C price in 2030 is £78 t CO_2e^{-1}

Table ES 6 Abatement potential and cost-effectiveness (with interactions, 2030, UK, CFP, d.r. 3.5%)

Mitigation measure	ID	CE	AP	Cumulative AP
		£ t CO_2e^{-1}	Mt CO_2e y^{-1}	Mt CO_2e y^{-1}
Probiotics as feed additive	13	-230	0.05	0.05
Shifting autumn manure application to spring	4	-155	0.03	0.08
Plant varieties with improved N-use efficiency	7	-139	0.08	0.16
Precision farming for crops	10	-108	0.17	0.33
Improving organic N planning	2	-107	0.01	0.34
Selection for balanced breeding goals in beef cattle	18	-52	0.05	0.38
Legume-grass mixtures	9	-49	0.08	0.47
Improving cattle health	16	-42	0.16	0.62
Anaerobic digestion: maize silage only	22	-41	0.06	0.69
Improving ruminant nutrition	12	-29	0.05	0.73
Anaerobic digestion: pig/poultry manure with maize silage	21	-19	0.07	0.80
Loosening compacted soils and preventing soil compaction	11	1	0.17	0.97
Improving sheep health	17	30	0.07	1.04
Afforestation on agricultural land	23	37	1.83	2.87
Nitrate as feed additive	14	82	0.33	3.20
Behavioural change in fuel efficiency of mobile machinery	24	90	0.03	3.23
Slurry acidification	19	96	0.12	3.35
Low emission manure spreading	3	126	0.07	3.44
Controlled release fertilisers	6	166	0.13	3.56
Anaerobic digestion: cattle slurry with maize silage	20	179	0.10	3.66
Improving synthetic N use	1	224	0.02	3.68
High fat diet for ruminants	15	225	0.18	3.85
Legumes in rotations	8	383	0.28	4.13
Catch and cover crops	5	6,408	0.00	4.13

1.6 Discussion of mitigation measures in the 2030 and 2035 MACCs

Key findings and additional considerations across the measures considered are set out below. The estimates of abatement potential and costs presented in this section are for the UK central feasible potential scenario in 2030 at the social discount rate of 3.5% and including interactions, unless otherwise stated.

1.6.1 Forestry measure

Afforestation of agricultural land provides the highest abatement potential of any mitigation measure in all four of the DAs. However the following points should be noted:

- It has been assumed that the business-as-usual case is one of no policy support for afforestation, and a consequent planting rate of 0ha/year, i.e. the abatement potential is based on the assumption that all planting is additional to what would have occurred. In practice, a proportion of the planting may occur as a result of other market and policy drivers.
- It has been assumed that the afforestation can be achieved without loss of agricultural production. In practice some agricultural production could be lost, leading to a displacement of production and emissions to outside the UK (and the risk of indirect land use change).
- The net effect on soil carbon (i.e. the losses during planting, and subsequent sequestration post-planting) have been included in the calculations, but are somewhat uncertain.
- There is good agreement over a number of studies that afforestation can achieve abatement at a reasonable cost (i.e. <£100 t CO2e); including the ancillary benefits of afforestation would further improve its cost-effectiveness.

1.6.2 Crop and soil measures

The crop and soil measures cumulative abatement potential in the UK in 2030 was 0.54 Mt CO_2e y^{-1} below the carbon price. The majority (62%) of this abatement was provided by *Precision farming for crops* and *Loosening compacted soils and preventing soil compaction*. Two additional measures had higher than 0.10 Mt CO_2e y^{-1} abatement potential (*Controlled release fertilisers* and *Legumes in rotations*), but neither of them was cost-effective when accounting for interactions, though the measure *Controlled release fertilisers* is cost-effective if applied alone (its cost-effectiveness is £37 t CO_2e^{-1} without interactions).

The mitigation measures aiming for optimal synthetic and organic N use (*Improving synthetic N use, Improving organic N planning* and *Shifting autumn manure application to spring*) had very low abatement potential (between 0.01

and 0.03 Mt CO_2e y^{-1}), mostly because of the estimated high current uptake of them leaving little room for additional uptake. However, *Shifting autumn manure application to spring* could provide a high per ha abatement on the limited areas where it is still applicable and not already existing practice (0.25 t CO_2e ha^{-1} y^{-1}).

Improving the organic manure spreading machinery (*Low emission manure spreading*) could provide higher abatement (0.07 Mt CO_2e y^{-1}), due to a combination of medium level abatement rate (0.11 t CO_2e ha^{-1} y^{-1}) and high potential additional uptake. These techniques are widely used in some European countries (e.g. the Netherlands, Denmark), but have not been commonly adopted in the UK, possibly partly due to the necessary capital investment in machinery or the higher cost of contractors.

Catch and cover crops proved to be a measure with a very low abatement potential and extremely high cost-effectiveness across all scenarios. Its mitigation was assumed to be a result of reduced nitrogen leaching during the winter, which translated to a medium level of abatement rate (UK average 0.094 t CO_2e ha^{-1} y^{-1}). As the proportion of spring crops in the UK is low, and the measure is not applicable on heavy soils, the low applicability resulted in very low abatement. Important positive environmental co-effects (soil protection and water quality) may make this measure desirable in some circumstances.

The options of using fertiliser additives or modified fertilisers were assessed in the MACC (*Controlled release fertilisers*) and in the additional measures (*Nitrification inhibitors*). Both measures had a high abatement potential without interactions, but interactions reduced their abatement potential and increased their abatement cost above the carbon price (in the case of *Nitrification inhibitors* the cost-effectiveness with interactions is £987 t CO_2e^{-1}.

Breeding *Plant varieties with improved N-use efficiency* is a mitigation measure which could be implemented with a gradual change in the crop breeding goals. The cost-effectiveness of it is negative due to the improved N use, and the measure could provide 0.08 Mt CO_2e y^{-1} GHG mitigation in the UK.

Planting more legumes (*Legumes-grass mixtures* and *Legumes in rotations*) could contribute 0.36 Mt CO_2e y^{-1} to GHG mitigation, though more than ¾ of this abatement was not cost-effective (*Legumes in rotations*), as grain legumes tend to have much lower gross margin than other crops.

Precision farming for crops comprises a range of technologies which contribute to improved resource use efficiency, including N fertiliser use, and therefore to GHG mitigation. Precision farming management approaches have been increasingly taken up, particularly by larger cereal farmers (though still to a low level). The analysis estimated that 165 kt CO_2e y^{-1} abatement potential could be achieved in the UK.

Loosening compacted soils and preventing soil compaction is a measure with 20% applicability across tillage land and temporary grasslands in the UK, and could provide a high abatement rate (0.41 t CO_2e ha^{-1} y^{-1}) via directly reducing N_2O emissions from soils. The increased yield nearly offseted the costs of the measure, and resulted in a low cost-effectiveness £1 t CO_2e^{-1}.

1.6.3 Livestock measures

The analysis considered four mitigation measures regarding ruminant livestock feeding practices (*Improving ruminant nutrition*, *Probiotics as feed additive*, *Nitrate as feed additive*, *High fat diet for ruminants*). The first two mitigation measures were cost effective and suggested a total of 0.08 Mt CO_2e y^{-1} GHG mitigation in the UK at negative cost, due to the possible efficiency gains. *Improving ruminant nutrition* is applicable to a proportion of beef and sheep herd, probiotics (e.g. yeast culture) could be administered to any ruminants when they are not grazing. *Nitrate as feed additive* was a measure which was cost-effective if interactions were not considered, and also cost-effective with interactions in 2035, but is slightly above the carbon price in 2030. Attributable to the high efficacy of the nitrate in reducing enteric methane emissions, its abatement potential was high: 0.33 Mt CO_2e y^{-1} GHG. However, its application requires the thorough mixing of the feed ingredients in order to avoid overdose. Finally, increasing the fat content of the diet (*High fat diet for ruminants*) could also reduce GHG emissions considerably (0.18 Mt CO_2e y^{-1}), but the costs seemed to be preventive in most cases (cost-effectiveness £225 t CO_2e^{-1}), as the oily ingredients are ~30% more expensive than the concentrate feeds they would partially replace.

The results indicate that improving sheep and cattle health could lead to substantial reductions in emissions by, for example, improving reproductive efficiency, reducing mortality and increasing growth rates and milk yields. The cost-effectiveness of improving health is difficult to quantify as it depends on the control options used and the starting (physical and economic) performance of the herd or flock.

Improving and the breeding goals in the national beef herd and accelerating the uptake of genetic improvements would mitigate 0.5 Mt CO_2e y^{-1}. However, with more ambitious goals (selection continues to 20 years instead of 10 and genomics and feed efficiency traits are incorporated into the breeding programme) the mitigation can be increased by a factor of 2.5.

Slurry acidification is a technique which well-established in some countries (e.g. Denmark) but so far not practiced in the UK. Its abatement potential is considerable; 0.12 Mt CO_2e y^{-1}, but on the MACC it is above the carbon price, due to interactions with anaerobic digestion measures. However, applying as a single measure it would be cost-effective. An additional liquid manure management measure was assessed quantitatively, *Covering slurry stores*. Since it reduces only the ammonia (and indirect nitrous oxide), but not the methane emissions from the storage, the abatement potential is much smaller, 0.03 Mt $CO_2e\ y^{-1}$, at a similar cost-effectiveness as slurry acidification.

The implementation of centralised anaerobic digesters was cost-effective for the bigger digesters and not for the 250kW capacity one (MM20: *Anaerobic digestion: cattle slurry with maize silage*). The 500kW (MM21: Anaerobic *digestion: pig/poultry manure with maize silage*) and the 1000kW (MM22: *Anaerobic digestion: maize silage only*) digesters were estimated to provide net financial savings. The GHG abatement of these two measures were 0.07 and 0.06 Mt $CO_2e\ y^{-1}$, respectively, for MM21 and MM22. From a farm manager's perspective, the inclusion of Feed-in Tariff would improve the profitability of these measures.

1.6.4 Energy use measure

The abatement potential of the measure *Behavioural change in fuel efficiency of mobile machinery* proved to be low as it was assumed that (market driven) improvements in machinery control and fuel efficiency would limit the scope for additional improvements via behavioural change. It is noted that further options exist to mitigate energy use related emissions (see e.g. AEA Technologies and FEC Services 2010).

1.6.5 Confidence in the estimates

Both the abatement potential and the cost-effectiveness can be sensitive to a range of inputs, though the importance of these varies with the mitigation measure. For example for the mitigation measure *Legume-grass mixtures*, assuming that the synthetic N fertiliser use would be reduced to 75 kg N ha^{-1} and not to 50 kg N ha^{-1} increases the cost-effectiveness from -£20 to £189 t CO_2e^{-1}, while assuming 75 kg N ha^{-1} fertilisation rate reduces it to -£82 t CO_2e^{-1}.

Table ES 7 shows a qualitative summary of the confidence in the abatement potential and cost-effectiveness estimates (columns "Abatement potential" and the "Cost-effectiveness"). The column "Significant abatement" indicates whether a significant contribution to agricultural mitigation can be expected from the measure at a UK level.

Table ES 7 Confidence in the estimates

ID	Mitigation measure	Significant abatement[1]	Abatement potential[1]	Cost-effectiveness[1]
MM1	Improving synthetic N use	H	M	L
MM2	Improving organic N planning	M	M	L
MM3	Low emission manure spreading	H	M	L
MM4	Shifting autumn manure application to spring	M	M	M
MM5	Catch and cover crops	L	M	M
MM6	Controlled release fertilisers	M	L	L

ID	Mitigation measure	Significant abatement[1]	Abatement potential[1]	Cost-effectiveness[1]
MM7	Plant varieties with improved N-use efficiency	M	M	M
MM8	Legumes in rotations	H	M	M
MM9	Legume-grass mixtures	H	M	M
MM10	Precision farming for crops	H	L	L
MM11	Loosening compacted soils and preventing soil compaction	H	M	M
MM12	Improving ruminant nutrition	H	L	L
MM13	Probiotics as feed additive	M	M	M
MM14	Nitrate as feed additive	H	M	L
MM15	High fat diet for ruminants	H	M	L
MM16	Improving cattle health	H	M	M
MM17	Improving sheep health	H	L	L
MM18	Selection for balanced breeding goals in beef cattle	H	M	M
MM19	Slurry acidification	H	M	M
MM20	Anaerobic digestion: cattle slurry with maize silage	H	M	L
MM21	Anaerobic digestion: pig/poultry manure with maize silage			
MM22	Anaerobic digestion: maize silage only			
MM23	Afforestation on agricultural land	H	M	M
MM24	Behavioural change in fuel efficiency of mobile machinery	M	L	L

Notes:
[1] H: high confidence, M: moderate confidence, L: low confidence

1.6.6 Mitigation measures for the longer term and demand side policies

Among the seven mitigation measures additionally assessed three are already implemented on some farms (*Agroforestry*, *Covering slurry stores*, *Precision livestock farming*), and their uptake could be increased by supporting policies. An additional one could be implemented instantly (*Nitrification inhibitors*), given barriers, like cost and distrust due to a perceived potential negative effect on milk quality could be removed. (*Nitrification inhibitors* and *Covering slurry stores* are described in Sections 1.6.2 and 1.6.3., respectively.)

Though common in some countries (e.g. France, Spain, Finland, Brazil), *Agroforestry* (silvoarable and silvopastoral systems) are not common in the UK. The carbon sequestration benefits could provide significant mitigation in the UK, by converting 1% of the grassland and arable land area, an estimated ~1 Mt CO_2e y^{-1} abatement could be achieved at a low cost, as the productivity of these systems is comparable to traditional ones.

Novel crops or increased planting of some crops which are rarely cultivated in the UK could improve resource efficiency (particularly N use) on farms and would have the potential to contribute to GHG mitigation. However, much research is needed for the development of such crops (particularly if significant breeding improvements or genetic engineering to be involved, for example, to create perennial or N-fixing wheat cultivars). Current knowledge about these potential effects is very limited.

Precision livestock farming, akin to *Precision farming for crops*, can improve farm efficiency by the use of additional information in decision support tools to tailor feeding, milking, grazing, and health intervention, etc. to the individual animals' needs. Given the wide ranging options regarding technology and management, the quantification of GHG effects at this stage is not possible, beyond acknowledging that it could contribute to agricultural mitigation.

In theory, *Genetic modification of livestock* could accelerate the achievement of abatement via breeding, however, it is difficult to predict, at present, the actual effect of GM livestock. Likewise, the increased uptake of the *Use of sexed semen in dairy reproduction* could also accelerate livestock improvement (and abatement) via breeding.

Evidence about *demand side measures* (i.e. dietary change) suggests that there is significant potential to reduce emissions by altering consumption patterns, though only part of these effects would change domestic emissions. Changing consumer behaviour is a complex socio-economic issue and requires concerted effort from government, industry and individuals across the supply chain.

1.7 Conclusion

According to the MACCs generated in this study, agricultural emissions in the UK could be reduced by between 0.53 Mt CO_2e (low) and 6.31 Mt CO_2e (high) in 2030, with afforestation providing much of this abatement potential.

Supportive policy instruments in the UK, in the devolved administrations and in the EU will be crucial in how much of this abatement will be realised. Market forces and changing technologies drive the uptake of some measures, but to realise an even higher uptake, more ambitious tools are needed. Previous studies also showed that even though some measures seem to be generating financial savings, certain barriers prevent farmers, or at least a proportion of farmers, from adopting them. A significant reduction of these barriers (which are present in the farm decision making, in the industry and supply chain, and in the governance a well) is required. The effort to increase on-farm mitigation should be complemented with demand side measures, even though a significant proportion of the GHG reduction achieved by these will not manifest in the national GHG inventories, which are production based.

It is important to emphasise that the biophysical, economic and social circumstances of farms vary, and therefore measures that do not look promising in the national level MACCs presented in this study may be able to achieve cost-effective mitigation in in certain circumstances. In addition, some measures not included in the MACCs may be able to provide significant additional abatement during the 4th and 5th budget periods. Furthermore, in the decisions about measure implementation, other important aspects of the measures have to be considered as well, like other environmental and social effects.

Agricultural RTD can unlock further abatement potential by improving our understanding of measures in areas such as: *Improving sheep health, Precision farming for crops*, *Precision livestock farming*, *Novel crops* and *Agroforestry*. Additionally, continuing technological development and innovation could improve the GHG mitigation and the cost-effectiveness which can be achieved by a number of measures, like precision farming technologies, and health and breeding related measures. The uptake of those measures which have been more widely implemented in other countries (e.g. *Slurry acidification*, anaerobic digestion measures, *Low emission manure spreading*), can be potentially increased by providing similar incentives to farmers.

2 Background

In the 2008 Climate Change Act the UK has committed to a 80% reduction in its GHG emissions by 2050 (compared to the 1990 baseline). The Climate Change Act requires the UK Government to set legally binding carbon budgets for five year periods, with a 50% reduction to be achieved by the end of the fourth carbon budget period in 2027 across all sectors. At the same time the European Council set a target of 30% emission reduction in the non-ETS sectors (comprising of transport, buildings, agriculture and waste) compared to a 2005 baseline. Agriculture, being part of the non-ETS sectors, does not have a binding emission reduction target in the UK, but the sector is expected to contribute to the domestic and international mitigation effort.

The Committee on Climate Change, established under the 2008 Climate Change Act, is responsible for advising the UK and Devolved Governments on setting emission targets and on pathways to achieve these targets across all sectors. In that role, in 2008 it commissioned a study to assess the cost-effectiveness and the feasible abatement potential of agricultural mitigation measures via MACC analysis (2008). This analysis was reviewed in 2009 by a Defra-commissioned project (AC0216) (EA 2009), and an updated MACC was developed in 2010 in a subsequent CCC project (MacLeod *et al.* 2010c). These studies provided the scientific evidence for setting the agricultural mitigation targets in the Devolved Administrations for the second, third and fourth carbon budget periods (Committee on Climate Change 2014).

Since these studies were conducted additional evidence has emerged both on the effectiveness and on the costs of mitigation measures and on related issues, like barriers to uptake, wider effects of mitigation, and uncertainties of the cost-effectiveness estimates. Numerous European and UK funded research projects have been exploring the technical and agronomic aspects, the whole farm effects, the social aspects, and opportunities for developing effective climate policies for the sector. With accumulating synthesis of primary research emerging as well, a robust revision of the assumptions in the earlier agricultural MACCs became possible.

The main objective of this project was to deliver a bottom-up MACC for the UK agriculture for the fourth and fifth carbon budget periods (2023-2027 and 2028-2032, respectively) using the latest evidence available on future reference projections for agricultural activities, the abatement effectiveness of the mitigation measures, the technical costs of the mitigation measures and the sensitivity of the results to the input data. The MACC calculations are provided in the form of a user-friendly Excel tool where key assumptions can be varied in order to analyse different scenarios, and the input data can be easily updated.

The tool is able to provide sensitivity analysis of the key output metrics. The mitigation measures include the main options to reduce on-farm N_2O and CH_4 emissions, C sequestration and CO_2 emissions from fossil fuel use. The scientific evidence is based on a rapid literature review, including published academic and 'grey' literature. Another objective was to provide a qualitative assessment of mitigation beyond 2032 up to 2050, highlighting the need for additional research investment and regulatory changes to achieve the mitigation potential. Additionally, the potential effects of dietary change of the UK population were assessed qualitatively, suggesting methodologies that are more suitable to assess such scenarios than the bottom-up MACC curve.

The report is structured as follows. The next section provides a background on the methodology. Section 4 considers the mitigation measures included in the MACC analysis, including a short description, assumptions, results and discussion of the individual measures. Section 5 presents the results of the MACC analysis, while the assessment of further mitigation measures is provided in Section 6. The human dietary change is discussed in Section 7.

3 Methodology

3.1 Marginal abatement cost curves

MACCs show the cost of reducing pollution by one additional unit as a function of the cumulative pollution reduction achieved against a future reference (business as usual) scenario. When compared to the marginal benefit arising from pollution reduction, the economic optimum of pollution reduction is defined as the intercept of these two curves (Figure 1). In the current analysis the marginal benefit of pollution reduction is approximated by the carbon price used for UK public policy appraisal (DECC 2014), with updated values received from the CCC in July 2015 (Table 1). The marginal cost at the economic optimum suggests a pollution price or tax level which would theoretically allow achievement of the optimal abatement. The mitigation measures which have lower cost-effectiveness than the economic optimum are suggested to have their uptake increased through supporting policy instruments.

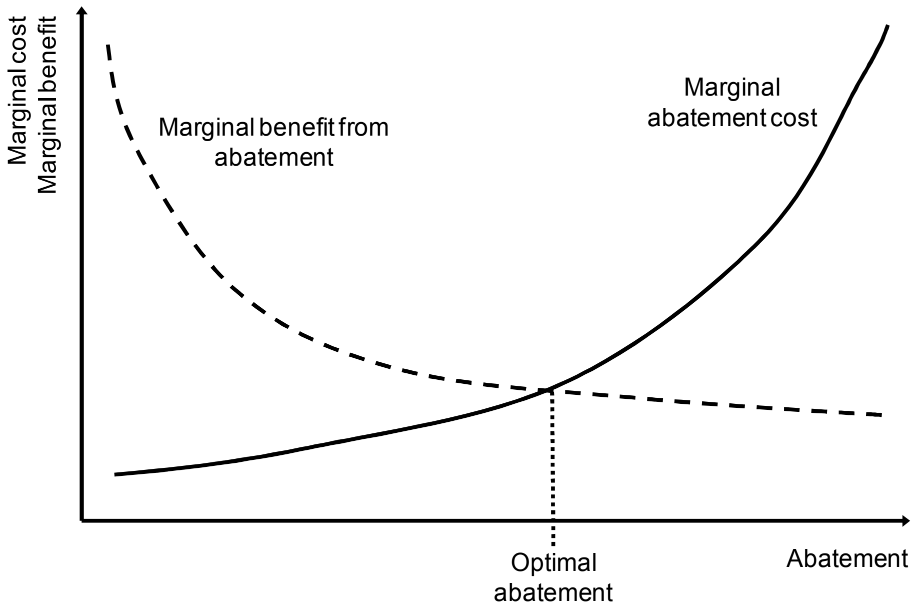

Figure 1 Optimal pollution abatement
Optimal pollution abatement is defined by the marginal cost of abatement and the marginal benefits from abatement (Pearce and Turner 1989)

Table 1 Central carbon price used in the analysis (£ t CO_2e^{-1})

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
C price	61	63	65	68	70	72	75	78	85	92	99	107	114

3.2 Boundaries of the assessment

In this report the GHG abatement potential of the agricultural sector of the UK is assessed at an annual basis up to 2035, with a breakdown of the abatement potential and cost-effectiveness for the four devolved administrations (England, Wales, Scotland and Northern Ireland). The basis of the differentiation at the DA level was activity data (e.g. land area of certain crops, crop yield, fertilisation rate); data were not available to present separate mitigation effects or cost elements at the DA level.

Regarding GHG emissions the boundary of the analysis was the farm. The farm management activities, emission factors and mitigation effects were estimated at the national (UK or DA) level for the range of crop and livestock production activities considered. The scope of the project did not allow more detailed disaggregation, e.g. by soil types, weather parameters or livestock productivity levels. Potential carbon leakage happening outwith the farm gate (e.g. in emissions related to imported livestock feed products) was discussed qualitatively.

This exercise considered the technological costs on the farm, for example investment in new machinery and savings in resource use. Other cost elements, like transaction costs and policy costs were not included, neither are non-financial barriers. The costs were estimated as a national average for the crop and livestock categories, where applicable distinguishing between three farm size categories in the calculations. Other heterogeneities of the sector are not considered. The costs and cost-effectiveness values are provided as a single average for the UK and DAs, rather than as a function of the uptake of the mitigation measure.

3.3 Mitigation measure selection

The scope of the report allowed the inclusion of a limited number of mitigation measures for quantitative analysis and a few additional mitigation measures for qualitative analysis. It is important to note that the mitigation measures analysed in the current report are not exclusive; additional abatement can be achieved by a range of other measures.

A list of 71 measures described in Frelih-Larsen et al. (2014) was used as a starting point, with some modifications (Appendix A). The measures on this list were scored by experts[1] according to the following criteria:

- High/medium potential abatement
- High/medium practical feasibility

[1] Experts: Bob Rees, Kairsty Topp, Eileen Wall, Michael MacLeod, Vera Eory, Jeremy Wiltshire

- No high risk of negative co-effects

The top scoring measures were selected to be on the draft shortlist (Appendix A), which was further modified in a discussion with experts, taking into consideration the comments from CCC and Defra and discussions at the Expert Workshop (see Section 3.11). The final list of measures for quantitative analysis is presented in Table 2, and the final list of measures for qualitative analysis is presented in Table 3.

Table 2 Final list of measures for quantitative analysis (inclusion in the MACC)

ID	Mitigation measure
MM1	Improving synthetic N use
MM2	Improving organic N planning
MM3	Low emission manure spreading
MM4	Shifting autumn manure application to spring
MM5	Catch and cover crops
MM6	Controlled release fertilisers
MM7	Plant varieties with improved N-use efficiency
MM8	Legumes in rotations
MM9	Legume-grass mixtures
MM10	Precision farming for crops
MM11	Loosening compacted soils and preventing soil compaction
MM12	Improving ruminant nutrition
MM13	Probiotics as feed additive
MM14	Nitrate as feed additive
MM15	High fat diet for ruminants
MM16	Improving cattle health
MM17	Improving sheep health
MM18	Selection for balanced breeding goals
MM19	Slurry acidification
MM20	Anaerobic digestion: cattle slurry with maize silage
MM21	Anaerobic digestion: pig/poultry manure with maize silage
MM22	Anaerobic digestion: maize silage only
MM23	Afforestation on agricultural land
MM24	Behavioural change in fuel efficiency of mobile machinery

Table 3 Final list of measures for qualitative analysis

Mitigation measure
Nitrification inhibitors
Novel crops
Agroforestry (with low tree density)
Covering slurry stores

Mitigation measure
Precision livestock farming
GM livestock
Using sexed semen in dairy cattle reproduction

3.4 Calculating the GHG abatement

Where possible, the mitigation calculations were aligned to the IPCC 2006 emission calculation methodology (IPCC 2006), with relevant parameters sourced from the 2012 UK greenhouse gas inventory (Webb *et al.* 2014) and the 2013 UK greenhouse gas inventory which is under preparation (MacCarthy *et al.* 2014). Expert opinion was used to identify those parameters and variables in the relevant Tier1/Tier2 2006 IPCC formulas which can *potentially* be used to reflect the effect of the mitigation measures (see Table 152 in Appendix B). For example, in the case of *Improving synthetic N use*, the management change implies reduced synthetic N fertiliser use without a reduction in the yield. This could be reflected by a reduced N application rate (F_{SN}) and, potentially, by a change in the emission factor of direct N_2O emissions (EF_1) and a change in the fraction of N leached ($Frac_{Leach}$).

The subsequent literature review specified whether there was direct or indirect evidence in the literature such that the suggested parameters/variables can be used to describe the abatement achieved by the measure. If there was evidence, the UK average value was estimated based on the literature review and the Expert Workshop (see Section 3.11). The literature review considered findings reported recently in peer-reviewed and grey literature. Information on the values was collected where possible, but such information was limited. The knock-on production and GHG effects of management changes at the farm level were not considered (e.g. changes in livestock feed composition if cover crops grown are fed to the livestock).

The abatement rate was estimated at an annual unitary basis (e.g. ha of land, head of animal). This was then multiplied by the applicability and the future additional uptake to calculate the annual abatement potential. The applicability is a metric to capture the agronomic feasibility of the measure, for example *Slurry acidification* is only applicable to liquid manure stored in tanks, not to other types of manure or slurry stored in other systems. The additional future uptake is an estimation of the additional uptake achievable in the time period considered, beyond the estimated future reference uptake of the measure (see more in Section 3.8).

For those mitigation measures which have a lifetime longer than a year and where the annual abatement is changing over time (e.g. *Afforestation on agricultural land*), the abatement expected in the relevant year is reported as annual abatement potential. However, the discounted full lifetime abatement is used to calculate the cost-effectiveness of these measures (see section 3.7).

3.5 Agricultural activities

3.5.1 Projection of crop areas, livestock numbers and farm structures

The annual projections of crop areas and livestock numbers are based on a combination of historic data (up to 2014), the latest (2015) FAPRI-UK modelling work (Agri-Food and Biosciences Institute 2015), and planting rate projections by the Forestry Commission (Forestry Commission 2015b) (FC 2015e). The calculations in the current project distinguish between 22 land use and 20 livestock categories (Table 4).

Table 4 Land use and livestock categories in the current study

Category
LAND USE
Total area on agricultural holdings
Total permanent grassland
Grass over 5 years old
Sole right rough grazing
Other land on agricultural holdings
Woodland
Land used for outdoor pigs and all other non-agricultural land
Total croppable area
Total crops
Arable crops
Cereals
Wheat
Winter wheat
Spring wheat
Barley
Winter barley
Spring barley
Oat
Other cereals
Rapeseed
Winter rapeseed
Spring rapeseed
Potatoes
Sugar beet (not for stockfeeding)
Peas for harvesting dry and field beans
Other arable crops not for stockfeeding (linseed, hops, other)
Fodder crops
Maize
Other fodder crops

Category
Horticultural crops
Peas and beans for human consumption
Other horticultural crops
Uncropped arable land
Temporary grass under 5 years old
LIVESTOCK
All cattle
Dairy cows
Dairy heifers
Dairy replacement females, 1-2y
Dairy replacement calves, 0-1y
Beef cows
Beef heifers
Beef replacement females, 1-2y
Beef replacement calves, 0-1y
Dairy cattle for meat, 6-18m, female
Dairy cattle for meat, 6-18m, male
Beef cattle for meat, 6-18m, female
Beef cattle for meat, 6-18m, male
All calves, 0-6m
Other cattle
All sheep
Ewes
Lambs, 0-1y
Other sheep
All pigs
Sows
Other pigs

The FAPRI-UK study, which estimates agricultural activities from 2010 to 2022, was used to be consistent with GHG emission projections used by the CCC for the C budget periods covered by the current study. To extend the FAPRI-UK projections to 2035, simple logarithmic trend lines were applied. The FAPRI-UK estimates include four arable crops, without projections provided for other crops, grassland areas or other croppable land. The Forestry Commission's study provides estimates for woodland areas. In the absence of consistent estimates for all the other land use types, these were held constant at 2014 values. However, the *Temporary grassland* area was assumed to change with the change in the *Arable crop* area (i.e. *Total croppable area* was held constant), and the *Sole right rough grazing* area was assumed to change with the change in the *Woodland* area. The following paragraphs explain the calculations and the source of data in more detail.

The land area statistics for 2014 are based on the following datasets:

- England: Structure of the agricultural industry in England and the UK at June (Defra 2015b)

- Wales: Welsh agricultural statistics (Welsh Government 2015)
- Scotland: Abstract of Scottish Agricultural Statistics 1982 to 2014 (Scottish Government 2015)
- Northern Ireland: Agricultural Census Historical Data (DARDNI 2015)

The annual projections of the individual land use categories used in this report are based on the following calculations and data:

- The total area on agricultural holdings is held constant at 2014 value.
- *Woodland* area follows the 2014 values plus the annual planting rates estimated by the Forestry Commission in their High Emission Scenario (Forestry Commission 2015b) (FC 2015e) (Table 5). The cumulative woodland planted by 2035 in the reference scenario is 98 thousand ha in the UK.

Table 5 Planting rates in the FC's High Emission Scenario (1000 ha y^{-1})

	2014-2020	2021-2035
England	3.340	0.229
Wales	0.929	0.021
Scotland	8.328	0.272
Northern Ireland	0.290	0.021

- *Sole right rough grazing* area is decreased by the increase in the *Woodland* area (98 thousand ha by 2035 in the UK, i.e. 2.5% of its 2014 value).
- *Grass over 5 years old* and *Land used for outdoor pigs and All other non-agricultural land* is constant at 2014 values, thus the sum of *Total permanent grassland* and *Other land on agricultural holdings* is constant.
- *Total croppable area* is held constant at 2014 rates.
- Wheat, barley, OSR and oats areas are taken from the FAPRI-UK projections extended with logarithmic trends, with proportioning of the area of winter and spring varieties based on historic (2010-2014) data (Table 6). The projections based on the FAPRI-UK study estimate a 2.2% increase (84 thousand ha) in the area of these four crops in the UK between 2014 and 2035. This results in an increase in the arable area of 1.8% in the same period.

Table 6 Land area proportions of winter and spring varieties

<table>
<tr><th></th><th>Wheat</th><th>Barley</th><th>OSR</th></tr>
<tr><td>England</td><td rowspan="3">5% spring wheat (Farmers Weekly 2012)</td><td colspan="2">Average in the years between 2010 and 2014 (Defra 2015b)</td></tr>
<tr><td>Wales</td><td>Average in the years between 2010 and 2014 (Welsh Government 2015)</td><td>NA</td></tr>
<tr><td>Scotland</td><td colspan="2">Average in the years between 2010 and 2014 (Scottish Government 2015)</td></tr>
</table>

	Wheat	Barley	OSR
Northern Ireland		Scottish average in the years between 2010 and 2014 (Scottish Government 2015)	

- *Total croppable* area, all other arable crops, *Horticultural crops* and *Uncropped arable area* are held constant at 2014 value. Following the CCC's request, the expected change in grain legumes' area due to the Common Agricultural Policy Greening measures introduced in 2015 is not reflected in the future reference activities.
- The changes in the areas of the four crops in the FAPRI-UK projections provoke a change in the *Temporary grassland* area, a 6% decrease from 2014 to 2035 (84 thousand ha).

Livestock numbers were calculated based on the available FAPRI-UK data and coefficients derived from more detailed livestock statistics of the UK (Defra 2015b), as described in Table 7.

Table 7 Coefficients for estimating livestock numbers

Livestock category	Estimation[a]	Note
Dairy heifers	DC * 0.25	UK average dairy replacement rate is 25% (DairyCo 2013)
Dairy replacement females, 1-2y	DC * 0.25	UK average dairy replacement rate is 25% (DairyCo 2013)
Dairy replacement calves, 0-1y	DC * 0.25	UK average dairy replacement rate is 25% (DairyCo 2013)
Beef heifers	BC * 0.15	UK beef replacement rate approximated with 15%
Beef replacement females, 1-2y	BC * 0.15	UK beef replacement rate approximated with 15%
Beef replacement calves, 0-1y	BC * 0.15	UK beef replacement rate approximated with 15%
Cattle fattened for meat, 1-2 year (from dairy and beef herd, males and females)	(DC + BC) * 0.3 + + DC * (0.4 – 0.25) + + BC * (0.4 – 0.15) = = DC * 0.45 + BC * 0.55	1-2y males and females are 30% and 40% of the dairy + beef breeding herd, respectively (Defra 2015b), and part of the females are kept as replacement
Cattle fattened for meat, 6-12 months (from dairy and beef herd, males and females)	0.5 * [(DC + BC) * 0.39 + + DC * (0.44 – 0.25) + + BC * (0.44 – 0.15)] = = DC * 0.29 + BC * 0.34	0-1y males and females are 39% and 44% of the dairy + beef breeding herd, respectively (Defra 2015b), and part of the females are kept as replacement; 50% of 0-1y calves are 6-12m calves
All calves, 0-6 months	0.5 * (DC + BC) * (0.39 + 0.44)	0-1y males and females are 39% and 44% of the dairy + beef breeding herd, respectively (Defra 2015b); 50% of 0-1y calves are 6-12m calves
Other cattle	Residue of TC less all the categories above	

Livestock category	Estimation[a]	Note
Ewes	0.47 * TS	Though the FAPRI projections include the number of ewes beside the total number of sheep, it was regarded as a too high value (62% of total sheep, allowing for only 0.73 lamb/ewe ratio), therefore the ewes / total sheep and lambs / total sheep ratio from the UK statistics was used (Defra 2015b)
Lambs, 0-1 year	0.5 * TS	50% of all sheep are lambs in the UK (Defra 2015b)
Other sheep	0.03 * TS	3% of all sheep are other sheep in the UK (Defra 2015b)

Notes:
[a] TC: total number of cattle, DC: number of dairy cows, BC: number of beef cows, TS: total sheep in the FAPRI-UK projections

The FAPRI projections only consider aggregate activity and not farm structures, i.e. the distribution of numbers of holdings or head of livestock across farms of different sizes; this may be important for the applicability of some mitigation measures. Two data sources were used to estimate future structures for the livestock and crops sectors.

Livestock structure projections were estimated using observed data reported by Defra in the UK Farm Size Statistics (Defra 2015c), these include observations for the years 2005 and 2010 to 2013 inclusive. Data for other years are available, however these do not report the same farm size categories so cannot be readily reconciled. As with the FAPRI-UK data, simple logarithmic trend lines were fitted to the data reported by the UK Farm Size Statistics to allow projections out to 2035. The logarithmic specification was found to produce the least extreme projections. The farm size data for livestock is available in terms of both the number of animals and the number of holdings within each size category. Consequently there is some overlap in terms of animal numbers between these projections and those produced from the FAPRI-UK data, although we would not expect these to be consistent with each other given the nature of the two datasets.

The future structures of arable farms were estimated using Eurostat[2] data on the characteristics of farms with arable land. As with livestock structure projections these are based on a small number of actual observations (2005, 2007 and 2010) rather than model outputs. Again logarithmic trend lines were fitted to the data as these offered the least extreme projections. The analysis allowed projections to be made of both the number of holdings and area of arable crops planted on farm within a range of size categories. The Eurostat data refers only to arable area so does not allow a more detailed examination of structures with

[2] http://ec.europa.eu/eurostat/web/agriculture/data/database

respect to particular crop types, assumptions therefore have to be made regarding the distribution of crops.

3.5.2 Farm management information

To assess the mitigation potential beyond the future reference scenario, expert judgement was used to translate available data on current farm management to likely mitigation measure uptake in the future reference scenario. The required farm management data was acquired from various statistical sources, like the UK Farm Practices Survey, the Scottish Farm Structure and Methods Survey, The British Survey of Fertiliser Practice and the Countryside Survey. More detail about these data sources and their use is provided in the description of the mitigation measures.

3.6 Net costs

The net costs of the measures were based on the estimated technical costs and benefits of the mitigation measures at the farm level, on a partial budget basis. This approach took into account the costs and benefits (both annual changes and capital investments) arising from the positive and negative change in expenses and income associated with the changes in farming activities and outputs. The costs and benefits are provided at 2014 values.

Due to the lack of data in the literature about the time requirements of the implementation of the mitigation measures, this cost element could not be included in the calculations. On-farm transaction costs were not considered either, due to lack of data. The scope of the study did not allow the inclusion of wider costs and benefits, such as public administration costs of mitigation policies, economic welfare effects, environmental impacts beyond the GHG mitigation, human health effects or animal welfare effects. Furthermore, non-financial barriers (e.g. social and behavioural aspects of the farmers' decision making, risk aversion, market constraints) were captured only in a limited way for some measure by reducing the maximum additional uptake of the measure. The absence of these cost elements should be borne in mind when interpreting the results.

Expert opinion was used to identify those expenses and income which might change due to the implementation of the measures on farm. The financial costs/benefits identified to be potentially relevant to each mitigation option are presented in Table 153 Appendix B. The subsequent literature review specified whether these expenses and income were affected, and if yes, what the extent of change was. In many cases the costs and benefits were presented in the literature in a way which did not allow the specification of financial costs/benefits at the level of detail described in Table 153. In these cases aggregate values were used in the calculations.

The costs represented are production costs rather than farm gate costs to achieve consistency with the CCC's approach. Where direct data on production costs were not available, the production cost was approximated by multiplying the farm gate costs by 0.8.

3.7 Cost-effectiveness

The cost-effectiveness was considered at a discounted lifetime basis, consistent with the approach of the CCC. The cost of the measure is the NPV of the unitary net costs over the lifetime of the measure. Two discounting scenarios were used, one with the social and one with the private discount rate (3.5% and 7%, respectively). The abatement of the measure was calculated as the unitary lifetime GHG abatement discounted with an annual rate of 3.5%. The cost-effectiveness was given by the ratio of the NPV and the discounted lifetime abatement:

$$CE_i = \frac{NPV_i}{DLA_i}$$

CE_i: cost-effectiveness of measure *i*
NPV_i: net present value of measure *i*
DLA_i: discounted lifetime abatement of measure *i*

$$NPV_i = \sum_{j=0}^{n} \frac{\left(Cost_{i,j} - Benefit_{i,j}\right)}{(1+r)^j}$$

$Cost_{i,j}$: financial costs of measure *i* in year *j* of the measure's lifetime
$Benefit_{i,j}$: financial benefits of measure *i* in year *j* of the measure's lifetime
r: discount rate (3.5% or 7%)
j: lifetime of the measure

$$DLA_i = \sum_{j=0}^{n} \frac{Abatement_{i,j}}{(1+r)^j}$$

$Abatement_{i,j}$: GHG abatement of measure *i* in year *j* of the measure's lifetime
r: discount rate (3.5%)
j: lifetime of the measure

3.8 Uptake scenarios

The abatement potential of a measure (before interactions were taken into account) is a linear function of the future additional uptake of the measure. In reality, the future additional uptake depends on many factors, including the current uptake, the financial and wider costs and benefits to the farmer, and the policy environment. Due to scarce data availability these effects are not included in the uptake scenarios used in the current study.

The maximum future additional uptake was estimated from the current uptake. This uptake was assumed to be achieved in 2035 only in the maximum technical potential scenario. In earlier years and in other policy scenarios a proportion of this maximum future uptake was assumed to be reached. A linearly increasing uptake was used, starting from zero additional uptake in 2015.

The scope of this exercise did not include the development of policy instruments to promote the mitigation measures. Rather, the aim was to present the abatement potential and the set of least cost mitigation measures to achieve it in order to serve as guidance for policy development. Therefore the analysis is done under different simple assumptions on policy environment and it also looks at the maximum abatement which is technically available. The four uptake scenarios used follow the policy assumptions and uptake values developed in the UK agricultural MACC analysis in 2008 (Moran *et al.* 2008), and summarised in Table 8. The required assumptions on the expected net costs and ease of monitoring and enforcement are presented in Table 9.

Table 8 Uptake scenarios as used in the current study

Uptake scenario	Policy assumption		Value
Low feasible potential (LFP)	Information/education policies	Measures with positive technical costs	7%
		Measures with negative technical costs	18%
Central feasible potential (CFP)	Financial incentives for uptake (or disincentives for emissions)	All measures	45%
High feasible potential (HFP)	Mandatory regulation	Measures which are difficult to monitor and enforce	85%
		Measures which are easy to monitor and enforce	92%
Maximum technical potential (MTP)	Theoretical maximum abatement if the measure is applied wherever it is agronomically possible	All measures	100%

Table 9 The mitigation measures' expected net cost and ease of monitoring/enforcement

ID	Short name	Expected net cost	Ease of monitoring/ enforcement
MM1	SynthN	Negative	Difficult
MM2	ManPlanning	Negative	Difficult
MM3	ManSpread	Positive	Difficult
MM4	SpringMan	Negative	Easy
MM5	CoverCrops	Positive	Easy
MM6	CRF	Positive	Easy
MM7	ImprovedNUE	Negative	Easy

ID	Short name	Expected net cost	Ease of monitoring/ enforcement
MM8	GrainLegumes	Positive	Easy
MM9	GrassClover	Negative	Easy
MM10	PF-Crops	Positive	Easy
MM11	SoilComp	Positive	Difficult
MM12	ImprovedNutr	Negative	Difficult
MM13	Probiotics	Negative	Easy
MM14	NitrateAdd	Positive	Easy
MM15	HighFat	Positive	Difficult
MM16	CattleHealth	Negative	Easy
MM17	SheepHealth	Positive	Easy
MM18	BeefBreeding	Negative	Easy
MM19	SlurryAcid	Positive	Easy
MM20	ADCattleMaize	Positive	Easy
MM21	ADPigPoultryMaize	Positive	Easy
MM22	ADMaize	Positive	Easy
MM23	Woodlands	Positive	Easy
MM24	FuelEff	Negative	Difficult

3.9 Interactions between the measures

The implementation of mitigation measures often involve making management and infrastructural changes on either the same production processes (e.g. reducing the N fertiliser applied and at the same time adding nitrification inhibitors to the fertiliser), or on processes which interact with each other on the farm (e.g. acidifying the slurry and also applying the slurry with low emission spreading technologies). The mitigation measures can be evaluated as a change on farm *ceteris paribus*, presenting an abatement potential and cost-effectiveness where no interactions are considered. However, the construction of a MACC (i.e. the derivation of the cumulative abatement potential) necessitates the interactions between the measures to be taken into account to avoid double counting of the potential abatement.

As the scope of this exercise did not allow the extensive whole farm modelling which would be needed to model the GHG and financial interactions between measures, expert opinion based interaction factors were used to adjust the GHG abatement of the measures. The financial interactions were considered to be marginal and thus interaction factors were not developed for the costs.

The methodology of the interaction calculations followed the methodology first developed in the 2008 UK agricultural MACC (Moran *et al.* 2008) which was subsequently modified in the 2010 update (MacLeod *et al.* 2010c). The interaction factors express how the total abatement achieved from the parallel implementation of two measures differ from the sum of the abatement achievable with the two measures implemented separately. It relates to the area (or livestock units, etc.) where both measures are implemented. Theoretically, it could be expressed as a factor reducing/increasing the combined abatement of the two measures:

$$DLA'_{k,l} = (DLA_k + DLA_l) * IF_{k-l}$$

> $DLA'_{k,l}$: combined discounted lifetime abatement of measures *k* and *l*, if implemented together on the same farm
> DLA_k, DLA_l: respective discounted lifetime abatement of measures *k* and *l*, if implemented separately
> IF_{k-l}: theoretical interaction factor for measures *k* and *l*

However, for computational reasons, the interactions were taken into account during the process of ordering the measures in the MACC. After the first measure was selected (the one which has the lowest CE), the abatement potentials of all the other measures were modified with the respective interaction factors. Then the second measure was selected, and the process was repeated for all measures.

The interaction factors therefore reflect the change in the abatement potential of the subsequent measure rather than the change in the abatement potential of the two measures combined:

$$DLA'_{k,l} = DLA_k + DLA_l * IF_{k,l}$$

> $IF_{k,l}$: interaction factor for measures *k* and *l*, (measure *k* being ranked higher on the MACC than measure *l*)

If the assumption is that the two measures don't have any synergies or trade-offs in their abatement, then $IF = 1$. If the subsequent measure is not applicable after the implementation of the first or its abatement is reduced to 0, then $IF = 0$.

As such, the interaction factors need to reflect the order of the two measures on the MACC, i.e.

$$IF_{k,l} \neq IF_{l,k}$$

As mentioned above, the interaction factors were estimated assuming combined implementation of the two measures. Therefore, when calculating a national MACC, the estimated uptake of the measures had to be taken into account: when the uptake of the considered measures increases, the probability of parallel uptake increases.

The abatement of the subsequent measure, considering the interactions:

$$DLA'_l = DLA_l * \left(1 + IF_{k,l} * \frac{Impl_{k,l}}{Impl_l}\right)$$

DLA′_l: respective discounted lifetime abatement of measure *l*, taking interactions into account

Impl_{k,l}: proportion of area/livestock where both measures *k* and *l* are implemented

Impl_l: proportion of area/livestock where measure *l* is implemented

Table 10 -

Table 12 detail the interaction factors used in the analysis. For the combination of measures where interaction factors are not presented in the tables below, the assumption was that $IF = 1$ (no interaction).

Table 10 Interaction factors, MM1-MM10

		MM1	MM2	MM3	MM4	MM5	MM6	MM7	MM8	MM9	MM10
		SynthN	ManPlanning	ManSpreader	SpringMan	CoverCrops	CRF	ImprovedNUE	GrainLegumes	GrassClover	PF-Crops
MM1	SynthN	1	1	1	1	0.95	0.97	0.95	0.98	0.6	0.6
MM2	ManPlanning	1	1	1	0.9	0.95	0.97	0.95	1	1	0.6
MM3	ManSpreader	1	1	1	1	0.95	0.97	0.9	1	1	1
MM4	SpringMan	1	0.5	1	1	0.4	0.75	1	1	1	1
MM5	CoverCrops	0.95	0.95	0.95	0.9	1	1	0.9	0.9	1	1
MM6	CFR	0.85	0.85	0.85	0.6	1	1	0.5	0.75	0.5	0.5
MM7	ImprovedNUE	0.8	0.8	0.8	1	0.8	0.75	1	0.95	0.7	0.8
MM8	GrainLegumes	0.8	1	1	1	0.1	0.1	0.8	1	1	0.7
MM9	GrassClover	0.1	1	1	1	1	0.3	0.7	1	1	0.2
MM10	PF-Crops	0.1	0.1	1	1	1	0.3	0.8	0.97	0.2	1

Table 11 Interaction factors, MM12-MM15

		MM12	MM13	MM14	MM15
		ImprovedNutr	Probiotics	NitrateAdd	HighFat
MM12	ImprovedNutr	1	0.8	0.8	0.8
MM13	Probiotics	0.8	1	0.8	0.8
MM14	NitrateAdd	0.8	0.8	1	1
MM15	HighFat	0.8	0.8	1	1

Table 12 Interaction factors, MM19-MM22

		MM19	MM20	MM21	MM22
		SlurryAcid	ADCattleMaize	ADPigPoultryMaize	ADMaize
MM19	SlurryAcid	1	0.5	0.2	1
MM20	ADCattleMaize	0.9	1	1	1
MM21	ADPigPoultryMaize	0.2	1	1	1
MM22	ADMaize	1	1	1	1

3.10 Sensitivity analysis

To assess the sensitivity of the results to the various parameters on applicability, uptake, abatement, costs and interaction factors, a sensitivity analysis was carried out. The details of that are reported in the sections describing the mitigation measures (Section 4), with the IF sensitivity described in Section 0.

3.11 Expert Workshop

An expert workshop was organised to review the findings of the literature review, focusing on the most uncertain areas and mitigation measures. The purpose of the Workshop was to discuss the potential abatement, likely on-farm costs, and likely uptake of a subset of the mitigation measures considered for quantitative analysis. The invitees included researchers (covering expertise in projects like GHG Platform, MinNo, Farmscoper), farm advisors, industry representatives and policy makers. The Workshop took place on 5th June 2015, in Edinburgh. The list of attendees and the notes of the Workshop are provided in Appendix C. The findings of the Workshop are incorporated in the description of the mitigation measures.

4 Description and analysis of the mitigation measures

4.1 MM1: Improved synthetic N use

4.1.1 Description of the measure

This measure is a reduction in N fertiliser use by doing the following actions on farm: carrying out soil analysis for pH and the application of lime (if required); using an N planning tool; decreasing the error of margin on N fertiliser application and not applying the fertiliser in very wet/waterlogged conditions. All of these can lead to a reduction in synthetic N application rate without negatively affecting the yield, i.e. improving the N use efficiency of the farm (Frelih-Larsen *et al.* 2014).

4.1.2 Applicability

The applicability of this measure is estimated based on what proportion of the land area receives synthetic N. This information is available from the British survey of fertiliser practice (BSFP) (Defra 2013b). In Great Britain, 91% of the tillage area and 61% of the grasslands receive synthetic N. The relevant crop-specific data are used as applicability, with DA level details, where available.

4.1.3 Abatement rate

The measure reduces GHG emissions by reducing the synthetic N used. Though with the changing application practice the actual emission factor (i.e. the proportion of applied N emitted as N_2O) might change, the abatement is estimated via the IPCC soil N_2O emission calculation (IPCC 2006), assuming a constant emission factor.

Abatement data from the literature is presented in Table 13. Note that the abatement rates presented do not include the reduction in GHG emissions achieved by the decrease in fertiliser production.

Table 13 Data from literature on abatement rate by improved synthetic N use

Abatement	Value	Country	Reference
N use	Potentially -40 kg N ha^{-1}	Germany	(Osterburg 2007) in (Frelih-Larsen *et al.* 2014)
N use	-10% N application rate, resulting in 0.4 t CO_2e ha^{-1} lower soil N_2O emissions (~ -16 and -9 kg N ha^{-1} on tillage land and grasslands, respectively, as derived from N fertiliser statistics (Defra 2013b))	UK	(Moran *et al.* 2008)
N use	-0.12 t CO_2e ha^{-1} of soil N_2O emissions (~ 25 kg N ha^{-1} reduction)	UK	(MacLeod *et al.* 2010c)

Abatement	Value	Country	Reference
N use	-208 kt CO_2e in England and Wales from using a N fertiliser recommendation system (no per ha values provided)	UK	(Defra 2012a)
N use	-19.7 kg N ha^{-1}, resulting in 0.19-0.22 t CO_2e ha^{-1} lower soil N_2O emissions	France	(Pellerin *et al.* 2013)
N use	-40 kt CO_2e in England and Wales from using a N fertiliser recommendation system (no per ha values provided)	UK	(Gooday *et al.* 2014)

The data above show that the estimated N saving range between 9-25 kg N ha^{-1} in UK studies, and is 20 kg in France and up to 40 in Germany. The Expert Workshop (see Appendix C) did not disagree with the initially suggested value of 5 kg N ha^{-1} fertiliser use reduction, which value, in turn, had been derived from the FARMSCOPER study (Gooday *et al.* 2014). However, given the higher estimates in the literature, the assumption here was that 10 kg N ha^{-1} reduction in synthetic N use can be achieved on average in the UK across tillage land and grasslands.

4.1.4 Current and additional future uptake

Advice has been given for many years to farmers to follow N fertiliser recommendation systems in order to avoid excess applications of N fertiliser. Indeed, historical trends show increasing use of fertiliser recommendation systems (Defra 2015a) and a decrease in synthetic N fertiliser use in the past 30 years (Defra 2013b). However, there seem to be a lack of scientific analysis regarding the casual relationship between using a recommendation system and decreasing synthetic N fertiliser in the UK. Still, there is expert opinion that some farmers are still not using N fertiliser recommendation systems and as a result may be using excess fertiliser N. On the other hand, Spadavecchia (2014) reported that there is emerging evidence from research projects indicating that many farmers are under-fertilising rather than over-fertilising crops and grasslands. In these cases improving synthetic N use could mean increased application rates and increased area-based emissions, even though the emission intensity of the products might decrease.

Overall, current and future uptake is difficult to assess as data on how actual N fertiliser applications compare with recommendations considering rotational effects and soil type do not exist. Information on N fertiliser use by crop provided by the British Survey of Fertiliser Practice (Defra 2013b) does not suggest that crops are, on average, given more N fertiliser than is required. However, that survey only reports average N application rates and does not relate them to rotational positions and soil type.

Given the scarce evidence on current practice, the following assumption is used in this report: following a nutrient management plan and carrying out soil testing leads to optimal N application rate, and, *vice versa*, not using such a plan or not testing the soil implies overapplication of synthetic N.

The Farm practices survey – Greenhouse gas mitigation (Defra 2015a) provides data on these activities, and the current additional uptake values are derived from these (Table 14). Thus, a reduction in synthetic N fertiliser use of 10 kg N ha^{-1} can be achieved on those areas which have been managed without a combination of nutrient management plan, soil pH testing and soil nutrient testing. This is estimated to be 5% of tillage area (derived from cropping farm data) and 50% of grasslands (derived from lowland and LFA livestock). Additionally, we assume that a reduction of 5 kg N ha^{-1} ("semi-improvement") can be achieved on those areas which have been managed with the above three activities in place but where the nutrient management plans are prepared without professional advice. This considers 20% of tillage land and 30% of grasslands. For simplified calculations a reduction of 10 kg N ha^{-1} is used on half of these "semi-improved" areas. Overall, current additional uptake is 15% of the tillage land and 65% of grassland. The future additional uptake is assumed to be equal to the current one. Furthermore, the English situation described by the Farm practices survey is extrapolated to the UK.

Table 14 Proportion of land under different nutrient management (Defra 2015a) and the additional uptake values derived for the current study

Management / Farm type	England average	Cereals and Other crops	Pigs & Poultry, Mixed and Dairy	Lowland and LFA livestock
I. No nutrient management plan	19%	5-6%	10-17%	42-51%
II. Nutrient management plan with no professional advice	22% 19%	18-23% 17-22%	19-25% 16-20%	31-36% 11-13%
III. No soil pH testing	13%	3%	8-12%	36-37%
IV. No soil nutrient testing	15%	2-3%	7-14%	45-48%
Additional uptake (UK)			**Tillage land**	**Grassland**
A. Full improvement (creating nutrient management plan and doing soil pH and nutrient testing): -10 kg N ha^{-1} (Derived from I., III., IV.)			5%	50%
Semi-improvement: -5 kg N ha^{-1} (Derived from II.)			20%	30%
B. Value used in the calculation for the semi-improvement			10%	15%
Total (A+B)			15%	65%

4.1.5 Cost

The cost of the measure is calculated considering the nutrient savings (based on the reduction in N fertiliser use) and the cost of the external nutrient planning advice. The fertiliser cost is approximated by assuming that ammonium nitrate (AN) and urea are the only sources of synthetic N on farms, used in a proportion of 83:17 on tillage land and 90:10 on grassland (based on the British use of these two fertilisers (Defra 2013b)). The price of ammonium nitrate (AN) and urea is £800 t N^{-1} and £650 t N^{-1}, respectively (average price during 2013-2014, (DairyCo 2015b)). With these prices, the 10 kg N saving provides £7.85 ha^{-1} cost savings.

The nutrient planning advice is approximated based on literature data, from a review by Frelih-Larsen *et al.* (2014) (first three rows in Table 15). The average values in the three reports, adjusted to 2014 levels, range from $£_{2014}$2.80 to $£_{2014}$10.00 ha^{-1}; we used the UK value of $£_{2014}$10.00 ha^{-1}.

Table 15 Data from literature on the costs and benefits of improved synthetic N use

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Sampling and advice	£0.70-3.60 ha^{-1}	Germany	2004	(Interwies *et al.* 2004) in (Frelih-Larsen *et al.* 2014)
Sampling and advice	£8.49 ha^{-1} (SD £5.60 ha^{-1}), range £0.70 - £21.00 ha^{-1}	UK	2008	(Crabtree *et al.* 2008) in (Frelih-Larsen *et al.* 2014)
Management tool	£6.70 ha^{-1}	France	2010	(Pellerin *et al.* 2013) in (Frelih-Larsen *et al.* 2014)
Fertiliser savings	£11.89 ha^{-1} (SD £5.83 ha^{-1}), range £0.00 - £23.00 ha^{-1}	UK	2008	(Crabtree *et al.* 2008) in (Frelih-Larsen *et al.* 2014)
Fertiliser savings	£12.90 ha^{-1}	France	2010	(Pellerin *et al.* 2013) in (Frelih-Larsen *et al.* 2014)

4.1.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 97 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 57, 12, 18 and 10 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 16). The UK abatement potential (without interactions, d.r. 3.5%) increased from 39 kt CO_2e y^{-1} with the low feasible potential to 217 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 29 to 163 kt CO_2e y^{-1}, respectively, in 2030 (Table 17). In all of the above cases the UK average cost-effectiveness of the measure without interactions was £35 t CO_2e^{-1} (which is below the C price).

Table 16 MM1 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	97	35
England	57	35
Wales	12	35
Scotland	18	35
Northern Ireland	10	35

Table 17 MM1 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	29	73	138	163
2035	3.5%	39	97	184	217
2030	7.0%	29	73	138	163
2035	7.0%	39	97	184	217

The sensitivity analysis showed that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 49 and 146 kt CO_2e y^{-1}; this analysis involved changing the assumptions on uptake, change in synthetic N use, cost of nutrient planning advice and fertiliser price (Table 18). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£46 and £196 t CO_2e^{-1} for the respective cases.

The abatement potential in the UK increased linearly with increasing uptake and with increasing synthetic N saving. The cost-effectiveness became higher than the 2035 C price with a 50% drop in the expected N savings or with a 50% increase in the cost of nutrient planning advice. ±20% change in the average fertiliser price did not affect the cost-effectiveness to an extent which would make it either negative or, on the other hand, higher than the C price.

Table 18 Sensitivity of MM1 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Maximum additional future uptake	Tillage land: 0.15 Grassland: 0.65	Tillage land: 0.05 Grassland: 0.55	73	35
Maximum additional future uptake	Tillage land: 0.15 Grassland: 0.65	Tillage land: 0.25 Grassland: 0.75	122	35
Change in synthetic N use (kg N ha^{-1})	-10	-5	49	196
Change in synthetic N use (kg N ha^{-1})	-10	-15	146	-19
Cost of nutrient planning advice (£ ha^{-1})	10	15	97	115
Cost of nutrient planning advice (£ ha^{-1})	10	5	97	-46
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 620 Grassland: 628	97	60
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 929 Grassland: 942	97	9

4.1.7 Discussion

This measure was (partially) comparable to one measure in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008) and to two measures in the FARMSCOPER studies (Gooday *et al.* 2014), see Table 132 and Table 133 for more details on how these mitigation measures relate to each other. The abatement potential of the FARMSCOPER measure *Use a fertiliser recommendation system* in the English agriculture was estimated to be 40 kt

CO_2e y^{-1} at a cost-effectiveness of -£175 t CO_2e^{-1} (Gooday *et al.* 2014), somewhat lower than the 57 kt CO_2e y^{-1} abatement potential in England estimated here. Defra (2012a) estimated the same measure to provide 208 kt CO_2e y^{-1} abatement with a cost-effectiveness of -£102 t CO_2e^{-1}.

This measure was also similar to the measure *Avoiding N excess* in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008). The abatement potential for the UK (without interactions, 2022, CFP, d.r. 7%) was 421, 64 and 2 kt CO_2e y^{-1}, respectively, in the 2008, 2010 Optimistic and 2010 Pessimistic MACC. The UK abatement potential estimated in the current study is 97 kt CO_2e y^{-1}. The main driver of the difference was the assumptions on the abatement rate of the measure. In the 2008 MACC the abatement was estimated to be 0.4 t CO_2e ha^{-1} y^{-1}; in the 2010 Optimistic and 2010 Pessimistic MACCs the respective values were 0.07 and 0.01 t CO_2e ha^{-1} y^{-1}. In the current assessment the assumed 10 kg N ha^{-1} y^{-1} saving corresponded to 0.06 t CO_2e ha^{-1} y^{-1} GHG mitigation on average in the UK. The applicability and uptake assumptions in the three previous MACCs meant that with the MTP uptake the measure was assumed to be implemented on 20% of tillage and grasslands. In the current study the combination of applicability (91% of the tillage area and 61% of the grasslands receive synthetic N) and maximum additional future uptake assumptions (15% on tillage land and 65% on grassland) gave a somewhat higher value: in the MTP scenario the measure would be implemented on 14% of tillage land and 39% of grassland. The cost-effectiveness values in the 2008, and in both 2010 MACCs were negative, as the assumption was that changing the current practice can be done without the cost of external advice, soil sampling or the purchase of an N management tool.

4.2 MM2-MM4: Improved organic N use

4.2.1 Description of the measure

These measures aim to improve the application of organic manures in order to reduce N losses from leaching and run-off and to improve the proportion of N utilised by the crops, and therefore allowing a reduction in synthetic N use. Three actions are distinguished and treated as separate mitigation measures:

i. MM2: Improving the planning of organic N use by using an N planning tool to take into account the full allowance of manure nutrients, decreasing the error of margin in manure applications and not applying the manure in very wet/waterlogged conditions (all these three actions to be implemented on farm together). Such actions improve the utilisation of N in the manure, increasing its fertiliser replacement value.

ii. MM3: Switching to low emission manure spreading technologies (slurry: band spreading or injection, farm yard manure (FYM): incorporation of the manure within 24 hours). By using fertiliser spreaders which place the organic N in the soil the proportion of N lost as NH_3 is greatly reduced, and the N available for plant uptake (and the fertiliser replacement value of the organic N) increases, allowing a reduced use of additional synthetic fertiliser.

iii. MM4: Shifting autumn manure application to spring where possible, without changing crop cultivars (i.e. autumn/winter slurry application to spring for all tillage crops, autumn/winter FYM application to spring for all spring sown crops). This measure greatly improves the fertiliser replacement value of the manures, thus allowing for the reduction in synthetic N use.

4.2.2 Applicability

The applicability of these measures is estimated based on what proportion of the land area receives manure. DA specific values available in the BSFP (Defra 2013b, Table D2.3a) are used for that purpose. On average in Great Britain, in 2012 24% of the tillage area and 46% of grasslands received manure.

4.2.3 Abatement rate

The abatement is measured via the avoided synthetic N application, which is a simplified approach compared to fully accounting for the changes in organic and synthetic N use and the changes in the emission parameters (e.g. fraction of the organic N volatilising). We assumed that on fields where only organic N is used the organic N will be reduced and used on other fields, ultimately reducing synthetic N use there.

Abatement data from literature relevant to the three measures is presented in Table 19. These estimates are very wide spread and difficult to compare, not only because of the varied metrics and the varied emission savings included (e.g. indirect N_2O mitigation from NH_3 reduction versus direct N_2O from reduced synthetic N use), but also because the definitions and boundaries of the mitigation measures differ between the studies.

Table 19 Data from literature on abatement by improved organic N use

Abatement	Value	Country	Reference
MM2: Soil N_2O	*Full allowance of manure N* 2008 MACC: -0.4 t CO_2e ha^{-1} 2010 Optimistic: -0.1 t CO_2e ha^{-1} 2010 Pessimistic: -0.01 t CO_2e ha^{-1} AND *Improved timing of manure N application* (part of this mitigation refers to shifting autumn to spring allocation) 2008 and both 2010 MACCs: -0.3 t CO_2e ha^{-1} (note that the mitigation effects of the two measures are not fully additive)	UK	(MacLeod *et al.* 2010c, Moran *et al.* 2008)

Abatement	Value	Country	Reference
MM2-MM3: N use	*Make better use of organic fertilisers:* -14.4 kg N ha^{-1}, as a combination of better manure N planning (relates to MM2), low volatilisation manure spreading (relates to MM3) and increasing the recycled waste volumes; together these result in 0.09-0.21 t CO_2e ha^{-1} lower soil N_2O emissions	France	(Pellerin *et al.* 2013)
MM3: NH_3 volatilisation	-10 – -90% NH_3 volatilisation	Europe	(Weiske *et al.* 2006)
MM3: N use	On average 0.1 increase in fertiliser replacement value (~ -16 and -9 kg N ha^{-1} on tillage land and grasslands, respectively, as derived from N fertiliser statistics (Defra 2013b))	Europe	(Olesen *et al.* 2004, Weiske *et al.* 2006)
MM3: N use	0.05 increase in fertiliser replacement value (~ -8 and -5 kg N ha^{-1} on tillage land and grasslands respectively, as derived from N fertiliser statistics (Defra 2013b))	UK	(Defra 2011b)
MM3: Soil N_2O	-0.05 t CO_2e ha^{-1} from *Placing N precisely in soil*	UK	(Moran *et al.* 2008)
MM4: Soil N_2O	-0.05 t CO_2e ha^{-1} from *Changing from winter to spring cultivars*	UK	(Moran *et al.* 2008)

i. MM2: The relevant Moran *et al.* (2008) and MacLeod *et al.* (2010c) estimates are a combination of *Full allowance of manure N* and *Improved timing of manure N application*. The former measure's abatement was reduced from -0.4 t CO_2e ha^{-1} to -0.1 t CO_2e ha^{-1} and -0.01 t CO_2e ha^{-1}, in the 2008 and 2010 MACCs, while the latter was estimated to be -0.3 t CO_2e ha^{-1}. However, part of this latter mitigation effect arises from delaying autumn to spring application, which is not relevant to MM2, and the rest of the effect is only marginally additional to the mitigation from *Full allowance of manure N*. The combined N reduction from MM2 and MM3 was estimated to be -14.4 kg N ha^{-1}, from in the French MACC Pellerin *et al.* (2013). Therefore, taking a value between the 2010 Optimistic and Pessimistic estimate of *Full allowance of manure N*, this report assumed that 10 kg N ha^{-1} synthetic N savings can be implemented, corresponding to 0.06 t CO_2e ha^{-1} y^{-1} GHG mitigation on average in the UK.

ii. MM3: To calculate the effect of reduced NH_3 volatilisation we reduced the volatilisation factor ($Frac_{GASM}$) by 50% to 0.1, taking the central value from (Weiske *et al.* 2006). Additionally, we accounted for the increased amount of available N by reducing the synthetic N rate by 10 kg N ha^{-1}, as a central value between the Defra fertiliser recommendation (Defra 2011b) and Olesen *et al.* (2004).

iii. MM4: based on the Expert Workshop discussion, we estimated the effect of this measure as a 50 kg N ha^{-1} reduction in synthetic N use (see Appendix C). This value is inclusive of the increased synthetic N replacement value of the manure and the changes in the emissions from manure storage and soil application. The abatement rate is 0.25 t CO_2e ha^{-1} y^{-1} on average in the UK, five times more than estimated in Moran *et al.* (2008). Since that estimate was a result of a rapid elicitation, and is only partly relevant to this measure, the current study used the values of the Workshop.

4.2.4 Current and additional future uptake

There has been considerable advisory effort made over the last 25 years to improve the utilisation of manure N in order to reduce ground and surface water pollution, particularly in Nitrate Vulnerable Zones (NVZs). Hence many farmers are making effective use of manure N. However, a large scope for improvement still exists.

i. MM2: In England, 33% of the land area where manure is applied is managed without having the manure tested before use (Defra 2015a). By farm type the proportions are 57-69% of grazing livestock farms and 12-24% of other farms. Based on these data we assumed that the current uptake of manure testing is 85% on tillage land and 40% on grassland. Regarding manure management plans the English statistics show that 76% of the farmed area where manure is used has manure management plans, with 58-62% of grazing livestock farms and 78-91% of other farms (Defra 2015a). Based on these data we estimated that the current uptake of manure management plan is 80% on tillage land and 60% on grassland. Expecting no increase of these values in the future reference, the maximum additional future uptake is 20% and 40% for tillage land and grassland, respecctively.

ii. MM3: The majority of cattle and pig slurry in Great Britain was applied by broadcast spreading rather than band spreading or injection: 82% and 61%, respectively (Defra 2013b). Using the weighted average of slurry volumes, (49% cattle slurry, 3% pig slurry in Great Britain (Defra 2013b)), we assumed that 81% of the slurry is broadcast spread in the UK, i.e. the current uptake of band spreading and injection together is 19%. Similarly, the larger proportion of farm yard manure (FYM) spread on tillage land (71%) is incorporated beyond 24 hours after spreading or never incorporated at all in Great Britain (Defra 2013b). Converting these values to grassland and tillage land applications we assumed maximum additional future uptake rates for low emission slurry and FYM spreading technologies in the UK of 74% and 56% on tillage land and grassland, respectively.

iii. MM4: This practice is already widely adopted, as can be deduced from the BSFP (Defra 2013b). 2% of cattle slurry, 3% of cattle FYM, 10% of pig slurry and 23% of pig FYM application could be improved, i.e. overall 94% of cattle and pig manure is applied in the proper season in Great Britain.

This 6% maximum additional future uptake (in terms of manure volume) can happen on tillage land, which gets 22% of the manure volume (calculated from BSFP data (Defra 2013b)). Therefore the maximum additional future uptake is 28% (6%/22%=28%) and 0% on tillage land and grassland, respectively.

4.2.5 Cost

The cost of the measure is calculated considering the nutrient savings (based on the reduction in N fertiliser use) and the cost of the various actions and equipment required for the farm actions.

The costs of MM2 are approximated based on literature data (Table 15). The cost of preparing the manure management plan is based on Crabtree *et al*. (2008) at $£_{2014}$1.60 ha^{-1}. The same authors also found that the change in manure spreading increases the manure spreading costs (even though the same equipment was used). They reported an increase in spreading costs of $£_{2014}$14 ha^{-1}. However, this cost can be considered as proportional to the improvement in manure use and the related fertiliser costs savings, which they found to be three times higher ($£_{2014}$25 ha^{-1}) than in our calculations ($£_{2014}$8 ha^{-1}), therefore we estimated the spreading cost as $£_{2014}$4.70 ha^{-1}.

The literature reviewed shows that the additional cost of low volatilisation fertiliser spreading (MM3) is in the range of $£_{2014}$0.04 ha^{-1} and $£_{2014}$100 ha^{-1}. We used a value of $£_{2014}$20 ha^{-1}, based on the UK study (Webb *et al.* 2010).

Based on the two report reviewed, we assume that the implementation of MM4 bears no additional cost to the farmer (it is important to note that we assumed that winter varieties are not replaced by spring varieties). However, it is possible that on some farms the extension of manure storage capacity is needed to implement this measure, and/or time constraints in spring might cause slightly suboptimal timing of other operations, offsetting some of the benefits from reduced organic fertiliser costs.

Table 20 Data from literature on costs of manure management

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
MM2: Overall costs	£0 ha^{-1}	UK	2008	(Moran *et al.* 2008)
MM2: Manure management plan preparation	£1.37 ha^{-1} (SD £2.03 ha^{-1}), range £0.00 - £7.50 ha^{-1})	UK	2008	(Crabtree *et al.* 2008)
MM2: Additional spreading cost	£11.90 ha^{-1} (SD £10.89 ha^{-1}), range £0.00 - £42.70 ha^{-1})	UK	2008	(Crabtree *et al.* 2008)
MM2: Fertiliser savings	- £22.20 ha^{-1} (SD £25.90 ha^{-1}), range - £112.60 - £0.00 ha^{-1})	UK	2008	(Crabtree *et al.* 2008)

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
MM2: Change in output	- £10.00 ha^{-1} (SD £40.00 ha^{-1}), range - £160.00 - £0.00- ha^{-1})	UK	2008	(Crabtree *et al.* 2008)
MM2: Fertiliser savings	-£9.40 ha^{-1}	France	2010	(Pellerin *et al.* 2013)
MM3: Additional spreading cost	£0.50 – £1.00 m^{-3} slurry (~ £20-40 ha^{-1} with 100 kg N ha^{-1} application rate and N content 2.6 kg N m^{-3} slurry)	Ireland	2012	(Schulte *et al.* 2012)
MM3: Additional spreading cost	£0.52 m^{-3} slurry (~ £20 ha^{-1} with 100 kg N ha^{-1} application rate and N content 2.6 kg N m^{-3} slurry)	UK	2010	(Webb *et al.* 2010)
MM3: Additional spreading cost	£1.40 ha^{-1}	France	2010	(Pellerin *et al.* 2013)
MM3: Additional spreading cost	£0.04 - £2.48 m^{-3} slurry (~ £2-100 ha^{-1} with 100 kg N ha^{-1} application rate and N content 2.6 kg N m^{-3} slurry)	Germany	2011	As cited in (Frelih-Larsen *et al.* 2014)
MM3: Fertiliser savings	-£8.00 ha^{-1}	France	2010	(Pellerin *et al.* 2013)
MM4: Additional storage and spreading costs	£0 (the change not increased costs on the farms in the sample)	UK	2008	(Crabtree *et al.* 2008)
MM4: Additional storage and spreading costs	£0	France	2010	(Pellerin *et al.* 2013)

4.2.6 Cost-effectiveness and abatement potential

The abatement potential of measure MM2 (*Improving organic N planning*), without interactions and assuming CFP uptake for the UK was 32 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), with cost-effectiveness of -£26 t CO_2e^{-1}. MM3 (*Low emission manure spreading*) had a respective abatement potential of 110 kt CO_2e y^{-1} with cost-effectiveness of £110 t CO_2e^{-1} (which is below the 2035 C price £114 t CO_2e^{-1}). Finally, MM4's (*Shifting autumn manure application to spring*) abatement potential was 38 kt CO_2e y^{-1} with cost-effectiveness of -£155 t CO_2e^{-1}. The abatement potential and cost-effectiveness in the four DAs are detailed in Table 21.

The UK abatement potential of MM2 (without interactions, d.r. 3.5%) increases from 13 kt CO_2e y^{-1} with the low feasible potential to 71 kt CO_2e y^{-1} assuming the maximum technical potential in 2035. The abatement potential of MM3 and MM4, respectively, changes from 17 to 245 kt CO_2e y^{-1} and 15 to 85 kt CO_2e y^{-1} with the same assumptions.

Table 21 MM2, MM3, MM4 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	MM2		MM3		MM4	
	AP	CE	AP	CE	AP	CE
	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}
UK	32	-26	110	110	38	-155
England	21	-26	79	108	32	-155
Wales	5	-25	12	118	1	-212
Scotland	4	-26	15	108	5	-147
Northern Ireland	2	-25	5	110	0	-150

Table 22 MM2, MM3, MM4 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r. %	MM2				MM3				MM4			
		LFP	CFP	HFP	MTP	LFP	CFP	HFP	MTP	LFP	CFP	HFP	MTP
2030	3.5	10	24	45	53	13	83	156	184	11	29	58	63
2035	3.5	13	32	60	71	17	110	208	245	15	38	78	85
2030	7.0	10	24	45	53	13	83	156	184	11	29	58	63
2035	7.0	13	32	60	71	17	110	208	245	15	38	78	85

The sensitivity analysis of MM2 demonstrated that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 16 and 48 kt CO_2e y^{-1}; this analysis involved changing the assumptions on uptake, change in synthetic N use, cost of nutrient planning advice, cost of additional spreading and fertiliser price (Table 24). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£65 and £80 t CO_2e^{-1} for the respective cases.

As expected, changes in the maximum additional future uptake linearly changed the UK abatement potential. If the eventual savings in synthetic N use was only half of the original assumption the abatement potential dropped by 50% and the cost-effectiveness became positive (£80 t CO_2e^{-1}), though still below the 2035 C price. If the synthetic N use savings increased by 50% so did the abatement potential, and the farmers' savings increased. Increasing the cost of nutrient planning advice or the cost of additional spreading by 50% or decreasing the N fertiliser price by 20% worsened the cost-effectiveness of the measure, though not as much as the reduction in N savings (the highest CE is £13 t CO_2e^{-1} amongst these assumptions).

Table 23 Sensitivity of MM2 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Maximum additional future uptake	Tillage land: 0.2 Grassland: 0.4	Tillage land: 0.1 Grassland: 0.3	23	-26
Maximum additional future uptake	Tillage land: 0.2 Grassland: 0.4	Tillage land: 0.3 Grassland: 0.5	41	-26

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Change in synthetic N use (kg N ha^{-1})	-10	-5	16	80
Change in synthetic N use (kg N ha^{-1})	-10	-15	48	-61
Cost of nutrient planning advice (£ ha^{-1})	1.6	2.4	32	-13
Cost of nutrient planning advice (£ ha^{-1})	1.6	0.8	32	-39
Cost of additional spreading (£ ha^{-1})	4.7	7.05	32	13
Cost of additional spreading (£ ha^{-1})	4.7	2.35	32	-65
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 620 Grassland: 628	32	0
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 929 Grassland: 942	32	-52

The sensitivity analysis of MM3 presented the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varying between 82 and 139 kt CO_2e y^{-1}; this analysis involved changing the assumptions on uptake, change in synthetic N use, change in the reduction in the fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x, cost of spreading equipment and fertiliser price (Table 24). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) ranged from £19 to £200 t CO_2e^{-1} for the respective cases.

The UK abatement potential increased linearly with the uptake. 50% lower reduction in synthetic N use decreased the abatement potential by 25% and increased the cost-effectiveness to £196 t CO_2e^{-1}. The cost of spreading equipment also had a big effect on the cost-effectiveness, with a 50% higher cost the cost-effectiveness becomes £200 t CO_2e^{-1}, and with a 50% lower cost it drops to £19 t CO_2e^{-1}. The fertiliser price had a much smaller effect on the cost-effectiveness. Finally, if $Frac_{GASM}$ improved not by 50% but only 40%, the abatement potential dropped by 10% and the cost-effectiveness increased by 10%.

Table 24 Sensitivity of MM3 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Maximum additional future uptake	Tillage land: 0.74 Grassland: 0.56	Tillage land: 0.64 Grassland: 0.46	93	109
Maximum additional future uptake	Tillage land: 0.74 Grassland: 0.56	Tillage land: 0.84 Grassland: 0.66	128	110
Change in synthetic N use (kg N ha^{-1})	-10	-5	82	196
Change in synthetic N use (kg N ha^{-1})	-10	-15	139	59
Change in $Frac_{GASM}$	-50%	-40%	100	121

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Change in $Frac_{GASM}$	-50%	-60%	121	100
Cost of spreading (£ ha^{-1})	20	30	110	200
Cost of spreading (£ ha^{-1})	20	10	110	19
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 620 Grassland: 628	110	124
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 929 Grassland: 942	110	95

The sensitivity analysis of MM4 showed that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 19 and 55 kt CO_2e y^{-1}; this analysis involved changing the assumptions on uptake, change in synthetic N use, cost of nutrient planning advice, cost of additional spreading and fertiliser price (Table 25). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£186 and -£115 t CO_2e^{-1} for the respective cases.

The abatement potential in the UK increased linearly with the uptake and the reduction in synthetic N use. The effect of increasing the cost of spreading or storage by 5 or 10 £ ha^{-1} diminished by the large per ha savings in N use, while the ±20% change in fertiliser price changed the cost-effectiveness by the same proportion. In all cases the cost-effectiveness remained negative.

Table 25 Sensitivity of MM4 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Maximum additional future uptake	Tillage land: 0.28 Grassland: 0	Tillage land: 0.18 Grassland: 0	25	-155
Maximum additional future uptake	Tillage land: 0.28 Grassland: 0	Tillage land: 0.38 Grassland: 0	52	-155
Change in synthetic N use (kg N ha^{-1})	-50	-25	19	-155
Change in synthetic N use (kg N ha^{-1})	-50	-75	55	-162
Cost of additional spreading (£ ha^{-1})	0	10	38	-115
Cost of additional spreading (£ ha^{-1})	0	5	38	-135
Cost of additional storage (£ ha^{-1})	0	10	38	-115
Cost of additional storage (£ ha^{-1})	0	5	38	-135
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 620 Grassland: 628	38	-124
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 929 Grassland: 942	38	-186

4.2.7 Discussion

A careful interpretation is needed when comparing mitigation measures between studies, notably with measures which can refer to a different combination of actions on farm, as is the case with manure management mitigation measures. Based on the detailed description of the mitigation measures in the relevant studies (Table 134), MM2 (*Improving organic N planning*) seemed to encompass the 2008 and 2010 MACC measure *Full allowance of manure N* and the FARMSCOPER measures *Integrate fertiliser and manure nutrient supply*, *Do not spread FYM to fields at high-risk times* (MacLeod *et al.* 2010c, Moran *et al.* 2008, Newell-Price *et al.* 2011). MM2 also overlapped with the FARMSCOPER measure *Do not spread slurry or poultry manure at high-risk time*, though this measure also partially related to MM4 (*Shifting autumn manure application to spring*).

The abatement potential of the FARMSCOPER measure *Integrate fertiliser and manure nutrient supply* in the English agriculture was estimated to be 80 kt CO_2e y^{-1} at a cost-effectiveness of -£1,726 t CO_2e^{-1}, with an additional 260 and 180 kt CO_2e y^{-1} to be provided, respectively, by the measures *Do not spread slurry or poultry manure high-risk times* and *Do not spread FYM to fields at high-risk times*, both at zero cost (Gooday *et al.* 2014). These are much higher than estimated here (21 kt CO_2e y^{-1} for England). Unfortunately available reports were not sufficient to explore the underlying reasons behind the difference.

The abatement potential for the UK of the measure *Full allowance of manure N* (without interactions, 2022, CFP, d.r. 7%) was 1386, 153 and 8 kt CO_2e y^{-1}, respectively, in the 2008, 2010 Optimistic and 2010 Pessimistic MACC. The result in the current study fell in the lower part of this range (UK abatement potential 32 kt CO_2e y^{-1}). The assumptions on the abatement rate and the applicability are the most important factors in these differences. In the 2008 MACC the abatement estimated was 0.4 t CO_2e ha^{-1} y^{-1}, in the 2010 Optimistic and 2010 Pessimistic MACCs the respective values were 0.1 and 0.01 t CO_2e ha^{-1} y^{-1}. In the current assessment the assumed 10 kg N ha^{-1} y^{-1} saving corresponded to 0.06 t CO_2e ha^{-1} y^{-1} GHG mitigation on average in the UK. The applicability and uptake assumptions in the four MACCs were different as well: highest in the 2008 MACC (45% on tillage land and 80% on grassland), and lowest in the current study, where the applicability (1/4 of the tillage area and 1/3 of the grasslands receive organic N) and maximum additional future uptake assumptions (20% on tillage land and 40% on grassland) resulted in an MTP implementation of 5% tillage land and 13% grassland. The cost-effectiveness of the measure in the 2008 and 2010 Optimistic MACCs were negative, while the 2010 Pessimistic MACC estimated the net cost to be £11.66 ha^{-1}, leading to a cost-effectiveness of £1,166 t CO_2e^{-1}.

MM3 (*Low emission manure spreading*) was not included in either the 2008 or the 2010 MACCs, however, on the medium list of the 2008 MACC a measure on low emission manure and synthetic N spreading (*Placing N precisely in soil*) were featured with an estimated 0.05 t CO_2e ha^{-1} y^{-1} abatement rate – the abatement arising from the reduction in $Frac_{GASM}$ and synthetic N use gave an average UK abatement rate of 0.11 t CO_2e ha^{-1} y^{-1}. MM3 can be compared to the

FARMSCOPER measure *Use slurry injection application techniques* as well, which could provide 20 kt CO_2e y^{-1} abatement in England – ¼ of what the current study estimated (again, a more in-depth comparison was not possible within the current study).

MM4 (*Shifting autumn manure application to spring*) did not have a matching measure in the 2008 and 2010 MACCs either, though it overlapped with the FARMSCOPER measure *Do not spread slurry or poultry manure at high-risk time*. While MM4 relates to all types of manures, the FARMSCOPER measure included only slurry and poultry manure, on the other hand, the latter also accounted for better timing of the manure spreading relating to weather and soil moisture conditions. The abatement potential of the FARMSCOPER measure for England was 260 kt CO_2e y^{-1} (cost-effectiveness £0 t CO_2e^{-1}), substantially higher than the estimate here (32 kt CO_2e y^{-1} in England, cost-effectiveness -£155 t CO_2e^{-1}). A similar measure existed also on the 2008 MACC medium list: *Changing from winter to spring cultivars*, with the difference that that measure assumed a change in cropping practice to allow shifting the manure application on larger areas. The estimated abatement rate in the 2008 MACC for this measure was 0.05 t CO_2e ha^{-1} y^{-1}, while the average UK abatement rate in the current study was 0.25 t CO_2e ha^{-1} y^{-1}.

4.3 MM5: Catch/cover crops

4.3.1 Description of the measure

Catch/cover crops are crops sown after harvest of cereals, OSR and other arable crops harvested in late summer. Catch/cover crops may be grown to reduce the risk of nitrate leaching over winter, reduce the risk of soil erosion, improve soil structure, increase carbon sequestration and provide a source of N to the subsequent spring-sown crop. Their growth in the early autumn recovers residual N from cultivation of the recently-harvested crop. These crops are then incorporated in prior to the establishment of spring-sown crops.

4.3.2 Applicability

Catch/cover crops need to be sown in late summer or very early autumn if they are to establish successfully and provide effective ground cover. They are most applicable to light to medium textured and free draining soils. Such soils enable better germination and growth and there is less chance of soil damage in spring from the incorporation of the crop. According to Graves *et al.* (2011) 34% of arable crops are cultivated on sandy or silty soils in England and Wales. Catch/cover crops are applicable to areas with spring-sown crops: potatoes, sugar beet, peas and beans, spring-sown cereals, spring OSR, maize, other fodder and horticultural crops. The applicability value is set to 34% for these crops and 0% for the other crops.

4.3.3 Abatement rate

Abatement data from the literature is presented in Table 26. Authors have different opinions regarding the origin of the mitigation effect, and their relative importance, in relation to the reduction in N applied, reduction in the proportion of N leached and increase in soil carbon stocks. Based on a recent study for the UK by Wiltshire (2014), we assume that the mitigation effect is due to reduced leaching, and taking the central value from that study FracLeach is reduced by 45%, i.e. from the default 0.30 to 0.165.

Table 26 Data from literature on abatement by catch/cover crops

Abatement	Value	Country	Reference
N use	No impact as no reduction in N fertiliser use is recommended in RB209 following cover crops	UK	(Defra 2011b)
N use	-11 kg N ha^{-1} in N use	France	(Pellerin *et al.* 2013)
Reduction in FracLeach	Compared with over-winter fallow can reduce nitrate leaching by 30-60%	UK	(Wiltshire 2014)
Soil N_2O	-0.1 t CO_2e ha^{-1}	UK	(Moran *et al.* 2008)
Soil N_2O	-0.49 t CO_2e ha^{-1}	Ireland	(Schulte *et al.* 2012)
Soil C	-0.48 – -1.26 t CO_2e ha^{-1}	France	(Pellerin *et al.* 2013)
Soil C	No net addition of soil C	UK	(Wiltshire 2014)

4.3.4 Current and additional future uptake

Without any information from the literature, a current uptake of 30% is estimated. Expecting no increase of this value in the future reference, the assumed maximum additional future uptake is 70%.

4.3.5 Cost

Cost data from the literature is presented in Table 27. Based on these data in this report we assumed that seed costs, cultivation costs and termination costs are £60, £25 and £30 ha^{-1} y^{-1}, respectively.

Table 27 Data from literature on costs/benefits of catch/cover crops

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Total of reduced fertiliser purchase, cover crop planting and destruction (average of 3 sub-measures, not all require planting)	£30 ha^{-1} y^{-1}	France	2010	(Pellerin *et al.* 2013)
Total of reduced fertiliser purchase, cover crop planting and destruction	£51 ha^{-1} y^{-1}	Ireland	2005	(Schulte *et al.* 2012), based on (O'Keeffe et al 2005)

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Annual cost of cover crop establishment (£/ha)	median £207.50 lower £100.00 upper £315.00	UK	Various	Wiltshire (2014), based on earlier works including (Cuttle *et al.* 2006) and (Nix 2008)
Seed (barley as cover crop)	£55 ha^{-1} y^{-1}	UK	Various	(Posthumus *et al.* 2013), based on (Cuttle *et al.* 2006) and (Nix 2008)
Cultivation cost of establishing the cover crop (fuel & machinery use)	£60 ha^{-1} y^{-1}			
Cover crop termination	£25 ha^{-1} y^{-1}			
Loss of production (if switching from winter to spring cultivars)	£175 ha^{-1} y^{-1}			
Seed (grass, under-sown to maize)	£50 ha^{-1} y^{-1}	UK	2009	(Posthumus *et al.* 2013), based on (Cuttle *et al.* 2006) and (Nix 2008)
Cultivation cost of establishing the cover crop (fuel & machinery use)	£0 ha^{-1} y^{-1}			
Cover crop termination	£25 ha^{-1} y^{-1}			
Seed (barley)	£50 ha^{-1} y^{-1}	UK	2006	(Cuttle *et al.* 2006)
Cultivation cost of establishing the cover crop (fuel & machinery use)	£17.5 ha^{-1} y^{-1}			

4.3.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 16 kt CO_2e y^{-1} in 2035, d.r. 3.5% (Table 28). The cost-effectiveness of the measure without interactions was between £1,140 and £1,246 t CO_2e^{-1} (which is well above the C price). Table 29 presents how the UK abatement potential changed with the different uptake scenarios and between 2030 and 2035.

Table 28 MM5 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential	Cost-effectiveness
	kt CO_2e y^{-1}	£ t CO_2e^{-1}
UK	16	1,226
England	12	1,223
Wales	1	1,140
Scotland	4	1,246
Northern Ireland	0	1,229

Table 29 MM5 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	2	12	25	27
2035	3.5%	3	16	34	37
2030	7.0%	2	12	25	27
2035	7.0%	3	16	34	37

The abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 12 and 21 kt CO_2e y^{-1} in the sensitivity analysis while changing the assumptions on applicability, uptake, change in $Frac_{LEACH}$, costs and fertiliser price (Table 30). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between £906 and £1,576 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the uptake, applicability and change in $Frac_{LEACH}$. The cost-effectiveness could be somewhat improved with decreasing costs, but still remained very high.

Table 30 Sensitivity of MM5 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Applicability	Spring crops: 0.34 Other crops: 0	Spring crops: 0.24 Other crops: 0	12	1,226
Applicability	Spring crops: 0.34 Other crops: 0	Spring crops: 0.44 Other crops: 0	21	1,226
Maximum additional future uptake	0.7	0.6	14	1,226
Maximum additional future uptake	0.7	0.8	19	1,226
Change in $Frac_{LEACH}$	-45%	-35%	13	1,576
Change in $Frac_{LEACH}$	-45%	-55%	20	1,003
Cost of seed (£ ha^{-1})	60	90	16	1,545
Cost of seed (£ ha^{-1})	60	30	16	906
Cost of cultivation (£ ha^{-1})	25	37.5	16	1,359
Cost of cultivation (£ ha^{-1})	25	12.5	16	1,092
Cost of cover crop termination (£ ha^{-1})	30	45	16	1,386
Cost of cover crop termination (£ ha^{-1})	30	15	16	1,066

4.3.7 Discussion

This measure was not included in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008), though its abatement rate was estimated in the 2008 MACC (medium list) to be 0.1 t CO_2e ha^{-1} y^{-1} – very similar to the average value calculated in the current study (UK average 0.094 t CO_2e ha^{-1} y^{-1}). The FARMSCOPER measure *Establish cover crops in the autumn* for England is 100 kt CO_2e y^{-1} (cost-effectiveness £420 t CO_2e^{-1}) (Gooday *et al.* 2014), ten times higher than the English abatement potential results of the current study (again, more detailed comparison was not possible).

The high per ha net costs (£115 ha^{-1} y^{-1}), even with relatively high per ha abatement, making the measure unattractive from a pure GHG perspective. However, financial benefits not included in the current study can occur on farms, most importantly long term improvement in soil fertility, avoided erosion and also a potential for reducing the N use on the subsequent crop and the opportunity to use the cover crop as livestock feed (e.g. ryegrass). More importantly, the soil and water quality benefits (Wiltshire 2014) and soil C sequestration (Poeplau and Don 2015) would justify the application of this measure in certain areas.

4.4 MM6: Controlled release fertilisers

4.4.1 Description of the measure

Controlled-release fertilisers are products that are intended to match nutrient release with crop demand by providing readily available N more slowly than conventional fertilisers (over the course of 2-6 months). Thus the pool of mineral-N in soil which may be used as a microbial substrate for nitrification and denitrification is reduced. The controlled release is achieved by coating the fertiliser prill with a material that slowly breaks down thereby delaying the availability of the N to crops and microbes. The objective, with respect to reducing GHG emissions, is to reduce N_2O emissions (Frelih-Larsen *et al.* 2014).

4.4.2 Applicability

The measure is applicable everywhere where synthetic N is applied. However, due to the low fertilisation rate of permanent grasslands we excluded those land areas. Allowing for agronomic and practical difficulties of the use of nitrification inhibitors, we assumed that the applicability is 70% on those tillage land and temporary grassland which receives synthetic N. Application could be made using the same equipment as for conventional fertilisers but may require a small adjustment to the timing of application.

4.4.3 Abatement rate

Li *et al.* (2013) reviewed the effectiveness of polymer-coated fertilisers (PCFs) and found that on average N_2O abatement of 35% was achieved. However, Jiang *et al.* (2010) measured N_2O emissions from N fertilisers coated with sulphur and with a potassium/magnesium/phosphorus coating, and observed no reduction in N_2O emissions.

Oenema *et al.* (2014), in a review of GHG mitigation options, considered CRFs could reduce N_2O emissions by up to 40%. Norse (2012) indicated that N_2O emissions may be reduced by c. 50% compared with the use of conventional N fertilisers. A meta-analysis indicated that the mean emission reduction of polimer-coated fertilisers is 35%, with a CI of 58% to 14% (Akiyama *et al.* 2010).

There is considerable overlap between this potential measure and the option of using nitrification inhibitors. Both measures are intended to reduce emissions of N_2O and both would do so by reducing the pool of mineral N available for nitrification and denitrification. Controlled-release N fertilisers act by physical reduction of the rate of dissolution of N fertiliser into the soil solution whereas nitrification inhibitors act by inhibiting the activity of the bacteria that oxidise ammonium ions to nitrate. Despite the difference in mechanisms it is unlikely both measures would be applied together and any abatement achieved as a result of the introduction of one of these measures would need to be deducted from the potential abatement that might be achieved by the introduction of the second measure.

4.4.4 Current and additional future uptake

Currently CRFs are used only to a very limited extent, and there is no prospect of their increased uptake in the future reference scenario, therefore the maximum additional future uptake is 1.

4.4.5 Cost

Controlled-release fertilisers have been available for decades but remain too expensive to be used on field crops (Norse 2012). The only crops for which these fertilisers have been adopted by commercial growers are container-grown nursery stock. Norse (2012) reported that recent developments have reduced the additional cost of controlled-release N fertilisers to only 5-10% more than conventional N fertiliser types. Here we assumed that the N cost would increase with 20%, on average by £14 ha^{-1} y^{-1}.

4.4.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake in the UK is 654 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 522, 20, 95 and 17 kt CO_2e y^{-1} in England, Wales, Scotland and Northern Ireland, respectively (Table 31). The UK abatement potential (without interactions, d.r. 3.5%) increases from 102 kt CO_2e y^{-1} with the low feasible potential to 1,454 kt CO_2e y^{-1} maximum technical potential in 2035, and from 76 to 1,090 kt CO_2e y^{-1}, respectively, in 2030 (Table 139). In all of the above cases the UK average cost-effectiveness of the measure without interactions is £37 t CO_2e^{-1} (below the C price).

Table 31 MM6 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	654	37
England	522	36

Country	Abatement potential	Cost-effectiveness
	kt CO_2e y^{-1}	£ t CO_2e^{-1}
Wales	20	40
Scotland	95	42
Northern Ireland	17	46

Table 32 MM6 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	76	491	1,003	1,090
2035	3.5%	102	654	1,337	1,454
2030	7.0%	76	491	1,003	1,090
2035	7.0%	102	654	1,337	1,454

The sensitivity analysis showed that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varies between 467 and 841 kt CO_2e y^{-1} when changing the assumptions on applicability, change in EF_1 and price premium paid for the fertiliser (Table 140). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between £18 and £55 t CO_2e^{-1}. The abatement potential increases linearly with the applicability and the reduction in EF_1. The cost-effectiveness was reduced to £29 t CO_2e^{-1} with a 10% higher GHG mitigation efficacy and dropped to £18 t CO_2e^{-1} a 50% reduction in the price premium. As the assumption was that the amount of N applied did not change, the cost-effectiveness was not sensitive to the average fertiliser price.

Table 33 Sensitivity of MM6 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Applicability	Tillage land: 0.7 Temporary grassland: 0.7 Permanent grassland: 0	Tillage land: 0.6 Temporary grassland: 0.6 Permanent grassland: 0	561	37
Applicability	Tillage land: 0.7 Temporary grassland: 0.7 Permanent grassland: 0	Tillage land: 0.8 Temporary grassland: 0.8 Permanent grassland: 0	748	37
Change in EF_1	-35%	-25%	467	52
Change in EF_1	-35%	-45%	841	29
Price premium for CRF (£ ha^{-1})	14	21	654	55
Price premium for CRF (£ ha^{-1})	14	7	654	18

4.4.7 Discussion

Previous estimates in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008) suggested a higher abatement at a higher cost-effectiveness: the UK abatement potential was (without interactions, 2022, CFP, d.r. 7%) 1.1 Mt

CO_2e y^{-1} with a cost-effectiveness of £152 t CO_2e^{-1} in those studies. The lower abatement found in the current study is due to a lower applicability (70% on fertilised tillage land and temporary grassland which receives synthetic N and 0% on permanent grassland, instead of 80-91% on tillage land and 58% on temporary and permanent grassland in the previous studies), even though the abatement rate is slightly higher in the current study (0.32 and 0.39 t CO_2e ha^{-1} y^{-1}, respectively, on temporary grassland and tillage land, versus 0.3 t CO_2e ha^{-1} y^{-1} in the 2008 and 2010 MACCs). The area based cost of the measure was estimated to be higher in the earlier studies, a 50% price premium on the fertiliser reduced by a 2% yield increase resulted in £46 ha^{-1} cost, while the corresponding value in the current study was £14 ha^{-1}.

4.5 MM7: Plant varieties with improved N-use efficiency

4.5.1 Description of the measure

This measure requires new crop varieties that either provide at least the same yield as those currently in use but require less N fertiliser or give greater yields without the need for increased N inputs. Such an approach is based on the evidence of the increased yield potential that has taken place over the last 30 years. Sylvester-Bradley *et al.* (2009) reported the optimum yield of 'new' varieties of spring barley, at 6.0 t ha^{-1}, was c. 1 t ha^{-1} greater than that of 'old varieties, but nitrogen use efficiency (NUE) had increased and hence the requirement for N fertiliser had increased by a smaller proportion than the increase in yield. If new varieties of other crops can be grown that combine greater yield with increased NUE then less N fertiliser will be needed to maintain current outputs.

4.5.2 Applicability

Providing appropriate new crop cultivars can be bred, and so long as there are no significant barriers to uptake by farmers, then improved varieties could be grown by all farmers. However, we assumed that this measure is not applicable on permanent grassland, due to the requirement of reseeding (however, even on permanent grassland improved N-use varieties can be introduced when the sward is renewed). Assuming that a proportion of farmers won't find suitable new low N use varieties for their purposes, we assumed that the applicability is 70% on tillage land and temporary grassland.

4.5.3 Abatement rate

Abatement data from the literature is presented in Table 34. We assumed that the N fertiliser requirement will decrease by 20% (mean of pessimistic and optimistic value in (MacLeod *et al.* 2010c)) with the yield maintained. In reality a combination of increased yield and decreased N is likely to happen, or, in some cases increased N application with an even higher yield increase is also possible (i.e. increasing absolute GHG emissions but improving emission intensity), as it happened with wheat varieties between the 1980s and the 2000s (Sylvester-Bradley and Kindred 2009).

Table 34 Data from literature on abatement by plant varieties with improved N use

Abatement	Value	Country	Reference
N use	-30% N use	UK	(Moran *et al.* 2008)
N use	Pessimistic (optimistic in brackets): It would take 15 (10) years to achieve a 10% (30%) reduction in fertiliser use	UK	(MacLeod *et al.* 2010c)
Soil N_2O	-528 kt CO_2e	UK	(Defra 2012a)
Soil N_2O	-500 kt CO_2e	UK	(Gooday *et al.* 2014)

4.5.4 Current and additional future uptake

Hitherto plant breeding has not focussed on improving NUE (Gooday *et al.* 2014) and so the current uptake is assumed to be zero. Farmers have shown a willingness to adopt new varieties where these offer advantages such as increased yield and are likely to adopt varieties bred to increase NUE and can offer either greater yields or a reduce requirement for N fertiliser. Hence the maximum additional future uptake is 100%.

This measure requires establishing new breeding goals and the development of breeding programmes before improved N-use varieties can be available to farmers. This significant lead-up time has to be considered when developing policy instruments and accounting for the timing of the mitigation effects. To reflect this, the additional uptake is assumed to start only from 2025 reaching a maximum additional uptake in 2045, as opposed to the other measures where uptake starts increasing in 2015 with a maximum in 2020.

4.5.5 Cost

The cost of this measure is zero for the farmers, assuming that the improved N-use varieties will be available at the same price as the other varieties, even though some authors estimate that there will be a price premium for the new varieties (MacLeod *et al.* 2010c). Financial benefits are provided by the N savings.

4.5.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 166 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 134, 5, 23 and 4 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 35). The UK abatement potential (without interactions, d.r. 3.5%) increased from 66 kt CO_2e y^{-1} with the low feasible potential to 368 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 33 to 184 kt CO_2e y^{-1}, respectively, in 2030 (Table

36). In all of the above cases the UK average cost-effectiveness of the measure without interactions was -£139 t CO_2e^{-1}.

Table 35 MM7 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt $CO_2e\ y^{-1}$	Cost-effectiveness £ t CO_2e^{-1}
UK	166	-139
England	134	-132
Wales	5	-184
Scotland	23	-165
Northern Ireland	4	-180

Table 36 MM7 abatement potential without interactions (kt $CO_2e\ y^{-1}$, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	33	83	169	184
2035	3.5%	66	166	339	368
2030	7.0%	33	83	169	184
2035	7.0%	66	166	339	368

The sensitivity analysis demonstrated that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 83 and 249 kt $CO_2e\ y^{-1}$; this analysis involved changing the assumptions on applicability, change in synthetic N use, cost of the seeds of the new varieties (Table 37). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£167 and -£78 t CO_2e^{-1}. The abatement potential increased linearly with the uptake and the reduction in synthetic N use. The cost-effectiveness was not affected by the N use assumption but declined with the assumption that seeds of the new varieties cost more than traditional seeds and with decreasing N fertiliser price. However, in all cases the cost-effectiveness was negative.

Table 37 Sensitivity of MM7 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt $CO_2e\ y^{-1}$	Cost-effectiveness £ t CO_2e^{-1}
Maximum additional future uptake	Tillage land: 0.7 Temporary grassland: 0.7 Permanent grassland: 0	Tillage land: 0.6 Temporary grassland: 0.6 Permanent grassland: 0	142	-139
Maximum additional future uptake	Tillage land: 0.7 Temporary grassland: 0.7 Permanent grassland: 0	Tillage land: 0.8 Temporary grassland: 0.8 Permanent grassland: 0	189	-139
Change in synthetic N use	-20%	-10%	83	-139
Change in synthetic N use	-20%	-30%	249	-139
Price premium for seeds (£ ha^{-1})	0	10	166	-78

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Price premium for seeds (£ ha^{-1})	0	5	166	-109
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 620 Grassland: 628	166	-111
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 929 Grassland: 942	166	-167

4.5.7 Discussion

This mitigation measure was included in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008) and in the FARMSCOPER studies (Gooday *et al.* 2014). The former ones identified lower UK abatement (369, 332 and 0 kt CO_2e y^{-1}, respectively, in the 2008 and 2010 Optimistic and MACC) than the FARMSCOPER study's estimate for England (500 kt CO_2e y^{-1}); the result of the current study fell in the lower range of the earlier findings (166 kt CO_2e y^{-1}). The 2010 Pessimistic MACC assumed that the GHG emissions could not be decreased by this practice (due to the unavailability of the appropriate plant varieties). In the current study the differences between the assumptions in the FARMSCOPER and the MACC studies could not be compared. The 2008 and 2010 MACCs had somewhat higher abatement rate (0.2 and 0.18 t CO_2e ha^{-1} y^{-1}, respectively) than what the 20% N reduction resulted in in the current study (0.12 and 0.18 t CO_2e ha^{-1} y^{-1}, respectively, on temporary grassland and tillage land), and the applicability of the measure was also higher on average in the UK in the earlier studies, providing a higher abatement potential in the UK.

The cost-effectiveness of the measure was -£104, -£68 and -£205 t CO_2e^{-1} in the FARMSCOPER 2008 MACC (without interactions) and 2010 MACCs (without interactions) studies, respectively. The result of the current study fell within this range (-£139 t CO_2e^{-1}). The current study estimated the net cost to be -£23 ha^{-1} y^{-1}, based on the fertiliser savings achieved. This compares to net costs (fertiliser savings) in the 2008 and 2010 Optimistic MACC of -£14 and -£39 ha^{-1} y^{-1}, respectively.

It is important to emphasise that this measure is not currently available, only if a plant breeding programme focusing on N use efficiency can be established. The breeding programme to produce improved N use plants might take 5 years, with another 5 years needed to increase awareness of the new varieties.

4.6 MM8: Legumes in rotations

4.6.1 Description of the measure

N fixing crops (legumes) form symbiotic relationships with bacteria in the soil that allows them to fix atmospheric N and use this in place of N provided by synthetic fertilisers. They are able to fix in excess of 300 kg N ha^{-1} y^{-1}, can supply N to subsequent crops, are valuable as a break crops in arable rotations and can provide biodiversity benefits (Rees *et al.* 2014). This measure is about increasing the area of grain legumes in arable rotations, thereby reducing N fertiliser use in two ways; by requiring no N fertiliser (so there will be a reduction per ha equivalent to the N fertiliser that would have been applied to the non-leguminous crop that would otherwise have been grown) and by having a residual N fertilising effect so that the crops grown after legumes require less N than when grown after non-legumes (Defra 2011b).

4.6.2 Applicability

The applicability of the measure covers all tillage land other than legumes (excluding land currently under legumes ensures that the only additionally planted legumes are included in the mitigation potential). The rotational and other constraints are dealt within the uptake (see Section 4.6.4).

4.6.3 Abatement rate

The abatement achievable is due to the change in crop areas (i.e. replacement of other arable crops with grain legumes in the rotation and applying no fertiliser on them) and a reduction in N fertiliser use of 30 kg ha^{-1} on the subsequent crop (Defra 2011b).

Table 38 Data from literature on abatement by legumes in rotations

Abatement	Value	Country	Reference
N use	-0.5 t CO_2e ha^{-1} of soil N_2O emissions	UK	(Moran *et al.* 2008)
N use	-0.5 t CO_2e ha^{-1} of soil N_2O emissions	UK	(MacLeod *et al.* 2010c)
N use	No fertiliser on the legume, -33 kg N ha^{-1} on the following crop; i.e. -0.64 t CO_2e ha^{-1} where legumes introduced (not rotation average)	France	(Pellerin *et al.* 2013)

4.6.4 Current and additional future uptake

There are several factors that limit the area of grain legumes in the UK. The frequency of legumes in the rotation depends on different factors according to the nature of the legume. For example, peas are grown only one year in 5 due to the need to reduce the risk of disease. This is less of a concern for field beans but these are harvested late and will delay sowing, and hence yield, of any subsequent cereal crop. Therefore in practice beans are also only likely to be grown one year in 5. The inclusion of peas and beans in rotations including OSR is limited to once in every 6 years, due to disease risk. Peas are unsuitable for 'heavy' soils (effectively clay loam and heavier), while beans are unsuited to light soils (sandy loam and equivalents). Therefore we limited the applicability of the grain legumes to 1/6 of the total arable crop area in any given year, i.e. 17% of it.

In the years between 2011 and 2014 field beans and peas were grown on 140-150 ha (3% of the arable crop area) in the UK – this was a fall from around 200-250 ha (4.5-5.5% of arable crop area) in the 1990's and 2000's (Defra 2014b). An additional 50-60 ha peas and beans were grown for human consumption, down from 60-70 ha in 1990's and 2000s (Defra 31072). Though we assumed that the recent introduction of Greening measures in the Common Agricultural Policy increases the area where field beans and peas are cultivated by 1.7% of the arable area (to 5%) in England and Scotland from 2015, this increase is not included in the future reference scenario, but included in the abatement of this measure. This was necessary to reconcile our results with the agricultural activity reference scenario used by the CCC for the carbon budgets. Therefore the maximum additional future uptake is 1 on all tillage land where legumes are not currently grown.

4.6.5 Cost

We estimated the cost of this measure from the difference of the gross margin in grain legumes (field beans and peas £380 ha^{-1}, (SAC 2013)) and other crops (weighted average: £809 ha^{-1}, (SAC 2013). The fertiliser savings from the reduced fertilisation of the following crop is accounted for as benefit (-£23.55 ha^{-1}). The net cost is in high contrast with the only data found in the literature, which estimates the net costs as £13.6 ha^{-1} for the area where legumes are introduced (Pellerin *et al.* 2013). This estimate consists of savings in fertilisers and their applications, elimination of tillage operation for the following crop and changes in the gross margins of the rotations.

4.6.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 435 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), with an average cost-effectiveness of £299 t CO_2e^{-1}. The abatement potential arose almost exclusively in England and Scotland, with £285 and £330 t CO_2e^{-1} cost-effectiveness, respectively (Table 39). The UK abatement potential (without interactions, d.r. 3.5%) increased from 68 kt CO_2e y^{-1} with the low feasible potential to 955 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 52 to 730 kt CO_2e y^{-1}, respectively, in 2030 (Table 40). The respective UK cost-effectiveness without interactions was between £274 and £316 t CO_2e^{-1} (which is above the C price).

Table 39 MM8 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	435	299
England	383	285
Wales	1	2,550

Country	Abatement potential	Cost-effectiveness
	kt CO_2e y^{-1}	£ t CO_2e^{-1}
Scotland	50	330
Northern Ireland	1	2,259

Table 40 MM8 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	52	331	672	730
2035	3.5%	68	435	880	955
2030	7.0%	52	331	672	730
2035	7.0%	68	435	880	955

The sensitivity analysis shows that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 184 and 701 kt CO_2e y^{-1}; this analysis involved changing the assumptions on uptake, change in synthetic N use on the following crop, difference in the gross margin of the legumes and the crops replaced and fertiliser price (Table 41). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between £141 and £457 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the uptake. The level of reduction in synthetic N use on the following crop had a relatively low, though positive impact on the abatement. Both changes improved the cost-effectiveness, but not to an extent to be enough to fall below the C price. A reduced difference in the gross margin of the crop replaced and the legume crop improved the cost-effectiveness substantially, though even the 50% reduction did not bring the measure under the C price. Increasing fertiliser price had a favourable, but marginal effect on the cost-effectiveness.

Table 41 Sensitivity of MM8 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Maximum additional future uptake	Tillage land (less legumes): 0.17 Grassland: 0	Tillage land (less legumes): 0.07 Grassland: 0	184	310
Maximum additional future uptake	Tillage land (less legumes): 0.17 Grassland: 0	Tillage land (less legumes): 0.27 Grassland: 0	701	287
Change in synthetic N use on the crop following the legume (kg N ha^{-1})	-30	-15	407	329
Change in synthetic N use on the crop following the legume (kg N ha^{-1})	-30	-45	464	273
Difference in gross margin (£ ha^{-1})	430	645	435	457
Difference in gross margin (£ ha^{-1})	430	215	435	141
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 620 Grassland: 628	435	302

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 929 Grassland: 942	435	296

4.6.7 Discussion

This measure together with MM9 (*Legume-grass mixtures*) was captured in the measure *Biological fixation* in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008). The results are compared in section 4.7.7.

4.7 MM9: Legume-grass mixtures

4.7.1 Description of the measure

As mentioned in Section 4.6.1, legumes have the ability to fix N from the atmosphere. In the legume-grass mixtures the leguminous crops (e.g. white clover) can provide a substantial part of the grass's N requirements, reducing the need for N fertilisation. This measure is about increasing the legume-grass mix areas on grasslands and increasing the proportion of legumes in the mixture.

4.7.2 Applicability

The measure is applicable to grass swards that currently have little or no legumes. According to a review by [Anthony et al. REF] the proportion of fertile grassland (i.e. agriculturally improved or semi-improved grassland, often intensively managed agricultural swards with moderate to high abundance of perennial ryegrass) with white clover in 2007 was 21, 35 and 44% in England, Wales and Scotland, respectively, based on the Countryside Survey). Anthony (*pers. comm.*) derived from the Farm Practice Survey (Defra 2015a) that 47% of temporary grassland in England is reported to be sown with clover mix. Additionally, he found that the clover content in Northern Ireland on pasture was around 70%. However, the clover content of these swards varies (due to a combination of different sowing rates and varying degree of clover persistency), and there are no available data on what proportion of these fields have sufficient clover to fix significant proportion of the N requirements.

The BSFP (Defra 2013b) reports that 31% of temporary grasslands in England and Wales and 25% of temporary grasslands in Scotland receives less than 50 kg ha^{-1} N synthetic fertiliser. It is likely that in most cases the reason for the low fertilisation rate is the presence of clover mixture. Though these data are not easily reconcilable with those found by Anthony (*pers. comm.*) due to different statistical methods, definitions and the not direct equivalence between low N fertilisation rate and clover content, the values are in a comparable range.

Based on Anthony's data above, the assumption here is that currently 21, 35, 44 and 70% of temporary and permanent grasslands have legume mixtures in England, Wales, Scotland and Northern Ireland, respectively. The applicability of the measure is assumed to be 79%, 65%, 56% and 30% on temporary grasslands in England, Wales, Scotland and Northern Ireland, respectively. However, as permanent grasslands are reseeded less frequently and managed more extensively, therefore we assumed 50% lower applicability on those land areas: 40%, 32%, 28% and 15% in England, Wales, Scotland and Northern Ireland, respectively.

4.7.3 Abatement rate

The main mitigation effect of this measure is a reduction in fertiliser use. In line with the fertiliser recommendations (Defra 2011b), we assumed that the fertiliser requirement of the mixed swards is 50 kg N ha^{-1}. Some studies also estimated the abatement, as seen in Table 42.

Table 42 Data from literature on abatement by legume-grass mixtures

Abatement	Value	Country	Reference
N use	-0.5 t CO_2e ha^{-1} of soil N_2O emissions	UK	(Moran *et al.* 2008)
N use	-0.5 t CO_2e ha^{-1} of soil N_2O emissions	UK	(MacLeod *et al.* 2010c)
N use	-29 kg N ha^{-1}, resulting in -0.28 t CO_2e ha^{-1} of soil N_2O	France	(Pellerin *et al.* 2013)

4.7.4 Current and additional future uptake

We assumed no increase in the clover-grass area until 2035 in the future reference scenario, therefore the maximum additional future uptake is 1.

4.7.5 Cost

Cost data from the literature is presented in Table 43.

Table 43 Data from literature on costs/benefits of legume-grass mixtures

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
White clover seed	£9.00 kg^{-1} seed, sowing rate: 3.5 kg ha^{-1}	UK	2015	http://www.grasslandseeds.co.uk/products/clover_blend_grass_seed.php
Drilling (grass) [no data for drilling clover]	£76.60	UK	2014	(Gooday *et al.* 2014)
White clover seed	£6.50 kg^{-1} seed, sowing rate: 5 kg ha^{-1}	Ireland	2014	Donal O'Brian, *pers. comm.*

As pastures with legumes only tend to be productive for less than 5 years (S. Anthony, *pers. comm.*), we calculated the costs separately for temporary and permanent grasslands. On temporary grasslands the cost of the measure consists only of the additional seed costs (£30 ha^{-1}), while on permanent grasslands a reseeding (drilling) is needed (costing £80 ha^{-1}) in every four years (mean clover reseeding frequency on livestock farms (Defra 2015a)), instead of every 15 years (the approximate average pasture renewal frequency, based on the 2012 Farm Practices Survey (Defra 2013a).

4.7.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 233 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 146, 31, 46 and 11 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 44). The UK abatement potential (without interactions, d.r. 3.5%) increased from 93 kt CO_2e y^{-1} with the low feasible potential to 519 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 70 to 390 kt CO_2e y^{-1}, respectively, in 2030 (Table 45). In all of the above cases the UK average cost-effectiveness of the measure without interactions was -£20 t CO_2e^{-1}.

Table 44 MM9 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	233	-20
England	146	-20
Wales	31	-22
Scotland	46	-17
Northern Ireland	11	-21

Table 45 MM9 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	70	175	359	390
2035	3.5%	93	233	477	519
2030	7.0%	70	175	359	390
2035	7.0%	93	233	477	519

The abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 107 and 359 kt CO_2e y^{-1} in the sensitivity analysis involving changing the assumptions on applicability, change in synthetic N use, additional seed costs and reseeding costs, reseeding frequency and fertiliser price (Table 46). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£101 and £189 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the applicability and decreased with increasing synthetic N use, the latter also had an important effect on the cost-effectiveness: an average 75 kg N ha^{-1} use on clover-grass swards instead of 50 kg N put the measure's cost-effectiveness above the C price. A 50% increase in the additional seed costs or a 20% decrease in the fertiliser price impaired the cost-effectiveness, making it positive, though still below the C price. On the other hand, changing the cost of reseeding and the reseeding frequency did not bring about an important change in the cost-effectiveness.

Table 46 Sensitivity of MM9 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt $CO_2e\ y^{-1}$	Cost-effectiveness £ t CO_2e^{-1}
Applicability	Temp. g. E: 0.79 Temp. g. W: 0.65 Temp. g. S: 0.56 Temp. g. NI: 0.30 Perm. g. E: 0.40 Perm. g. W: 0.32 Perm. g. S: 0.28 Perm. g. NI: 0.15	Temp. g. E: 0.69 Temp. g. W: 0.55 Temp. g. S: 0.46 Temp. g. NI: 0.20 Perm. g. E: 0.30 Perm. g. W: 0.22 Perm. g. S: 0.18 Perm. g. NI: 0.05	183	-23
Applicability	Temp. g. E: 0.79 Temp. g. W: 0.65 Temp. g. S: 0.56 Temp. g. NI: 0.30 Perm. g. E: 0.40 Perm. g. W: 0.32 Perm. g. S: 0.28 Perm. g. NI: 0.15	Temp. g. E: 0.89 Temp. g. W: 0.75 Temp. g. S: 0.66 Temp. g. NI: 0.40 Perm. g. E: 0.50 Perm. g. W: 0.42 Perm. g. S: 0.38 Perm. g. NI: 0.25	284	-17
Synthetic N use (kg N ha^{-1})	50	75	107	189
Synthetic N use (kg N ha^{-1})	50	25	359	-82
Additional seed cost (£ ha^{-1})	30	45	233	62
Additional seed cost (£ ha^{-1})	30	15	233	-101
Permanent grassland reseeding frequency with clover (y)	4	3	233	-14
Permanent grassland reseeding frequency with clover (y)	4	5	233	-23
Permanent grassland reseeding frequency without clover (y)	15	18	233	-19
Permanent grassland reseeding frequency without clover (y))	15	12	233	-21
Cost of reseeding operation (£ ha^{-1})	80	120	233	-13
Cost of reseeding operation (£ ha^{-1})	80	40	233	-26
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 620 Grassland: 628	233	19
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 929 Grassland: 942	233	-59

4.7.7 Discussion

The measure *Use clover in place of fertiliser nitrogen* in the FARMSCOPER work was estimated to give GHG reduction at a similar level (120 kt $CO_2e\ y^{-1}$ in England), though providing 80 times more financial savings (Gooday *et al.* 2014). MM9 together with MM10 (*Legumes in rotations*) was captured in the measure *Biological fixation* in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008). *Biological fixation* was estimated to provide 1,121 and 1,465 kt $CO_2e\ y^{-1}$ abatement in the 2010 and 2008 MACCs, respectively, in both cases at cost-effectiveness of £83 t CO_2e^{-1} (UK, without interactions, 2022, CFP, d.r. 7%). The sum of the abatement potential of the two N fixation measures in the current estimate was 668 kt CO_2e y^{-1}, the weighted average cost-effectiveness is £188 t CO_2e^{-1}. The two drivers of the lower abatement potential in this current study were, the lower per ha abatement rate and the lower combined applicability and uptake values. The abatement rate in the 2008 and 2010 MACCs was 0.5 t CO_2e ha^{-1} y^{-1}, while it was 0.535 and 0.120-0.331 t CO_2e ha^{-1} y^{-1}, respectively, for MM8 and MM9. The combined applicability and uptake was 17% of tillage land for MM8 and 15%-79% of grassland for MM9 in the current study, while the corresponding values in the 2010 MACCs were 20% and 58%.

The current results suggest that at a UK average level establishing clover in pastures is a far more cost-effective way of GHG mitigation than increasing the share of grain legumes on the tillage area. Nevertheless, the average cost of the latter measure is mainly defined by the average difference in the profitability of the grain legumes versus the crops they would replace. The latter varied greatly with the type of crop (£293 to £4000 ha^{-1} for spring OSR and potatoes, respectively, (SAC 2013)), suggesting that a proportion of the 435 kt CO_2e y^{-1} abatement from MM8 in the UK can achieved below the C price.

4.8 MM10: Precision farming (crops)

4.8.1 Description of the measure

Precision farming (PF) is a management practice using developments of the past three decades in information technology and remote sensing. A wide variety of technologies are covered by this term, which are all based on obtaining more precise information on the soil and crop qualities and responding to in-field variations by differentiated management (e.g. fertiliser and pesticide use). It can be beneficial on fields where yield varies according to a predictable pattern due to differences in soil quality, weed infestation, drainage, etc. PF can also reduce emissions from fuel use by reducing machinery passes (Eory 2012).

Given the wide range of technologies (and their resource efficiency and costs), following other authors (Godwin *et al.* 2003, Jochinke *et al.* 2007) we distinguished between basic, medium and advanced systems, and assumed the implementation of the medium one. While a basic system would rely on manual speed control and steering based on low accuracy GPS and visual aids, the medium system is capable of 10cm accuracy auto-steering and includes yield monitoring/mapping and variable rate application. The advanced system has higher accuracy and collects more data (e.g. soil maps, biomass index).

Precision agriculture technologies are also available for livestock farming; a qualitative summary of that is presented in Section 6.2.

4.8.2 Applicability

Precision farming is theoretically available to both arable crops and grasslands, however, currently used only on arable land (Schellberg *et al.* 2008). Expecting technical improvements we assume that this measure will be applicable to arable and temporary grasslands.

4.8.3 Abatement rate

The measure reduces GHG emissions and emission intensity by reducing the N applied on fields and by increasing the yield. Based on the wide range of data in the literature (see Table 47), in this report we use a central assumption of 20% N reduction with no effect on yield, as this value is closer to the German values (German farming practices are closer to the UK circumstances than North American ones).

Table 47 Data from literature on abatement by precision farming

Abatement	Value	Country	Reference
N fertiliser use	-68% (winter wheat)	USA	In a review by Diacono *et al.* (2013)
N fertiliser use	-59 – -82% (winter wheat)	USA	In a review by Diacono *et al.* (2013)
N fertiliser use	-10 – -12% (winter wheat)	Germany	In a review by Diacono *et al.* (2013)
Yield increase	-0.46 t ha^{-1} (winter and spring wheat)	Germany	In a review by Diacono *et al.* (2013)
Soil N_2O	-0.02 – -0.621 t CO_2e ha^{-1}	Germany	From various sources in Frelih-Larsen *et al.* (2014)
Soil N_2O	-0.2 t CO_2e ha^{-1}	UK	(Moran *et al.* 2008)
N fertiliser use	-57% (forage maize)	UK	(Mantovani et al 2011)

4.8.4 Current and additional future uptake

A survey conducted in England in 2012 showed that 2-22% of farms use various PF technologies: 22% of them using GPS (including autosteering), 20 and 11% soil and yield mapping, respectively, 16% using VRA and 2% using telemetry (Defra 2013a). These uptake rates mean a 20% to 200% increase between 2009 and 2012 (Defra 2009). The implementation rates are higher for cereal and cropping farms, lower for dairy and mixed farms and lowest for pigs and poultry and cattle farms. The rates increase with farm size.

As this mitigation measure focuses on a combination of auto-steering, VRA and yield mapping, for current uptake we use the arithmetic mean of the lowest uptake of these three methods on cereal and cropping farms (yield mapping at 25 and 18%, respectively on the two farm types), i.e. 22%. In 2009 this value was 14%. As a quickly developing technology, we can expect that the uptake in 2030 and 2035 in the future reference scenario will be higher: 40% of arable land. Due to the capital expenses implications and the practicality of the measure, we exclude farms under 20 ha from the maximum additional uptake

(5% of croppable land in the UK). The maximum additional future uptake is therefore 55%.

4.8.5 Cost

Cost data from the literature is presented in Table 48.

Table 48 Costs and benefits of precision farming

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Cost of precision farming	£11 ha^{-1}		2012	In a review by Diacono *et al.* (2013)
Equipment and monitoring cost	Basic system (with auto-steering): £48,000 $farm^{-1}$, i.e. £16 ha^{-1} y^{-1} (500 ha farm), £4 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Jochinke *et al.* 2007)
Equipment and monitoring cost	Advanced system: £119,000 $farm^{-1}$ + £8 ha^{-1} y^{-1}, i.e. £37 ha^{-1} y^{-1} (500 ha farm), £14 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Jochinke *et al.* 2007)
Equipment cost	Basic system (without auto-steering): £4,500 $farm^{-1}$ Advanced system: £11,363 - £16,150 $farm^{-1}$	UK	2001	(Godwin *et al.* 2003)
Monitoring cost	£7 ha^{-1} y^{-1}	UK	2001	(Godwin *et al.* 2003)
Training cost	£300 $farm^{-1}$ in every 5 years	UK	2001	(Godwin *et al.* 2003)
Maintenance	3.5-7.5% of capital cost	UK	2001	(Godwin *et al.* 2003)
Benefits (yield + fertilisers)	£ -22 ha^{-1} y^{-1}	UK	2001	(Godwin *et al.* 2003)
Equipment and monitoring cost	Basic system (with auto-steering): £3,500 $farm^{-1}$, i.e. £1 ha^{-1} y^{-1} (500 ha farm), £0.2 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Robertson *et al.* 2007)
Equipment and monitoring cost	Medium system: £19,000 $farm^{-1}$, i.e. £7 ha^{-1} y^{-1} (500 ha farm), £2 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Robertson *et al.* 2007)
Equipment and monitoring cost	Advanced system: £43,000 $farm^{-1}$, i.e. £16 ha^{-1} y^{-1} (500 ha farm), £4 ha^{-1} y^{-1} (2000 ha farm)	Australia	2007	(Robertson *et al.* 2007)

According to expert advice (Jim Wilson, *pers. comm.*), currently the cost of a basic system in the UK with autosteer is around £5,000 per vehicle, with a £250 per vehicle per year signal fee and yield monitor costs are about the same. (An advanced system costs around £12,000, with an annual signal cost of £750 per year). The financial benefits of PF are reduced resource use not only from better targeting but from reduced overlaps. Variable costs of winter cereals and OSR is around £450 (SAC 2013), therefore the 3% reduction in overlaps reduces costs by £13.50 ha^{-1} (Jim Wilson, *pers. comm.*). The N fertiliser savings from better targeting is also considered, and maintenance costs (annual 5% of capital expenses) and training costs (£500 in every five years) are also included in the total costs.

4.8.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 248 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 200, 7, 34 and 6 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 49). The UK abatement potential (without interactions, d.r. 3.5%) increased from 39 kt CO_2e y^{-1} with the low feasible potential to 550 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 29 to 412 kt CO_2e y^{-1}, respectively, in 2030 (Table 50). In all of the above cases the UK cost-effectiveness of the measure without interactions was -£95 t CO_2e^{-1}. However, due to the investment required in technology and machinery, the profitability of the measure depended on farm size. With the costs and benefits described in Section 4.8.5, the breakeven croppable area size for measure to generate savings on farms was around 60 ha (Table 51).

Table 49 MM10 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	248	-95
England	200	-90
Wales	7	-125
Scotland	34	-112
Northern Ireland	6	-123

Table 50 MM10 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	29	186	379	412
2035	3.5%	39	248	506	550
2030	7.0%	29	186	379	412
2035	7.0%	39	248	506	550

Table 51 Annualised net cost of MM10 as a function of the size of croppable area on farm

Croppable area on farm (ha)	6	33	71	230	Average UK
Net cost (£ ha^{-1} y^{-1})	326	35	-3.5	-26.1	-15.6

The sensitivity analysis showed that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 124 and 371 kt CO_2e y^{-1}; this analysis involved changing the assumptions on uptake, change in synthetic N use, cost and benefits of precision farming and fertiliser price (Table 52). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£165 and -£11 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the uptake and the reduction in synthetic N use, while the cost-effectiveness increased with increasing costs of the technology, reducing benefits from avoided overlaps and reducing fertiliser price. However, the cost-effectiveness was negative even with a 50% increase in the cost at a UK average farm size.

Table 52 Sensitivity of MM10 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt $CO_2e\ y^{-1}$	Cost-effectiveness £ t CO_2e^{-1}
Maximum additional future uptake	Tillage land: 0.55 Temp. gr.: 0.55	Tillage land: 0.45 Temp. gr.: 0.45	203	-95
Maximum additional future uptake	Tillage land: 0.55 Temp. gr.: 0.55	Tillage land: 0.65 Temp. gr.: 0.65	293	-95
Change in synthetic N use (%)	-20%	-10%	124	-50
Change in synthetic N use (%)	-20%	-30%	371	-110
Costs: Auto-steer, 10cm (£ farm^{-1}) Signal cost (£ farm^{-1}) Yield monitor (£ farm^{-1}) Maintenance/capital expense ratio Training (£ farm^{-1})	 5,000 250 5,000 0.05 500	 7,500 375 7,500 0.08 750	248	-11
Costs: Auto-steer, 10cm (£ farm^{-1}) Signal cost (£ farm^{-1}) Yield monitor (£ farm^{-1}) Maintenance/capital expense ratio Training (£ farm^{-1})	 5,000 250 5,000 0.05 500	 2,500 125 2,500 0.03 250	248	-165
Reduced variable costs from reduced overlaps (£ ha^{-1})	-13.5	-6.8	248	-54
Reduced variable costs from reduced overlaps (£ ha^{-1})	-13.5	-20.3	248	-136
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 620 Grassland: 628	248	-67
Average fertiliser price (£ t N^{-1})	Tillage land: 774 Grassland: 785	Tillage land: 929 Grassland: 942	248	-123

4.8.7 Discussion

This measure was not included in either the FARMSCOPER work or the previous MACC studies, apart from *Precision farming* assessed on the medium list in the 2008 MACC. The abatement rate estimate in that work was 0.2 t $CO_2e\ ha^{-1}\ y^{-1}$ (Moran *et al.* 2008), 0.12 and 0.18 t $CO_2e\ ha^{-1}\ y^{-1}$ abatement, respectively, for temporary grassland and tillage land calculated in the current study.

4.9 MM11: Loosening compacted soils and preventing soil compaction

4.9.1 Description of the measure

Soil compaction has been reported to increase N_2O emissions (Ball *et al.* 1999b, Cranfield University *et al.* 2007) and strongly reduce the soil's ability to be a CH_4 net sink (Ruser *et al.* 1998). Therefore reducing soil compaction and preventing its re-occurrence can contribute to GHG mitigation, amongst providing other benefits, e.g. improved soil function and increased yield. Prevention of soil compaction requires better planning of field operations to avoid traffic on wet soil, avoiding or strongly reducing tillage of wet soil and reducing stocking density (Frelih-Larsen *et al.* 2014). At the same time, for the best long-term results, there should be a regular assessment of drainage and improvements carried out when needed; however, in this current study this is not included in the measure. Where soils become compacted, loosening of the soil is required: in case of moderate compaction cultivation is appropriate, otherwise sub-soiling of tillage land and ploughing and re-seeding grassland might be required (Cranfield University *et al.* 2007).

4.9.2 Applicability

Loosening compacted soils is applicable where currently compaction occurs, while preventing soil compaction is applicable on soils which are susceptible for compaction. Sporadic data sources exist about compaction and land liable to compaction. The 2012 Farm Practice Survey on Current Issues reported on the proportion of farms where soil compaction was a problem in the previous 12 months. This survey showed that there was there was 51%, 43% and 20% respectively of topsoil, plough depth and whole soil profile compacted on English farms (Defra 2013a). However, no information was provided on the spatial extent of compaction at the farms (i.e. what proportion of the fields on the farm is compacted, and what proportion of these fields is compacted), therefore these values are of limited use for estimating the proportion of land area which is compacted. A grassland survey in England showed that 16% of the soils were compacted (ADAS 2012). Another survey in England and Wales estimated that 42% of arable land and 39% of grassland is liable to compaction (Graves *et al.* 2011).

Based on the information summarised above we assumed that, for both tillage land and grasslands, 20% of the land area was compacted in the UK, and another 20% was susceptible to compaction. Furthermore, we assumed that on land susceptible to compaction but not compacted good practice was already in place to avoid compaction. Thus the applicability of loosening soil compaction is 20%. Within this area, based on the Farm Practice Survey data (Defra 2013a), we estimated that topsoil compaction affects 45% of the area, deep compaction affects 38% of the area, while whole soil profile compaction occurs on 18% of the area. These proportions were taken into account in the cost calculations.

4.9.3 Abatement rate

Abatement data from the literature is presented in Table 53. The measure reduces GHG emissions by reducing the proportion of N being transformed to N_2O, therefore the mitigation is calculated by changing the soil N_2O emission factor EF_1. A 40% reduction in EF_1 is assumed both on arable and grasslands, taken as a central value from the studies in Table 53.

Table 53 Data from literature on abatement by loosening compacted soils and preventing soil compaction

Abatement	Value	Country	Reference
Direct N_2O	-25 – -65% at plot level	UK	(Ball *et al.* 2000)
Direct N_2O	-0.05 t CO_2e ha^{-1} y^{-1} (roughly equivalent to 6% reduction in EF_1) at field level	UK	(Moran *et al.* 2008)
Direct N_2O	-20 – -50% at field level	The Netherlands	(Mosquera *et al.* 2007)
Direct N_2O	-100 kt CO_2e	UK	(Gooday *et al.* 2014)

4.9.4 Current and additional future uptake

We assume that compaction problems are not going to improve in the future reference scenario, i.e. the reference uptake of the measure will be 0. Therefore the maximum additional future uptake is 100%.

4.9.5 Cost

Cost data from the literature is presented in Table 54. In general the cost of alleviating moderate compaction by cultivation is lower than the cost of alleviating deep compaction with sub-soiling. We used the latest estimates of £60.00 ha^{-1} for sub-soiling (Gooday *et al.* 2014) and £25.00 ha^{-1} for surface cultivation (Newell-Price *et al.* 2011), assuming that for topsoil compaction (45% of the area) surface cultivation is sufficient while for deep and whole soil profile compaction (55% of the area) sub-soiling is necessary. Furthermore, we assumed that these actions only have to be repeated every 10 years, given a subsequent continuous good practice to avoid compaction. Without any data found in the literature we estimated the cost of the latter at £10 ha^{-1} y^{-1}.

The additional income from the yield benefit is calculated using average UK yield and price data and assuming 2% and 1% increase, respectively, for tillage crops and grass (based on Graves *et al.* (2011)). The average UK value used is £13.03 ha^{-1} y^{-1}. This is comparable to the ranges in the other two estimates from the literature (Graves *et al.* 2011, Wiltshire 2014). The reduced fuel use is estimated using the value of -£1.9 ha^{-1} y^{-1} provided by Graves *et al.* (2011).

Table 54 Costs and benefits of alleviating and preventing soil compaction

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Loosening compaction	Tillage land, subsoiling: £60.00 ha^{-1} (±22%), annual cost Grassland, topsoiling: £60.00 ha^{-1} (±22%), annual cost	UK	2014	(Gooday *et al.* 2014)
Loosening compaction	Tillage land, topsoil cultivation: £25.00 ha^{-1}, annual cost Grassland, shallow spiking or subsoiling: £40.00 ha^{-1}, annual cost	UK	2011	(Newell-Price *et al.* 2011)
Loosening compaction	Tillage land, topsoil cultivation: £4.00 ha^{-1}, annual cost Grassland, shallow spiking or subsoiling: £10.80 ha^{-1}, annual cost	UK	2006	(Cuttle *et al.* 2006)
Loosening compaction	Tillage land, topsoil cultivation: Median £4.50 ha^{-1} Lower £4.00 ha^{-1} Upper £5.00 ha^{-1} (annual cost)	UK	2014	(Wiltshire 2014), based on (Cuttle *et al.* 2006) and (Newell-Price *et al.* 2011)
Additional income from improved yield	Arable land: 2% (on compacted fields); -£24.1 ha^{-1} Grassland: 1% (on compacted fields); -£6.5 ha^{-1} Overall average: -£15.1 ha^{-1}	UK	2011	(Graves *et al.* 2011)
Additional income from improved yield	By soil type: Heavy: -£10.50 ha^{-1} Medium: -£13.70 ha^{-1} Silty/sandy: -£5.20 ha^{-1} Peaty: -£16.60 ha^{-1} Chalk and limestone: -£20.60 ha^{-1}	UK	2014	(Wiltshire 2014)
Reduced fuel cost due to looser soil	Arable land: -£3.9 ha^{-1} Grassland: £0 ha^{-1} Overall average: -£1.9 ha^{-1}	UK	2011	(Graves *et al.* 2011)

4.9.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 225 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 180, 7, 32 and 6 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 55). The UK abatement potential (without interactions, d.r. 3.5%) increased from 35 kt CO_2e y^{-1} with the low feasible potential to 499 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 26 to 374 kt CO_2e y^{-1}, respectively, in 2030 (Table

56). In all of the above cases, with d.r. 3.5% the cost-effectiveness of the measure in the UK without interactions was £1 t CO_2e^{-1}, and with d.r. 7% the cost-effectiveness was £2 t CO_2e^{-1} (which is below the C price).

Table 55 MM11 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	225	1
England	180	1
Wales	7	1
Scotland	32	1
Northern Ireland	6	1

Table 56 MM11 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	26	168	318	374
2035	3.5%	35	225	424	499
2030	7.0%	26	168	318	374
2035	7.0%	35	225	424	499

The sensitivity analysis demonstrated that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 112 and 337 kt CO_2e y^{-1}; this analysis involved changing the assumptions on uptake, change in EF_1, costs and benefits of loosening soil (Table 57). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£18 and £19 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the applicability and also increases with an increasing reduction in EF_1. The cost-effectiveness was still below the C price with either a 50% increase in the per ha costs or a 50% drop in the additional revenues from increased yield. Changing the fuel cost reduction to an additional expense of £5 ha^{-1} resulted in a cost-effectiveness which is still below the C price.

Table 57 Sensitivity of MM11 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Applicability	Tillage land: 0.2 Grassland: 0.2	Tillage land: 0.1 Grassland: 0.1	112	1
Applicability	Tillage land: 0.2 Grassland: 0.2	Tillage land: 0.3 Grassland: 0.3	337	1
Change in EF_1	-40%	-30%	169	1
Change in EF_1	-40%	-50%	281	0
Costs: Subsoiling (£ ha^{-1}) Topsoil cultivation (£ ha^{-1}) Avoiding re-occurrence of compaction (£ ha^{-1})	60 25 10	90 37.5 15	225	19

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Costs: Subsoiling (£ ha^{-1}) Topsoil cultivation (£ ha^{-1}) Avoiding re-occurrence of compaction (£ ha^{-1})	60 25 10	30 12.5 5	225	-18
Reduced fuel cost (£ ha^{-1})	-1.9	5	225	17
Reduced fuel cost (£ ha^{-1})	-1.9	-5	225	-7
Increased yield (£ ha^{-1})	-13	-6.5	225	16
Increased yield (£ ha^{-1})	-13	-20	225	-15

4.9.7 Discussion

This measure was not included in the final list of the previous MACC studies, though its abatement rate was estimated in the 2008 MACC as 0.05 t CO_2e ha^{-1} y^{-1} (Moran *et al.* 2008). The abatement rate as calculated in the current study was 0.44 and 0.32 t CO_2e ha^{-1} y^{-1} for tillage land and temporary grassland, respectively. The FARMSCOPER study estimated the English abatement potential to be 180 kt CO_2e y^{-1} on grasslands and 100 kt CO_2e y^{-1} on tillage lands (Gooday *et al.* 2014).

4.10 MM12: Improving beef and sheep nutrition

4.10.1 Description of the measure

This measure describes the improvement of ration nutritional values (i.e. digestibility of the ration), in order to improve yield and reduce enteric CH_4 emissions. It involves getting advice from an animal nutritionist to improve the composition of the diet, complemented with forage analysis and improved grazing management.

4.10.2 Applicability

The measure is applicable to all livestock, though mostly relevant to beef and sheep, as the nutritional planning of dairy and monogastric animals is already well developed. We assume 100% applicability to all beef and sheep livestock.

4.10.3 Abatement rate

Hristov *et al.* (2013) provided a detailed literature review on experimental results looking at the relationship between forage quality (in particular digestibility), yield and enteric CH_4 emissions. They concluded that “increased forage digestibility is expected to increase animal production and decrease enteric CH_4 emission intensity”. As an exploratory analysis, we assume that the improved diet formulation and grazing management increases the digestibility of the roughage and concentrate by 2% from their original values (i.e. from 70% to 71.4%), and results in a 2% higher yield.

4.10.4 Current and additional future uptake

7% and 58% of dairy and grazing (lowland and LFA) farms, respectively, rarely or never use nutritional advice when planning the feeding regime of the livestock (Defra 2014a). Though in the next 15 years we can anticipate an increased uptake of nutritional planning, we expect that the maximum additional uptake of improved nutrition will be in 40% of beef herds and sheep flocks (and 0% of dairy herd).

4.10.5 Cost

The cost of the measure is estimated by accounting for the cost of nutritional advice (£100 twice a year, for an average sized farm) and forage analysis (£30 twice a year, for an average sized farm). The additional revenue from the increased meat production was included as a benefit, using the following farmgate prices (for the year 2014): £1.90 kg liveweight^{-1} for beef meat (FarmingUK 2015a) and £4.00 deadweight kg^{-1} (£2.00 deadweight kg^{-1}) for sheep meat (FarmingUK 2015b).

4.10.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 67 kt CO_2e y^{-1} in 2035 (d.r. 3.5%) (Table 49). The UK abatement potential (without interactions, d.r. 3.5%) increased from 27 kt CO_2e y^{-1} with the low feasible potential to 148 kt CO_2e y^{-1} assuming the maximum technical potential in 2035 (Table 50). The UK cost-effectiveness of the measure without interactions was -£26 t CO_2e^{-1}.

Table 58 MM12 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	67	-26
England	31	-26
Wales	9	-36
Scotland	16	-22
Northern Ireland	11	-21

Table 59 MM12 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	20	50	95	112
2035	3.5%	27	67	126	148
2030	7.0%	20	50	95	112
2035	7.0%	27	67	126	148

The sensitivity analysis showed that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 44 and 89 kt $CO_2e\ y^{-1}$; this analysis involved changing the assumptions on uptake, change in the digestibility of the feed materials, change in yield, costs of the measure and the prices of livestock products (Table 60). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£73 and -£21 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the uptake and also increased with an increased improvement in the digestibility of the feed materials. The cost-effectiveness remained negative in all cases but a 50% increase in the cost of advice, still then it was under the C price.

Table 60 Sensitivity of MM10 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt $CO_2e\ y^{-1}$	£ t CO_2e^{-1}
Maximum additional future uptake	0.4	0.3	50	-26
Maximum additional future uptake	0.4	0.5	83	-26
Change in roughage DE (%)	2%	1%	44	-39
Change in roughage DE (%)	2%	3%	89	-19
Change in concentrate DE (%)	2%	1%	56	-30
Change in concentrate DE (%)	2%	3%	77	-22
Change in yield (%)	2%	1%	67	21
Change in yield (%)	2%	3%	67	-73
Advisor (nutritionist) (£ $farm^{-1}$)	200	300	67	1
Advisor (nutritionist) (£ $farm^{-1}$)	200	100	67	-52
Forage analysis (£ $farm^{-1}$)	60	90	67	-18
Forage analysis (£ $farm^{-1}$)	60	30	67	-34
Cattle meat price (£ kg LW^{-1})	1.88	1.5	67	-16
Cattle meat price (£ kg LW^{-1})	1.88	2.26	67	-35
Sheep meat price (£ kg DW^{-1})	4.00	3.2	67	-16
Sheep meat price (£ kg DW^{-1})	4.00	4.8	67	-35

4.10.7 Discussion

This measure was not investigated in either the FARMSOPER or the MACC studies.

4.11 MM13: Probiotics

4.11.1 Description of the measure

Probiotics are direct-fed microbials fed to ruminants as supplementary feed ingredients. Most comment are yeast products (*Saccheromyces cerevisiae)*, which are often used to increase productivity (Grainger and Beauchemin 2011), while in the UK they are usually only used to reduce the incidence of acidosis.

4.11.2 Applicability

The measure is applicable for all ruminant livestock. It is assumed to be not administered to calves (0-1 year) and to the category 'other cattle' and 'other sheep' (mainly includes adult males).

As the practicalities of this measure requires the daily administration of the additive, it is only applicable on farms where animals are daily supplemented with concentrates in a way that the additive can be mixed in the concentrate (or the ration), for even distribution to the animals. We assumed that for these practical reasons probiotics are not applicable on LFA grazing farms (but applicable on all other farm types, including lowland grazing). The proportion of livestock on these farms are projected to 2025 by Shepherd *et al.* (2007) (Table 61).

Table 61 Proportion of livestock on LFA grazing farms in 2025 (Shepherd et al. 2007)

Livestock	England	Wales	Scotland	Northern Ireland
Dairy cows and heifers	0%	5%	1%	1%
Beef and other cattle	14%	59%	48%	35%
Sheep	41%	89%	81%	72%

Furthermore, as the enteric CH_4 abatement potential decreases with higher yields and lower forage intake (Robinson and Erasmus 2009), we assumed that this measure is not applicable to the 20% of animals which have the highest yield, and often the highest concentrate intake. The applicability is presented in Table 62. For young animals, as well as dairy/beef replacement animals, the applicability is 0%.

Table 62 Applicability of probiotics

Livestock	England	Wales	Scotland	Northern Ireland
Dairy cows and heifers	80%	76%	79%	79%
Beef and other cattle	69%	33%	42%	52%
Sheep	47%	9%	15%	23%

4.11.3 Abatement rate

The some authors argue that there is not sufficient *in vivo* evidence yet to support long-term CH_4 emission reduction effect (Grainger and Beauchemin

2011, Hristov *et al.* 2013), a recent meta-analysis concluded pro-and prebiotics reduce enteric CH_4 emissions by 3% on average across ruminant livestock (Veneman 2014). Moreover, Newbold and Rode (2006) suggest that selection of yeast strains for improved CH_4 reduction is possible. Beyond the effect on enteric CH_4 emissions, probiotics improve milk yield (Table 63).

Table 63 Data from literature on abatement by probiotics

Abatement	Value	Country	Reference
Enteric CH_4	-7.5%	UK	(Moran *et al.* 2008) and (MacLeod *et al.* 2010c) based on (Moss *et al.* 2000) and (Van Nevel and Demeyer 1996)
Yield	+10%	UK	(Moran *et al.* 2008) and (MacLeod *et al.* 2010c) based on (Moss *et al.* 2000) and (Van Nevel and Demeyer 1996)
Yield	+2.7% (3.5% FCM)	various	(de Ondarza *et al.* 2010)
Enteric CH_4	effect size: 0.98	various	(Veneman *et al.* 2014)
Enteric CH_4	effect size (95% CI): 0.97 (0.93-1.01)	various	(Veneman 2014), p44

Based on Veneman (2014) in this report we use the following equation to quantify the effect of probiotics on methane emissions:

$$Y_m = 6.5\% * (1 - M)$$

$M = 0.03$, 95% CI: -1% - 7%

The yield increase is assumed to be 2.7%, based on (de Ondarza *et al.* 2010). However, the yield effect decreases with increasing yield (Robinson and Erasmus 2009), and might depend on the concentrate:forage ratio of the diet (Ingale *et al.* 2013). This is taken into account as a restriction in the applicability of the measure (see previous section).

4.11.4 Current and additional future uptake

Currently probiotics are not commonly used in the UK as part of the diet (Expert Workshop, Appendix C). With an increasing emphasis on productivity their use might increase in the next decade, therefore the future reference uptake was estimated as 20%, leaving 80% for maximum additional future uptake.

4.11.5 Cost

Cost data from the literature is presented in Table 64. For cattle we estimated the cost as £11.00 head^{-1} year^{-1}, while for sheep 1/5 of this cost was used. The production benefits described above were also accounted for. The additional revenue from the increased production was included, using the farmgate prices described in Section 4.10.5 and the milk price 31.5p l^{-1} (DairyCo 2015a).

Table 64 Data from literature on costs of probiotics

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Probiotic cost	£13.70 $head^{-1}$ $year^{-1}$	UK	2008	(Moran *et al.* 2008) based on (IGER 2001)
Yeast cost	£5.60 - £14.70 $head^{-1}$ $year^{-1}$	UK	2014	(Beauchemin 2012)

4.11.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 68 kt CO_2e y^{-1} in 2035 (d.r. 3.5%) (Table 65). The UK abatement potential (without interactions, d.r. 3.5%) increased from 27 kt CO_2e y^{-1} with the low feasible potential to 150 kt CO_2e y^{-1} assuming the maximum technical potential in 2035 (Table 66). In all of the above cases the UK cost-effectiveness of the measure without interactions was -£230 t CO_2e^{-1}.

Table 65 MM13 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential	Cost-effectiveness
	kt CO_2e y^{-1}	£ t CO_2e^{-1}
UK	68	-230
England	42	-232
Wales	6	-363
Scotland	10	-109
Northern Ireland	10	-266

Table 66 MM13 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	20	51	104	113
2035	3.5%	27	68	138	150
2030	7.0%	20	51	104	113
2035	7.0%	27	68	138	150

In the sensitivity analysis the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -67 and 202 kt CO_2e y^{-1}; this analysis involved changing the assumptions on applicability, uptake, change in Y_m and yield, cost of the yeast culture and the prices of livestock products (Table 67). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between -£696 and £42 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the applicability and maximum additional future uptake. The value of the Y_m effect was varied according to the 95% CI described in Section 4.11.3, which meant that at the lower end of the range Y_m was increased by 1% instead of the original 3% decrease, causing an increase in GHG emissions. The measure's cost-effectiveness remained negative even with a 50% change in the cost of the yeast culture or 20% change in the price of milk, cattle meat and sheep meat. A reduced improvement in yield (1.4% instead of 2.7%) made the cost-effectiveness positive, but it was still below the C price.

Table 67 Sensitivity of MM13 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Applicability Dairy >1y – E Dairy >1y – W Dairy >1y – S Dairy >1y – NI Dairy <1y Beef & other >1y – E Beef & other >1y – W Beef & other >1y – S Beef & other >1y – NI Beef & other <1y Ewes & lambs – E Ewes & lambs – W Ewes & lambs – S Ewes & lambs – NI Other sheep	 0.8 0.76 0.79 0.79 0 0.69 0.33 0.42 0.52 0 0.47 0.09 0.15 0.23 0	 0.7 0.66 0.69 0.69 0 0.59 0.23 0.32 0.42 0 0.37 0 0.05 0.13 0	55	-261
Applicability Dairy >1y – E Dairy >1y – W Dairy >1y – S Dairy >1y – NI Dairy <1y Beef & other >1y – E Beef & other >1y – W Beef & other >1y – S Beef & other >1y – NI Beef & other <1y Ewes & lambs – E Ewes & lambs – W Ewes & lambs – S Ewes & lambs – NI Other sheep	 0.8 0.76 0.79 0.79 0 0.69 0.33 0.42 0.52 0 0.47 0.09 0.15 0.23 0	 0.9 0.86 0.89 0.89 0 0.79 0.43 0.52 0.62 0 0.57 0.19 0.25 0.33 0	80	-209
Maximum additional future uptake	0.8	0.7	59	-230
Maximum additional future uptake	0.8	0.9	76	-230
Change in Y_m	-3%	1% (i.e. increase in emissions)	-67	NA
Change in Y_m	-3%	-7%	202	-77
Change in yield	2.7%	1.4%	84	42
Change in yield	2.7%	4.1%	51	-696
Yeast culture (£$head^{-1}$ y^{-1})	Dairy/beef: 11 Sheep: 2.20	16.5 3.3	68	-63
Yeast culture (£$head^{-1}$ y^{-1})	Dairy/beef: 11 Sheep: 2.20	5.5 1.1	68	-398
Milk price (£ l^{-1})	0.315	0.252	68	-135
Milk price (£ l^{-1})	0.315	0.378	68	-326
Cattle meat price (£ kg LW^{-1})	1.88	1.5	68	-220
Cattle meat price (£ kg LW^{-1})	1.88	2.26	68	-241
Sheep meat price (£ kg DW^{-1})	4.00	3.2	68	-223

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt $CO_2e\ y^{-1}$	£ t CO_2e^{-1}
Sheep meat price (£ kg DW^{-1})	4.00	4.8	68	-237

4.11.7 Discussion

This measure is included in the 2008 and 2010 MACCs, where its UK abatement potential (together for dairy and beef, without interactions, 2022, CFP, d.r. 7%) was estimated to be 397 kt $CO_2e\ y^{-1}$, at a cost-effectiveness of -£21 and -£2,032 t CO_2e for dairy and beef, respectively. The change in values was mainly due to the different abatement rates. The abatement rate assumption in the 2008 and 2010 MACCs was a 7.5% reduction in the enteric CH_4 emissions as opposed to the 3% reduction assumed here. The assumed yield increase was also higher in the 2008 and 2010 MACCs: 10% (with a 5% increase in feed intake) in contrast to the 2.7% in the current study. The applicability assumption in the earlier MACCs was also higher: 90% of the beef and dairy herd (0% for sheep), while in the current study we assumed that the applicability in the UK is around 80% for dairy, 60% for beef and 30% for sheep (weighted average of the DA applicability values).

4.12 MM14: Nitrate as feed additive

4.12.1 Description of the measure

This measure requires mixing 1.5% NO_3^- homogeneously into ruminant diets, e.g. in the form of $Ca(NO_3)_2$ (e.g. the product Bolifor CNF). The $Ca(NO_3)_2$ would (partially) replace non-protein N (NPN) sources (e.g. urea), or, if NPN is not present in the diet, then high protein content components, like soya. It would also (partially) replace limestone as a calcium source.

4.12.2 Applicability

The nitrate can be mixed into concentrate feeds and in total mixed ration, but cannot be fed on their own, as it is toxic if consumed in higher dose, requiring throughout mixing with the majority of the total feed intake. Therefore nitrate administration is only feasible for animals which are fed with total mixed ration. Based on a discussion at the Expert Workshop (see Appendix C), it is estimated that in the UK farms with more than 80 dairy cows (85% of the dairy herd, estimated from size band proportions (Defra 2015c)) and 20% of the beef farms have feed mixers. It is assumed that nitrate would not be administered to calves (0-1 year) and to the category 'other cattle' (mainly includes adult males). We assume that it would not be applied in the sheep flock.

4.12.3 Abatement rate

In the MitiGate database (Veneman *et al.* 2014) the effect of nitrate additions across livestock categories is 20% reduction in enteric CH_4 emissions, with a 95% CI of ±7%. Veneman (Veneman 2014, p239) provides the following equation to calculate the size of the effect, as dependent on the nitrate dose (95% CI in brackets):

$$M = e^{-0.012(\pm 0.0042)} * x - 0.01(\pm 0.0847)$$

x: nitrate dose (g kg DMI^{-1})

With a 1.5% nitrate dose the reduction in Y_m is 17.5%, with a 95% CI of 3.6% - 31%.

4.12.4 Current and additional future uptake

As it is a relatively new mitigation measure, not based on existing practice, and has a positive cost, the future reference uptake is assumed to be zero, and the maximum additional future uptake is 100%.

4.12.5 Cost

The cost of the measure includes the cost of the nitrate and the induced changes in the ration, which could include the purchase of feed mixers (£15,000-£40,000) and the establishment of additional feed storage facilities. However, we assumed that the measure would only be implemented by those farms which are already using feed mixers (see section 4.12.2).

The cost Bolifor© (63.1% nitrate content) was €550 t^{-1} last year (Hink Perdok, *pers. comm.*), which gives £620 t^{-1} nitrate price. The urea price is £388 t^{-1} (average of price at two feed companies in 2015). Limestone price is estimated at £35 t^{-1}.

4.12.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 540 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 323, 63, 67 and 86 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 68). The UK abatement potential (without interactions, d.r. 3.5%) increased from 84 kt CO_2e y^{-1} with the low feasible potential to 1.2 Mt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 63 to 901 kt CO_2e y^{-1}, respectively, in 2030 (Table 69). In all of the above cases the UK average cost-effectiveness of the measure without interactions was £62 t CO_2e^{-1} (which is below the C price).

Table 68 MM14 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential	Cost-effectiveness
	kt CO_2e y^{-1}	£ t CO_2e^{-1}
UK	540	62
England	323	62
Wales	63	62
Scotland	67	61
Northern Ireland	86	62

Table 69 MM14 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	63	405	829	901
2035	3.5%	84	540	1103	1199
2030	7.0%	63	405	829	901
2035	7.0%	84	540	1103	1199

The sensitivity analysis demonstrated that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 111 and 957 kt CO_2e y^{-1}; this analysis involved changing the assumptions on applicability, the change in Y_m, and the price of feed components (Table 70). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between £12 and £299 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the uptake and the reduction in Y_m. The Y_m effect is varied according to the 95% CI described in Section 4.12.3, and had a profound effect both on the abatement potential and the cost-effectiveness. The cost-effectiveness decreased (i.e. improved) with lower nitrate, higher urea or higher limestone price. In all but one case, the cost-effectiveness remained below the C price.

Table 70 Sensitivity of MM14 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Applicability	Dairy >1y: 0.85 Beef & other >1y: 0.2	Dairy >1y: 0.75 Beef & other >1y: 0.1	442	62
Applicability	Dairy >1y: 0.85 Beef & other >1y: 0.2	Dairy >1y: 0.95 Beef & other >1y: 0.1	637	62
Change in Y_m	All cattle: -17%	All cattle: -4%	111	299
Change in Y_m	All cattle: -17%	All cattle: -31%	957	35
Nitrate price (£ t^{-1})	391	587	540	111
Nitrate price (£ t^{-1})	391	196	540	12
Urea price (£ t^{-1})	388	310	540	68
Urea price (£ t^{-1})	388	466	540	55
Limestone price (£ t^{-1})	35	28	540	62
Limestone price (£ t^{-1})	35	42	540	61

4.12.7 Discussion

This measure was not considered in either the previous UK MACC studies nor in the FARMSCOPER work (Gooday *et al.* 2014, MacLeod *et al.* 2010c, Moran *et al.* 2008).

4.13 MM15: High fat diet (dietary lipids)

4.13.1 Description of the measure

This measure involves increasing the fat content (unsaturated fatty acids) of ruminant feed to reduce enteric CH_4 emissions. Unsaturated fatty acids reduce enteric emissions via three mechanisms: controlling some of the rumen microbes, acting as a hydrogen sink and partially replacing feed components which are digested in the rumen with ones which are digested in the intestine (Johnson and Johnson 1995, Martin *et al.* 2010).

From the various possible supplementary fat sources (various whole seeds and plant oils) the use of whole rapeseed or whole linseed is suggested (Frelih-Larsen *et al.* 2014). The current fat content of a typical ruminant diet is 1.5-3 DM% (Richard Dewhurst, *pers. comm.*), and the fat content should not exceed 6-7 DM% to avoid digestive problems and a reduction in weight gain or milk yield. Therefore an additional 3 DM% fat supplementation is suggested (10 DM% rapeseed in the diet). The assumption is that the fat source replaces concentrates in the diet.

4.13.2 Applicability

High-fat feed ingredients can be easily blended into the ruminant concentrate diet either on farm (where facilities exist) or at the feed mill, but it is not practical in situations where animals are grazing and not receiving concentrate supplements. Therefore it is not applicable on lowland and LFA grazing farms; the proportion of livestock on these farms is presented in Table 71.

Table 71 Proportion of livestock on lowland and LFA grazing farms in 2025 (Shepherd et al. 2007)

Livestock	England	Wales	Scotland	Northern Ireland
Dairy cows and heifers	2%	8%	2%	2%
Beef and other cattle	49%	76%	54%	84%
Sheep	66%	96%	84%	86%

It is assumed not to be used with calves (0-1 year) or the category ‘other cattle’ and ‘other sheep’ (which mainly includes adult males).

4.13.3 Abatement rate

Abatement data from the literature is presented in Table 72. Based on the meta-analysis done for the UK (McBride *et al.* 2015) we used the following equation and parameters to quantify the enteric CH_4 mitigation effect:

$$Y_m = 6.5\% * (1 - M_i * (Fat_M - Fat_B))$$

$M_{dairy} = 0.0338$, SE: ±40%

$M_{beef} = 0.0196$, SE: ±70%

$M_{sheep} = 0.0692$, SE: ±60%

$Fat_M = 0.05$ kg (kg DM)$^{-1}$

$Fat_B = 0.02$ kg (kg DM)$^{-1}$

The reduction in Y_m with the 3% additional fat is 10.1, 5.9 and 20.8% for dairy, beef and sheep, respectively. The land use change effects were assumed to be negligible if using oil seeds grown in the UK replacing forages and concentrates mostly comprised of UK-grown cereal products.

Table 72 Data from literature on abatement by feeding more fat

Abatement	Value	Country	Reference
Enteric CH_4	cattle: CH_4 emissions (g/kgDM) = 24.55(±1.029) – 0.102(±0.0147) × fat[g/kgDM]}, i.e. CH_4 red. = 4.16% CH_4 / DM% fat sheep: CH_4 emissions (g/kgDM) = 32.06(±2.129) – 0.260(±0.033) × fat[g/kgDM]}, i.e. CH_4 red. = 8.11% / DM% fat	various	(Grainger and Beauchemin 2011)
Enteric CH_4	Dairy cow (lipid <8%): CH_4 emissions (g/kgDM) = 24.27(±1.693 – 0.0821(±0.0255) × fat[g/kgDM]}, i.e. CH_4 red. = 3.38% CH_4 / DM% fat Growing beef (all treatments): CH_4 emissions (g/kgDM) = 21.97(±3.42) – 0.043(±0.0193) × fat[g/kgDM]}, i.e. CH_4 red. = 1.96% / DM% fat Sheep (lipid <8%): CH_4 emissions (g/kgDM) = 27.15(±3.645) – 0.1879(±0.0723) × fat[g/kgDM]}, i.e. CH_4 red. = 6.92% / DM% fat	various	(McBride *et al.* 2015)
Enteric CH_4	Cattle: -14% CH_4 / DMI for 5 DM% fat content (assuming a baseline of 1.5 DM%) CH_4 red. = 4±0.8% × DM% fat	France	(Pellerin *et al.* 2013)
Land use	dairy cows: +191 kg CO_2e/animal/year beef cows and cattle 1-2 years: +100 - +130 kg CO_2e/animal/year other cattle: < +130 kg CO_2e/animal/year	France	(Pellerin *et al.* 2013)

<table>
<tr><th>Abatement</th><th>Value</th><th>Country</th><th>Reference</th></tr>
<tr><td>Land use</td><td>Whole farm:<table><tr><td></td><td>On-farm</td><td>Pre-farm</td></tr><tr><td>Control</td><td>2,030</td><td>568</td></tr><tr><td>Brewers grain</td><td>2,020</td><td>536</td></tr><tr><td>Hominy</td><td>1,990</td><td>524</td></tr><tr><td>Whole cotton seed</td><td>2,010</td><td>585</td></tr></table></td><td>Australia</td><td>(Williams et al. 2014)</td></tr>
</table>

4.13.4 Current and additional future uptake

The diet of high-productivity dairy and beef animals are already supplemented with fats to boost the energy content of the diet, though the total fat content might still be lower than 5% (Dave Roberts, *pers. comm.*). Pellerin *et al.* (2013) estimated that in France 5% of dairy cows receive feed supplemented with fats. The Farm Practice Survey reported that in 2014 20% of livestock holdings increased the fat content of the diet (though the extent of total fat content was not revealed) (Defra 2015a). Further increase in productivity and efficiency in the future reference scenario is expected, the reference future uptake is estimated to be 30%, leaving 70% for maximum additional future uptake.

4.13.5 Cost

The costs of this measure is a change in average feeding costs, in particular an increase in the oilseeds and a decrease in the concentrates they are replacing. Cost data from the literature is presented in Table 72.

Table 73 Data from literature on costs of increased fat content in the diet

Costs/savings	Value ('-' sign for savings)	Country	Reference
Change in average feed price	Dairy cows: £77 animal^{-1} year^{-1} Other animals > 1 year: £33 - £55 animal^{-1} year^{-1}	France	(Pellerin *et al.* 2013)
Extruded linseed product	£476 t DM^{-1}	The Netherlands	(Van Middelaar *et al.* 2014)

As the fat content of the rapeseed is 46 DM% (INRA *et al.* 2015), and the fat content of the standard concentrate is 7.5 DM% (DairyCo 2014), therefore 7.8 DM% of the diet has to be replaced by rapeseed. The price of cracked rapeseed is £430 t fresh matter^{-1}, derived from a HGCA report (Moss 2002) and historic feed price data (DairyCo 2014), the price of concentrate is £320 t fresh matter^{-1} (DairyCo 2014). Thus the cost of diet change is £8.6 t DM^{-1}, and for the dairy, beef and sheep it is, on average, £38, £21 and £4 head^{-1} year^{-1}, respectively.

4.13.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 298 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 190, 28, 39 and 40 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 74). The UK abatement potential (without interactions, d.r. 3.5%) increased from 46 kt CO_2e y^{-1} with the low feasible potential to 661 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 35 to 497 kt CO_2e y^{-1}, respectively, in 2030 (Table 75). In all of the above cases the cost-effectiveness of the measure in the UK without interactions was £171 t CO_2e^{-1} (which is above the C price).

Table 74 MM15 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	298	171
England	190	170
Wales	28	166
Scotland	39	186
Northern Ireland	40	164

Table 75 MM15 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	35	223	422	497
2035	3.5%	46	298	562	661
2030	7.0%	35	223	422	497
2035	7.0%	46	298	562	661

The sensitivity analysis showed that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 161 and 435 kt CO_2e y^{-1}; this analysis involved changing the assumptions on applicability, uptake, additional fat content, the effect of fat content on Y_m, and feed raw material prices (Table 76). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between £27 and £317 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with the uptake, applicability and the additional fat content. The Y_m effect was varied according to the 95% CI described in Section 0, and had an important effect on both the abatement potential and the cost-effectiveness. However, the cost-effectiveness did not drop below the C price within the 95% CI of the Y_m effect. On the other hand, a 20% decrease in the price of the cracked rapeseed or a 20% increase in the price of the concentrates made the measure cost-effective.

Table 76 Sensitivity of MM15 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Applicability Dairy >1y – E Dairy >1y – W Dairy >1y – S Dairy >1y – NI Dairy <1y Beef & other >1y – E Beef & other >1y – W Beef & other >1y – S Beef & other >1y – NI Beef & other <1y Ewes & lambs – E Ewes & lambs – W Ewes & lambs – S Ewes & lambs – NI Other sheep	 0.98 0.92 0.98 0.98 0 0.51 0.24 0.46 0.16 0 0.34 0.04 0.16 0.34 0	 0.88 0.82 0.88 0.88 0 0.41 0.14 0.36 0.06 0 0.24 0 0.06 0.24 0	249	169
Applicability Dairy >1y – E Dairy >1y – W Dairy >1y – S Dairy >1y – NI Dairy <1y Beef & other >1y – E Beef & other >1y – W Beef & other >1y – S Beef & other >1y – NI Beef & other <1y Ewes & lambs – E Ewes & lambs – W Ewes & lambs – S Ewes & lambs – NI Other sheep	 0.98 0.92 0.98 0.98 0 0.51 0.24 0.46 0.16 0 0.34 0.04 0.16 0.34 0	 1 1 1 1 0 0.61 0.34 0.56 0.26 0 0.44 0.14 0.26 0.44 0	333	172
Maximum additional future uptake	0.7	0.6	255	171
Maximum additional future uptake	0.7	0.8	340	171
Change in fat content	3%	2%	198	171
Change in fat content	3%	4%	397	171
Effect of fat content on Y_m	Dairy: -3% Beef: -2% Sheep: -7%	Dairy: -2% Beef: -1% Sheep: -3%	161	317
Effect of fat content on Y_m	Dairy: -3% Beef: -2% Sheep: -7%	Dairy: -5% Beef: -3% Sheep: -11%	435	117
Price of cracked rapeseed (£ t^{-1})	430	516	298	315
Price of cracked rapeseed (£ t^{-1})	430	344	298	27
Price of concentrate feed (£ t^{-1})	320	256	298	281
Price of concentrate feed (£ t^{-1})	320	384	298	61

4.13.7 Discussion

This measure was not considered in the previous UK MACC studies or in the FARMSCOPER work (Gooday *et al.* 2014, MacLeod *et al.* 2010c, Moran *et al.* 2008).

4.14 MM16 and MM17: Improving cattle and sheep health

4.14.1 Description of the measure

Improving animal health could in principle lead to significant reductions in emissions intensity by, for example, improving the feed conversion ratio of individual animals and reducing the herd/flock breeding overhead (through improved fertility and reduced mortality). Improving health is not yet widely recognised as a mitigation measure, although the Irish marginal abatement costs curve noted that it was "likely to be included in future iterations of the MACC for Irish agriculture, when more detailed information is available on their overall extent and impact" (Schulte *et al.* 2012). The growing interest in this area is shown by the recent establishment of the Global Research Alliance's "Animal Health & Greenhouse Gas Emissions Intensity Network".

4.14.2 Applicability

Improving health could reduce emissions across all the main UK livestock species. This measure focuses on cattle and sheep because they have a greater potential for reducing UK inventory emissions than improvements in monogastric health for the following reasons:

- Ruminants account for a greater amount of the UK's GHG emissions.
- Ruminants tend to have greater exposure to pathogens.
- The controlled environments and short life-cycle of monogastrics arguably provide fewer opportunities for health improvement.
- Improvements in monogastric health are likely to lead to reductions in feed conversion ratio and feed-related GHG emissions, much of which would not be captured by the UK inventory.

Finally, the small number of studies that have looked at the links between health and GHG emissions have mainly focussed on ruminants.

4.14.3 Literature review on abatement

Evidence on the abatement potential is limited to a small number of studies of ruminants (Table 77 and Table 78).

Table 77 Cattle health and GHG studies

Abatement	Country	Reference
Mastitis prevention: Reduction in the incidence of clinical mastitis from 25% to 18%, and a reduction in sub-clinical from 33% to 15% leading to a reduction in GHG emissions intensity of 2.5%	Spain	(Hospido and Sonesson 2005)

Abatement	Country	Reference
BVD eradication programme: Dairy herd: 2% improvement in milk production per animal and a 3% reduction in replacement rate. Beef herd: 3% improvement in replacement rate leading to a 1.5% reduction in GHG emissions	N. Ireland	(Guelbenzu and Graham 2013)
Disease measures for ten cattle diseases in the UK: Reduction in emissions intensity across the UK cattle herd of between 2% to 6%, depending on the disease control scenario.	UK	(ADAS 2014)

Table 78 Sheep health and GHG studies

Abatement	Country	Reference
Increasing routine disease treatment -***Treating for all common ailments*** 5% reduction in EI compared to treating for common ailments 22% reduction in EI compared to treating only when sick. -***Treating for some common ailments*** 18% reduction in EI (compared with treating only when sick)	Scotland	(Stott *et al.* 2010)

4.14.4 Quantification of the effect of improving cattle health

The abatement potential and cost-effectiveness are based on the scenario analysis undertaken in ADAS (2014). The MACCs in the current study indicated abatements (at <£100 t CO_2e^{-1}) of: 3.0 Mt CO_2e y^{-1} (dairy cattle), 0.68 Mt CO_2e y^{-1} (suckler beef) and 0.48 Mt CO_2e y^{-1} (dairy beef). However, these abatements do not take into account interactions between the health measures. As ADAS (2014) note: "It is important to recognise that the model does not deal explicitly with interactions between MMs and given the extensive links between diseases, these are likely to be significant. As such abatement values for each of the MMs cannot be aggregated to estimate sector abatement potential." In order to assess the total abatement from improving cattle health, ADAS (2014) used a scenario based approach to quantify the effects of a 20% and 50% movement from reference to a healthy cattle population (see Table 79).

Table 79 Change in emissions from a 20% and 50% movement from reference to a healthy cattle population (adapted from (ADAS 2014, p24)

	Baseline	Healthy	20% movement	50% movement
Total emissions (kt CO_2e)	25,826	22,953	25,251	24,389
Change from reference (kt CO_2e)		-2,873	-575	-1,436
Change from reference (%)		-11%	-2%	-6%

In this MACC, we have assumed the movements in health under each scenario outlined in Table 80. The smaller changes in health status in the low and central scenarios may be achievable via relatively modest uptake of a subset of the health measures outlined in ADAS (2014). This subset could focus on a relatively small number of cost-effective measures with limited negative interactions (or even positive interactions) so the mitigation should therefore be achievable at low or negative cost. The bigger improvements in health status assumed in the high and maximum scenarios may be achievable within the fourth or fifth C budget period, however these would require uptake of a wider range of health measures and it is less clear what how these measures might interact and what the combined abatement and cost-effectiveness might be.

Table 80 Movement from reference to healthy performance and abatement potential in 2035 for UK cattle

Scenario	Move from reference to healthy	AP (kt CO_2e y^{-1})
LFP	9%	188
CFP	23%	469
HFP	46%	958
MTP	50%	1,042

In order to estimate the cost-effectiveness, the weighted average CE of measure costing < £52 t CO_2e^{-1} was calculated (based on ADAS 2014, p18, p21, p23), see Table 81.

Table 81 Assumed costs (UK average, 2015 prices)

Costs/savings	Value ('-' sign for savings)
Dairy cattle	-35
Suckler beef	-19
Dairy beef	-101
All cattle	-42

4.14.5 Quantification of the effect of improving sheep health

In order to estimate the GHG abatement potential that could be achieved by improving sheep health, a similar approach was adopted to the scenario approach used in ADAS (2014). The main steps were:

1. Identify the main parameters changing in response to changing health status.
2. Estimate the change in the parameters arising from a move from average health status to high health status (i.e. flocks following a comprehensive health plan, with no major health issues).
3. Calculate the output of meat and GHG for reference and high health flocks.
4. Calculate the change in gross margin arising from the health plan by subtracting the increase in gross margin (from increased output) from the cost of implementing the health plan.
5. Estimate the cost-effectiveness by calculating the change in gross margin arising from the implementation of a comprehensive health plan and dividing it by the change in GHG.

4.14.6 Estimating the change in key parameters

A brief literature review was undertaken to identify the key sheep diseases and parameters likely to change with disease treatment (AHDB 2015, Bennett and Ijpelaar 2003, Defra 2012b, Nieuwhof and Bishop 2005, Sargison 2008, Scott 2013, Scott *et al.* 2007, Skuce *et al.* 2014, Stott *et al.* 2010, Stott *et al.* 2005). In light of the review and discussion of sheep health during the Expert Workshop (see Appendix C), a survey was designed and circulated to 24 sheep experts. In total, 17 responses were received, including seven questionnaires either fully or partially completed. High health values were estimated by taking the average of responses, excluding values worse than the reference values (see Table 82). The following observations are made regarding the results:

- Higher health status flocks should have lower emissions intensity (i.e. lower emissions per unit of output), due to:
    - Lower ewe death rates
    - Lower rates of barren ewes (particularly in hills)
    - Lower lamb mortality
    - More lambs sold per ewe mated (a function of conception rate, fecundity and lamb mortality).
    - Faster growth rates.
- Differences in performance seem less marked in the upland systems compared to hill and lowground.
- Note that these differences are for moving from average to high health status. Mitigation from moving from below average to average may be greater.

Table 82 Results of the high health values reported in the sheep health questionnaire

	Average health-status	High health value	% change
System: HILL Breed: Blackface, South Country & Lairg type Cheviot			
Ewe replacement rate	0.26	No change	0%
Ewe death rate %	11%	6%	-45%
Barren ewes %	7%	4%	-46%
Lamb mortality during pregnancy (scanning to birth) %	3.6%	3%	-7%
Lamb mortality (birth - weaning) %	10.7%	9%	-20%
Lamb mortality (~scanning to sale) %	14.3%	12%	-16%
Lambs sold/retained per 100 ewes mated	87	100	15%
Birth-weaning growth rate, g/day	178	203	14%
LW of finished lambs (kg)	34	No change	0%
System: UPLAND Breed: Blackface to a terminal or crossing sire			
Ewe replacement rate	0.23	No change	0%
Ewe death rate %	3%	No change	0%

	Average health-status	High health value	% change
Barren ewes %	5%	4.0%	-20%
Lamb mortality during pregnancy (scanning to birth)%	5%	3.5%	-30%
Lamb mortality (birth - weaning) %	9%	7.3%	-19%
Lamb mortality (~scanning to sale)	14%	12.0%	-14%
Lambs sold/retained per 100 ewes mated	140	148	6%
Birth-weaning growth rate, g/day	250	268.75	8%
LW of finished lambs (kg)	36	No change	0%
System: LOWGROUND Breed: Crossbred ewe x terminal sire ram			
Ewe replacement rate	0.22	No change	0%
Ewe death rate, %	5%	3%	-35%
Barren ewes %	3%	2%	-20%
Lamb mortality during pregnancy (scanning to birth) %	7%	5%	-23%
Lamb mortality (birth - weaning) %	8%	5%	-33%
Lamb mortality (~scanning to sale)	15%	11%	-27%
Lambs sold/retained per 100 ewes tupped	160	179	12%
Birth-weaning growth rate, g day^{-1}	250	285	14%
LW of finished lambs (kg)	42	No change	0%

4.14.7 Quantification of the abatement potential of improving sheep health

In order to quantify the effects of improved health on GHG emissions, the three sheep systems (hill, upland and lowground) were modelled in GLEAM using the average and high health values in Table 82. The results are given in Table 83 - Table 85.

Table 83 Difference in emissions intensity between flock with average flocks and those with high health status and comparison of the results from the current study with other studies

Study	Units	Hill average	Hill high health	Upland average	Upland high health	Lowground average	Lowground high health
The current study	kg CO_2e kg CW^{-1}	49.3	34.5	20.9	19.7	16.6	14.3
	kg CO_2e kg LW^{-1}	24.6	17.2	10.5	9.8	8.3	7.2
(EBLEX 2012)	kg CO_2e kg LW^{-1}	14.4		10.9		11.0	
(Jones *et al.* 2014)	kg CO_2e kg LW^{-1}	17.9		12.8		10.8	

Table 84 % change in EI arising from changing the values of all parameters simultaneously and of changing parameters individually from average to high health status value

	Hill	Upland	Lowground
ALL parameters	-30%	-6%	-13%
Increased ewe fertility	-3.4%	-0.9%	-0.5%
Increased lambs scanned per ewe mated	-11.1%	-2.0%	-5.5%
Decreased lamb mortality from scanning to birth	-0.3%	-1.3%	-1.5%
Decreased mortality aged 0-1 year	-1.9%	-1.0%	-1.6%
Decreased mortality >1 year	-17.8%	0.0%	-3.9%
Reduced time to target weight	-0.6%	-0.6%	-1.2%

Table 85% change in EI arising from changing the values of single parameters by + or – 5%

	Hill	Upland	Lowground
Ewe fertility +5%	-4.8%	-3.9%	-4.0%
Lambs scanned per ewe mated +5%	-4.8%	-4.0%	-4.0%
Lamb mortality from scanning to birth -5%	-0.2%	-0.2%	-0.3%
Mortality aged 0-1 year -5%	-0.5%	-0.3%	-0.2%
Mortality >1 year -5%	-2.3%	-0.4%	-0.6%
Time to target weight -5%	-0.3%	-0.5%	-0.5%

4.14.8 Discussion of the abatement results

There is a large decrease in EI in hill and lowground systems, arising mainly from increased numbers of lambs scanned and decreased mortality of animals older than 1 year (primarily ewes and their replacements). Both of these changes increase the number of lambs sold per breeding animal (ewes, rams and their replacements), thereby reducing the size of the breeding overhead. The change in EI in the upland system is modest, reflecting the smaller difference between the average and high health values for these parameters. The sensitivity depends on the starting value, e.g. the EI of flocks with high levels of enzootic abortions would be much more sensitive to changes in pre-birth death rates.

4.14.9 Cost-effectiveness

The cost-effectiveness of improving health depends on:

1. The cost of implementing the health measures.
2. The change in flock performance that arises from the health measures.
3. The change in emissions and output (lambs, ewes and wool) that arises from the health measures.

These, in turn, are dependent on how the improvement is achieved, i.e. the specific health measures used, and the starting (physical and economic) performance of the flock. As there are many possible combinations of health challenges and treatments, the cost-effectiveness of achieving mitigation via improved sheep health is likely to vary considerably. Table 86 illustrates how the cost-effectiveness can vary with different assumptions about (a) change in health costs, (b) change in physical performance (c) different gross margins per lamb sold. Note that an increase in gross margin per lamb changes the CE from -£18 t CO_2e^{-1} to -£104 t CO_2e^{-1}, illustrating its sensitivity to changes in farm economic performance and, in turn, to the prices of inputs and outputs, and farm productivity.

Table 86 Illustrative calculations of the cost-effectiveness of health improvement

Scenario	Reference scenario	Scenario A: 20/0	Scenario B: 50/0	Scenario C: 50/20
Health costs (£ $flock^{-1}$ y^{-1})	1000	4000	5000	5000
Move from average to high health status	0%	20%	50%	50%
Gross margin per lamb sold (% above reference scenario value)	0%	0%	0%	20%
Production and emissions				
Total GHG (t CO_2e^{-1} y^{-1})	557	549	548	548
Total CW (t CW y^{-1})	33.6	34.6	36.1	36.1
No of lambs sold	1,279	1,321	1,384	1,384
Ewes sold	170	174	179	179
Costs				
Additional health costs (£ y^{-1})	0	3,000	4,000	4,000
Benefits				
Gross margin (£ lamb $sold^{-1}$)	34	34	34	41
Extra lambs	0	41	105	105
Extra income from lambs	0	1,403	3,537	4,244
Cast ewe price	70	70	70	70
Extra ewes sold	0	4	9	9
Extra income from ewes	0	245	613	613
Total extra income	0	1,648	4,149	4,857
Cost-effectiveness				
Net cost/benefit of health plan (£ y^{-1})	0	1,352	-149	-857
GHG reduction (t CO_2e y^{-1})	0.0	7.8	8.3	8.3
CE (£ t CO_2e^{-1})	NA	172.6	-18.1	-103.6

4.14.10 Current and additional future uptake

The Farm Practices Survey (Defra 2015a) found that in England, in the "Grazing livestock-LFA" category:

- 47% of respondents did not have a written or recorded farm health plan

- 47% of respondents either did not undertake animal health and welfare/disease management training

The abatement potentials for each scenario, and the assumptions on which they are based, are outlined in Table 87.

Table 87 Movement from reference to healthy performance and abatement potential in 2035 for UK sheep (all systems average)

Scenario	Move from reference to healthy	AP (kt CO_2e year^{-1})
LFP	4%	87
CFP	23%	218
HFP	46%	445
MTP	50%	484

4.14.11 Cost-effectiveness

Based on Table 86 and (2010) (who concluded that improving sheep health could provide mitigation at cost of between £31 and £135 t CO_2e^{-1} depending on the health management strategy employed), it is assumed that the 20% improvement can be achieved at a cost of £30 t CO_2e^{-1} by targeting health measures that provide production benefits to offset much of the costs. This should be treated with some caution as the CE can vary a great deal and further work is required in order to better quantify the CE for different combinations of farm types, health challenges and treatments.

4.14.12 Conclusions and issues

Improving sheep health seems to have potential to provide cost-effective GHG abatement, however these estimates are preliminary, and the following should be borne in mind:

- CE will vary a great deal depending on the starting performance of the flock, the lowground average flock used in the example is relatively healthy, hence the improvements in performance and reduction in GHG are relatively modest. Flocks with below average health status are likely to provide scope for larger and more cost-effective reductions in GHG.
- The reference situation needs to be specified more precisely, in terms of current health costs and (economic and physical) performance.
- Calculation of change in gross margin needs to be refined, to distinguish between (a) increased animal output where additional costs will be incurred and the benefits should be measured minus costs of rearing (e.g. increased fertility) and (b) increased output where much of the costs are incurred already (e.g. decreased mortality, where much of costs of feeding, vet care, tagging etc. are incurred, so reducing mortality should be based on the sale value of the extra animals, not their gross margin.

- Some market benefits are not included, e.g. increased digestive efficiency arising from reduced parasite loads can reduce feed costs and emissions, thereby lowering the cost-effectiveness (Houdijk *et al.* 2014).
- Improving sheep health could have significant (positive and negative) ancillary effects, such as improved animal welfare or decreased treatment efficacy (e.g. via increased anthelminthic resistance).
- GHGs arising from the production of the treatments not included.

4.15 MM18: Selection for balanced breeding goals in beef cattle

4.15.1 Description of the measure

This measure relates to the broader uptake of genetic improvement in beef cattle and is in addition to the included measures on dairy breeding goals in previous iterations of the MACC (MacLeod *et al.* 2010c, Moran *et al.* 2008). Previous studies focused on the UK have shown that current methods of genetic improvement not only increases farm profitability (Amer *et al.* 2007) but also contributes to greenhouse gas (GHG) mitigation (Genesis Faraday 2008, Moran *et al.* 2008). Although a large part of the breeding goal for the beef value index, carcass traits are currently not directly recorded in the UK, with selection being based on correlated live weights, ultrasound measures of fat and muscle depth and visual assessment of muscling. Directly measuring carcass traits could potentially improve the rate of genetic improvement and benefits through selection.

The UK beef breeding industry can typically be described as having a pyramid like structure, where all genetic improvement (and the supporting performance recording) is undertaken in purebred populations which is then disseminated through to the rest of the industry through the purchase of the improved stock by commercial producers.

Given all these expectations, this measure considered the likely impact both in terms of increased profit and reduced GHG, of the genetic improvement achieved being disseminated through to the commercial herd level and by increasing the uptake/dissemination of improved genetics through to commercial animals.

4.15.2 Applicability

The measure could be targeted to all beef animals as it is based on improving the entire population by using real industry data. If the population as a whole is improved most, if not all farms, will be affected as available breeding animals will be improved based on gene flows through the population. The speed with which this measure can be fully achieved is related to the users taking an active and direct decision to introduce (or retain) particular breeding stock based on the new breeding tools or not. Also the proportion of top animals retained from one generation to the next, or intensity of selection, will affect the speed with which this measure is achieved. If user behaviour is slow to make this change to use such additional information the rate of flow of genes is slowed down. We have looked at alternative rates of uptake and selection intensity.

4.15.3 Abatement rate

The abatement rate was estimated building on detailed modelling of genetic improvement in a Defra funded project (IF0207) (Bioscience Network Limited 2012). The potential abatement rate was modelled by estimating the likely change in selection response by adding new traits directly the selection index. Results for all alternative indices were compared relative to expected improvement rates and impact from selection using a base (current) index. The base index was constructed to mimic the terminal sire index that is currently provided for some UK breeds through Signet, namely the Beef Value index which includes recorded traits on birth weight, weight at 200 and 400 days, muscle score, fat depth, muscle depth, gestation length and calving difficulty. The traits in the breeding goal were carcass weight, carcass fat score, carcass conformation, gestation length (as a trait of the calf) and calving difficulty (as a trait of the calf). The additional value of including direct measures of carcass performance as a recorded trait as well as part of the goal was modelled. The genetic and phenotypic parameters estimates assumed were primarily based on those used in genetic evaluations in the UK (Amer *et al.* 1998) and were added to by parameters from wider studies (Roughsedge *et al.* 2005, Roughsedge *et al.* 2011).

4.15.4 Current and additional future uptake

Economic return at the whole industry level from uptake of different selection approaches in the purebred population were calculated assuming that only 50% of animals slaughtered each year were the progeny of recorded animals. More details on the modelling assumptions made are described in Amer *et al.* (2007).

Discounted incomes were calculated for each of the goal traits based on the annual genetic gain in the trait units and their economic values discounted by the specific genetic expression coefficients considering time and number of expressions of the genetic progress, and the number of bulls from the breeding programmes required to mate the industry females. A discount rate of 3.5% and 7% was used when discounting genetic expressions of goal traits over time. The cumulative marginal net discounted return from 10 or 20 years of selection (at a steady state) with benefits considered over a 20-year horizon were calculated. Impacts at the industry level were quantified in terms of overall GHG reduction, the economic value of that GHG reduction, the expected increase in profit at the farm level and the cumulative economic benefit.

In all initial investigations it was assumed that only 50% of cows that produce progeny destined for slaughter in the UK are mated to bulls that flow from recorded pedigree populations undergoing genetic improvement. This was assumed as it reflected the current estimate level of use in the UK. As part of the current study the effect of increasing the percentage of cows mated from to 100% was also investigated.

4.15.5 Cost

The costs of this measure were developed using the economic weights routinely used in breeding goals. These economic weights are based on whole farm bio-economic models where each of the goal traits are changed by one unit and the impact on total farm profit of that change is calculated. These economic weights are used to weight different traits in an overall balanced breeding goal but then can also be used to estimate the economic benefit of alternative selection focus goals. The estimates of economic weights used in the base index were as reported in Amer *et al.* (1998) for the Beef value index, namely £1.2 kg^{-1} for carcass weight, £-6.0 unit $score^{-1}$ for carcass fat, £7.0 unit $score^{-1}$ for carcass conformation £-1.0 day^{-1} for gestation length and £-2.47 $\%^{-1}$ for calving difficulty.

Improvement in some of the goal traits under consideration in the balanced breeding goal are known to have an impact of the GHG emissions from a beef production system. As part of a previous Defra study (FG0808), a biological model was developed to quantify the impact of an independent change in a selected trait on overall greenhouse gas emissions from an "average" beef system. This information was used to develop selection index weights that focus solely on their value in relation to reducing GHG emissions per unit for two units of interest: CO_2e kg saleable $meat^{-1}$ and CO_2e breeding cow^{-1}. Index weights, taking account of the discounted genetic expressions were then used to derive alternative breeding goals for the two scenarios. These weights were also used to quantify the impact of response to selection on GHG emission from a beef system and multiplied by the prevailing carbon price (Price *et al.* 2007) when disseminating genetic improvement to the wider population.

4.15.6 Cost-effectiveness and abatement potential

Table 88 describes the potential change in different traits that drive economic and GHG efficiency in beef systems compared to the status quo and those changes that would be partially modelled in the FAPRI reference scenario. This is therefore additive change to the future reference.

Table 88 Relative change in genetic trends in traits in the breed goal for the two new breeding goal scenarios

	WITH genomics and feed efficiency	WITHOUT genomics and feed efficiency
Carcass weight	3.21	2.38
Carcass fat score	0	0
Carcass conformation score	0.03	0.02
Gestation length	0.04	0.03
Calving difficulty	0	0
Feed efficiency	-14.62	-10.83

Table 89 maps out the potential impact of the alternative breeding goals assuming that selection were to commence in the baseline year and continue at the same rate of change throughout the report window (20 years). Assuming that all cows where mated to genetic improved bulls enhanced by genomics and the inclusion of direct measures of feed efficiency the amount of GHG abated after 20 years of selection would be 578 kt CO_2e y^{-1} and the economic benefit to farmers wold be M£27 (d.r. 3.5%). A less optimistic scenario (included in the MACC as the maximum technical potential) is that selection continues to 10 years and genomics and feed efficiency traits are not incorporated into the breeding programme.

4.15.7 Discussion

Improving beef breeding programmes to incorporate new information and help increase uptake at the commercial level has the potential to provide significant cost-effective GHG abatement. It should be noted that this would require a step change in the beef breeding industry which is currently dominated by a small proportion of the population undertaking the recording and driving the genetic improvement. This means that breeding tools are not widely understood by commercial beef producers and therefore hard to bring about behavioural change. However, a number of initiatives are underway in the industry that will increase the interest in the recording of new traits such as feed efficiency (Defra funded Beef Feed Efficiency Programme) as well as increasing commercial animal recording and use of genetic improvement (e.g. Scottish Government Beef Efficiency Scheme).

Table 89 Movement from reference scenario of limited genetic improvement to 100% of dams being mated to improved bulls based on alternative discounting rates and alternative approaches of ongoing selection whereby carcass records are included in the in the breeding goal and as a recorded trait and the use of genomics is included

	2011	2015	2020	2025	2030	2032
Beef cows (,000 head) 100% cows impacted	1,638	1,560	1,517	1,490	1,471	1,464
3.5% d.r. - ongoing selection						
Mitigation t CO_2e y^{-1}	-8,616	-97,241	-210,986	-321,479	-429,971	-428,074
Farmer profit increase M£ y^{-1}		£8.5	£15.6	£20.0	£22.5	£22.4
7% d.r. - ongoing selection						
Mitigation t CO_2e y^{-1}	-8,616	-97,241	-210,986	-321,479	-429,971	-428,074
Farmer profit increase M£ y^{-1}		£6.7	£10.4	£11.3	£10.8	£10.8
3.5% d.r. - ongoing selection, with genomics and feed efficiency recording						
Mitigation t CO_2e y^{-1}	-11,631	-131,275	-284,830	-433,997	-580,461	-577,899
Farmer profit increase M£ y^{-1}		£10.3	£18.8	£24.1	£27.2	£27.0
7% d.r. - ongoing selection, with genomics and feed efficiency recording						
Mitigation t CO_2e y^{-1}	-11,631	-131,275	-284,830	-433,997	-580,461	-577,899
Farmer profit increase M£ y^{-1}		£8.2	£12.6	£13.7	£13.1	£13.0

4.16 MM19: Slurry acidification

4.16.1 Description of the measure

Slurry acidification is achieved by adding strong acids (e.g. sulfuric acid or hydrogen chloride) to the slurry to achieve a pH of 4.5-6.8 depending on the slurry type, the acid used (Fangueiro *et al.* 2015). There are three main types of technology relating to the stage at which the acid is added to the slurry: in-house, in the storage tank, or before field application.

4.16.2 Applicability

This technique is applicable to slurry which is stored in tanks, regardless of the livestock type. For dairy, beef and pig excreta, 41%, 4% and 38% respectively is stored in liquid form (Webb *et al.* 2014), half of which is stored in slurry tanks as opposed to slurry lagoons (Defra 2014a). Therefore the applicability of the measure is 21%, 2% and 19% for dairy cattle, beef cattle and pigs.

4.16.3 Abatement rate

According to a review by Fangueiro *et al.* (2015), reductions of 67-87% of manure CH_4 emissions were achieved using H_2SO_4, and 90%, 40-65% and 17-75% reduction was observed with lactic acid, hydrochloric acid and nitric acid, respectively. Ammonia emissions also decreased by 50-88% with sulphuric acid and 27-98% with other acids – therefore indirect N_2O emissions must have decreased as well.

In the current study we assume a 75% reduction in the methane conversion factor and 70% decrease in the fraction of the manure N which is volatilised.

On the other hand, N_2O emissions after manure spreading can increase by 23% (Fangueiro *et al.* 2015), this increase is deducted from the GHG mitigation.

4.16.4 Current and additional future uptake

This technique is established and commonly used in a few countries, like Denmark, where in 2013 25% of the slurry was acidified (Fangueiro et al 2013), but hasn't been adopted yet in the UK. We assume that uptake will not happen on smaller farms (< 50 dairy cows: 6% of the herd, up to 30 beef cows: 28% of the herd, up to 25 sows: 5% of the herd (Defra 2014b)). Therefore the maximum additional future uptake is estimated as 94%, 72% and 95% of dairy cattle, beef cattle and pigs, respectively.

4.16.5 Cost

The cost of implementing a measure is £2.40 (t slurry)$^{-1}$, according to the Baltic Deal farmers' organisation (Baltic Deal 2015). With annual slurry production of 0.35, 0.2 and 0.03 t for dairy, beef and pigs this translates to £44, £25 and £4 head^{-1} y^{-1}, respectively. Kai *et al.* (2008) provided a cost estimate of £43 y^{-1} for a 500 kg livestock unit, which is roughly the same value for dairy and slightly lower than the previous values for beef and pigs. We use the value of Kai *et al.* (2008) in the current study.

On the benefit side, the reduced N loss can increase the N content of the slurry, increasing the mineral fertiliser equivalent value of the manure by 39-100% (Fangueiro *et al.* 2015), thus reducing the need for additional synthetic N fertilisation. These savings in synthetic N equivalent were reported to be 26 kg N (100 kg slurry N)$^{-1}$ (Kai *et al.* 2008). This benefit is approximated here by assuming that every 100 kg N excreted slurry which is subsequently stored as acidified is worth an additional 10 kg synthetic N.

4.16.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 276 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 185, 26, 25 and 40 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 90). The UK abatement potential (without interactions, d.r. 3.5%) increased from 43 kt CO_2e y^{-1} with the low feasible potential to 613 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 32 to 461 kt CO_2e y^{-1}, respectively, in 2030 (Table 91). In all of the above cases the UK cost-effectiveness of the measure without interactions was £45 t CO_2e^{-1} (which is below the C price).

Table 90 MM19 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential	Cost-effectiveness
	kt CO_2e y^{-1}	£ t CO_2e^{-1}
UK	276	45
England	185	44
Wales	26	49
Scotland	25	48
Northern Ireland	40	47

Table 91 MM19 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	32	207	424	461
2035	3.5%	43	276	564	613
2030	7.0%	32	207	424	461
2035	7.0%	43	276	564	613

The sensitivity analysis showed that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 138 and 440 kt CO_2e y^{-1}; this analysis involved changing the assumptions on applicability, uptake, change in the proportion of N volatilised from the slurry tanks, change in the CH_4 conversion factor of the slurry tanks, change in the soil N_2O emission after spreading, annualised cost of the measure and the benefits from N savings (Table 92). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between £17 and £74 t CO_2e^{-1} for the respective cases. The abatement potential increased linearly with uptake and applicability. Increasing the effect on the MCF or the N volatilisation by 10% did not have a big impact on the abatement potential, and increasing the soil N_2O emissions by 10% decreased the abatement potential by only 0.4%. A 50% increase in the annualised cost of the measure (capital costs and maintenance) increased the cost-effectiveness by 64%, though it still remained under the C price. Increasing the benefits from N savings by 50% improved the cost-effectiveness only by 11%.

Table 92 Sensitivity of MM19 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Applicability	Dairy: 0.21 Beef: 0.02 Pigs: 0.19	Dairy: 0.11 Beef: 0 Pigs: 0.09	138	45
Applicability	Dairy: 0.21 Beef: 0.02 Pigs: 0.19	Dairy: 0.31 Beef: 0.12 Pigs: 0.29	440	47
Maximum additional future uptake	Dairy: 0.94 Beef: 0.72 Pigs: 0.95	Dairy: 0.84 Beef: 0.62 Pigs: 0.85	247	45

Parameter	Original value	New value	Abatement potential	Cost-effectiveness
			kt CO_2e y^{-1}	£ t CO_2e^{-1}
Maximum additional future uptake	Dairy: 0.94 Beef: 0.72 Pigs: 0.95	Dairy: 1 Beef: 0.82 Pigs: 1	294	46
Change in MCF	-75%	-65%	245	51
Change in MCF	-75%	-85%	307	41
Change in N volatilisation	-70%	-60%	270	46
Change in N volatilisation	-70%	-80%	282	45
Change in soil N_2O emission after spreading	23%	33%	275	46
Change in soil N_2O emission after spreading	23%	13%	277	45
Annualised costs (£ (500 kg LW $y)^{-1}$)	43	64.5	276	74
Annualised costs (£ (500 kg LW $y)^{-1}$)	43	21.5	276	17
Benefit from N savings (kg N (100 kg N $excreted)^{-1}$)	10	15	276	40
Benefit from N savings (kg N (100 kg N $excreted)^{-1}$)	10	5	276	51

4.16.7 Discussion

This measure was not considered in the previous UK MACC studies or in the FARMSCOPER work (Gooday *et al.* 2014, MacLeod *et al.* 2010c, Moran *et al.* 2008).

4.17 MM20-MM22: Anaerobic digestion

4.17.1 Description of the measure

This mitigation measure implies that anaerobic digesters are built and used to treat livestock excreta what would otherwise be stored in slurry tanks or lagoons. The assumption is that the manure and biomass is transported to a nearby digester from surrounding farms. Three options are investigated:

i. MM20: 250 kW capacity digester to be supplied with cattle manure and maize silage (annual supply of substrate from 1,800 dairy cattle, 360 beef cattle and 5,000 fresh t maize silage)

ii. MM21: 500 kW capacity digester to be supplied with pig and poultry manure and maize silage (annual supply of substrate from 2,000 sows, 100,000 layers and 300,000 broilers with 10,000 fresh t maize silage)

iii. MM22: 1000 kW capacity digester to be supplied with maize silage (annual supply of substrate: 40,000 fresh t maize silage)

4.17.2 Applicability

The applicability of the measures is based on farm size statistics: farms above 100 dairy cows and 100 sows are assumed to export their manure to the plants, i.e. the applicability is 78% and 88%, respectively, for MM20 and MM21. The applicability of MM22 is restricted as 2% of arable land.

4.17.3 Abatement rate

The abatement is calculated as the sum of the GHG savings, i.e. reduced emissions from storage (including pre-digestion losses and emissions from the AD plant) and replaced emissions from energy production. The main parameters are presented in Table 96.

4.17.4 Current and additional future uptake

The future uptake is estimated based on the Defra report AC0409 (Mistry *et al.* 2011), which suggested that 194 AD plants would be viable in England and Wales (without food waste co-digestion). Extrapolating to the UK this could mean around 240 AD plants. The maximum additional future uptake is set to 0.5 so that the CFP scenario (in 2035) results in a similar number of AD plants in the UK.

4.17.5 Cost

The main parameters are presented in Table 96. The capital and maintenance cost estimates are based on Mistry *et al.* (2011):

$$Capex = 79.5 * Substrate \ + 516{,}000$$

Capex: capital cost (£)

Substrate: annual amount of substrate (fresh t y^{-1})

$$Opreational\ cost = 218 * Capacity^{-0.306}$$

Operational cost: annual operational cost (£ y^{-1})

Capacity: capacity of the AD plant (fresh t y^{-1})

The electricity price is based on data provided by the CCC, the heat price is assumed to be half of the electricity price (as of p kW^{-1}). The feed-in tariff is not included in the calculations. The cost of the manure is assumed to be 0, while the maize silage costs £22 (fresh t)$^{-1}$ (Mistry *et al.* 2011). The transport cost is calculated considering the fuel and other costs of road transport, assuming an average distance of 5 km.

4.17.6 Cost-effectiveness and abatement potential

The abatement potential of MM20, MM21 and MM22, respectively, without interactions and assuming CFP uptake in the UK were 176, 89 and 78 kt CO_2e y^{-1}

in 2035 (d.r. 3.5%) (Table 93). This could be achieved by 175, 47 and 19 AD plants, respectively, for MM20, MM21 and MM22. The land are required for the maize silage production was 136, 272 and 1,087 ha for each AD plant for the three measures (MM20, MM21, MM22), respectively. The UK abatement potential (without interactions, d.r. 3.5%) increased from 27 to 392, 14 to 198 and 12 to 173 kt CO_2e y^{-1} from low feasible potential to maximum technical potential in 2035 for the three respective mitigation measures (Table 94). The two larger capacity AD measures were cost-effective in 2035 with both discount rate 3.5% and 7%, while MM20 was above the C price (Table 95).

Table 93 MM20, 21 and 22 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	MM20 AP kt CO_2e y^{-1}	MM20 CE £ t CO_2e^{-1}	MM21 AP kt CO_2e y^{-1}	MM21 CE £ t CO_2e^{-1}	MM22 AP kt CO_2e y^{-1}	MM22 CE £ t CO_2e^{-1}
UK	176	131	89	-20	78	-43
England	111	131	77	-20	66	-43
Wales	21	131	1	-20	1	-43
Scotland	18	131	4	-20	10	-43
Northern Ireland	28	131	7	-20	1	-43

Table 94 MM20, 21 and 22 abatement potential without interactions (kt CO_2e y^{-1}, 2035, UK)

	d.r.	LFP	CFP	HFP	MTP
MM20	3.5%	27	176	361	392
MM20	7.0%	27	176	361	392
MM21	3.5%	14	89	183	198
MM21	7.0%	14	89	183	198
MM21	3.5%	12	78	159	173
MM21	7.0%	12	78	159	173

Table 95 MM20, 21 and 22 cost-effectiveness without interactions (£ t CO_2e^{-1}, 2035, UK)

	d.r.	LFP	CFP	HFP	MTP
MM20	3.5%	131	131	131	131
MM20	7.0%	139	139	139	139
MM21	3.5%	-20	-20	-20	-20
MM21	7.0%	9	9	9	9
MM21	3.5%	-43	-43	-43	-43
MM21	7.0%	-19	-19	-19	-19

The sensitivity analysis is presented in Table 96. The abatement potential of MM20 (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 2130 and 265 kt CO_2e y^{-1}, the cost-effectiveness ranged between £21 and £336 t CO_2e^{-1}. The abatement potential of MM21 (without interactions, 2035, UK, CFP, d.r. 3.5%) was between 66 and 137 kt CO_2e y^{-1}, with cost-effectiveness ranging from -£91 to £114 t CO_2e^{-1}. Finally, the abatement potential of MM22 (without interactions, 2035, UK, CFP, d.r. 3.5%) was between 62 and 117 kt CO_2e y^{-1}, with cost-effectiveness between -£86 and £33 t CO_2e^{-1}.

Table 96 Sensitivity of MM20, MM21 and MM22 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Relevance	Parameter	Original value	New value	MM20 AP kt CO_2e y^{-1}	MM20 CE £ t CO_2e^{-1}	MM21 AP kt CO_2e y^{-1}	MM21 CE £ t CO_2e^{-1}	MM22 AP kt CO_2e y^{-1}	MM22 CE £ t CO_2e^{-1}
MM20	Applicability	0.78	0.68	154	131	NA	NA	NA	NA
MM20	Applicability	0.78	0.88	199	131	NA	NA	NA	NA
MM20	Maximum additional future uptake	0.5	0.4	141	131	NA	NA	NA	NA
MM20	Maximum additional future uptake	0.5	0.6	212	131	NA	NA	NA	NA
MM20	Number of dairy cows (head AD $plant^{-1}$)	1,800	900	265	130	NA	NA	NA	NA
MM20	Number of dairy cows (head AD $plant^{-1}$)	1,800	2,700	147	125	NA	NA	NA	NA
MM20	Amount of maize silage co-digested (fresh t AD $plant^{-1}$ y^{-1})	5,000	2,500	132	197	NA	NA	NA	NA
MM20	Amount of maize silage co-digested (fresh t AD $plant^{-1}$ y^{-1})	5,000	7,500	221	91	NA	NA	NA	NA
MM21	Applicability	0.88	0.78	NA	NA	89	-20	NA	NA
MM21	Applicability	0.88	0.98	NA	NA	89	-20	NA	NA
MM21	Maximum additional future uptake	0.5	0.4	NA	NA	79	-20	NA	NA
MM21	Maximum additional future uptake	0.5	0.6	NA	NA	99	-20	NA	NA
MM21	Number of breeding pigs (head AD $plant^{-1}$)	2,000	1,000	NA	NA	71	-20	NA	NA
MM21	Number of breeding pigs (head AD $plant^{-1}$)	2,000	3,000	NA	NA	107	-20	NA	NA
MM21	Amount of maize silage co-digested (fresh t AD $plant^{-1}$ y^{-1})	10,000	5,000	NA	NA	137	1	NA	NA
MM21	Amount of maize silage co-digested (fresh t AD $plant^{-1}$ y^{-1})	10,000	15,000	NA	NA	73	-36	NA	NA
MM22	Applicability	0.02	0.01	NA	NA	NA	NA	39	-43
MM22	Applicability	0.02	0.03	NA	NA	NA	NA	117	-43
MM22	Maximum additional future uptake	0.5	0.4	NA	NA	NA	NA	62	-43
MM22	Maximum additional future uptake	0.5	0.6	NA	NA	NA	NA	93	-43
MM22	Amount of maize silage digested (fresh t AD $plant^{-1}$ y^{-1})	40,000	20,000	NA	NA	NA	NA	78	-15
MM22	Amount of maize silage digested (fresh t AD $plant^{-1}$ y^{-1})	40,000	60,000	NA	NA	NA	NA	78	-56

Relevance	Parameter	Original value	New value	MM20 AP kt $CO_2e\ y^{-1}$	MM20 CE £ t CO_2e^{-1}	MM21 AP kt $CO_2e\ y^{-1}$	MM21 CE £ t CO_2e^{-1}	MM22 AP kt $CO_2e\ y^{-1}$	MM22 CE £ t CO_2e^{-1}
MM20-MM22	MCF of the digester	85%	80%	182	151	92	5	80	-18
MM20-MM22	MCF of the digester	85%	90%	171	109	87	-46	76	-70
MM20-MM22	MCF of the alternative slurry store	17%	20%	223	106	113	-14	99	-32
MM20-MM22	MCF of the alternative slurry store	17%	14%	130	175	66	-31	57	-62
MM20-MM22	Efficiency of electricity generation (% of CH_4 energy content)	36%	31%	174	177	88	24	77	0
MM20-MM22	Efficiency of electricity generation (% of CH_4 energy content)	36%	41%	179	86	91	-62	79	-85
MM20-MM22	Efficiency of heat generation (% of CH_4 energy content)	40%	35%	170	150	86	-7	75	-31
MM20-MM22	Efficiency of heat generation (% of CH_4 energy content)	40%	45%	183	113	93	-32	81	-55
MM20-MM22	Electricity used by the AD plant (% produced)	12%	15%	176	142	89	-9	78	-33
MM20-MM22	Electricity used by the AD plant (% produced)	12%	9%	177	120	90	-31	78	-54
MM20-MM22	Heat used by the AD plant (% produced)	9%	11%	175	134	89	-18	77	-41
MM20-MM22	Heat used by the AD plant (% produced)	9%	7%	178	128	90	-22	78	-45
MM20-MM22	Electricity used on the farm or exported (% of net production)	100%	80%	172	198	87	44	76	20
MM20-MM22	Electricity used on the farm or exported (% of net production)	100%	90%	174	164	88	12	77	-12
MM20-MM22	Heat used on the farm or exported (% of net production)	60%	40%	158	186	80	18	70	-8
MM20-MM22	Heat used on the farm or exported (% of net production)	60%	50%	167	157	85	-2	74	-26
MM20-MM22	Operational engine hours (kWh*kW $year^{-1}$)	7,000	6,500	176	131	89	-20	78	-43
MM20-MM22	Operational engine hours (kWh*kW $year^{-1}$)	7,000	7,500	176	131	89	-20	78	-43
MM20-MM22	AD plant lifetime (y)	20	15	176	170	89	5	78	-29
MM20-MM22	AD plant lifetime (y)	20	25	176	108	89	-35	78	-52
MM20-MM22	Capital cost equation - α	79.5	95.4	176	157	89	-2	78	-32
MM20-MM22	Capital cost equation - α	79.5	63.6	176	105	89	-38	78	-54

Relevance	Parameter	Original value	New value	MM20 AP kt CO_2e y^{-1}	MM20 CE £ t CO_2e^{-1}	MM21 AP kt CO_2e y^{-1}	MM21 CE £ t CO_2e^{-1}	MM22 AP kt CO_2e y^{-1}	MM22 CE £ t CO_2e^{-1}
MM20-MM22	Capital cost equation - β	516,000	619,200	176	138	89	-16	78	-41
MM20-MM22	Capital cost equation - β	516,000	412,800	176	124	89	-24	78	-45
MM20-MM22	Operating cost equation - α	218	262	176	179	89	10	78	-26
MM20-MM22	Operating cost equation - α	218	174	176	83	89	-50	78	-60
MM20-MM22	Operating cost equation - β	-0.306	-0.245	176	336	89	114	78	33
MM20-MM22	Operating cost equation - β	-0.306	-0.367	176	21	89	-91	78	-83
MM20-MM22	Average travel distance (km)	5	15	176	209	89	34	78	-11
MM20-MM22	Average travel distance (km)	5	10	176	170	89	7	78	-27
MM20-MM22	Truck load (fresh t $truck^{-1}$)	11	9	176	140	89	-14	78	-40
MM20-MM22	Truck load (fresh t $truck^{-1}$)	11	13	176	125	89	-24	78	-46
MM20-MM22	Fuel consumption (miles $gallon^{-1}$)	9.1	10.1	176	131	89	-20	78	-43
MM20-MM22	Fuel consumption (miles $gallon^{-1}$)	9.1	8.1	176	131	89	-20	78	-43
MM20-MM22	Other running costs of lorry (£ km^{-1})	0.14	0.17	176	131	89	-20	78	-43
MM20-MM22	Other running costs of lorry (£ km^{-1})	0.14	0.11	176	130	89	-20	78	-43
MM20-MM22	Fixed costs of lorry + wages (£ day^{-1})	220	264	176	137	89	-16	78	-41
MM20-MM22	Fixed costs of lorry + wages (£ day^{-1})	220	176	176	124	89	-24	78	-46
MM20-MM22	Distance travelled a day (km day^{-1})	150	130	176	136	89	-17	78	-41
MM20-MM22	Distance travelled a day (km day^{-1})	150	170	176	127	89	-23	78	-45
MM20-MM22	Maize silage price (£ fresh t^{-1})	22	26.4	176	153	89	3	78	0
MM20-MM22	Maize silage price (£ fresh t^{-1})	22	17.6	176	109	89	-43	78	-86
MM20-MM22	Energy price scenario	Central	Low	176	146	89	-5	78	-27
MM20-MM22	Energy price scenario	Central	High	176	107	89	-44	78	-67

4.17.7 Discussion

Anaerobic digestion was assessed in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008), both the potential for on-farm and centralised anaerobic digesters. The latter was comparable to the mitigation measures described here, though with the main difference of co-digestion: in the 2008 and 2010 MACCs the substrate was assumed to be animal excreta only, without any biomass. The combined abatement potential of the dairy and beef CAD was 463 kt CO_2e y^{-1} (without interactions, 2022, CFP, d.r. 7%) (Table 97), which compares to 176 kt CO_2e y^{-1} of MM20 (*AD: cattle manure with maize slurry co-digestion*) found in the current study. Likewise, MM21 (*AD: pig/poultry manure with maize slurry co-digestion*) was estimated to have lower abatement potential (89 kt CO_2e y^{-1}) than the combined pig and poultry CAD abatement potential in the 2008/2010 MACCs (67+219 kt CO_2e y^{-1}).

Table 97 Centralised anaerobic digestion (5MW) abatement potential and cost-effectiveness without interactions in earlier MACC work (2022, UK, CFP, d.r. 7%)

		AP kt CO_2e y^{-1}	CE £ t CO_2e^{-1}
2010 MACC, Pessimistic/Optimistic	CAD-Dairy-5MW	308	37
2010 MACC, Pessimistic/Optimistic	CAD-Beef-5MW	155	99
2010 MACC, Pessimistic/Optimistic	CAD-Pig-5MW	67	24
2010 MACC, Pessimistic/Optimistic	CAD-Poultry-5MW	219	0
2008 MACC	CAD-Dairy-5MW	308	49
2008 MACC	CAD-Beef-5MW	155	111
2008 MACC	CAD-Pig-5MW	67	36
2008 MACC	CAD- Poultry -5MW	219	12

Comparing the 2008/2010 MACC estimates with the current ones are difficult due to the complexity of the calculations. The main differences are the following:

- The 2008/2010 MACCs did not include biomass digestion (MM22) or co-co-digestion (MM20 and MM21).
- Though the applicability of the measures in both the 2008/2010 and the current MACCs were based on farm size, the values were slightly higher in the previous MACCs (dairy 91%, beef 85%, pigs 93%, poultry 92%) than in the current study (dairy-beef 78%, pigs-poultry 88%).
- The proportion of annual manure production available for AD is lower in the current study than in the previous ones: 41% dairy, 6% beef, 35-38% pigs, 91-99% poultry versus 59%, 50%, 90% and 73% for dairy, beef, pigs and poultry, respectively, in the previous MACCs.
- The 2008/2010 MACCs assumed full utilisation of the generated heat, while the current study assumes 60% utilisation.
- The CH_4 emission from pre-digestion storage was not included in the 2008/2010 MACCs.

- The CH_4 leakage from the digester is assumed to be 3% in the current study while it was 1% in the previous studies.
- The efficiency of heat production is lower in the current study: 40% versus 50% in the previous MACCs, while the electricity production efficiency is only slightly higher (36% versus 35%, respectively, in the current and previous works).
- The emission factor for replaced electricity is lower in the current study (0.071 kg CO_2e kWh^{-1}) than it was in the previous MACCs (0.430 kg CO_2e kWh^{-1}), though the replaced heat emissions were not considered previously (in the recent study the emission factor for heat is 0.269 kg CO_2e kWh^{-1}).
- The capital and operating cost equations used in the current study produce higher costs than the equation used in the 2010 MACC.
- The electricity and heat prices were lower in the 2008/2010 MACCs than in the current MACC. The electricity price was 5.4 to 6.0 p kWh^{-1} between 2008 and 2022 in the former MACC and increasing from 10.15 to 15.20 p kWh^{-1} between 2015 and 2035 in the latter MACC. In both cases the heat price was assumed to be half of the electricity price.
- In the 2008/2010 MACCs the Renewable Obligation Certificates were included, at a decreasing price from 5.8 to 3.3 p kWh^{-1} between 2008 and 2022. The Feed-In-Tariff in the current MACC was not included.

4.18 MM23: Afforestation on agricultural land

4.18.1 Approach

Table 98 Summary of the approach

Parameter	Basis
Additional planting rates	Based on rates set out in FC (Forestry Commission 2015f).
Systems and species	The additional planting is assumed to be a combination of Forest Woodland and Broadleaf 1 (Crabtree 2014, p2).
Abatement rates	Sequestration in trees and soil C losses from planting are based on the Woodland Carbon Code lookup tables. Soil C sequestration post-planting is based on the CDM approach outlined in West (2011).
Abatement potential	Based on the weighted average AR and planting rates.
Costs	Based on the costs in FC (Forestry Commission 2015b, Forestry Commission 2015d).
Cost-effectiveness	CE over 100 years for discount rates of 3.5% and 7%

4.18.1.1 *Quantifying additional planting rates*

In the MACC, we need to distinguish between abatement that will be achieved in the reference scenario and the additional abatement that could be achieved with a changed policy context. The additional planting is defined as the difference between the planting rates in the Forestry Commission's Mid-emissions and the 'no policy' Business as usual (BAU) emissions scenarios. The BAU emissions scenario is based on cessation of the current policy of RDP forestry payments and no afforestation after 2010. The Mid emissions planting rates are those likely to occur with policy aspirations akin to those in the 2013 Forestry and Woodlands Policy Statement. These planting rates are quantified by the Forestry Commission (Forestry Commission 2015b, Forestry Commission 2015f) and set out in Table 99.

Table 99 Additional planting due to policy (ha y^{-1})

Year	Reference[1]	Additional[2]	E	W	S	NI
2015	0	11,287	3,470	22	7,500	295
2016	0	16,680	3,870	2,465	10,000	345
2017	0	17,080	4,270	2,465	10,000	345
2018	0	17,480	4,670	2,465	10,000	345
2019	0	17,880	5,070	2,465	10,000	345
2020	0	18,180	5,370	2,465	10,000	345
2021	0	17,636	5,115	2,011	10,000	511
2022	0	17,736	5,115	2,011	10,000	611
2023	0	15,422	5,115	2,011	7,636	661
2024	0	15,422	5,115	2,011	7,636	661
2025	0	15,472	5,115	2,011	7,636	711
2026	0	15,522	5,115	2,011	7,636	761
2027	0	15,572	5,115	2,011	7,636	811
2028	0	15,622	5,115	2,011	7,636	861
2029	0	15,622	5,115	2,011	7,636	861
2030	0	15,622	5,115	2,011	7,636	861
2031	0	15,622	5,115	2,011	7,636	861
2032	0	15,622	5,115	2,011	7,636	861
2033	0	15,622	5,115	2,011	7,636	861
2034	0	15,622	5,115	2,011	7,636	861
2035	0	15,622	5,115	2,011	7,636	861
2036	0	15,622	5,115	2,011	7,636	861
2037	0	15,622	5,115	2,011	7,636	861
2038	0	15,622	5,115	2,011	7,636	861
2039	0	15,622	5,115	2,011	7,636	861
2040	0	15,622	5,115	2,011	7,636	861
2041	0	13,922	4,915	511	7,636	861
2042	0	13,722	4,715	511	7,636	861
2043	0	13,522	4,515	511	7,636	861
2044	0	13,322	4,315	511	7,636	861
2045	0	13,122	4,115	511	7,636	861
2046	0	12,922	3,915	511	7,636	861
2047	0	12,722	3,715	511	7,636	861
2048	0	12,522	3,515	511	7,636	861

Year	Reference[1]	Additional[2]	E	W	S	NI
2049	0	12,322	3,315	511	7,636	861
2050	0	12,122	3,115	511	7,636	861

Notes:
[1] BAU projections which has no afforestation after 2010
[2] Additional planting that could occur with policy aspirations akin to those in the 2013 Forestry and Woodlands Policy Statement

4.18.1.2 *Systems and species planted*

The additional planting is assumed to be a combination of Forest Woodland and Broadleaf 1 (Crabtree 2014, p2), i.e. a mixture of sycamore, ash, birch (SAB), douglas fir (DF) and oak (OK) (see Table 100).

Table 100 Composition of the additional planting (expressed in terms of the Carbon Lookup Table categories)

	E	W	S	NI
SAB, yield class 6 – unthinned	0%	0%	25%	0%
SAB, yield class 8 – unthinned	27%	29%	0%	27%
SAB, yield class 6 – thinned	0%	0%	36%	0%
SAB, yield class 8 – thinned	33%	31%	0%	33%
DF, yield class 10 – thinned	0%	0%	14%	0%
DF, yield class 14 – thinned	13%	12%	0%	13%
OK, yield class 4 – unthinned	27%	29%	25%	27%

4.18.1.3 *Abatement rates*

The following (positive and negative) emissions are included in the calculations:

- CO_2 from soil carbon losses arising from tree planting.
- CO_2 from soil carbon sequestered in forests post-planting.
- CO_2 from carbon sequestered in growing trees.

The analysis does not include changes in emissions arising from the substitution of forest products for other products (such as fossil fuels, steel or concrete); however the impact of these omissions is limited because the calculations are based on forest systems with no clearfell and limited thinning.

The abatement rates were based on the Carbon Lookup Tables v1.5 (Forestry Commission 2015a). The soil C loss during planting was based on the following assumptions (Table 101):

- The proportions of new woodland planted on mineral and organo-mineral soil types provided by the Forestry Commission (2015e),
- Previous land use pasture and
- Volume of soil disturbed during planting is 380 m^3 ha^{-1}, which leads to 5% of topsoil C being lost from organo-mineral soils and 0% of topsoil C lost being lost from mineral soils (Forestry Commission 2015c).

Table 101 Determination of the % of topsoil carbon lost during planting, by DA

	E		W		S		NI		Source
Soil type[1]	OM	M	M	M	OM	M	OM	M	
% of new woodland planted on different soil types	13%	87%	29%	29%	71%	71%	71%	29%	(Forestry Commission 2015e)
Assumed topsoil carbon loss	5%	0%	0%	0%	5%	5%	5%	0%	(Forestry Commission 2015c, step 1)
Weighted average % topsoil carbon loss	0.6%		0.8%		3.5%		3.5%		
t CO_2e ha^{-1} for 1% soil C loss	2.9		3.3		5.9		4.8		(Forestry Commission 2015c, step 2)
Soil C losses at planting (t CO_2e ha^{-1})	1.8		2.6		20.5		16.7		

Notes:
[1] OM: organo-mineral soils; M: mineral soils

Soil C sequestration post-planting was estimated using the CDM approach outlined in West (2011).

4.18.1.4 *Abatement potential*

The abatement potential was calculated for each year by multiplying the weighted average AR for each of the DA (t CO_2e ha^{-1} $year^{-1}$) by the additional areas planted each year.

4.18.1.5 *Costs and cost-effectiveness*

The cost assumptions used are based on Forestry Commission data (Forestry Commission 2015b, Forestry Commission 2015d) and outlined in Table 102. The cost-effectiveness was calculated for the lifetime of the forests, assuming a lifetime of 100 years.

Table 102 Costs of afforestation (£ ha^{-1})

	Type of cost	E	W	S	NI
Planting and fencing (grant)	One-off	4,246	4,242	3,267	2,400
Planting and fencing (private costs)	One-off	849	848	653	480
Planting and fencing (total)	One-off	5,095	5,090	3,920	2,880
Government admin costs	One-off	637	636	490	360
Income foregone	Recurring	220	350	120	100

4.18.2 Results

Table 103 Abatement potential (kt $CO_2e\ y^{-1}$) for 2030 and 2035 by DA and for the UK (mid emissions planting scenario, CFP, d.r. 3.5% and d.r. 7%)

	UK total	E	W	S	NI
AP in 2030	1,829	742	317	709	61
AP in 2035	3,642	1,285	537	1,689	130

Table 104 Cost-effectiveness CE (£ t CO_2e^{-1}) for different time periods (mid emissions planting scenario, CFP, year 2030 and year 2035)

Discount rate	UK weighted average	E	W	S	NI
3.5%	37	39	51	33	21
7%	27	29	35	26	16

4.18.3 Comparison with other studies

Table 103 gives the total UK abatement potential (CFP) for 2030 and 2035. The latest FC estimates of the abatement had not been published at time of writing, but were expected to be of a similar magnitude. However, it should be noted that the estimation of abatement via afforestation is sensitive to the assumptions made and other studies have come up with different estimates. Crabtree concluded that "woodland creation could make no useful contribution to meeting short-term policy targets" (i.e. to 2030) and "carbon emissions from soil – when planted on organo-mineral soils – and low rates of sequestration in early life limit the short-term abatement (to 2030) achieved by many forest systems." (2014, p1 and p6).

In the 2008 MACC study Moran *et al.* (2008) estimated that a significant (albeit lower than this study) abatement could be achieved via afforestation in the short term (Table 105). The differences between the abatement potential in the current study and the 2008 MACC are due to differences in the assumed planting rates, the types of forest systems planted and the methods used to calculate the abatement rates. Differences in the forest systems and the cost assumptions (in particular the revenue from timber sales) can lead to different estimates of CE, though there is greater agreement between studies regarding the cost-effectiveness of afforestation (Table 106).

Table 105 Comparison with MACC 2008

	This study	MACC 2008
Forest system	A mixture of sycamore, ash, birch (SAB), douglas fir and oak. Some thinning. No clearfell	Sitka spruce Thinned. Clearfell after 49 years.
Planting rate and period	Variable, average ~16,170 ha y^{-1}	10,750 ha y^{-1} * Central estimate
Abatement rate method	Based on Carbon Code (Forestry Commission 2015a)	Based on CEH projections

	This study	MACC 2008
Abatement potential	0.47 Mt CO_2e y^{-1} between 2015-2029 (CFP) 2.93 Mt CO_2e y^{-1} between 2015-2050 (CFP)	0.98 Mt CO_2e y^{-1} between 2008-2057 (CFP)
CE (£ t CO_2e^{-1})	37 (21 to 51 by DA) (d.r. 3.5%) 27 (16 to 35 by DA) (d.r. 7%)	£7 (d.r. 3.5%)

Notes:
* MTP additional planting rate = 30,000 – 8,500 = 21,500 ha y^{-1} (Moran *et al.* 2008, p91); CFP = MTP * 50% = 10,750 ha y^{-1}

Table 106 Comparison of cost-effectiveness of abatement with other estimates

Study	Costs/benefits included	Discount rate	Period	CE (£ t CO_2e^{-1})
This study	Planting and fencing Govt admin costs Income foregone	3.5%	100 years	21 to 51 by DA
		7%	100 years	16 to 35 by DA
(Forestry Commission 2015b)	Planting and fencing Govt admin costs Income foregone	3.5%	2015-3032	53
		3.5%	~100 years	~15
(Crabtree 2014)	Planting fencing and management Income forgone (p36)	Declining from 3.5% to 2% (p12)	2014-2200	Farm woodland: 48 to 108 Broadleaf: 32 to 84
(Nijnik *et al.* 2013)	Planting costs, timber revenues, income forgone	3.5%	Over rotation	27 to 65

4.18.4 Sensitivity to key assumptions

4.18.4.1 *Planting rates*

As planting rates increase, it is likely that the quality of land planted will increase, increasing the income foregone and the yield class (and therefore rate of carbon sequestration) of the trees.

4.18.4.2 *Timing*

Afforestation leads to net emissions in the years immediately after planting when the loss of soil carbon is greater than the carbon sequestered by tree growth (Figure 2). A period of more rapid sequestration 10 to 40 years after planting is followed by slower sequestration as the trees mature. The abatement is therefore highly sensitive to the period over which it is measured.

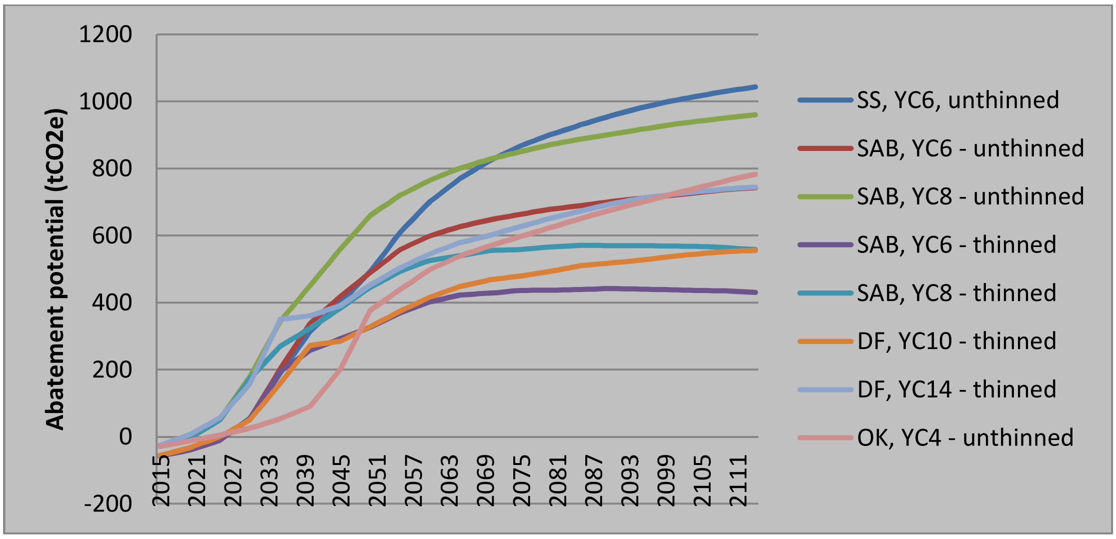

Figure 2 Cumulative abatement from planting one hectare in 2015 (assuming 10% soil C loss at planting)

4.18.4.3 *Forest systems*

Figure 2 also illustrates the differences in abatement potential between forest systems. For example, to 2035 the oak system has a much lower abatement potential, and therefore substituting oak with faster growing species will increase the abatement potential in the short term (see **Error! Reference source not found.**) but not necessarily in the medium (up to 2050) or long (up to 2100) term.

Table 107 CFP abatement potential (kt $CO_2e\ y^{-1}$) for England in 2030 and 2035 with baseline forest systems (27% unthinned SAB, 33% thinned SAB, 27% oak and 13% douglas fir) and with oak replaced with SAB

	Baseline	Oak replaced with SAB
England, 2030	741	923
England, 2035	1,285	1,570

Note that none of the systems in Figure 2 are clearfelled. Clearfelling fundamentally changes the abatement potential by:

- reducing the amount of C sequestered in living trees,
- increasing the amount of C stored in wood products,
- reducing emissions through the substitution of timber products for higher emission intensity materials (e.g. steel or concrete) or fuels.

4.18.4.4 *Costs and cost-effectiveness*

Clearfelling changes the cost-effectiveness by providing a significant income from the sale of timber when the stand is felled. In theory the sales should make the cost-effectiveness negative, however because the income is received 40 or 50 years after planting, the cost-effectiveness of clearfelled plantations is highly sensitive to the discount rate used.

In this analysis, the agricultural income foregone is assumed to range from £100 to £350 ha^{-1} y^{-1} – see Table 102. In fact on much of the (lower productivity) land likely to be afforested, the income (before subsidies) may be low or negative (Bell 2014, p3). Table 108 and **Error! Reference source not found.** illustrate the effect of different rates of income foregone on cost-effectiveness.

Table 108 Effect of different income foregone rates on NPV and CE in England

Income foregone	Parameter	d.r. 3.5%	d.r. 7%
Reference value: £220 ha^{-1} y^{-1}	Discounted (3.5%) 100y AR (t CO_2e ha^{-1})	298	298
	NPV (£ ha^{-1})	11,634	8,497
	CE (£ t CO_2e^{-1})	39	29
Reference +10%: £242 ha^{-1} y^{-1}	Discounted (3.5%) 100y AR (t CO_2e ha^{-1})	298	298
	NPV (£ ha^{-1})	12,190	8,782
	CE (£ t CO_2e^{-1})	41	30
Change in CE		*+4.8%*	*+3.4%*

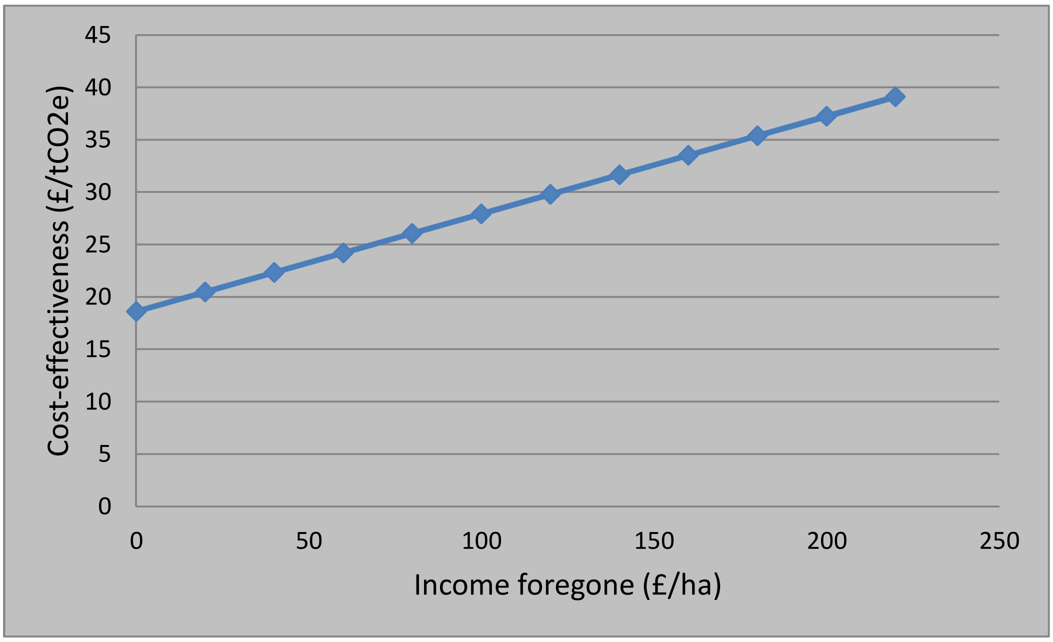

Figure 3 The relationship between agricultural income forgone and the cost-effectiveness of abatement from tree planting in England (CE over 100 years, d.r. 3.5%)

4.18.4.5 *Soil C losses during establishment*

The Woodland Code provides estimates of CO_2 emissions arising from soil carbon loss during tree planting (see FC 2015d). The rates of CO_2 per ha vary with:

- soil type (mineral or organo-mineral),
- site preparation method (13 options),
- previous land use (semi-natural, pasture or arable) and
- location (i.e. DA: England, Wales, Scotland, Northern Ireland).

The weighted average topsoil C loss (Table 109) was estimated by combining the proportions of new woodland planted on mineral and organo-mineral soil types (Forestry Commission 2015e) with the soil C losses (Forestry Commission 2015c). The baseline assumption was of a rate of soil disturbance of 380 m^3 ha^{-1}. Assuming a rate of 710 or 1,030 m^3 ha^{-1} leads to significant changes in the abatement potential in 2030 and 2035 (Table 110).

Table 109 % of topsoil carbon loss in year one from planting

	Volume of soil disturbed (m^3 ha^{-1})		
	380	710	1,030
England	0.6%	3.0%	6.9%
Wales	0.8%	3.3%	7.5%
Scotland	3.5%	7.7%	15.6%
Northern Ireland	3.5%	7.7%	15.6%

Table 110 UK abatement potential (kt CO_2e y^{-1}) for different rates of soil disturbance during planting (CFP)

	Volume of soil disturbed (m^3 ha^{-1})			
	0	380	710	1,030
UK, 2030	1,880	1,829	1,578	1,106
UK, 2035	3,653	3,642	3,393	2,921

4.18.4.6 ***Soil C sequestration post-planting***

Carbon can be sequestered in woodland soils post-planting, particularly in woodlands with limited thinning and no clearfell (such as the systems in this analysis). However, soil C accumulation is not currently quantified in the Carbon Code approach, so the CDM approach outlined in West (2011) was used to calculate it. This leads to a significant increase in the abatement and a reduction in the CE (Table 111).

Table 111 UK abatement potential (kt CO_2e y^{-1}) with and without post-planting soil C sequestration (CFP, assuming a soil disturbance rate of 380 m^3 ha^{-1})

	No soil C seq'n	Soil C seq'n
UK, 2030	1,133	1,829
UK, 2035	2,721	3,642

4.18.5 Displaced emissions

Planting trees on agricultural land can lead to a reduction in agricultural output and a consequent displacement of production and emissions to outside the UK. This can lead to a net increase in emissions if (a) the emissions intensity of the displaced production is higher than the domestic production lost or (b) if the displaced production leads to land use change.

Potential ways of approaching this issue include:

1. Assuming that displacing production does not lead to land use change elsewhere, and that the production induced outwith the UK occurs with a similar carbon footprint to the displaced production (Crabtree 2014, p22).
2. Assuming that trees are only planted in ways that do not reduce production (e.g. on fallow, buffer strips, possibly via agroforestry). However, it is uncertain what fraction of the additional planting could be achieved without reducing production.
3. Use consequential life-cycle analysis (LCA) to calculate the net change in emissions, based on the emissions intensity of the marginal production (including the land use change induced by it).

The assumption in the first approach that a reduction in UK production could be offset by increasing production elsewhere in the world at the same or lower EI is debatable as increasing production outside the UK may induce land use change. Simply assuming that somewhere would produce with the same or lower EI could create perverse outcomes. The second approach is valid but requires further work to quantify the fraction of the additional planting that could be achieved without reducing production. Using consequential LCA is arguably the most appropriate approach; however it is complex and outwith the scope of this project.

An alternative way to gain insight into the extent to which afforestation could occur without a net increase in emissions would be to identify areas where the abatement per kg of lost output is higher than the emissions arising from the displaced production, e.g. map the abatement and the current production and identify areas where the abatement per kg of CW lost is greater than the emissions arising from the displaced production. An example of this type of calculation is provided in Table 112. In this example, the results indicate that afforestation is likely to lead to an abatement of 137 kg CO_2e for each kg of CW lost. The emissions arising from the displaced production depend on where and how it is produced. For comparison, potential substitutes for the lost UK red meat production have emissions intensities ranging from 15 kg CO_2e kg CW^{-1} (small ruminant meat, Oceania) to 73 kg CO_2e kg CW^{-1} (beef, Latin America) (Opio *et al.* 2013, p44 and p29).

Table 112 Comparison of abatement from planting and the lost production over 100 years

Assumptions		
Upland sheep system, Scotland		
Ewes (and associated lambs) (ha^{-1})	2.0	
CW output (kg ha^{-1} y^{-1})	60	
Discount rate		3.5%
Results		
Abatement from afforestation, 100y, discounted by 3.5% (t CO_2e ha^{-1})		235.8

Production, 100y, discounted by 3.5% (t CW ha^{-1})	1.7
kg CO_2e abated per kg CW lost	137.2

4.18.6 Ancillary costs and benefits of afforestation

Afforestation of agricultural land reduces food availability at a time when demand for livestock commodities is increasing. It therefor likely to have a negative effect on food security, though this effect is likely to be small given the low productivity of the land afforested.

Woodland creation can have a wide range of ancillary benefits, such as contributing to climate change adaptation, economic growth and improving the quality of the environment. FC (2015b) cite the following benefits of woodland creation:

- rural growth,
- recreation,
- renewable energy,
- habitat creation and biodiversity,
- flood alleviation,
- water quality and cooling and
- air quality and shade.

4.19 MM24: Behavioural change in fuel efficiency of mobile machinery

4.19.1 Description of the measure

This measure is the uptake of a change in behaviour by farm operatives to actively manage energy (fuel use), to carry out regular maintenance of all farm machinery and to improve driving style. Energy management is the use of energy data and knowledge bases to monitor and control energy use. It usually involves tracking energy consumption against influencing factors (e.g. production levels, weather conditions, workrates) to identify areas of inefficiency. Regular maintenance requires inspections, repairs and maintenance to ensure that equipment operates at optimum efficiency. For field machinery this includes complying with recommended service schedules, tyre choice / optimum ballasting and matching of tractors and implements. Eco-driving techniques include, among other things, improved speed and gear control techniques and planning routes ahead.

4.19.2 Applicability

This measure could be applied to all mobile farm machinery.

4.19.3 Abatement rate

Abatement data from literature is presented in Table 113. Estimates of total achievable fuel savings range from 11.5% to 30%. Expecting a considerable improvement in fuel efficiency and in technology to aid driving by the fourth and fifth C budget period, we assumed that an additional 10% improvement can be achieved in the future.

Table 113 Data from literature on abatement by behavioural change in fuel efficiency of mobile machinery

Abatement	Value	Country	Reference
Fuel use	-10% by improved energy management -5% by improved maintenance	UK	(AEA Technologies and FEC Services 2010)
Fuel use	-11.5% by correct machinery settings and driving technique	UK	(Warwick HRI and FEC Services 2007)
Fuel use	-10% by improved engine adjustment -20% by eco-driving	France	(Pellerin *et al.* 2013)

Reference mobile machinery energy use was sourced from a report from Warwick HRI and FEC Services (2007) on a crop/livestock type basis.

4.19.4 Current and additional future uptake

We assumed that in the cropping and diary sectors 50% uptake will happen without additional policy intervention, leaving the additional maximum future uptake at 50%. In the beef and sheep sectors we assumed that only 20% uptake will happen in the future reference scenario, allowing for 80% additional maximum future uptake.

4.19.5 Cost

Cost data from the literature is presented in Table 114. In the current study we used the UK values provided by AEA Technologies and FEC Services (2010), with the additional assumption that the net costs for livestock will be £0.01 kWh^{-1}.

Table 114 Costs and benefits of behavioural change in fuel efficiency of mobile machinery

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Net cost of implementing the measure	Combinable crops: £0.002 kWh^{-1} Root crops: £0.185 kWh^{-1} Field vegetables: £0.048 kWh^{-1} Horticulture: £0.185 kWh^{-1}	UK	2010	(AEA Technologies and FEC Services 2010)
Costs	Engine adjustment (every 6 years): £141 tractor^{-1} Training (every 6 years): £155 tractor^{-1}	France	2010	(Pellerin *et al.* 2013)

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Fuel saving	Engine adjustment: £0.16-0.32 engine hour^{-1} Training: £0.32-0.64 engine hour^{-1}	France	2010	(Pellerin *et al.* 2013)
Net cost	Engine adjustment: -£65 – -£156 tractor^{-1} y^{-1} Training: -£154 – -£337 tractor^{-1} y^{-1}	France	2010	(Pellerin *et al.* 2013)

4.19.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 45 kt CO_2e y^{-1} in 2035 (d.r. 3.5%) (Table 115). The UK abatement potential (without interactions, d.r. 3.5%) increased from 18 kt CO_2e y^{-1} with the low feasible potential to 99 kt CO_2e y^{-1} assuming the maximum technical potential in 2035 (Table 116). In all of the above cases the UK average cost-effectiveness of the measure without interactions was £90 t CO_2e^{-1} (which is below the C price).

Table 115 MM24 abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
UK	45	90
England	33	95
Wales	2	48
Scotland	7	89
Northern Ireland	2	58

Table 116 MM24 abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	13	34	63	75
2035	3.5%	18	45	84	99
2030	7.0%	13	34	63	75
2035	7.0%	18	45	84	99

The sensitivity analysis demonstrated the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varying between 22 and 67 kt CO_2e y^{-1}; this analysis involved changing the assumptions on uptake, change in fuel use and net cost of the measure (Table 117). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between £45 and £135 t CO_2e^{-1} in the respective cases. The abatement potential increased linearly with the uptake and the change in fuel use, and increasing the net costs by 50% increased the cost-effectiveness beyond the C price.

Table 117 Sensitivity of MM24 abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Maximum additional future uptake	Crops: 0.5 Dairy: 0.5 Beef: 0.8 Sheep: 0.8	Crops: 0.4 Dairy: 0.4 Beef: 0.7 Sheep: 0.7	36	89
Maximum additional future uptake	Crops: 0.5 Dairy: 0.5 Beef: 0.8 Sheep: 0.8	Crops: 0.6 Dairy: 0.6 Beef: 0.9 Sheep: 0.9	53	90
Change in fuel use	-10%	-5%	22	90
Change in fuel use	-10%	-15%	67	90
Net cost (£ kWh^{-1})	Combinable crops: 0.002 Root crops: 0.185 Field vegetables: 0.048 Horticulture: 0.185 Livestock: 0.01	Combinable crops: 0.003 Root crops: 0.278 Field vegetables: 0.072 Horticulture: 0.278 Livestock: 0.015	45	135
Net cost (£ kWh^{-1})	Combinable crops: 0.002 Root crops: 0.185 Field vegetables: 0.048 Horticulture: 0.185 Livestock: 0.01	Combinable crops: 0.001 Root crops: 0.093 Field vegetables: 0.024 Horticulture: 0.093 Livestock: 0.005	45	45

4.19.7 Discussion

This measure was not considered in the previous UK MACC studies or in the FARMSCOPER work (Gooday *et al.* 2014, MacLeod *et al.* 2010c, Moran *et al.* 2008).

5 Results and discussion of the MACC analysis

5.1 Abatement potential in the UK

The analysis demonstrated that the cost-effective abatement potential in the UK in 2030 is 2.87 Mt $CO_2e\ y^{-1}$, with central feasible potential and 3.5% discount rate (in Table 118 and on Figure 4 the cumulative abatement of measures up to CE with interactions < £78 t CO_2e^{-1}). Part of this abatement, specifically 0.80 Mt $CO_2e\ y^{-1}$, could be avoided in "win-win" situations, while the abatement of an additional 1.26 Mt $CO_2e\ y^{-1}$ would require mitigation beyond the 2030 C price of £78 CO_2e^{-1}. The contributions of England, Wales, Scotland and Northern Ireland to the UK's cost-effective abatement potential were 1.46, 0.79, 0.48 and 0.14 Mt $CO_2e\ y^{-1}$, respectively (Table 119). The 2.87 Mt $CO_2e\ y^{-1}$ cost-effective abatement potential is 7% of the estimated GHG emissions from UK agriculture in 2030 (Defra 2011c) (Table 122), consisting of 5%, 18%, 7% and 3% mitigation of agricultural emissions for England, Wales, Scotland and Northern Ireland, respectively. The abatement of the same measures that deliver 2.87 Mt $CO_2e\ y^{-1}$ cost-effective abatement would be 3.01 Mt $CO_2e\ y^{-1}$ if interactions between them have been ignored.

The cost-effective abatement potential in 2035 in the UK (CFP, d.r. 3.5%) was 6.09 Mt $CO_2e\ y^{-1}$ (in Table 120 and on Figure 5 the cumulative abatement of measures up to CE with interactions < £114 t CO_2e^{-1})), England, Wales, Scotland and Northern Ireland providing 47%, 32%, 15% and 6% of this abatement (Table 121). Of the total UK abatement, 1.37 Mt $CO_2e\ y^{-1}$ is potentially "win-win", while an additional 1.01 Mt $CO_2e\ y^{-1}$ could be abated at an abatement cost higher than the C price. The projected increase for the five years 2030 to 2035 was due to a combination of increasing uptake of the measures and the increase in the C price from £78 to £114 CO_2e^{-1}.

The order of the measures on the MACCs does not change substantially between the years or with discount rate 3.5% and 7%, and all but one measure stay either cost-effective or not cost-effective across the scenarios.

Further MACC tables describing other scenarios are provided in Appendix D.

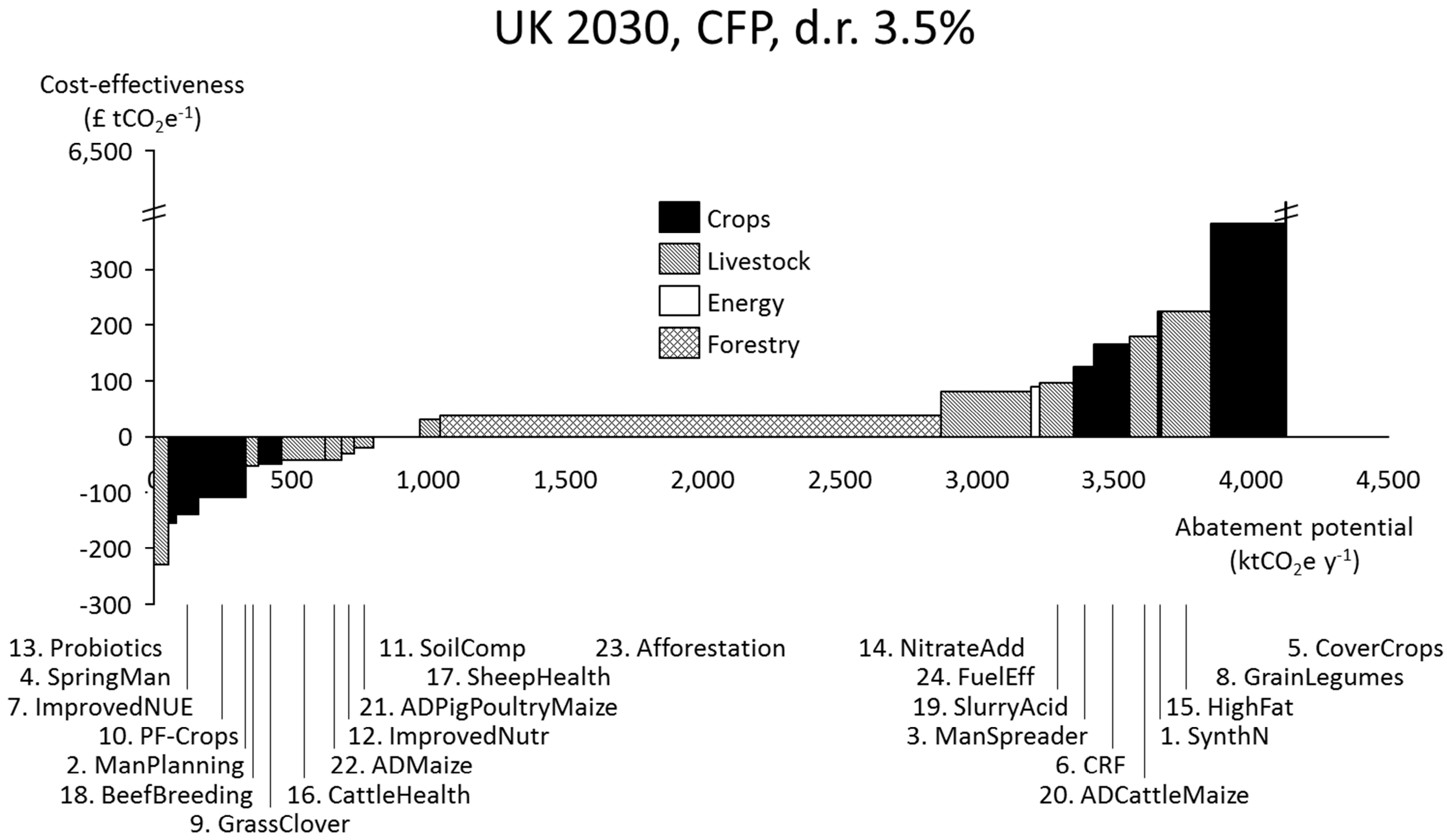

Figure 4 Marginal abatement cost curve (with interactions, 2030, UK, CFP, d.r. 3.5%), note that the C price in 2030 is £78 t CO_2e^{-1}

Table 118 Abatement potential and cost-effectiveness, with and without interactions (2030, UK, CFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
Probiotics	13	-230	51	-12	51	-230	51
SpringMan	4	-155	29	-4	79	-155	29
ImprovedNUE	7	-139	83	-12	162	-139	83
PF-Crops	10	-108	165	-18	328	-95	186
ManPlanning	2	-107	9	-1	336	-26	24
BeefBreeding	18	-52	46	-2	382	-52	46
GrassClover	9	-49	83	-3	465	-20	175
CattleHealth	16	-42	159	-7	624	-42	159
ADMaize	22	-41	61	-3	685	-41	61
ImprovedNutr	12	-29	45	-1	730	-26	50
ADPigPoultryMaize	21	-19	70	-1	800	-19	70
SoilComp	11	1	168	0	969	1	168
SheepHealth	17	30	74	2	1,042	30	74
Afforestation	23	37	1,829	68	2,871	37	1,829
NitrateAdd	14	82	326	25	3,197	62	405
FuelEff	24	90	34	3	3,231	90	34
SlurryAcid	19	96	123	9	3,354	45	207
ManSpreader	3	126	74	9	3,428	110	83
CRF	6	166	132	18	3,560	37	491
ADCattleMaize	20	179	100	17	3,659	125	139
SynthN	1	224	15	3	3,675	35	73
HighFat	15	225	179	38	3,853	171	223
GrainLegumes	8	383	275	99	4,128	300	331
CoverCrops	5	6,408	4	15	4,132	1,226	12

Table 119 Cost-effective abatement potential by DA (2030, CFP, d.r. 3.5%)

Country	Cumulative AP
	kt CO_2e y^{-1}
UK	2,871
England	1,462
Wales	791
Scotland	482
Northern Ireland	140

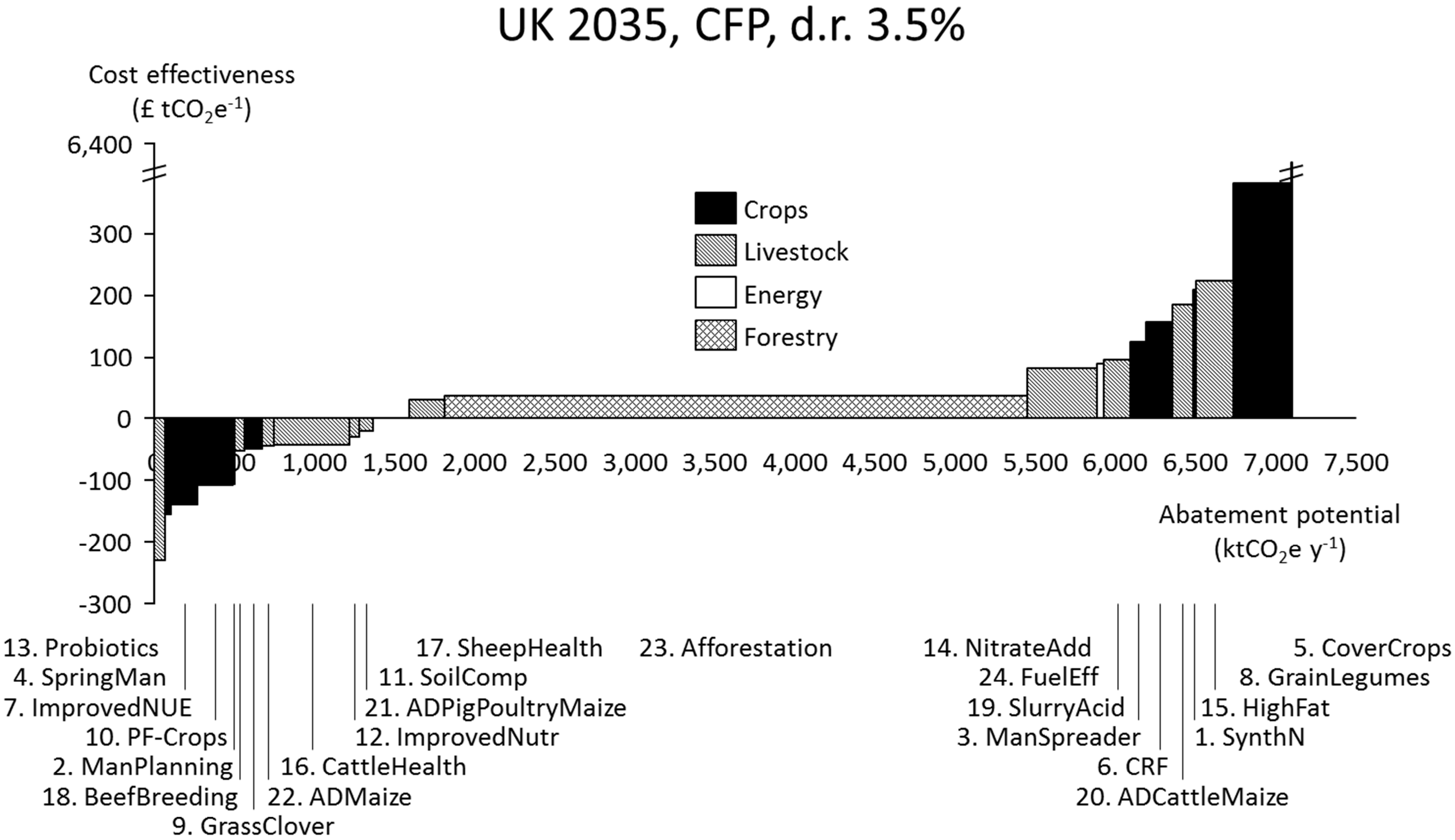

Figure 5 Marginal abatement cost curve (with interactions, 2035, UK, CFP, d.r. 3.5%), note that the C price in 2035 is £114 t CO_2e^{-1}

Table 120 Abatement potential and cost-effectiveness, with and without interactions (2035, UK, CFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
Probiotics	13	-230	68	-16	68	-230	68
SpringMan	4	-155	38	-6	106	-155	38
ImprovedNUE	7	-139	166	-23	272	-139	166
PF-Crops	10	-108	220	-23	491	-95	248
ManPlanning	2	-105	11	-1	502	-26	32
BeefBreeding	18	-52	62	-3	564	-52	62
GrassClover	9	-48	108	-5	673	-20	233
ADMaize	22	-43	78	-3	750	-43	78
CattleHealth	16	-42	469	-20	1,219	-42	469
ImprovedNutr	12	-29	59	-2	1,278	-26	67
ADPigPoultryMaize	21	-20	89	-2	1,368	-20	89
SoilComp	11	1	225	0	1,592	1	225
SheepHealth	17	30	218	7	1,810	30	218
Afforestation	23	37	3,642	136	5,452	37	3,642
NitrateAdd	14	81	433	33	5,885	62	540
FuelEff	24	90	45	4	5,930	90	45
SlurryAcid	19	96	164	13	6,093	45	276
ManSpreader	3	125	98	12	6,192	110	110
CRF	6	157	167	24	6,358	37	654
ADCattleMaize	20	185	125	23	6,483	131	176
SynthN	1	209	19	3	6,502	35	97
HighFat	15	224	237	51	6,738	171	298
GrainLegumes	8	382	360	130	7,099	299	435
CoverCrops	5	6,370	5	20	7,104	1,226	16

Table 121 Cost-effective abatement potential by DA (2035, CFP, d.r. 3.5%)

Country	Cumulative AP
	kt CO_2e y^{-1}
UK	6,093
England	2,876
Wales	1,925
Scotland	909
Northern Ireland	381

Table 122 GHG emissions from UK agriculture to 2030, central estimate ($MtCO_2e$ y^{-1}) (Defra 2011c)

Country	2015	2020	2025	2030
UK	43.9	43.8	43.8	43.8
England	28.1	28.1	28.1	28.1
Wales	4.6	4.5	4.5	4.5

Country	2015	2020	2025	2030
Scotland	6.7	6.7	6.7	6.7
Northern Ireland	4.6	4.6	4.6	4.6

The cost-effective abatement potential in the UK ranged from 0.53 Mt CO_2e y^{-1} for low feasible potential to 6.99 Mt CO_2e y^{-1} for maximum technical potential in 2030 and from 1.26 to 13.48 Mt CO_2e y^{-1} in 2035, with both 3.5% and 7% discount rate (Table 123). The discount rate does not change the cost-effective abatement, as even the AD measures, which have a large capital cost, do not change from being cost-effective to being not cost-effective with the changing discount rate. As this analysis does not capture the heterogeneity of farmers' financial situation, the UK abatement remains static with the changing discount rate. In reality an increasing discount rate could imply decreasing uptake of the capital intensive measures.

The total annualised costs of the measures up to the economic optimum varied between –M£22 and M£198 y^{-1} for the same scenarios (Table 124).

Table 123 Cost-effective abatement potential (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	534	2,871	6,313	6,988
2035	3.5%	1,256	6,093	12,361	13,484
2030	7.0%	534	2,871	6,313	6,988
2035	7.0%	1,256	6,093	12,361	13,484

Table 124 Cumulative annualised cost of the measures up the C price (M£ y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	-8	7	5	3
2035	3.5%	-2	89	182	198
2030	7.0%	-9	-5	-19	-22
2035	7.0%	-6	62	126	138

Regarding the cost-effective abatement in 2030 in the UK (CFP, d.r. 3.5%), 65% of it is provided by the single measure *Afforestation* (Table 125). Cropping (19%) and livestock (16%) related measures contributed levels similar to one another to this abatement. In 2035 the share of mitigation by Afforestation increased to 67%, cropping and livestock measures providing 14% and 19%, respectively. The contribution of these elements was different in the DAs, *Afforestation on agricultural land* providing the highest share of the cost-effective abatement in Wales (90%), and the lowest contribution in Northern Ireland (46%).

Table 125 Contribution of cropping, livestock, forestry and energy use related mitigation measures to the cost-effective abatement by DA (2030, CFP, d.r. 3.5%)

	UK		E		W		S		NI	
	kt CO_2e y^{-1}	%	kt CO_2e y^{-1}	%	kt CO_2e y^{-1}	%	kt CO_2e y^{-1}	%	kt CO_2e y^{-1}	%
Cropping	537	19%	417	29%	25	3%	80	17%	15	11%
Livestock	460	16%	283	20%	49	6%	74	16%	55	41%
Forestry	1,829	65%	741	51%	709	90%	317	67%	61	46%
Energy use	0	0%	0	0%	2	0%	0	0%	2	1%

The role of the interactions is important in the MACC, particularly for some measures, e.g. which are targeting the same emission source (like synthetic and organic N fertilisers). The reduction of the abatement potential due to these interactions ranged from -79% to 0% in the 2030 UK CFP MACC (d.r. 3.5.%), the measure *Improved synthetic N use* achieved only 21% of the abatement wit would have achieved without any other interacting measure being applied. With increasing uptake (either moving from low feasible to maximum technical potential or from 2030 to 2035), the interactions increased, in the 2035 UK MTP MACC (d.r. 3.5%) the same measure mentioned before could mitigate only 14% of its potential without interactions.

5.2 Confidence in the results and sensitivity analysis

The sensitivity of the abatement potential and cost-effectiveness of the individual measures are presented in Section 4. The sensitivity of the results to the interaction factors is presented in Table 126. A 0.1 increase in the interaction factors reduced the cost-effective abatement by 1.6% (from 6.09 Mt CO_2e y^{-1} to 5.99 Mt CO_2e y^{-1}), while a similar decrease in the IFs increased the abatement by 5.7% (from 6.09 Mt CO_2e y^{-1} to 6.44 Mt CO_2e y^{-1}) (UK, 2035, CFP, d.r. 3.5%).

Table 126 Sensitivity of the cost-effective abatement potential and the cumulative annualised cost of the measures up the C price to the interaction actors (UK, 2035, CFP, d.r. 3.5%)

IF	Cost-effective AP	Cumulative annualised cost of the measures up to the C price
	M£ y^{-1}	kt CO_2e y^{-1}
Higher (+0.1)	5,993	130
Original	6,093	89
Lower (-0.1)	6,443	113

The uncertainties regarding the calculations and the assumptions used for the various measures were qualitatively assessed by the project team and their comments are summarised in Table 127. The context provided by Table 127 reflects how robust the abatement potential results and the cost-effectiveness results were considered to be by the assessors.

It is also important to emphasise that this MACC describes the average UK situation, the actual values on farms for both abatement and costs can be very different. For this reason it is important to view the results as providing guidance about what could happen in the UK at the national average level, and to note that the policy instruments to promote GHG mitigation should be flexible enough to allow for the sometimes very significant – differences between farms.

Table 127 Confidence in the estimates

ID	Mitigation measure	Confidence that significant abatement can be achieved via this measure	Confidence in the estimated value of the abatement potential	Confidence in the estimated value of cost-effectiveness
MM1	Improving synthetic N use	High	Moderate: the scope for optimising the N amount at a field basis is difficult to estimate; the current uptake of the measure is uncertain, as it is based on self-reporting about the use of the tools	Low: the balance between financial gains due to N savings and the cost of additional planning is difficult to estimate, this, together with uncertainties in the abatement leads to low confidence in the cost-effectiveness
MM2	Improving organic N planning	Moderate: some improvement in manure N use had happened in the past years, therefore the potential for additional abatement has been reduced; nevertheless improved planning tools, advice and fertiliser recommendations will contribute to abatement	Moderate: the scope for optimising manure N use and its direct effects on emissions and effects on replacing synthetic N use are difficult to estimate and; the current uptake of the measure is uncertain, as it is based on self-reporting about the use of the tools	Low: the balance between financial gains due to N savings and the cost of additional planning is difficult to estimate, this, together with uncertainties in the abatement leads to low confidence in the cost-effectiveness
MM3	Low emission manure spreading	High	Moderate: the estimated effect is well understood but it's size is still uncertain (based on reviews rather than meta-analysis); the current uptake of the measure has good certainty	Low: the balance between financial gains due to N savings and the cost of additional planning is difficult to estimate, this, together with uncertainties in the abatement leads to low confidence in the cost-effectiveness
MM4	Shifting autumn manure application to spring	Moderate: the scope for further shifting autumn application to spring without changing the crop cultivars has been greatly reduced, therefore, even though the abatement rate is high, the total abatement is very restricted	Moderate: the N gain due to the shift in timing is difficult to estimate; though the applicability and the current uptake of the measure has good certainty (based on fertiliser use statistics)	Moderate: the N savings are very likely to outweigh the additional costs of spreading and storage
MM5	Catch and cover crops	Low: the abatement potential is low as it is assumed that the main GHG effect is the mitigation for indirect N2O from N leaching and rather than N savings for the following crop; however, other environmental benefits are important	Moderate: the N gain due to the shift in timing is difficult to estimate; though the applicability of the measure has high certainty (based on fertiliser use statistics)	Moderate: the costs of the measure is uncertain and very context dependent (farm type, rotation, etc.), and the abatement is also uncertain
MM6	Controlled release fertilisers	Moderate: the abatement effect has not been well documented yet	Low: the direct and indirect mitigation effects are not fully explored yet	Low: scarce information is available on the additional cost, this, together with the uncertainty of the GHG effect leads to low confidence
MM7	Plant varieties with improved N-use efficiency	Moderate: if NUE can be built in the plant breeding goals then uptake results directly in reduced N use	Moderate: approximations of the effect exist, but future work required for a realistic modelling of NUE improvements	Moderate: the N savings are very likely to outweigh any potential price premium

ID	Mitigation measure	Confidence that significant abatement can be achieved via this measure	Confidence in the estimated value of the abatement potential	Confidence in the estimated value of cost-effectiveness
MM8	Legumes in rotations	High	Moderate: difficult to estimate how farmers will actually reduce their N use on the following crop	Moderate: though the cost-effectiveness seem to be very high, well beyond the C price, differences between farms and regions mean that the actual cost-effectiveness on farm can take a wide range of values
MM9	Legume-grass mixtures	High	Moderate: difficult to estimate how farmers will actually follow the fertiliser recommendations for the grass-legume mixtures	Moderate: depends on the cost of maintaining the clover content and also on the actual fertilisation and N savings
MM10	Precision farming for crops	High	Low: data on the GHG effects of PF techniques are rare, the evidence on the current uptake of PF techniques (and their combinations) is not comprehensive	Low: high uncertainty in the GHG effects, the N savings benefits, and in the implementation and running costs
MM11	Loosening compacted soils and preventing soil compaction	High	Moderate: comprehensive meta-analysis of experimental data provides good evidence on the uncertainty of the effect	Moderate: the costs of the measure is uncertain and very context dependent (climate, soil type, etc.), and the abatement is also uncertain
MM12	Improving ruminant nutrition	High	Low: evidence on the characterisation of the current diet and potentials for improvement is patchy	Low: the balance between financial gains due to increased yield and the cost of additional planning and forage analysis is difficult to estimate, this, together with uncertainties in the abatement leads to low confidence in the cost-effectiveness
MM13	Probiotics as feed additive	Moderate: the abatement effect is not well established yet, R&D is needed to develop yeast strains targeting CH_4 emissions	Moderate: comprehensive meta-analysis of experimental data provides good evidence on the uncertainty of the effect, which is moderate	Moderate: cost data about the relevant yeast strains are hardly available, the abatement is also uncertain
MM14	Nitrate as feed additive	High	Moderate: comprehensive meta-analysis of experimental data provides good evidence on the uncertainty of the effect; uptake might be constrained by the acceptance of the method by farmers, the effect of this barrier is uncertain	Low: the relative price of the relevant feed components can vary in time and between farms, and this uncertainty has an important effect on whether the measure is cost-effective or not
MM15	High fat diet for ruminants	High	Moderate: comprehensive meta-analysis of experimental data are available both for the UK and at wider level. Uptake might be constrained by the high cost of the measure	Low: the relative price of the relevant feed components can vary in time and between farms, and this uncertainty has an important effect on whether the measure is cost-effective or not

ID	Mitigation measure	Confidence that significant abatement can be achieved via this measure	Confidence in the estimated value of the abatement potential	Confidence in the estimated value of cost-effectiveness
MM16	Improving cattle health	High	Moderate: a conservative assumption of 20% improvement has been used; greater improvement (and abatement) may be achievable	Moderate: the actual CE is difficult to quantify but it is likely that a 20% improvement could be achieved at low/negative cost
MM17	Improving sheep health	High	Low: while the same assumption of 20% improvement has been used for sheep and cattle, further work is required to quantify key parameters for average and high health status flocks	Low: CE is sensitive to starting health status, the specific measures employed and the resulting change in performance
MM18	Selection for balanced breeding goals	High	Moderate: the actual uptake of the measure is uncertain	Moderate: the efficiency savings are very likely to outweigh any potential price premium on the semen
MM19	Slurry acidification	High	Moderate: there is a wide range of abatement rate in the literature	Moderate: data is also scarce on the cost of implementation, therefore there is only moderate confidence in the cost-effectiveness results
MM20	Anaerobic digestion: cattle slurry with maize silage	High	Moderate: though the GHG abatement per AD plant can be well estimated, the total uptake of the measure is highly uncertain	Low: the estimation of the capital and maintenance costs, transportation costs and the revenues from heat is uncertain, and also uncertain how much the AD plant can run on full capacity
MM21	Anaerobic digestion: pig/poultry manure with maize silage			
MM22	Anaerobic digestion: maize silage only			
MM23	Afforestation on agricultural land	High	Moderate: abatement potential will depend on specifics of: forest systems, timing of planting, planting rates, planting method	Moderate: cost-effectiveness will depend on specifics of: forest systems, cost assumptions, income from thinning and clearfell, input and output prices
MM24	Behavioural change in fuel efficiency of mobile machinery	Moderate: due to the low contribution of fuel use emissions to the total agricultural emissions, the abatement potential is small	Low: the abatement is not well researched yet and is highly sensitive to market-driven changes in drivers' behaviour and to changes in the fuel-efficiency of mobile machinery	Low: very limited information is available on the costs of this measure

5.3 Relationship to the reference emissions projections

A MACC analysis, as described in the methodology, considers potential emission savings achievable by *additional* policy instruments, i.e. mitigation *additional* to a future reference scenario. This future reference scenario, in theory, should already account for ongoing and further expected changes in farming practices and also for the effects of foreseeable policy changes. As such, it should provide an estimate on how much GHG emissions are going to change compared to a past baseline year (e.g. 1990). However, the existing GHG emission projections (Agri-Food and Biosciences Institute 2015) might be underestimating the emission reduction happening autonomously, due to two main reasons:

- Limited representation of mitigation options in the GHG inventory methodology, this means that some GHG emission reduction that has happened during recent years through changes in farm practices is unaccounted, and
- Limited representation of future agricultural activities in the agricultural GHG emission projections, not including some GHG emission reduction that is expected to happen in the future due to technological, market and policy changes.

On the other hand, the above presented MACC assumed that the maximum additional future uptake of the mitigation measures was additional to the expected future reference uptake of them. This assumption leaves the mitigation provided by the future reference uptake (i.e. the autonomous uptake) unaccounted, as these are not included either in the MACC or in the GHG emission projections. For carbon budgeting purposes, this mitigation should be considered as much as possible.

Figure 6 illustrates the relationship between the GHG emission projections, the unaccounted GHG mitigation explained above and the mitigation represented in in the MACC.

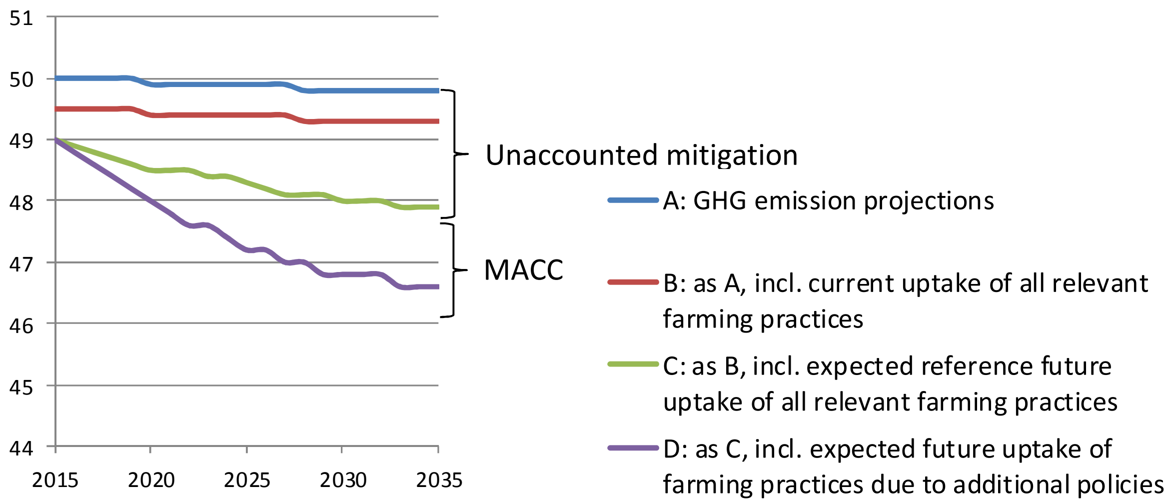

Figure 6 Illustration of the relationship between GHG emission projections and the MACC

In an attempt to better represent the potential emission savings described above and illustrated in Figure 6, an additional assessment was carried out. This assessment calculated the abatement potential using the future uptake of measures from both the reference scenario and the mitigation scenario. This was achieved by changing the assumptions on maximum additional future uptake (and in one case applicability) to reflect the full difference in uptake between GHG emission projections and GHG emissions with the uptake of farming practices due to additional policies. The changes in assumptions are reported in Table 128.

This abatement potential gives a crude estimate of the total mitigation which can happen compared to the GHG emission projections.

Table 128 New assumptions to reflect full emission savings compared to emission projections

	Applicability	Maximum future uptake	Notes	Notes
MM1	No change	Tillage land: 1 Grassland: 1	Uptake is set assuming all synthetic N use can be reduced without reducing yield. The UK GHG Inventory captures the year by year N savings made as it is based on fertiliser use statistics, therefore it might already include some of these GHG savings.	These assumptions might overestimate the difference between the future reference GHG projections and the mitigation scenario.
MM2	No change	Tillage land: 1 Grassland: 1	Uptake is set assuming all manure N can be better used thus providing synthetic N savings. The UK GHG Inventory captures the year by year synthetic N savings made as it is based on fertiliser use statistics, therefore it might already include some of these GHG savings.	These assumptions might overestimate the difference between the future reference GHG projections and the mitigation scenario.

	Applicability	Maximum future uptake	Notes	Notes
MM3	No change	Tillage land: 1 Grassland: 1	Uptake is set assuming no manure is spread via low emission manure spreading technologies. The UK GHG Inventory captures the year by year synthetic N savings made as it is based on fertiliser use statistics, therefore it might already include some of these GHG savings.	These assumptions might overestimate the difference between the future reference GHG projections and the mitigation scenario.
MM4	No change	Tillage land: 1 Grassland: 0	Uptake is set assuming all manure spread on tillage land is spread in the winter and could be shifted for spring spreading. The UK GHG Inventory captures the year by year synthetic N savings made as it is based on fertiliser use statistics, therefore it might already include some of these GHG savings.	These assumptions might overestimate the difference between the future reference GHG projections and the mitigation scenario.
MM5	No change	Spring crops: 1 Winter crops: 0 Grassland: 0	Uptake is set assuming no catch/cover crops are planted in the future reference scenario. The current inventory does not capture the leaching effect of the catch/cover crops.	These assumptions might reflect the full difference between the future reference GHG projections and the mitigation scenario.
MM6	No change	No change	Zero current and future uptake is assumed in the original scenarios.	NA
MM7	No change	No change	Zero current and future uptake is assumed in the original scenarios.	NA
MM8	No change	No change	The legumes currently planted are included in the UK GHG Inventory via fertiliser use statistics.	NA
MM9	All grasslands: 1	No change	Uptake is set assuming no grasslands have legume-grass mixtures. The UK GHG Inventory captures the year by year synthetic N savings made as it is based on fertiliser use statistics, therefore it might already include some of these GHG savings.	These assumptions might overestimate the difference between the future reference GHG projections and the mitigation scenario.

	Applicability	Maximum future uptake	Notes	Notes
MM10	No change	All grassland and tillage land: 0.95	Uptake is set assuming synthetic N use can be improved by PF application all tillage and grassland on farms above 20 ha. Currently there is some (estimated as 22%) uptake of PF technologies, and the year by year N savings generated is captured by the UK GHG Inventory as it is based on fertiliser use statistics, therefore some of these GHG savings might already be included. However, the estimated additional uptake (18%) to happen by 2035 in the future reference scenario is not included in the GHG Inventory.	These assumptions might slightly overestimate the difference between the future reference GHG projections and the mitigation scenario.
MM11	No change	No change	Zero current and future uptake is assumed in the original scenarios.	NA
MM12	No change	Beef and sheep: 1	Uptake is set assuming that the nutrition of all beef and sheep can be improved. The UK GHG Inventory does not capture the year by year nutritional improvements as it is based on an average digestibility of the diet for beef cattle and constant animal weight, and uses Tier 1 default emission factor for sheep.	These assumptions might reflect the full difference between the future reference GHG projections and the mitigation scenario.
MM13	No change	Dairy, beef and sheep >1y: 1	Uptake is set assuming that no uptake will happen in the future reference scenario by 2035. The UK GHG Inventory does not capture the year to year GHG savings provided by this measure.	These assumptions might reflect the full difference between the future reference GHG projections and the mitigation scenario.
MM14	No change	No change	Zero current and future uptake is assumed in the original scenarios.	NA
MM15	No change	Dairy, beef and sheep >1y: 1	Uptake is set assuming that no uptake will happen in the future reference scenario by 2035. The UK GHG Inventory does not capture the year to year GHG savings provided by this measure beyond accounting for the fat content in the baseline diet.	These assumptions might reflect the full difference between the future reference GHG projections and the mitigation scenario.

	Applicability	Maximum future uptake	Notes	Notes
MM16	No change	All cattle: 1	Uptake is set assuming that no uptake will happen in the future reference scenario by 2035. The UK GHG Inventory does only partially capture the year to year GHG savings provided by this measure via the changing weight and yield of dairy cows and the proportion of animals in productive and non-productive age cohorts.	These assumptions might reflect the full difference between the future reference GHG projections and the mitigation scenario.
MM17	No change	All sheep: 1	Uptake is set assuming that no uptake will happen in the future reference scenario by 2035. The UK GHG Inventory does only partially capture the year to year GHG savings provided by this measure via the changing weight and yield of dairy cows and the proportion of animals in productive and non-productive age cohorts.	These assumptions might reflect the full difference between the future reference GHG projections and the mitigation scenario.
MM18	No change	All beef: 1	Uptake is set assuming that no uptake will happen in the future reference scenario by 2035. The UK GHG Inventory does only partially capture the year to year GHG savings provided by this measure via the changing yield of beef cattle and the proportion of animals in productive and non-productive age cohorts.	These assumptions might reflect the full difference between the future reference GHG projections and the mitigation scenario.
MM19	No change	No change	Zero current and future uptake is assumed in the original scenarios.	NA
MM20	No change	No change	Zero current and future uptake is assumed in the original scenarios. The UK GHG Inventory could capture the year to year increase in AD plants via the changing waste management systems proportion, though the existing uptake (5% of farms) (Defra 2015a) is not included.	NA
MM21	No change	No change	Zero current and future uptake is assumed in the original scenarios. The UK GHG Inventory could capture the year to year increase in AD plants via the changing waste management systems proportion, though the existing uptake (5% of farms) (Defra 2015a) is not included.	NA

	Applicability	Maximum future uptake	Notes	Notes
MM22	No change	No change	Zero current and future uptake is assumed in the original scenarios.	NA
MM23	NA	No change	Future uptake according to FC.	NA
MM24	No change	All farms: 1	Uptake is set assuming that no uptake will happen in the future reference scenario by 2035.	These assumptions might reflect the full difference between the future reference GHG projections and the mitigation scenario.

The results show (Table 129) that for the UK the cost-effective abatement potential (2030, CFP, d.r. 3.5%) calculated with these assumptions in place was 15% higher (0.43 Mt CO_2e y^{-1}) than with the original uptake values, the difference ranging between 5-28% in the four DAs (Table 130). The ranking of the measures did not change substantially (Table 129), since in the analysis the uptake has no effect on either the cost of the measure or its abatement effectiveness (the ranking is affected only via the interactions). The total annualised cost of all the measures included in the cost-effective abatement reduced from M£ 28 y^{-1} to -M£1 y^{-1}, due to the increased uptake of cost saving measures. This is a consequence of the higher uptake of cost saving measures in the reference scenario, which is not included in the original MACC.

Table 129 Abatement potential and cost-effectiveness with full uptake, with and without interactions (2030, UK, CFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions £ t CO_2e^{-1}	AP with interactions kt CO_2e y^{-1}	Total annualised cost M£ y^{-1}	Cumulative AP kt CO_2e y^{-1}	CE WITHOUT interactions £ t CO_2e^{-1}	AP WITHOUT interactions kt CO_2e y^{-1}
Probiotics	13	-230	64	-15	64	-230	64
SpringMan	4	-155	102	-16	166	-155	102
ImprovedNUE	7	-139	83	-12	249	-139	83
PF-Crops	10	-108	283	-30	532	-95	321
ManPlanning	2	-100	23	-2	555	-27	70
BeefBreeding	18	-52	57	-3	612	-52	57
CattleHealth	16	-42	198	-8	810	-42	198
ADMaize	22	-41	61	-3	871	-41	61
ImprovedNutr	12	-29	110	-3	981	-26	125
ADPigPoultryMaize	21	-19	70	-1	1,051	-19	70
GrassClover	9	-2	161	0	1,212	-1	378
SoilComp	11	1	168	0	1,381	1	168
SheepHealth	17	30	92	3	1,473	30	92
Afforestation	23	37	1,829	68	3,301	37	1,829
NitrateAdd	14	82	326	25	3,627	62	405
FuelEff	24	93	63	6	3,690	93	63
SlurryAcid	19	96	123	9	3,813	45	207
ManSpreader	3	127	117	15	3,930	111	132

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
SynthN	1	151	31	6	3,961	35	183
CRF	6	169	130	18	4,091	37	491
ADCattleMaize	20	179	100	17	4,190	125	139
HighFat	15	223	254	55	4,444	171	319
GrainLegumes	8	383	275	99	4,719	300	331
CoverCrops	5	6,359	6	22	4,724	1,226	18

Table 130 Comparison of abatement potential and total annualised cost with interactions in the original scenarios and in the scenarios with accounting for full uptake (CFP, 2030, d.r. 3.5%)

Country	AP with interactions		Total annualised cost	
	kt CO_2e y^{-1}		M£ y^{-1}	
	Original 2015 MACC	Full uptake	Original 2015 MACC	Full uptake
UK	2,871	3,301	7	-22
England	1,462	1,738	-14	-36
Wales	398	437	12	11
Scotland	875	950	15	10
Northern Ireland	140	179	-4	-5

Table 131 Comparison of abatement potential and total annualised cost with interactions in the original scenarios and in the scenarios with accounting for full uptake (UK, 2030, d.r. 3.5%)

Uptake scenario	AP with interactions		Total annualised cost	
	kt CO_2e y^{-1}		M£ y^{-1}	
	Original 2015 MACC	Full uptake	Original 2015 MACC	Full uptake
LFP	534	671	-8	-16
CFP	2,871	3,301	7	-22
HFP	6,313	7,237	5	-56
MTP	6,988	8,012	3	-64

5.4 Comparison with previous MACC studies

A proportion of the mitigation measures assessed in the 2008 and 2010 UK MACC work (MacLeod *et al.* 2010c, Moran *et al.* 2008) were re-assessed in the current study. Some mitigation measures included in the earlier MACCs were considered to be of less relevance this time and therefore not assessed (like *Use composts, straw-based manures in preference to slurry* or *Dairy/Beef concentrates*), while some new mitigation measures (like *Slurry acidification or Improving sheep health*) were added to the MACC (Table 132). Due to the diversity of the N management mitigation measures, the relationship between those (both in the MACCs and in the FARMSCOPER studies) is described in more details in Table 133 and Table 134.

Table 135 presents how the 2008, 2010 Optimistic, 2010 Pessimistic and the current MACC compare to each other regarding the abatement potential and cost-effectiveness of the measures with interactions accounted for (note that the time periods and the discount rates differ between the MACCs). The detailed comparison of the abatement potential and cost-effectiveness of the mitigation measures without interactions can be found in the Discussion section of each measure's description (within Section 4).

Table 132 Mitigation measures in the current and 2008/2010 MACCs

2015 MACC	2008/2010 MACC	Notes
MM1: Improving synthetic N use	Avoid N excess Mineral N timing	Not additive to the new MACC. The new results are to replace the old results. MM1 encompasses two mitigation measures in the previous MACCs with updated assumptions.
MM2: Improving organic N planning	Full manure Organic N timing	Not additive to the new MACC. The new results are to replace the old results. MM2 encompasses two mitigation measures in the previous MACCs with updated assumptions.
MM3: Low emission manure spreading	NA	
MM4: Shifting autumn manure application to spring	NA	
NA	Slurry mineral N delayed	Not additive to the new MACC. This measure is partially covered by MM2 in the new MACC.
NA	Using composts	Not additive to the new MACC. This measure was not considered in the current MACC as it might be less feasible and more costly than previously thought (would require a change in the manure management systems of the farms).
MM8: Legumes in rotations MM9: Legume-grass mixtures	Biological fixation	Not additive to the new MACC. The new results are to replace the old results. MM8 and MM9 cover one mitigation measure in the previous MACCs, with updated assumptions.
NA	Reduce N fertilisation	Not additive to the new MACC. Due to emission leakage (reduced production will be replaced somewhere else) this measure should not be included in the MACC, unless a full LCA analysis is provided, considering export/import effects as well.
NA	Improved drainage	Could be additive to the new MACC. A re-assessment would be required to update assumptions on applicability, abatement and costs.
NA	Species introduction	Could be additive to the new MACC. A re-assessment would be required to update assumptions on applicability, abatement and costs.
MM6: Controlled release fertilisers	Controlled release fertilisers	Not additive to the new MACC. The new results are to replace the old results.
Nitrification inhibitors - quantitative assessment in Section 6	Nitrification inhibitors	Not additive to the new MACC. The new results (Section 6) are to replace the old results.

2015 MACC	2008/2010 MACC	Notes
NA	Systems less reliant on inputs	Could be additive to the new MACC. A re-assessment would be required to update assumptions on applicability, abatement and costs.
MM7: Plant varieties with improved N-use efficiency	Plant varieties with improved N-use efficiency	Not additive to the new MACC. The new results are to replace the old results
NA	Reduced tillage	Not additive to the new MACC. Abatement potential (increase in soil C content) is likely to be much lower in the UK than previously thought.
MM5: Catch and cover crops	NA	
MM10: Precision farming for crops	NA	
MM11: Loosening compacted soils and preventing soil compaction	NA	
NA	Dairy/Beef concentrates	Not additive to the new MACC. Due to emission leakage (land use change resulted from replacing grass with grains in the diet) this measure should not be included in the MACC.
NA	Dairy maize silage	Not additive to the new MACC. Due to emission leakage (land use change resulted from replacing grass with grains in the diet) this measure should not be included in the MACC.
NA	Dairy/Beef propionate precursors	Could be additive to the new MACC. Interactions (potential exclusivity) with other dietary measures have to be considered. A re-assessment would be required to update assumptions on applicability, abatement and costs.
NA	Dairy/Beef ionophores	Could be additive to the new MACC. The current regulatory environment makes this measure illegal. Interactions (potential exclusivity) with other dietary measures have to be considered. A re-assessment would be required to update assumptions on applicability, abatement and costs.
MM13: Probiotics as feed additive	Dairy/Beef probiotics	Not additive to the new MACC. The new results are to replace the old results.
MM12: Improving ruminant nutrition	NA	
MM14: Nitrate as feed additive	NA	
MM15: High fat diet for ruminants	NA	

2015 MACC	2008/2010 MACC	Notes
NA	Dairy genetics: improved productivity	Not additive to the new MACC. Dairy genetic improvement is likely to continue happening by market forces, additional policies might achieve a smaller additional abatement. A re-assessment would be required to update assumptions on abatement and additional uptake.
NA	Dairy genetics: improved fertility	Not additive to the new MACC. Dairy genetic improvement is likely to continue happening by market forces, additional policies might achieve a smaller additional abatement. A re-assessment would be required to update assumptions on abatement and additional uptake.
MM18: Selection for balanced breeding goals	Beef improved genetics	Not additive to the new MACC. The new results are to replace the old results
NA	Dairy bST	Could be additive to the new MACC. The current regulatory environment makes this measure illegal. A re-assessment would be required to update assumptions on uptake, abatement and costs.
GM livestock - qualitative assessment in Section 6	Dairy transgenics	Could be additive to the new MACC. A re-assessment would be required due to update assumptions on abatement. A qualitative assessment is provided in Section 6.
MM16: Improving cattle health	NA	
MM17: Improving sheep health	NA	
Covering slurry stores - quantitative assessment in Section 6	Dairy/Beef/Pig manure: covering lagoons Dairy/Beef/Pig manure: covering slurry tanks Dairy/Beef/Pig manure: slurry tank aeration Dairy/Beef/Pig manure: lagoon aeration	Not additive to the new MACC. The new results (Section 6) are to replace the old results.
MM19: Slurry acidification	NA	
NA	OFAD-DairyMedium / DairyLarge	
NA	OFAD-BeefMedium / BeefLarge	
NA	OFAD-PigsMedium / PigsLarge	
MM20: AD: cattle slurry with maize silage	CAD-Dairy-1MW / 2MW / 3MW / 4MW / 5MW CAD-Beef-1MW / 2MW / 3MW / 4MW / 5MW	Not additive to the new MACC. The new results are to replace the old results.

2015 MACC	2008/2010 MACC	Notes
MM21: AD: pig/poultry manure with maize silage	CAD-Pig-1MW / 2MW / 3MW / 4MW / 5MW CAD-Poultry-1MW / 2MW / 3MW / 4MW / 5MW	Not additive to the new MACC. The new results are to replace the old results.
MM22: AD: maize silage only	NA	
MM23: Afforestation on agricultural land	Afforestation (only in 2008 MACC)	Not additive to the new MACC. The new results are to replace the old results.
NA	Increased rotation length (only in 2008 MACC)	Could be additive to the new MACC. A re-assessment would be required to update assumptions on abatement (incl. indirect emission savings) and costs.
MM24: Behavioural change in fuel efficiency of mobile machinery	NA	

Table 133 Relationship between the synthetic N related management actions on farms and the mitigation measures

Study[1]	a	b	b	b	b	c	c	c	c	c
Actions on farm / Mitigation measures	MM1: Improving synthetic N use	Reduce N fertiliser	Avoiding N excess	Improved timing of mineral fertiliser N application	Separate slurry applications from fertiliser applications by several days	Fertiliser spreader calibration	Use a fertiliser recommendation system	Reduce manufactured fertiliser application rates	Avoid spreading manufactured fertiliser to fields at high-risk times	Use manufactured fertiliser placement technologies
Reduce N fertiliser below the economic optimum		X						X		
Use an N planning tool	X		X				X			
Soil nutrient sampling	X									
Decrease the error of margin in synthetic N fertiliser applications	X									
Do not apply synthetic N fertiliser in very wet/waterlogged conditions	X								X	
Separate slurry applications from fertiliser applications by several days					X				X	
Do not apply synthetic N during autumn/winter when there is little/no crop uptake									X	
Match the timing of the synthetic N application with plant N uptake				X						
Use low emission synthetic N spreading technologies										X
Calibrate synthetic N fertiliser spreaders						X				

Notes:
[1] a: the current study, b: 2008 and 2010 MACCs (MacLeod et al. 2010c, Moran et al. 2008), c: FARMSCOPER, as described in Newell-Price et al. (2011)

Table 134 Relationship between the manure N related management actions on farms and the mitigation measures

Study[1]	a	a	a	b	b	b	c	c	c	c	c	c
Actions on farm / Mitigation measures	MM2: Improving organic N planning	MM3: Low emission manure spreading	MM4: Shifting autumn manure application to spring	Full allowance of manure N supply	Improved timing of slurry and poultry manure application	Use composts, straw-based manures in preference to slurry	Integrate fertiliser and manure nutrient supply	Manure spreader calibration	Do not apply manure to high-risk areas	Do not spread slurry or poultry manure at high-risk times	Do not spread FYM to fields at high-risk times	Use slurry band spreading application techniques
Use an N planning tool to take into account the full allowance of manure nutrients	X			X			X					
Decrease the error of margin in manure applications	X											
Do not apply the manure in very wet/waterlogged conditions	X									X	X	
Match the timing of the manure N application with plant N uptake					X							
Do not apply manure to high-risk areas									X			
Shift autumn manure application to spring where possible without changing crop cultivars			X							X		
Use low emission manure spreading technologies		X										X
Use composts, straw-based manures in preference to slurry						X						
Calibrate manure N fertiliser spreaders								X				

Notes:
[1] a: the current study, b: 2008 and 2010 MACCs (MacLeod et al. 2010c, Moran et al. 2008), c: FARMSCOPER, as described in Newell-Price et al. (2011)

Table 135 Cost-effectiveness and abatement potential with interactions in the current study (2035, UK, CFP, d.r. 3.5%) and in the 2008 and 2010 MACCs (2022, UK, CFP, d.r. 7%)

2015 MACC[1]	CE with interactions	AP with interactions	2008/2010 MACC[1]	2008 CE with interactions[2]	2008 AP with interactions[2]	2010 Optimistic CE with interactions[1,2]	2010 Optimistic AP with interactions[1,2]	2010 Pessimistic CE with interactions[1,2]	2010 Pessimistic AP with interactions[1,2]
	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}		£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}
MM1: Improving synthetic N use	209	19	Avoid N excess	-50	276	-260	64	-196	2
			Mineral N timing	-103	1,150	-106	1,056	-104	161
MM2: Improving organic N planning	-105	11	Full manure	-149	457	-159	86	17,633	1
			Organic N timing	-68	1,027	-64	468	-56	192
MM3: Low emission manure spreading	125	98	NA						
MM4: Shifting autumn manure application to spring	-155	38	NA						
NA			Slurry mineral N delayed	0	47	0	78	0	77
NA			Using composts	0	79	0	123	0	107
MM8: Legumes in rotations	382	360	Biological fixation	14,280	8	858	108	2,769	34
MM9: Legume-grass mixtures	-48	108							
NA			Reduce N fertilisation	2,045	136	432	511	429	514
NA			Improved drainage	46	1,741	-31	1,891	155	54
NA			Species introduction	174	366	70	915	52	1,216

2015 MACC[1]	CE with interactions	AP with interactions	2008/2010 MACC[1]	2008 CE with interactions[2]	2008 AP with interactions[2]	2010 Optimistic CE with interactions[1,2]	2010 Optimistic AP with interactions[1,2]	2010 Pessimistic CE with interactions[1,2]	2010 Pessimistic AP with interactions[1,2]
	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}		£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}
MM6: Controlled release fertilisers	157	167	Controlled release fertilisers	1,068	166	332	509	208	814
Nitrification inhibitors (see Section 6)	903	109	Nitrification inhibitors	294	604	59	1008	698	427
NA			Systems less reliant on inputs	4,434	10	210	212	277	161
MM7: Plant varieties with improved N-use efficiency	-139	166	Plant varieties with improved N-use efficiency	-68	369	-205	332	NA	NA
NA			Reduced tillage	-432	50	-170	127	-153	142
MM5: Catch and cover crops	6,370	5	NA						
MM10: Precision farming for crops	-108	220	NA						
MM11: Loosening compacted soils and preventing soil compaction	1	225	NA						
NA			Dairy concentrates	*	*	*	*	*	*
NA			Beef concentrates	2,705	81	2,705	81	2,705	81
NA			Dairy maize silage	-263	96	-263	96	-263	96

2015 MACC[1]	CE with interactions	AP with interactions	2008/2010 MACC[1]	2008 CE with interactions[2]	2008 AP with interactions[2]	2010 Optimistic CE with interactions[1,2]	2010 Optimistic AP with interactions[1,2]	2010 Pessimistic CE with interactions[1,2]	2010 Pessimistic AP with interactions[1,2]
	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}		£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}
NA			Dairy propionate precursors	NA	NA	NA	NA	-15	661
NA			Beef propionate precursors	*	*	*	*	*	*
NA			Dairy ionophores	-49	740	-49	740	*	*
NA			Beef ionophores	-1,748	347	-1,748	347	*	*
MM13: Probiotics as feed additive	-230	68	Dairy probiotics	*	*	*	*	*	*
			Beef probiotics	*	*	*	*	*	*
MM12: Improving ruminant nutrition	-29	59	NA						
MM14: Nitrate as feed additive	81	433	NA						
MM15: High fat diet for ruminants	224	237	NA						
NA			Dairy genetics: improved productivity	0	377	-144	308	-144	205
NA			Dairy genetics: improved fertility	0	346	-101	439	-86	344
MM18: Selection for balanced breeding goals	-52	62	Beef improved genetics	-3,603	46	-3,603	46	-3,603	46
NA			Dairy bST	224	132	224	132	224	132

2015 MACC[1]	CE with interactions	AP with interactions	2008/2010 MACC[1]	2008 CE with interactions[2]	2008 AP with interactions[2]	2010 Optimistic CE with interactions[1,2]	2010 Optimistic AP with interactions[1,2]	2010 Pessimistic CE with interactions[1,2]	2010 Pessimistic AP with interactions[1,2]
	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}		£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}
NA			Dairy transgenics	1692	504	1692	504	1692	504
MM16: Improving cattle health	-42	469	NA						
MM17: Improving sheep health	30	218	NA						
NA (In semi-quantitative assessment, see Section 6)	446	9	Dairy manure: covering lagoons	*	*	25	33	25	33
			Beef manure: covering lagoons	*	*	9	10	9	10
			Pig manure: covering lagoons	*	*	*	*	*	*
			Dairy manure: covering slurry tanks	*	*	70	35	70	35
			Beef manure: covering slurry tanks	*	*	24	12	24	12
			Pig manure: covering slurry tanks	*	*	*	*	*	*
			Dairy manure: slurry tank aeration	*	*	*	*	*	*

2015 MACC[1]	CE with interactions	AP with interactions	2008/2010 MACC[1]	2008 CE with interactions[2]	2008 AP with interactions[2]	2010 Optimistic CE with interactions[1,2]	2010 Optimistic AP with interactions[1,2]	2010 Pessimistic CE with interactions[1,2]	2010 Pessimistic AP with interactions[1,2]
	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}		£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}
			Beef manure: slurry tank aeration	*	*	*	*	*	*
			Pig manure: slurry tank aeration	*	*	*	*	*	*
			Dairy manure: lagoon aeration	*	*	*	*	*	*
			Beef manure: lagoon aeration	*	*	*	*	*	*
			Pig manure: lagoon aeration	*	*	*	*	*	*
MM19: Slurry acidification	96	164	NA						
NA			OFAD-DairyLarge	11	251	*	*	*	*
NA			OFAD-DairyMedium	27	44	*	*	*	*
NA			OFAD-BeefLarge	6	98	*	*	*	*
NA			OFAD-BeefMedium	20	51	*	*	*	*
NA			OFAD-PigsLarge	5	48	17	48	17	48
NA			OFAD-PigsMedium	8	16	33	16	33	16

2015 MACC[1]	CE with interactions	AP with interactions	2008/2010 MACC[1]	2008 CE with interactions[2]	2008 AP with interactions[2]	2010 Optimistic CE with interactions[1,2]	2010 Optimistic AP with interactions[1,2]	2010 Pessimistic CE with interactions[1,2]	2010 Pessimistic AP with interactions[1,2]
	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}		£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}	£ (t CO_2e)$^{-1}$	kt CO_2e y^{-1}
MM20: AD: cattle slurry with maize silage	185	125	CAD-Dairy-5MW	*	*	*	*	*	*
			CAD-Beef-5MW	*	*	*	*	*	*
MM21: AD: pig/poultry manure with maize silage	-20	89	CAD-Pig-5MW	*	*	*	*	*	*
			CAD-Poultry-5MW	12	219	0	219	0	219
MM22: AD: maize silage only	-43	78	NA						
MM23: Afforestation on agricultural land	37	3,642	Afforestation	0	-17	NA	NA	NA	NA
NA			Increased rotation length	0	11,610	NA	NA	NA	NA
MM24: Behavioural change in fuel efficiency of mobile machinery	90	45	NA						

Notes:
[1] *NA: Not assessed in the study*
[2] **: Excluded from the MACC due to interactions (i.e. another, mutually exclusive measure was more cost-effective; results without interactions still available)*

6 Abatement by 2050: assessment of additional mitigation measures

Potential future abatement from a selection of mitigation measures were additionally assessed from. The analysis explored the mitigation potential and the main barriers of these measures beyond the fifth carbon budget period, based on a literature review. Where data allowed, quantitative assessment was carried out. The following mitigation measures are described here:

- Nitrification inhibitors
- Novel crops
- Agroforestry (with low tree density)
- Covering slurry stores
- Precision livestock farming
- GM livestock
- Using sexed semen in dairy cattle reproduction

It is important to note that some of these measures (particularly *Agroforestry*, *Nitrification inhibitors* and *Precision livestock farming*) are feasible for immediate implementation, and will be feasible during the fourth and fifth carbon budget period as well, even though they are only included in the qualitative assessment.

6.1 Nitrification inhibitors

6.1.1 Description of the measure

Nitrification inhibitors (NIs) are compounds that inhibit the oxidation of ammonium ions to nitrate with the aim of providing better synchrony between nitrate supply and crop uptake. By doing so there is less likelihood of nitrate being available in soils when they are wet and the denitrification potential and, consequently, N_2O emissions are high. Beyond reducing direct N_2O emissions, NIs can potentially lower emissions and improve emission intensity also by reducing nitrate leaching and subsequent indirect N_2O emissions and increasing grass/crops yield (MacLeod *et al.* 2015a).

Here the application of dicyandiamide (DCD) was considered – at rate of 15 kg DCD ha^{-1} –, as in field trials in England this compound proved to have significant reduction on N_2O emissions (Misselbrook *et al.* 2014).

6.1.2 Applicability

Nitrification inhibitors work on all types of fertilised land, regardless the origin of the N (synthetic N, manure spread or N originating from excretion via grazing), however, here we assume that the measure will only be applied on land areas where synthetic N is used. Moreover, due to the low fertilisation rate (regarding synthetic or organic applied N but not N deposited during grazing) of permanent grasslands we excluded those land areas. Allowing for agronomic and practical difficulties of the use of nitrification inhibitors, we assumed that the applicability is 70% on tillage land and temporary grassland which receives synthetic N.

6.1.3 Abatement rate

Abatement data from the literature is presented in Table 136.

Table 136 Data from literature on abatement by nitrification inhibitors

Abatement	Value	Country	Reference
N_2O emission factor	Direct N_2O emissions: -39%, -69%, -70% and -56% for AN, urea, cattle urine and cattle slurry, respectively (although non-significant for the cattle slurry)	UK	(Misselbrook *et al.* 2014)
N_2O emission factor	-51%	Germany	(Weiske and Michel 2007)
N use	-10.2 kg N ha^{-1}, resulting in 0.10 t CO_2e ha^{-1} lower soil N_2O emissions	France	(Pellerin *et al.* 2013)
N_2O emission factor	Direct N_2O emissions: -38% (95% confidence interval: -44% to -31%)	various	(Akiyama *et al.* 2010)
N_2O emission factor	-0.3 t CO_2e ha^{-1} $year^{-1}$ (~50% reduction)	UK	(MacLeod *et al.* 2010c, Moran *et al.* 2008)
N_2O emission factor	Direct N_2O emissions: -20 – -40%, N fertiliser use: -6.5 – -13% OR yield: +7.5 – +15%	New Zealand	(Pape *et al.* 2008)

The main effect of the measure is reducing GHG emissions by reducing the proportion of N being transformed to N_2O, therefore the mitigation is calculated by changing the soil N_2O emission factor EF_1. A 48% reduction in the soil emission factor EF_1 is assumed across fertiliser and manure types, taking the average of the most widely used fertiliser (AN) and manure type (cattle slurry) value from the UK trial experiments (Misselbrook *et al.* 2014). Though this might underestimate the effect on N_2O emissions from organic N, the disaggregation between fertiliser types was not possible within the scope of the project. Though some experiments report on improved yield, reduced N leaching or a reduction in N requirements, none of these effects were taken into account due to the so far inconclusive experimental results in the UK.

6.1.4 Current and additional future uptake

NIs have been used in some other countries, e.g. New Zealand and Ireland, although concerns about contamination of milk products have led to them being withdrawn from commercial use in New Zealand. At present little if no NIs are used in the UK (Gooday *et al.* 2014), therefore the maximum additional future uptake is 100%.

6.1.5 Cost

Cost data from the literature is presented in Table 137. The estimated cost of the measure is £50 ha^{-1}, based on 10 kg ha^{-1} application rate and £5 kg^{-1} DCD price, accounting for no increase in yield or decrease in N fertiliser use. It is assumed that the cost of spreading will be zero. This requires the availability of combined fertiliser+DCD products for synthetic N fertilisation, automatic mixing process in slurry for organic N application and animal delivery (via feeding the animals with DCD) for N deposition through grazing.

Table 137 Data from literature on costs/benefits of nitrification inhibitors

Costs/savings	Value ('-' sign for savings)	Country	Year	Reference
Fertiliser cost increase of 50%, yield increase of 2%, labour reduced by 5%	£25 - £48 ha^{-1}	UK	2008	(Moran *et al.* 2008)
Net costs	£2 ha^{-1}	UK	2014	(Gooday *et al.* 2014)
Cost of NI	£64 ha^{-1}	New Zealand	2008	(Longhurst and Smeaton 2008)
Cost of NI	£49 ha^{-1}	Ireland	2002	(Schulte *et al.* 2012), based on (Di and Cameron 2002)
Price and application rate	£5 kg^{-1}, application rate: 10 kg ha^{-1}	Ireland	2014	Donal O'Brian, *pers. comm.*

6.1.6 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake for the UK was 897 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), consisting of abatement potentials of 716, 28, 130 and 23 kt CO_2e y^{-1} for England, Wales, Scotland and Northern Ireland, respectively (Table 138). The UK abatement potential (without interactions, d.r. 3.5%) increased from 140 kt CO_2e y^{-1} with the low feasible potential to 1,994 kt CO_2e y^{-1} assuming the maximum technical potential in 2035, and from 105 to 1,495 kt CO_2e y^{-1}, respectively, in 2030 (Table 139). In all of the above cases the UK average cost-effectiveness of the measure without interactions was £96 t CO_2e^{-1} (which is below the C price).

Table 138 Nitrification inhibitor abatement potential without interactions by DA (2035, CFP, d.r. 3.5%)

Country	Abatement potential	Cost-effectiveness
	kt CO_2e y^{-1}	£ t CO_2e^{-1}
UK	897	96
England	716	92
Wales	28	104
Scotland	130	110
Northern Ireland	23	120

Table 139 Nitrification inhibitor abatement potential without interactions (kt CO_2e y^{-1}, UK)

Year	d.r.	LFP	CFP	HFP	MTP
2030	3.5%	105	673	1,375	1,495
2035	3.5%	140	897	1,834	1,994
2030	7.0%	105	673	1,375	1,495
2035	7.0%	140	897	1,834	1,994

The sensitivity analysis shows that the abatement potential (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between 710 and 1,084 kt CO_2e y^{-1}; this analysis involved changing the assumptions on applicability, change in EF_1 and cost of nitrification inhibitor (Table 140). The cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%) varied between £48 and £144 t CO_2e^{-1}. The abatement potential increased linearly with the applicability and the reduction in EF_1. The cost-effectiveness got reduced to £80 t CO_2e^{-1} with a 10% higher GHG mitigation efficacy of the nitrification inhibitors and dropped to £48 t CO_2e^{-1} a 50% reduction in the price of the product. As the assumption was that the amount of N applied does not change, the cost-effectiveness was not sensitive to the average fertiliser price.

Table 140 Sensitivity of nitrification inhibitor abatement potential and cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%)

Parameter	Original value	New value	Abatement potential kt CO_2e y^{-1}	Cost-effectiveness £ t CO_2e^{-1}
Applicability	Tillage land: 0.7 Temporary grassland: 0.7 Permanent grassland: 0	Tillage land: 0.6 Temporary grassland: 0.6 Permanent grassland: 0	769	96
Applicability	Tillage land: 0.7 Temporary grassland: 0.7 Permanent grassland: 0	Tillage land: 0.8 Temporary grassland: 0.8 Permanent grassland: 0	1,025	96
Change in EF_1	-48%	-38%	710	121
Change in EF_1	-48%	-58%	1,084	80
Cost of nitrification inhibitor (£ ha^{-1})	50	75	897	144
Cost of nitrification inhibitor (£ ha^{-1})	50	25	897	48

6.1.7 Discussion

The use of nitrification inhibitors were assessed in the 2008 and 2010 MACCs (MacLeod *et al.* 2010c, Moran *et al.* 2008) and in the FARMSCOPER studies (Gooday *et al.* 2014). The latter one identified an abatement potential in England of 20 kt CO_2e y^{-1}, but having no detailed information on the assumptions underlying this result an analysis of the difference could not be carried out. The two MACC studies estimated a much higher abatement for the UK of around 1 Mt CO_2e y^{-1}. Specifically, the UK abatement potential without interactions (CFP, 2022) in the 2008 MACC was 1,168 kt CO_2e y^{-1}, while it was 1,126 kt CO_2e y^{-1} in both the Optimistic and Pessimistic 2010 MACCs, higher than the current estimate of 775 kt CO_2e y^{-1}. The 2008 and 2010 MACCs assumed that the abatement would be 0.3 t CO_2e ha^{-1} y^{-1}, while the abatement calculations in the current study showed 0.30 and 0.42 CO_2e ha^{-1} y^{-1} average abatement in the UK on temporary grasslands and tillage land, respectively. However, the higher per hectare abatement was counterbalanced by the lower assumptions on applicability (the main difference was that the current study assumed that the measure is not applicable on permanent grassland). A recent study by Misselbrook *et al.* (2014) stated that 5.6 Mt CO_2e y^{-1}, 3.3 times higher than the 2035 MTP estimate in the current study (1.7 Mt CO_2e y^{-1}), due to the assumption that nitrification inhibitors could be used on all types of land to 100% of fertiliser application and grazing excreta.

The cost-effectiveness of the measure was £800 t CO_2e^{-1} in the FARMSCOPER study (no further assumptions available), and varied between £53 and £265 t CO_2e^{-1} in the 2008 and 2010 MACCs (without interactions). The 2008 and 2010 MACC studies included a 2% yield effect and assumed that the fertiliser cost will increase by 50%, the net cost was between £16.60 and £82.98 ha^{-1} y^{-1} in the 2008, 2010 Optimistic and 2020 Pessimistic MACCs. The current study estimated the net cost to be £50 ha^{-1} y^{-1}, consisting of the cost of DCD, without any effect on yield or fertiliser needs, and showed £96 t CO_2e^{-1} cost-effectiveness (without interactions, 2035, UK, CFP, d.r. 3.5%).

6.2 Novel crops

Due to the lack of papers or reports specifically evaluating this individual option the text below has been prepared based on 'first principles'. It may be there are more general papers, addressing overall strategies to reduce GHG emissions from agriculture. However, of the many peer-reviewed papers and project reports evaluated as part of this project none refer to novel or new crops as an option to reduce GHG emissions.

6.2.1 Description of the measure

The cultivation of new species of crop, or existing crops greatly modified by selective breeding (see below) to replace a current crop either grown with large inputs of N fertiliser or leading to other GHG emissions.

6.2.2 Expected impacts on GHG emissions

The action is considered to be introducing crops into the UK, hitherto not cultivated on any significant scale, that can provide alternative sources of carbohydrate or protein (or both) to current crops, but which require less N fertiliser or other energy-intensive input than the corresponding current crop.

The nearest reference to this found in the literature is in the Defra report which cites the example of triticale (itself not a new crop) being grown instead of second wheats with N fertiliser input reduced from 254 to 188 kg ha^{-1}). Such novel crops could have three origins:

- Crops, such as quinoa, which are currently grown on only a very small area within the UK but which may be grown as an alternative to current crops. There is interest in increasing the area of this crop in the UK to meet demand for what is seen as a very healthy food.
- Existing crops significantly modified by conventional breeding to exhibit characteristics very different to the currently-grown cultivars. An example would be perennial wheat which by virtue of maintaining permanent cover would enable carbon sequestration in soil.
- Existing crops modified by genetic engineering to exhibit radically different growth patterns that enable a large reduction in fertiliser N or other energy-intensive inputs. An example would be leguminous wheat which would not require any fertiliser-N, albeit grain yield is likely to be substantially reduced due to the carbohydrate demands of the symbiotic bacteria. Another example would be the inclusion of the enzyme alanine aminotransferase, involved in the production of proteins and originally isolated from barley, to other crops. This has been investigated as a means of increasing N use efficiency, thereby reducing the need for fertiliser N. It acts by boosting the ability to take up N from the soil in a wide range of plants. Field trials over five growing seasons appear to show that GM oilseed rape can either produce about the same yield using just a third of the fertiliser, or boost yield by a third using current quantities[3].

Although the aim of the work was not focussed on reducing GHG emissions Defra project WQ0131 (Warwick HRI 2009) evaluated the likely environmental impacts of novel crops to 2050. The conclusions were that the predicted uptake of novel crops, all of which were crops expected to be grown to meet market demand, would have only a negligible impact on the environment. The report also concluded that it is extremely difficult to accurately project changes to farming over the long term, including changes to cropping, due to the complex nature of farming globally and perhaps as importantly, changes to legislation. Due to diversity of UK novel crops and factors (known and unknown) that could potentially influence their uptake, the authors considered it would be prudent to keep the timescale for considering potential changes relatively short (e.g. 10 years) to maximise the confidence in any projection.

[3] http://www.soyatech.com/news_story.php?id=6269

6.2.3 Ancillary effects

The introduction of crops that require less N fertiliser will also reduce nitrate leaching and new crops may also increase biodiversity.

6.2.4 Expected financial impacts on farm

The introduction of novel crops could improve farm income. Where new crops are introduced to meet consumer demand, e.g. quinoa and where new crops can give equivalent returns with less N fertiliser, farm income is likely to increase. However, new crops that produce less yield but without a commensurate increase in price per tonne, will have an adverse impact on income unless a scheme is introduced to compensate for any decrease in returns.

6.2.5 Potential policy instruments to promote uptake

Single Farm Payment to compensate for lack of income should the use of novel crops to be introduced with the sole intention of reducing N fertiliser inputs.

6.3 Agroforestry (with low tree density)

6.3.1 Description of the measure

Agroforestry is defined here as "the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or livestock production systems to benefit from the resulting ecological and economic interactions" (AGFORWARD 2015). IAASTD (2009) identified agroforestry as a win-win multi-functional land use approach because of its ability to balance production with environment, culture and landscape services. Agroforestry systems usually combine plant species with different spatial and temporal growth characteristics and thus have the potential to utilise resources more efficiently than single species systems. The woody vegetation can be trees or shrubs and can be arranged in different ways – either systematically or randomly. Agroforestry is often classified as silvoarable or alley cropping systems with arable or horticultural crops grown between rows of trees or silvopastoral with trees at wide spacing in grazed pasture. However, agroforestry also includes the use of trees in buffer zones around water courses for the reduction of nutrient and sediment loss and the production of fruit in hedgerows. The woody vegetation can be used for timber, fuel or fruit. Trees can also provide browsing for animals in systems with mature trees. In young systems there is a requirement to protect trees from damage by grazing livestock. There is increasing interest in Europe in combining agriculture with short-rotation coppice.

Agroforestry systems can be as productive as or more productive than monocropped systems. Using the Land Equivalent Ratio (LER) concept (Mead and Willey 1980) designed for measuring productivity in intercrops Graves et al. (2007) predicted an LER of 1-1.4 for European agroforestry systems. Where LER is equal to 1 there is no benefit of multi-species systems but where LER > 1 then there is a productivity benefit from the agroforestry system. There will always however be a trade-off between increased productivity due to improved microclimate between trees and loss of productivity from shade and other forms of competition dependent on species and location.

Agroforestry is not directly recorded as a UK land use so the best estimate of current area is from records hedgerows, orchards etc. These areas are currently very small compared to the total UAA. The area of wood pasture and parklands has been estimated at between 10,000 and 20,000 ha (Anon. 2010) and traditional orchards at 25,350 ha (Robertson *et al.* 2010). The area of hedgerows with high value trees in England, Scotland and Wales have been estimated as approx. 117,000 ha (Forestry Commission 2001a, Forestry Commission 2001b, Forestry Commission 2001c).

The area of uptake of specific agroforestry practices which utilise productive land is very difficult to measure at the present time and is even more difficult to predict or estimate. Nair et al. (2009) estimated land under agro-forestry under agroforestry worldwide is 1,023 million ha.

Closer to home den Herden et al. (2015) have reported the extent of a range of traditional agroforestry systems and of more novel newer systems and provided estimates of land cover under agroforestry as a proportion of UAA. The figure for UK is 0.9% cover, whilst the European average is 6.9%. This latter figure does not include large areas of Northern Sweden and Finland where reindeer undergraze sparse woodlands (41 million hectares!), but is dominated by dehesa and montado in Spain and Portugal and undergrazed extensive forest and shrubland in Greece.

Using different methodology (satellite imagery sampling), Plieninger et al. (2015) estimates 'wood-pasture' cover in the EU-27 as 20.3 M ha (4.7% of land cover) and in the UK as 800,000 ha (3.3% of land cover). However, pastures with cultivated trees were estimated at 14,000 hectares in the UK (0.06% of the grassland area).

An appropriate comparison for silvoarable area for UK conditions is with France where 6,300 ha (den Herden *et al.* 2015) are believed to be planted in 'modern' tree alleys with arable intercropping, contributing approximately 0.02% cover to that country. There has been modest policy and financial support for establishing and managing agroforestry systems with continued payments under Common agricultural Policy Single Farm Payments regimes in France for the last cycle.

For the UK, areas of 'new' agroforestry are dramatically less. There has been limited policy support in Northern Ireland, Wales in particular. It would be unrealistic to think that recent uptake of agroforestry systems have been anything approaching 0.01% of Utilised Agricultural Area of UK.

For the future uptake largely depends upon two factors; policy support (including finance) and land manager interest. Whilst there are pockets of interest, conventional farmers will still require much convincing to adopt silopastoral or silvoarable systems. Thus a wide range of possible implementation is included based upon different levels of support and interest; low support/low interest (0.1% UAA); high support/low interest (1%); high support/high interest (10%). Whilst 10% change in land use is theoretically feasible over a 20-50 year time horizon, this is extremely unlikely. The intermediate 1% is considered a much more realistic figure, effectively doubling the amount of current agricultural land currently tied up in hedgerows and shelter belts (such a major part of the UK countryside) with new integrated land use.

6.3.2 Expected impacts on GHG emissions

The amount of carbon in soils generally decreases in the order of forest>pasture>arable (Watson *et al.* 2000) and forest ecosystems usually contain more carbon than agricultural systems. It is widely suggested in the literature that agroforestry stores more carbon than agricultural systems but there is relatively little evidence in temperate systems. Future research needs to have both agricultural and forestry controls to show the real value of agroforestry for carbon sequestration. The potential for agroforestry to sequester carbon will depends on multiple factors including the initial carbon content of soil and existing biomass, the tree and understorey species and the environmental conditions. The fine root carbon in the soil under UK silvoarable agroforestry has been shown to be up to 79% greater than an arable control (Upson and Burgess 2013). Palma et al. (2007) predicted mean carbon sequestration through immobilization in trees in European agroforestry systems from 0.1 to 3.0 t C ha^{-1} y^{-1} (5–179 t C ha^{-1}) over a 60 year period depending on tree species and location. Recent figures for silvopastoral agroforestry in NE Scotland suggest that after 24 years soil carbon stocks were slightly higher than a control pasture (Beckert *et al.* 2015). The same study estimated that a Scots Pine based silvopastoral systems had similar or even greater soil carbon stocks than woodland plots and that the proportions of protected carbon fractions were similar to pasture. Estimates in North America for above and belowground components in buffer zones, alley-cropping systems, silvopastoral systems, and windbreaks are 2.6, 3.4, 6.1, and 6.4 Mg C ha^{-1} y^{-1} respectively (Udawatta and Jose 2011). In attempting to produce estimates on national and international scales for Brazil Alves et al. (2015) calculated from high growth eucalyptus that carbon stock (in CO_2 equiv.) would be 84 Mg CO_2e ha^{-1} y^{-1}. Brazil is aiming to include these levels of Carbon storage in their new national estimates.

Improved estimates of carbon storage in agroforestry systems would allow tree and stocking densities to be manipulated so that the carbon benefits of the trees offset methane emissions from the livestock. For Brazil, the high level of productivity of high potential Eucalyptus, adding in estimates of increased soil carbon from integrated systems of crop and then livestock use within alleyway systems combined with a current baseline of relatively low productivity of current cattle grazing systems are enabling Brazilian scientists to estimate Carbon neutral beef within new agroforestry systems (Alves et al 2015). Within the UK, for both silvopastoral and silvoarable systems small reductions in the cultivated or grazeable areas will reduce the effective stocking density. Small increases in productivity in crops (arable crops and grass) and livestock (some through improved shelter and shade) could contribute towards improved emissions intensity. Reduced productivity are widely predicted as the tree species mature, canopies move to cover and tree harvesting approaches (Sibbald *et al.* 2001). Manipulating pasture composition and tree species could also be a mechanism for manipulating diet and thus methane emissions.

For UK conditions, for estimating future impacts, given these high levels of uncertainty, emissions intensity from the crop/animal system are thus best left unchanged.

The smaller area of pasture or arable crop per unit land area reduces use of fossil fuels (machinery and agrochemicals including fertiliser) per unit land area. There is also the potential for reduced nitrate leaching as a result of luxury uptake of N by trees (Bergeron *et al.* 2011) and by increasing the volume and depth of soil explored by roots. This could also reduce the soil N readily available for the production on N_2O. The use of either leguminous tree species or leguminous understorey species can reduce the need for fertiliser nitrogen per unit area although N_2O loss can also occur from legume based systems.

Within the UK, agroforestry is not envisaged as just tree planting but as the creation of new agricultural systems. In lowland areas silvoarable systems could have advantages over traditional arable systems in terms of emissions. In the uplands, silvopastoral should have advantages over current grazing systems.

6.3.3 Mitigation impacts

As described above, to estimate national impacts of agroforestry measures and land use change, the range of levels of uptake are used. For bio-physical components of the systems, a single standard figure of average carbon stocks within the tree component is proposed for simplicity. Aertsens et al. (2013) in reviewing C sequestration in European agriculture supported the estimate of Hamon et al. (2009) of 2 t C ha^{-1} y^{-1} (7.34 t CO_2e ha^{-1} y^{-1}).

For soil carbon, a zero change value is used for existing grassland systems that are adapted to silvoarable systems, but for current arable land changing to silvoarable systems an increment in soil carbon is included. These estimates ignore the large impacts of different tree species, soil types and environmental effects upon productivity and carbon fluxes. These all add extra variability and uncertainty to overarching estimates. The Soil Carbon Code (Forestry Commission 2014) provides look up tables to enable estimation of specific case study areas or to model a more stratified series of systems. Upson et al. (2013) measured soil carbon gains of 12.4 t C ha^{-1}. For silvo-arable systems, converting to CO_2 and dividing by 30 years, this provides an estimate of 1.5 t CO_2 ha^{-1} yr^{-1}.

Burgess et al. (2003) has produced estimated the costs of establishment of silvoarable systems and costs of site maintenance year. For silvopastoral systems, increased costs (due to tree guards and staking increases) are included in the calculations.

Table 141 and Table 142 present the results of the UK abatement potential and cost-effectiveness calculations. Results by DAs are provided in Table 143. Note that the apportioning between the DAs are done solely on the basis on the relevant land areas, not considering the agronomic differences between the regions.

Table 141 GHG abatement and cost-effectiveness of agroforestry on temporary and permanent grassland in the UK

Proportion of land converted		0.1%	1%	10%
Area	1000 ha	7	75	746
GHG abatement	t CO_2e ha^{-1} y^{-1}	kt CO_2e y^{-1}	kt CO_2e y^{-1}	kt CO_2e y^{-1}
In growing timber	7.34	55	548	5,477
In soils	0	0	0	0
Total		55	548	5,477
Costs	£ ha^{-1} y^{-1}	M£ y^{-1}	M£ y^{-1}	M£ y^{-1}
Establishment	150	1	11	112
Maintenance	70	1	5	52
Total		2	16	164
Cost-effectiveness	£ t CO_2e^{-1}	30	30	30

Table 142 GHG abatement and cost-effectiveness of agroforestry on arable land in the UK

Proportion of land converted		0.1%	1%	10%
Area	1000 ha	5	45	455
GHG abatement	t CO_2e ha^{-1} y^{-1}	kt CO_2e y^{-1}	kt CO_2e y^{-1}	kt CO_2e y^{-1}
In growing timber	7.34	33	334	3,338
In soils	1.5	7	68	682
Total		40	402	4,020
Costs	£ ha^{-1} y^{-1}	M£ y^{-1}	M£ y^{-1}	M£ y^{-1}
Establishment	83	0	4	38
Maintenance	50	0	2	23
Total		1	6	61
Cost-effectiveness	£ t CO_2e^{-1}	15	15	15

Table 143 GHG abatement (t CO_2e ha^{-1} y^{-1}) by DA for the 1% land area conversion

	UK	E	W	S	NI
Grassland					
Land area (1000 ha)	74	39	14	13	8
GHG abatement (t CO_2e ha^{-1} y^{-1})	548	289	105	96	58
Arable land					
Land area (1000 ha)	46	39	1	6	0
GHG abatement (t CO_2e ha^{-1} y^{-1})	401	341	7	49	4

6.3.4 Ancillary effects

The integration of trees into land use systems has a number of potential benefits in relation to productivity, carbon sequestration, soil fertility and nutrient cycling, improving water quality, and biodiversity. Where trees and understorey have resource requirements separated in space and /or time, agroforestry systems have the potential to conserve nutrients. In some pasture species shading can improve nutrient and protein content. There may however be a trade-off between competition and resource use complementarity between species that can be manipulated using different tree/understorey combinations.

From a production perspective, for the first 12 years after planting trees at 400 ha^{-1} in a silvopastoral system in the UK had only marginal negative effects on sheep productivity (Sibbald *et al.* 2001). The tree species will significantly effect canopy closure and therefore production, with systems with coniferous trees likely to retain agricultural productivity at a higher level for longer than broadleaved species. In silvoarable systems the production per unit land is likely to be smaller than a traditional arable system. Egg production can increase in agroforestry based poultry systems (Bright and Joret 2012).

Livestock based agroforestry systems can have welfare benefits, and there are well established links in poultry between trees and welfare, for example, by reduced feather pecking. Silvopastoral systems can also be extensive systems which provide welfare benefits to grazing livestock. The shelter provided can also be beneficial to production in exposed environments, particularly to young stock.

As silvopastoral systems mature the understorey vegetation changes which can attract beneficial invertebrates which can in turn provide a food source for attracting farmland birds. Changing the structural diversity of agricultural systems also provides enhanced cover and opportunities for nesting birds. Within silvoarable systems, tree rows also provide wildlife corridors. The biodiversity benefits of agroforestry are likely to be greatest in landscapes without other woodland habitats.

Adaptation through agroforestry includes diversifying the use of plant species and therefore potentially improved biodiversity including pollinators. The ability of rows of trees to alter the microclimate provides enhanced shelter for livestock (production and welfare implications). It also buffers climate extremes in terms of crop and grass production and thus associated risk reduction. Conversely, the buffered climate and reduced wind could however have negative impacts on crop diseases.

Agroforestry designed into the landscape is seen as an opportunity for mitigating ammonia emissions as trees are effective scavengers of atmospheric pollutants due to their effect on turbulence. Most work on ammonia and trees focuses on using trees around intensive livestock production facilities but Bealey et al. (2014) demonstrated the potential of trees for reducing ammonia from outdoor poultry production. There will be a trade-off between canopy density and livestock production.

6.3.5 Expected financial impacts on farm

Agroforestry systems have the potential to reduce risk by spreading enterprises and also providing more sheltered conditions for crop or livestock production. This diversity will influence economics depending on market price fluctuations of timber as well as crops and/or livestock. Financial return is a long-term investment in trees although the agricultural component of agroforestry means that establishment costs are recouped more quickly than in conventional forestry.

In the early years of agroforestry systems establishment costs are associated with weed control to achieve tree establishment. Different options available include the use of herbicides and mulches and choice will depend on the environmental/topographic conditions, whether the system is basically or arable or pastoral and other conditions such as organic management. Tree protection can be a major cost in silvopastoral systems and again choices depend very much on system design with options to use individual tree guards or to fence groups of trees. Replacement of trees which fail to establish or are subsequently damaged must also be taken into consideration.

6.3.6 Potential policy instruments to promote uptake and potential uptake by 2050

Within the new Common Agricultural Policy there is support for agroforestry under Pillar II, Article 23 of the new Rural Development Regulation 1305/2013 focuses on the establishment of agroforestry systems. This covers establishment and maintenance over 5 years with up to 80% of eligible investments. The details, in terms of tree spacing, are determined by Member States and this is a devolved responsibility in the UK. Payments in Scotland begin in 2016 but focused on sheep based silvopastoral systems. There are further constraints on amount of land per farm and a very limited total budget and it will unlikely that any new agroforestry would exceed a few hundred hectares. Similar constrained support is avialble in Wales and Northern Ireland. There is currently no support in England. A major change in financial support (to modify the cost benefit argument) but also in terms of extension and advice (to change farmer behaviour and reduce cultural barriers to uptake) would be needed.

One of the barriers to increasing planting of farm woodlands and agroforestry is the attitude of farmers to tree planting. Reasons include lack of land and the idea that trees should only be planned on farmland that is not useful for other things (Campbell *et al.* 2012, Duesberg *et al.* 2014). McAdam et al. (2009) suggest that a lack of skills and understanding relating to optimising agroforestry systems are a handicap to the development and uptake of agroforestry and also suggest that more tertiary education is needed in this subject. Agroforestry could potentially help to achieve a number of goals including Carbon targets as well as biodiversity (particularly birds) and water quality. Increased emphasis on agroforestry within relevant policy documents could help in this regard.

6.4 Covering slurry stores

6.4.1 Description of the measure

Liquid manure storage produces only small amount of N_2O, but the anaerobic environment is ideal for methanogen microorganisms, making slurry stores an important source of CH_4 emissions. Besides GHGs, NH_3 is an important gaseous emission from these stores. Covers can substantially reduce NH_3 emissions from the slurry stores, but the direct GHG effects are highly variable and inconclusive (VanderZaag *et al.* 2008). The reduced NH_3 emissions provide savings in indirect N_2O emissions, but could also increase direct N_2O emission after having been spread on the soil, unless low NH_3-emission spreading techniques are implemented.

The technical options for covering slurry stores are wide ranging, from natural crust through synthetic floating covers to tent-like or wooden structures. The practical feasibility of the options depends on the storage type (particularly on the surface area, i.e. whether the store is a tank or a lagoon), and the choice of cover has a major impact both on the costs and on the GHG and NH_3 effects of the cover (Anon. 2015).

6.4.2 Applicability

The measure is applicable on all slurry tanks and lagoons, i.e. to most of the liquid manure stored in the UK. The proportion of manure stored in liquid form is 0-41%, 0-5.6% and 37.7-45%, respectively, for dairy, beef and pig animals (depending on livestock category) (Webb *et al.* 2014, Table A 3.5.11). The proportion of slurry stored in tanks and lagoons can be approximated from the Farm Practices Survey (Defra 2015a), which reports on the proportion of livestock holdings with storage facilities for manure. Based on those data the current study assumes that 47% and 36% of liquid dairy manure is stored in tanks and lagoons, respectively, while the respective values for beef and pigs are 48% and 29%, and 62% and 30%. Thus the applicability is approximately 25%, 2% and 37% of all dairy, beef and pig manure.

6.4.3 Expected impacts on GHG emissions

The type of cover has a major influence on the rate and composition of gaseous emissions from the storage unit. Regarding NH_3 emissions, rigid (e.g. wooden or concrete lid) and impermeable covers (tent or floating cover) provide the highest mitigation, up to 80%. Floating permeable covers (synthetic, clay or straw) reduces emissions by 50-65%, while the development of natural crust reduces NH_3 emissions by 40%.

A reduction in CH_4 emissions was observed with some types of covers in some cases (see a summary in Eory *et al.* 2015). Rigid covers tend to reduce CH_4 emissions by 14-18% as demonstrated in two experimental papers (Amon *et al.* 2006, Clemens *et al.* 2006), however, a wider experimental basis would be needed to extrapolate such results. Additionally, such structures and impermeable floating covers can also be equipped with a flaring mechanism to convert the CH_4 to CO_2, thus reducing the GWP of the emissions. The energy from the burning can captured as well, akin to anaerobic digestion plants, though without providing controlled environment for the digestion process. So far the results on the CH_4 effect are inconclusive for other cover types. Though (the very low) N_2O emissions from slurry stores are usually not affected heavily by covering the stores, straw and crust cover provoke a dramatic increase in N_2O emissions, particularly in dry weather (Berg *et al.*, 2006; Sommer *et al.*, 2000).

The scope of the current study allows the estimation of the abatement potential for only one type of cover. Due to the inconclusive effects on CH_4 emission reduction, the basis for the selection of the cover type is the cost-efficiency of the NH_3 mitigation, as calculated in (Anon. 2015, Table 5.7), with ruling out straw and natural crust cover because of their unfavourable effect on N_2O emissions. The most cost-effective cover type to reduce NH_3 emissions without a major effect on N_2O emissions is floating permeable synthetic cover. The NH_3 abatement rate is 60%, and the current study assumes no effect on CH_4 or N_2O emissions. However, as every technology reducing the N loss during manure storage, this cover type also has the potential to increase N_2O emissions from manure spreading. As an approximation, here it as assumed that the N_2O emission increases by 9% if no action is taken to counterbalance the effects of the increased N content. (50% of the N in manure is ammoniacal N (Defra 2011b), approximately 10% and 50% of this ammoniacal N is emitted as NH_3 from tanks and lagoons without cover, and 60% of this emitted NH_3 would be retained with covering the store. This increases the total N content of the manure before spreading by 3% and 20%, respectively, for tanks and lagoons. Approximating the ratio of manure stored in tanks and lagoons as 2:1, based on the FPS (Defra 2015a), the weighted average N content increase is 9%. The soil N_2O emissions are assumed to increase proportionally.)

For a comparison, the measure *Covering slurry tanks* and *Covering slurry lagoons* in the 2008 and 2010 MACCs assumed 20% mitigation from the CH_4 emissions from manure storage with no effect on either direct or indirect N_2O emissions.

6.4.4 Current and additional future uptake

According to the Farm Practices Survey, on dairy farms 25% of slurry tanks and 2% of slurry lagoons are covered, the corresponding values on beef and pig farms are 24% and 0%, and 61% and 5% (Defra 2015a). Coverage seems to be increasing based on the FPS statistics of the last four years, so here the assumption is that an additional 10% increase will happen in the future reference scenario, leaving an maximum additional future uptake of 65% and 88% (dairy), 66% and 90% (beef) and 49% and 85% (pig) for tanks and lagoons, respectively.

6.4.5 Expected financial impacts on farm

The annualised cost (including capital and maintenance costs) of the different types of slurry covers are estimated in (Anon. 2015, Table 5.6), showing that floating permeable covers cost £0.39 m^{-3}, with a range of £0.09 to £0.65 m^{-3}, depending on the ratio of the surface area and the volume of the manure store. With an estimated 14 m^3 (500 kg LW)$^{-1}$ y^{-1} manure production across the livestock species, the annual cost is £5.5 (500 kg LW)$^{-1}$ y^{-1}.

6.4.6 Interactions with other measures

There are several measures in the MACC analysis in the current study which would have interactions with this measure. The combined NH_3 mitigation effect of this measure and *Slurry acidification* would be lower than the sum of the individual effects, thus increasing the cost-effectiveness of the measures. Covering the manure for the period before it is transferred to an anaerobic digester is good practice. Still, in the MACC calculations the UK abatement potential from *Covering slurry stores* is lower with an increasing uptake of AD, as the length of the period the manure spends in the tank/lagoon is substantially reduced. This current measure also has impact on the soil N management measures through increasing the N content of the manure spread, and thus, *ceteris paribus*, increasing the direct and indirect soil N_2O emissions in the future reference scenario. Most importantly, the manure management measures (MM2-MM4) and the *Nitrification inhibitors* measure would provide higher abatement if the slurry would have been covered.

6.4.7 Cost-effectiveness and abatement potential

The abatement potential of the measure without interactions and assuming CFP uptake in the UK is 37 kt CO_2e y^{-1} in 2035 (d.r. 3.5%), at a cost-effectiveness of £52 t CO_2e^{-1}; results by DA is presented in Table 144. Considering interactions with measures MM1-MM18 and MM20-MM24 (i.e. all measures but *Slurry acidification*), the UK CFP abatement potential in 2035 is 9 kt CO_2e y^{-1} at a cost-effectiveness of £52 t CO_2e^{-1} (Table 145).

Table 144 Abatement potential of Covering slurry stores, without interactions, by DA, for 2030 and 2035 (CFP, d.r. 3.5%)

Country	2030 AP kt CO_2e y^{-1}	2030 CE £ t CO_2e^{-1}	2035 AP kt CO_2e y^{-1}	2035 CE £ t CO_2e^{-1}
UK	28	52	37	52
England	18	52	24	52
Wales	3	49	4	49
Scotland	3	51	4	51
Northern Ireland	4	51	6	51

Table 145 Abatement potential of Covering slurry stores, with interactions, by DA, for 2030 and 2035 (CFP, d.r. 3.5%). Note that interactions with the measure Slurry acidification are not included

Country	2030 AP kt CO_2e y^{-1}	2030 CE £ t CO_2e^{-1}	2035 AP kt CO_2e y^{-1}	2035 CE £ t CO_2e^{-1}
UK	7	52	9	52
England	4	52	6	52
Wales	1	49	1	49
Scotland	1	51	1	51
Northern Ireland	1	51	1	51

Previous estimates in the 2008 and 2010 MACCs suggested that the UK abatement potential is (without interactions, 2022, CFP, d.r. 7%) 99 kt CO_2e y^{-1}, the cost-effectiveness ranging between £9 and £105 t CO_2e^{-1}, depending on the animal and manure storage type (Table 146).

Table 146 Abatement potential and cost-effectiveness results of Covering slurry tanks and Covering slurry lagoons (without interactions, 2022, UK, CFP, d.r. 7%) (MacLeod et al. 2010c, Moran et al. 2008)

Measure	AP kt CO_2e y^{-1}	CE £ t CO_2e^{-1}
BeefManure-CoveringLagoons	10	9
BeefManure-CoveringSlurryTanks	12	24
DairyManure-CoveringLagoons	33	25
DairyManure-CoveringSlurryTanks	35	70
PigsManure-CoveringLagoons	4	38
PigsManure-CoveringSlurryTanks	5	105

6.5 Precision livestock farming

The terms Precision Farming and Precision Agriculture (PA) are sometimes related only to crop management techniques. More correctly they span across all farming and agricultural production. The term, Precision Livestock Farming (PLF), has been widely in use for more than a decade. There is a temptation to think of Precision Farming or PLF only being primarily about equipment/technology.

A SRUC working group has recently defined precision farming, using the term SMART FARMING: *"Farming, using equipment, data or software which allows the use of information at a more individual level (animal, plant, field) for targeting decisions, inputs and treatments more precisely, with the aims including improving profitability, product quality, reducing environmental damage or having more efficient workloads."*

A similar definition specific to PLF has been provided by Banhazi et al. (2012); *"The main purpose of Precision Livestock Farming (PLF) is to improve the efficiency of production, while increasing animal and human welfare, via applying advanced information and communication technologies (ICT), targeted resource use and precise control of the production process."*

Another important review by Wathes at al. (2008), sums up the current state of PLF by its title, *"Is precision livestock farming an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall?"*

The key thing about these definitions is that they do not focus wholly upon the technology or piece of equipment or a sensor, but look broader at how information is used. Nevertheless, technology and the capacity to measure and communicate data are at the heart of PLF. In dairying alone, Bewley (2010) listed many technical capabilities including daily milk yield recording, milk component monitoring, pedometers, automatic temperature recording devices, milk conductivity indicators, automatic oestrus detection monitors, and daily body weight measurements, which are already available as commercial products and utilised by dairy producers. Other prospective technologies included measuring jaw movements, ruminal pH, reticular contractions, heart rate, animal positioning and activity, vaginal mucus electrical resistance, feeding behaviour, lying behaviour, odour, glucose, acoustics, progesterone, individual milk components, colour (as an indicator of cleanliness), infrared udder surface temperatures, and respiration rates. Since Bewley's review in 2012, some of these possibilities have moved forward towards commercial exploitation.

A common theme in discussion of technologically driven innovation is the key issue of uptake, which many authors have noted has been slow, or slower than expected. Sheng Tey and Brindal (2012) commented that the scientific literature on the agronomic, socioeconomic and environmental impacts of precision agriculture technologies is highly dispersed and has significant gaps in empirical evidence, with field studies missing in particular. Whilst there are many studies linked to the development of PLF technology, once products move into practice and under commercial production, publication of simple efficacy and economic data in the scientific literature is much less evident. This creates a problem when attempting to take the next step in looking at the advantages for GHG mitigation.

6.5.1 Rationale of GHG mitigation

Inherently, PLF techniques are unlikely to have an impact on direct emissions from farming systems. Indeed, as there is likely to be an equipment or infrastructure investment, this will have its own embedded emissions. Taking the two definitions above though, one about improving profitability, the other about improving efficiency the clear presumption of successful outcomes of PLF deployment is that they should result in systems which are more biologically and financially efficient thus likely have lower emissions intensity. More targeted inputs, less waste, improved output and better product specifications are attributes that fit well with a lower emissions future.

PLF approaches have a number of operational impacts ranging from substitution of labour through to transforming systems of production. Simple substitution of labour with equipment or knowledge gained through technology may improve profitability, but not necessarily production efficiency. So there is a case to say that there would be no benefit in terms of improving emissions intensity. However, other routes of action offer prospects of environmental gain alongside productive gain. Amongst a long list of very worthy public-good benefits Banhazi et al. (2012) considered that PLF would "reduce GHG emission and improve environmental performance of farms". This review also noted there was very little evidence for the impacts of PLF. Looking in more detail at some examples provides a way to examine this statement.

6.5.2 Expected impacts on GHG emissions

Corkery et al. (2013) proposed that the use of sensors could be used to reduce CO_2 and particularly NH_3 from poultry systems. Whilst CO_2 emissions from livestock systems do not register in national or international inventories, NH_3 does. The authors reviewed the complex interaction between ammonia production, ventilation rates (with direct impact on electricity use) and poultry performance. Higher ammonia levels depress production and increase mortality and high ammonia emissions threaten both the business (with statutory controls of large poultry and pig units) but also environmental. Attempts to save energy by reducing ventilation rates leads to increased ammonia emissions from more humid environments and particularly from shaving bedding. High ammonia is an external emission but also decreases animal performance and increases mortality. Using sensors, more sophisticated and optimised control of heating and ventilation would reduce ammonia and maintain productivity, a classic series of win-win–win (costs down, output up, emissions low) everything is managed well. In this case there should be reduced direct NH_3 emissions and improved GHG emissions intensity.

Emissions from ruminant and non-ruminant waste stores should benefit from smart technology to optimise storage, reduce volatilised losses (emissions) and optimise use as fertiliser replacement or in digesters. Unfortunately, there does not seem to be a similar route with enteric methane in core element of ruminant systems.

A useful area to look for potential impacts of PLF approaches that relate to nutrition. In non-ruminants nutrition affects emissions efficiency and emissions output of animal waste. For ruminants, there is potential to influence methane output, emissions intensity of the system and emissions related to animal waste. Feeding animals more precisely, according to data collected on their estimated needs, avoiding digestive issues that link to health and reproduction are all opportunities for greater efficiency. PLF approaches in pigs and dairy cows have had considerable study and the technology to achieve both the data collection and equipment to deliver more efficiently targeted feeding is commercially available and continuing to develop.

Precision feeding systems for pigs offer prospects of improved emissions intensity through better net fed conversions (e.g. van Milgen *et al.* 2012). Such systems rely upon automated weighing, modifying ration balances automatically on a per pen basis or provision of individual feeding stations. Different levels of sophistication in equipment and software will take this area forward significantly in the future. Impacts were reviewed by Pomar et al. (2011) with growing pigs with daily tailored diets having reduced nitrogen and phosphorus intakes by 25% and 29%, respectively and nutrient excretions of excess inputs were reduced both by more than 38%. Feed cost was 10.5% lower for pigs fed daily tailored diets. In terms of reducing emissions, fuller LCA approaches would be needed to identify the impact on overall net emissions, but Cherubini et al. (2015) showed that pig diets low in protein had improved carbon footprints, principally through lower need for imported soya.

For dairy cattle, precision feeding opportunities lie in the capacity to offer individually tailored supplements to cows in out of parlour feeders (which have been available for over 30 years using neck based transponders) or to individual cows in standard milking parlours, or through automated milking systems (milking robots). Combining milk recording and automated weighing systems with milking parlour visits provides good data on which to provide tailored supplement levels. Hills et al. (2015), in a comprehensive review of individual feeding of pasture based dairy cows, however, highlights the complexity in determining responses to supplementary feeds and provided compelling evidence that both cow-level (e.g. genotype, parity, days in milk, cow body weight, condition score, feed intake) and system-level (e.g. pasture allowance and other grazing management strategies and climate) parameters can influence the marginal milk production response to supplementary feeding. Basically, the responses are likely to be system and farm specific.

In trying to establish a global figure, a recent report by GRA (2015), rather more boldly states that customised balanced feeding programmes in grazing dairy cattle systems have been shown to increase productivity and reduce enteric methane emissions intensity (15-20%) and also reduce N excretion (20-30%), which results in reduced emissions from manure. These statements appear to be based upon the studies relating to smallholder dairy and buffalo herds and whilst they provide useful indication of the gains made in moving from a baseline to a balanced feeding regime (Garg *et al.* 2013), they probably do not reflect a more typical dairy system in the UK, or other high output dairy systems.

For a more typical western Europe system, Andre et al. (2010b) conducted simulation studies and compared standard herd level feeding with individually tailored feeding and saw an overall individual feeding, rather than population gave improved financial margins of 0.20 to 2.03 euro per cow (10% improvement in financial efficiency.) This was achieved through both an overall increase in herd concentrate supplementation (there being less of constraint in giving high levels of supplements to highly producing cows), but proportionately higher increases in milk yields. GHG were not estimated in the current study, but it appears realistic to presume a similar magnitude of GHG emissions intensity improvement would occur. Overall, with higher milk yields and higher supplement levels the net emissions of a static herd/population size would rise.

The reality is that farmers are likely to combine innovations. Automatic Milking System (AMS, milking robots) offer the opportunity to manage milking, but can collect much more individual cow data and provide a means to easily achieve a balanced feeding system in practice. In further simulations, Andre et al. (2010a) found that when maximizing daily milk revenues per automated milking system by optimizing individual milking intervals, the average milking interval was reduced from 0.421 d to 0.400 d, the daily milk yield at the herd level was increased from 1,883 to 1,909 kg d^{-1}, and milk revenues increased from €498 to €507 d^{-1} (a 2 % increase). If AMS occupation rate (OR) of 85% could be reached with the same herd size, the optimal milking interval would decrease to 0.238 d, milk yield would increase to 1,997 kg d^{-1}, and milk revenues would increase to €529 d^{-1} (an 6% increase). Consequently, more labour would be required for fetching the cows, and milking duration would increase. Alternatively, an OR of 85% could be achieved by increasing the herd size from 60 to 80 cows without decreasing the milking interval. Milk yield would then increase to 2,535 kg d^{-1} and milk revenues would increase to €673 d^{-1} (37% improvement).

Castro et al. (2012) studying AMS in Galicia also suggested that an increase in capacity would yield further system improvements. As average capacity was 52 cows per AMS, but an extra 16 cows could be added, increasing herd size and total yield and thus likely improving emission efficiency over indirect emissions. Sitkowska et al. (2015) showed that cows introduced to AMS quickly adapt to the new way of milking, and farmers with milking robots can precisely track many parameters related to the milking performance of their cows. Milk yield, milking frequency, intermilking interval, teat-cup attachment success rate and the length of the milking procedure are only some parameters that can be analysed with the use of robots. In addition to AMS changing the efficiency by which cows are milked by selecting cows that adapt best, or are genetically more efficient in AMS characteristics, then the cows themselves would be selected differently and genotype change.

AMS and balanced feeding with cows well adapted to an optimised management regime offer a view of the future. Efficient digestion with reduced nutritional waste and improved output, probably with increased herd size (as with less waste food, more cows can be kept) per unit land area (on the farm, or external farm land for imported feed).

Improved animal health also offers a great many opportunities for improved emissions intensity. PLF approaches provide means to achieve health gains. Rutten et al. (2013) provide a wide list of sensors that could be used to enhance health. Such systems consist of the device itself plus the software that processes the data to produce information or advice. Examples of sensors include milk electrical conductivity, milk colour sensors, accelerometer sensors and rumen pH sensors. Health management improvements should be partially additive to those of nutrition noted above, though typically nutrition and health interact.

PLF is less evident in sheep systems. A mature PLF technology is a very useful example of how PLF can aid management achieve gains but still have no GHG data readily obtainable from the literature. Pregnancy or ultrasonographic scanning was rapidly introduced, with rapid uptake rates in UK sheep farming in the 1980's (Logue *et al.* 1987). Simple evidence of the performance gain (fewer lambs lost, increased weaning weight by lambs was described by Parker and Waterhouse (Anon. 1986). Increases in output for those ewes carrying twins was dramatic (increase of 9kg lambs weaned per ewe 32%), though spread over the whole flock the benefit of ultrasound scanning was 1 kg of lamb per ewe. This should equate to improvements in emissions intensity. It is widely accepted to enable more efficient use of labour. It is typically increases supplementary feed provision to twin bearing ewes in hill flocks, though it may also reduce feed provision to single bearing ewes in lowland flocks. Such technology is so well embedded in current practice that in recent SRUC survey precision farming technology in use on sheep farms, no farmers included this simple PLF approach when asked to list their use of PLF.

Banhazi et al. (2012) noted that gains in efficiency could occur through greater information flow and better decision making in the wider food chain. Feed and feed input providers can greatly improve the composition of their products if they have access to slaughterhouse statistics resulting from the feeding profiles applied on the farm; Farms can use such a system for the selection of the right feed (or right feed provider). They can also optimise their feed use/intake from the statistics of other farms on the network; Abattoirs can use the system as a basis for cooperation with farms to produce and source more animals on weight and conformation specification.

Farmers use technology to ease their workload and improve their management (Alvarez and Nuthall 2006), but often not inherently any impact upon biological efficiency. These authors expected that farmers would seek information and develop their information systems until they feel confident that more information activity will cost less than the marginal return of the information. Consequently, farmers' belief in the adequacy of their current information system influences whether they change (e.g. invest in a computer).

In conclusion, there is a wide spectrum of PLF technology already in use and available commercially, but an increasing range of PLF that will be coming soon, with greater sophistication of data collection and data. Little data or publications relate to GHG emissions, but improved biological efficiency should transfer to reduced emissions intensity.

6.5.3 Ancillary effects

To date, mechanisation and use of technology has enabled farmers to increase farm size, flock and herd sizes. In the future, stocking densities, scale of waste management risk would typically increase but theoretically the capability to manage, control and make beneficial use (of waste) also increase with systems with well-informed managers. The relationship between PLF and animal welfare is debated generally by Wathes et al. (2008) and for AMS specifically by Millar and Mepham (2001). There are strong benefits to animals if PLF approaches are used well, and potential for a loosening of the animal-human connection with potentially negative consequences. Inherently, there appears to be no over-arching reason for welfare to be at greater risk and every reason for optimism that systems tailored around individual animals and their needs should have better welfare protection.

In terms of enabling farmers and there systems to be responsive and adaptive to weather events and changes in climate then more tailored approaches to animal care should also be better. Systems which collect data should also be more robust. However, with higher levels of automated systems and electronic controls, then extreme weather events potentially pose greater risk through technology collapse.

6.5.4 Expected financial impacts on farm

There is a scant publication record for the financial benefits of PLF. There are good examples of how uptake in practice is achieved, or often the future prospects of novel technology and systems and publications tend to focus on early adoption phases.

Current examples of PA or PLF have typically related to efficiency savings and either 1) substitutive, replacing human power with machine power, 2) complementary, improving productivity and employee effectiveness through new ways of accomplishing tasks, and 3) innovative, obtaining a competitive edge and 4) transformational, changing system structure and characteristics dramatically. Many introductions of PLF are multi-stranded, with equipment being part of a change in management system and potential to use a different type of animal. Costs of technology are often high for early adopters and Banhazi et al. (2012) noted risks of more 'controlled systems'. Many producers perceive that adopting high productive management systems involves increased risk. The perceived risks include financial failure because of unforeseen environmental or market circumstances, damage to the farm infrastructure such as soils and pasture, compromises to animal health and welfare, and increased stress on farmers from managing an intensified system.

A further dairy example shows the impacts on farm profitability (Rutten *et al.* 2013). The economic benefits of an automated oestrus detection system have been studied, such as the simulation study based on the average characteristics of a Dutch dairy herd (e.g. 7,500 kg of milk, oestrus detection rate of 50%, and conception rate of 40% (van Asseldonk *et al.* 1999)). Under the assumption that oestrus detection was improved from 50 to 90%, gross margin would increase by 1.25 Dutch guilders (€0.57) per 100 kg of fat- and protein-corrected milk (van Asseldonk *et al.* 1999) the resulting net return to investment equipment and labour was 4.8% pa.

Despite efforts to formalize the rational decision making analysis of investment in information technologies, many business executives ultimately make their investment decisionbased on "gut feel" or "acts of faith" Bannister and Remenyi (2000). Farmers are likely to follow the same route.

6.5.5 Potential policy instruments to promote uptake and potential uptake by 2050

Banhazi et al. (2012) predicted the short term future: "in the next 10 years, it is very unlikely that PLF will revolutionise the livestock industries". However, in the next 5-10 years, sensors will be deployed routinely around animals that might allow farmers to effectively monitor a range of useful parameters for all livestock species. This will enable a range of new services to be developed and implemented on farms, such as individual feeding, heat detection, health monitoring and animal localisation. Mobile robots will emerge for milking and other tasks both in the shed as well as in the open.

Virtual fencing will contribute to better herd and meadow management and improve financial returns for grazing enterprises. Most farms in Europe will be computerised in 10 years and use software tools for their management". The farm of 2050 is likely to be very different in terms of technology in use. Interestingly, Banhazi et al. (2012) also predicted that within 10 years most producers would know how much GHG they are emitting. This looks optimistic.

These authors also looked at uptake and noted that limiting factor of uptake rate of PLF technologies on farms is the lack of co-ordination between researchers, developers and technology suppliers. Achieving better co-ordination between the developers and suppliers of PLF tools is very difficult, but would result in the development of better integrated systems. That in turn would result in greater commercialisation of PLF systems as integrated systems to serve the farmers better. In addition, many of the PLF "products" actually never have been developed into a proper "product"; but they went directly from the lab to the farm.

Uptake of precision agriculture techniques (in crops and animals) has been pushed by policy in many developing countries, though uptake of more technically advanced systems has been slower than many might expect (Pierpaoli *et al.* 2013, Tey and Brindal 2012).

Banhazi et al. (2012) suggested the steps needed to improve uptake, namely (1) establish a new service industry; (2) verify, demonstrate and publicise the benefits of PLF; (3) better coordinate the efforts of different industry and academic organisations interested in the development and implementation of PLF technologies on farms; and (4) encourage the commercial sectors to assist with professionally managed product development.

There are some examples of policy intervention for example in the Irish Republic where a main vision of the Irish Government's Food Strategy "Food Harvest 2020" is to Act Smart using wireless technology to gather data through the so-called Internet of Things (Corkery *et al.* 2013).

In terms of policy approaches to improve PLF uptake, it is clear that there is often elements of market failure, or market slowness with slow uptake. The elements that could provide support for uptake and implementation of PA/PLF would be;

1. Awareness and demonstration
2. Training, including training the trainers
3. Financial support of product development
4. Direct support for equipment, software, implementation (i.e. proof of collecting and using the information, rather than just purchase of software)

The new RDP support package in England is directly supporting farmers to purchase number of PLF applications. Previously, Scotland provided support for livestock recording equipment.

Lack of uptake and uncertainty over both the practical and financial benefits of previous and current PLF technologies is also matched by lack of data and uncertainty of the net emissions characteristics of uptake. Amongst the issues with resolving the benefit of improved uptake of technology is that increased outputs, reduced labour would likely result in increased overall livestock emissions per farm. Activity data, numbers of animals and sales data for milk or meat would reflect this. Input data is harder to calculate for national inventory purposes and it would be difficult to allocate any emission intensity saving to any individual or basket of measures. Good data of 'before' and 'after' intervention for certain PLF applications, with production, profitability, broader environmental impacts and greenhouse gases budgets all measured would be worthwhile to justify policy action, but also support uptake.

6.6 Genetic modification of livestock

6.6.1 Description of the measure

Genetic modification (GM) involves altering its genetic material by adding, changing or removing certain DNA sequences. It aims to modify specific characteristics of an animal or introduce a new trait, such as disease resistance or enhanced growth. There are a range of technologies that can be captured by the term "genetic modification" however one of the more recent techniques that is gaining ground is the "gene-editing" technique. This technique is proven to be more effective than other GM techniques (10-100 times) and it crucially does not involve the use of antibiotic resistance genes.

Genome editing technologies involve identifying and modifying specific DNA sequence(s) whereas more traditional GM techniques where the aim is to insert new DNA fragments into an organism. There are a range of studies that how shown (or are showing) the utility of using genome editing approaches for emerging infectious diseases such as bird flu and African Swine fever, but also to finally be able to control diseases which already have a significant impact on animal production, such as TB and trypanosomosis in cattle and the porcine reproductive and respiratory syndrome virus (PRRS) in pigs. This technology generally targets information on natural occurring variants of the DNA (and therefore genes) and modifications of the underlying DNA sequence that affect traits, be they production traits, health/resistance traits or potentially even GHG emissions. This means that the changes could be seen as similar to those we target via traditional genetic selection but potentially they could be achieved more speedily.

GM laboratory animals are widely used but most other GM animals are still at the research stage or market feasibility stage. The first GM animal likely to be marketed as food is a GM salmon, which is awaiting approval for human consumption in the USA. Further, UK company Oxitec is releasing GM mosquitoes to tackle mosquito-borne disease dengue fever, which is currently being reviewed by the US Food and Drug Administration Center for Veterinary Medicine for field trials in the Florida Keys. The company wants to release GM agricultural pests, including olive flies and fruit flies, in the future. Such technologies could have major impacts on livestock (and wider agricultural) production and reduce major losses from disease and potential improvements in production potential and reductions in GHGs.

6.6.2 Applicability

Applicability is currently limited by the fact the GM in animals, particularly those destined for the food chain are under strict regulatory frameworks around the globe. Within the EU GM animals for food production are generally banned with 19 member states (Germany, Scotland, Northern Ireland) taking the "opt-out" clause to abstain from growing GMO crops. *Within the European Union (EU), the application of GM technology is strictly regulated for domestic and imported goods. The EU has established a legal framework regulating GM food and feed derived products as well as the release of living GMOs into the environment in order to ensure a high level of protection of human and animal health, and the environment* (European Food Safety Authority).

If the regulatory barriers were relaxed/removed the potential applicability of GM technologies helping to either directly or indirectly reduce the GHG emissions in livestock production could be high. It is likely that many of the species that have a high uptake rate of genetic improvement (pigs and poultry and potentially dairy) would be the early adopters of such technology, perhaps tackling traits that are currently hard to address via conventional selection and/or alternative management options – these being disease resistance, particularly in environments where the challenge level is high. One of the potential routes to disseminate the technology to a wider population would be to genetically modify key parent stock and allow the gene flow from pedigree populations transfer the "improved" genetics to the wider population. Examples include GM grandparent stock lines in pigs and poultry or GM elite dairy bulls from which semen is distributed globally. In these cases the GM would work alongside other measures studied here including balanced breeding goals and sexed semen and would be additive to these measures.

6.6.3 Expected impacts on GHG emissions

The abatement potential for GM is currently theoretical and would initially focus on indirect reductions on GHG emissions based on examples for disease resistance given earlier (e.g. reduced wastage resulting from improved health and longevity). To the best of our knowledge there is limited work ongoing looking at using GM to directly reduce GHG arising from livestock production – such as GM to reduce methane emissions or to alter the nitrogen profile of excreta. The Enviropig™ was created by the University of Guelph (funding of this programme has since ceased) and is a GM line of Yorkshire pigs with the capability of digesting plant phosphorus more efficiently than conventional Yorkshire pigs. When manure from conventional pigs is spread on land, there is a build-up of phosphorus in the soil which could then leach into water courses and cause environmental damage. Since the Enviropigs excrete less phosphorus in the manure, there is less opportunity for pollution of water sources. Such an example provides the evidence that GM could be used to directly target environmental impact of livestock production.

In theory, if GM for some target disease and production traits is possible and could be regulated for we expect that a proportion of the GHG emission reductions estimated from measures such as improved animal health and balanced breeding could be achieved and achieved more quickly that the trajectory described above. However, it would be impossible to predict, at present, the actual proportions.

6.6.4 Cost

The costs associated with GM would currently include (i) R&D costs for further developing and refining the techniques and establishing the proof of concept (public R&D funding and public-private partnership); (ii) costs associated with moving the technology along the innovation pipeline to a higher level of technology readiness (private investment); (iii) costs for regulatory change/approval (private investment); (iv) commercialisation costs.

6.6.5 Discussion

Concerns about GM animals include concerns about animal welfare issues (particularly for mammals) and complex and unpredictable impacts on ecosystems, including wild species and diseases (particularly for birds, fish and insects released or escaping into the environment). There are also concerns about introducing meat, milk and fish from GM or cloned animals into the human diet and about contamination of the human food chain with GM insects, if they are used in agriculture.

6.7 Using sexed semen in dairy cattle reproduction

6.7.1 Description of the measure

Sexed semen is semen in which the sperm are sorted into those containing Y and X chromosomes. The semen is then used for artificial insemination, leading to approximately 90% of the calves being one sex. In dairy systems sexed semen can be used to increase the proportion of pure dairy (i.e. dairy x dairy) calves that are female (and required for replacing cows), thereby reducing the number of (often unwanted) male pure dairy calves and increasing the number of dairy x beef calves (of both sexes) for rearing as beef animals. Increasing the number of dairy x beef calves means that less suckler cows are required to produce the same total beef output, thereby reducing the total emissions and the emissions per kg of beef produced.

6.7.2 Applicability

Applicability currently limited by expense, but could potentially be applied to the entire dairy herd. In the calculations of abatement below, it is assumed that sexed semen is only used on maiden heifers. Studies indicate that sexed semen yield reduced pregnancy rates when compared with conventional semen (e.g. see Hall and Glaze 2014), which may prevent optimal reproductive performance of the herd. However, with recent advances in semen sorting and freezing, the difference in pregnancy rates is reducing.

Sexed semen is ideal for use in maiden heifers as each subsequent calving reduces fertility. Cows that have had health problems such as mastitis or lameness should not be served with sexed semen.

6.7.3 Expected impacts on GHG emissions

Table 147 Change in production emissions and emissions intensity arising from the use of sexed semen on a medium sized dairy farm with 149 cows

	Cow replacement rate							
Parameter	0.33	0.33	0.25	0.25	0.2	0.2	0.167	0.167
Sexed semen	NO	YES	NO	YES	NO	YES	NO	YES
% of male dairy calves culled at birth	0	0	0	0	0	0	0	0
female dairy calves	62	62	47	47	37	37	31	31
male dairy calves	62	26	47	19	37	15	31	13
dairy x beef calves	31	68	50	78	62	84	70	88
Meat (t LW y^{-1})	49	67	51	64	51	62	52	61
Milk sold standard (t y^{-1})	894	894	894	894	894	894	894	894
Dairy male calves culled	0	0	0	0	0	0	0	0
Dairy male calves sold	62	26	47	19	37	15	31	13
Total emissions (t CO_2e y^{-1})	2226	2423	2210	2359	2200	2320	2194	2293
Beef emissions avoided	765	1056	795	1015	814	990	827	974
Veal calf emissions avoided	45	19	34	14	28	11	23	10

	Cow replacement rate							
Milk emissions (total GHG - avoided GHG)	1416	1348	1381	1330	1359	1318	1344	1310
EI of milk (kg CO2e kg milk^{-1})	1.58	1.51	1.54	1.49	1.52	1.47	1.50	1.47

Notes: Calculated using GLEAM (M MacLeod, May 2015). Assumed that sexed semen is only used to service maiden heifers.

Table 148 Summary of the changes in milk EI with different cow replacement rates

					Change in EI with RF		
Cow replacement rate (RF)	0.33	0.25	0.2	0.17	0.33 to 0.25	0.25 to 0.2	0.2 to 0.17
EI of milk (kg CO_2e kg^{-1} milk) - unsexed semen	1.58	1.54	1.52	1.50	*-2.5%*	*-1.6%*	*-1.1%*
EI of milk (kg CO_2e kg^{-1} milk) - sexed semen	1.51	1.49	1.47	1.47	*-1.4%*	*-0.9%*	*-0.6%*
Change in EI from sexed semen	*-4.8%*	*-3.7%*	*-3.0%*	*-2.5%*			

6.7.4 Current and additional future uptake

The economic benefits associated with sexed semen, are dependent on the balance between the increased infertility and sexed semen costs and the increased heifers born under the sexing scenarios (Shalloo *et al.* 2014). Roberts et al. (2008) cited the following barriers to uptake of sexed semen:

- Low fertility.
- Sexed semen not available for most popular sires.
- Use natural service.
- Cost of sexed semen.

The Workshop suggested that abatement is possible via this measure, but it is not readily targeted by policy and the measure is more likely to be adopted for business reasons.

6.7.5 Cost

Cost type	Cost	Notes
Expenditure	Insemination costs	-Cost of additional service -Premium for sexed semen per straw (see Roberts et al. 2008, p10). Between £10 and 30 per straw (Dairy Site 2010)
Expenditure	External expertise	Hiring specialist inseminator?
Revenue	Change in number of animals or in herd structure	Yes - changed proportions of male dairy and male dairy x beef calves
Revenue	Change in milk output	Possible decrease if calving interval extended by unsuccessful insemination attempt (each day of delay results in lost production costing up to £4/day (Roberts et al. (2008, p9).

Revenue	Change in meat output	Yes, additional dairy x beef calves for rearing
Revenue	Reduced losses	Potential reduction in male dairy calves culled at birth.
Revenue	Change in output quality/value	Changed proportions of male dairy and male dairy x beef calves
Time	Labour: learning	Training/learning how to use SS efficiently (heat detection, SS handling and thawing).

7 Human dietary change and its impact on agricultural on-farm abatement

7.1 Methodology

This review is primarily based on work carried out for a recent Rapid Evidence Review of consumer behaviour in relation to sustainable diets (Garnett *et al.* 2015), for which a standard Rapid Evidence Assessment protocol was used (Petticrew and Roberts 2005). Previous similar reviews were also consulted, particularly Lucas *et al.* (2008), Reynolds et al. (2015), Defra (2011a), and Southerton et al. (2011). This review summarises the key areas of literature, as well as the key findings and recommendations from these reports which are relevant to on farm mechanisms for GHG emission reduction.

7.2 Key findings from modelling work

There is a sizable body of work which applies a variety of modelling methods to dietary change. These can be separated into three categories. First, models of specific diets such as reduced meat, Mediterranean, Nordic, for example, and the associated GHG emissions. Second, models which link consumption and agricultural production, either by assuming changes in consumption patterns, or by assuming limits to growth in terms of agricultural production, and increased demands. Thirdly, modelling studies which explore taxation and the impacts on food consumption – these are either from a public health perspective, or greenhouse gas production.

This review focuses on the first two types of modelling study, as the third is predominantly situated in the public health literature and so has limited relevance to agricultural production.

Table 149 summarises the key studies reviewed concerning modelling dietary change.

The sample of modelling work indicates that some emphasis is placed on GHG emissions in this literature, with fewer studies considering other environmental metrics such as water use, biodiversity, and fewer still consider social impacts.

The models indicate the potential for significant health benefits from reduced meat consumption, reduced fat consumption and increased fruit and vegetable consumption. If these reductions lead to substitutions which are in themselves healthy there is a potential for a shift to a more nutritionally balanced diet.

Reynolds et al. (2015) indicates that these consumption patterns are differentiated according to socio-economic position, therefore any interventions will need to be context specific.

The models indicate potential environmental benefits that can be achieved from shifts in food consumption patterns. These benefits however assume that changes in consumption would have impacts in terms of production. Two studies (Tukker *et al.* 2011, Wolf *et al.* 2011) make the important point that changes in EU food consumption are unlikely to impact EU food production as producers would focus more on export markets, and so environmental gains will be significantly reduced. These 'rebounds' are crucial to identify to avoid unintended consequences.

Table 149 Studies reviewed and key findings

Reference	Summary	Key points
(Aston *et al.* 2012)	Based on current data on British red and processed meat (RPM) consumption, a model of health and GHG emissions was constructed. Estimates of reduced health risks (obesity and diabetes) and GHG emissions were made if consumption trends change toward reduced consumption and increased vegetarianisms. Some scenarios showed reduced public health risks and reduced GHG emissions of up to 3% of current total.	Suggests that in some scenarios, there are multiple health and environmental benefits for encouraging reduced RPM consumption in the British population.
(Biesbroek *et al.* 2014)	A study based on data from 4011 Dutch participants. The study looked at mortality, land use and GHG emissions and modelled the impact on these of meat substitution in the participant diets. The model found little interaction between land use, mortality and GHG emissions. When a proportion of meat in diets was substituted for vegetables and nuts, there were reductions in mortality and GHG emissions apparent in the model.	Uses a large sample of actual dietary data. Indicates that with some substitution of meat in a diet there are potential reductions in the health and environmental burden of diets.
(Edjabou and Smed 2013)	A modelling study which investigates the potential of consumption taxes to internalise social costs of GHG emissions from 23 different foods. Heath impacts were also considered - where there was consumer compensation, and net daily Kj intake was affected. In all scenarios saturated fat intake decreased.	Indicate environmental and health benefits of consumption taxes to reduce GHG emissions from food.
(Green *et al.* 2015)	Model of shifting the average UK diet for adults towards meeting the WHO guidelines would reduce GHG emissions by 17%, with higher reductions possible with realistic modifications in reducing animal products and increasing fruit and vegetable consumption.	Reductions beyond 40% of current GHG emissions are unlikely without radical changes in consumption patterns, and may have nutritional implications.
(Peters *et al.* 2007)	A modelling study measuring the impact of fat and meat consumption on the land requirements of food production in New York State (USA).	The model indicates that decreasing meat in the diet decreases per capita land requirements, decreased total dietary fat decreases land requirements of high meat diets but increases the land needed for low meat diets.
(Reynolds *et al.* 2015)	An input-output analysis modelling the environmental impacts of food consumption of Australian households based on income. The model showed that the environmental impacts (water, energy, CO2, and waste) of the top income brackets were higher than the lower income brackets.	Conclusions presented suggest that changing consumption patterns should differentiate between income brackets. Change for lower brackets should emphasis reduced meat, bakery and dairy consumption, while for the higher brackets it should focus on the impact of eating outside of the home.

Reference	Summary	Key points
(Temme *et al.* 2013)	Nutrient and environmental impact (land use and GHG emissions) assessed for actual consumption patterns and two replacement scenarios. The replacement scenarios were to replace 30% or 100% of meat and dairy foods with comparable plant derived foods.	The model indicates that replacement of meat and dairy foods has benefits for health and the environment, however, from a nutritional perspective, there must be care taken for certain groups and micronutrients such as zinc, vitamin B1 and iron in young girls.
(Tukker *et al.* 2011)	Compares the environmental impacts (climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, ecotoxicity, abiotic resource depletion) of current consumption patterns and three simulated diets baskets – consumption according to universal recommendations, the same pattern but with reduced meat consumption and, a 'Mediterranean ' diet with reduced meat consumption.	The models indicate significant environmental benefits from reduced meat consumption, but also indicate that the livestock sector is likely to respond by increasing exports to other regions to compensate, so environmental impacts of production are not likely to be reduced.
(Westhoek *et al.* 2014)	A study applying biophysical models to assess the consequences of replacing 25-50% of animal derived foods with plant based foods. Environmental impacts assessed were nitrogen emissions, GHG emissions and land use.	The model predicted that halving the consumption of meat, dairy products and eggs in the EU would achieve a 40% reduction in nitrogen emissions, 25-40% reduction In GHG emissions and 23% less use of crop land.
(Wolf *et al.* 2011)	An input-output and equilibrium model of EU agricultural production responses to reduced food consumption	Concludes that EU agriculture would not decrease outputs significantly due to reduced consumption.

7.3 Policy instruments

7.3.1 Soft policy approaches

7.3.1.1 *Sustainable diet guidance and its effect on consumer choices*

There is a large body of evidence relating to what constitutes a sustainable diet (Auestad and Fulgoni 2015), or a diet that meets nutritional and health needs, while reducing social and environmental impacts. This evidence has guided a number of governments and international organisations to develop guidance outlining sustainable diets. The World Health Organisation has detailed dietary guidelines for nutrition. Reynolds et al. (2015) used these guidelines to assess for environmental impact and found that meeting these guidelines would reduce environmental burdens from food consumption. More specific consideration of the environmental impact of dietary guidelines is however desirable in order to address areas where nutrition does not satisfy environmental needs – in the case of fish consumption for example.

Examples of national governments who have produced dietary guidance which include nutritional and environmental considerations are Sweden, the USA, Brazil and the Netherlands. The UN Food and Agricultural Organization (FAO) and WWF are global organisations which have produced sustainable dietary guidance. Summaries of these guidelines can be found via the FAO website (FAO 2015).

Issues to consider include questions of competition and open markets, especially when guidance encourages localism in the food system to reduce GHGs. The EU Commission and WHO have both been involved in questioning this sort of recommendation in guidance documents.

The link between these guidelines and agricultural production have been the subject of some studies (Tukker *et al.* 2011) which indicate that following existing dietary guidelines has the potential to reduce GHG emissions from food consumption. However, we must stress that these models rarely consider the response of producers. Much of the work also assumes that meat and dairy alternatives have fewer environmental impacts, but this might not be the case, particularly if water consumption and land use are considered.

7.3.1.2 *Empirical evidence of consumers' attitudes to sustainable diets*

There are a number of studies which have focused on attitudes of consumers towards sustainable diets, and sustainable food. The majority of these studies are within developed countries, primarily the USA and the European Union. Some studies have very large sample sizes and are multi country (Grunert *et al.* 2014, Grunert *et al.* 2012, National Geographic 2015)(Grunert 2012, Grunert, Hieke, and Wills 2014, Hoek et al 2011, Greendex 2014).

These studies give us a good understanding of: i) the attitudes of Western consumers towards sustainable diets, and food, and ii) attitudes of particular groups such as students which are highly represented in the survey studies reviewed. While some studies do sample the wider population in question, other specific groups are not specifically represented, such as ethnic groups, the very young, very old, or those with specific health needs such as chronic of mental health illnesses.

These studies suggest that key motivating attitudes relating to food consumption behaviour are price and taste, with convenience and habit also influencing purchases (Garnett *et al.* 2015). Some studies identified a stated willingness to pay for the environmental benefits of certain foods (Barber *et al.* 2014), however, very few people in these studies show a significant concern towards sustainable food. For example a focus group study by Owen et al. (2007) discussed five recommendations for sustainable diets made by Defra: Switching to a diet with lower environmental and social impacts; Wasting less food in the home; Avoid fish from uncertified or unsustainable stocks; buy certified fish; Switching to more seasonal and local food; Increasing consumption of organic or certified / assured food and drink (including Fairtrade). The 14 focus groups found that eating a low impact diet had the lowest appeal, while people were more positive about changing purchasing habits and wasting less.

To complicate matters, these behaviours differ between countries. A study of consumers attitudes to refined and wholegrain cereals in Finland, Germany Italy and the UK found significant differences in attitudes and beliefs associated with these food items – for example perceptions of health benefits of wholegrain products are highly evident in Finland, while hardly in Italy (Shepherd *et al.* 2012). In a comparison of attitudes and motivation towards buying fruit and vegetable boxes, Brown et al. (2009) carried out a longitudinal study of 182 French and 148 UK customers of local box schemes. The study found significant differences in the primary motivation behind purchases – in the UK this was local, with less food miles – seen as an altruistic motivation, in France it was the quality of the produce.

A study of promoting the 'Nordic' diet in Denmark by Micheelsen et al. (2013) investigated attitudes and barriers to the diet in a small sample size of 38 households. The investigation included a trial meal. The study identified social and cultural barriers that might need to be overcome if attempting to promote such a diet: a perception of elitism in such a diet, concern over product availability and a desire not to fully exclude non Nordic foods/meals completely.

When studies concentrate on behaviour rather than attitudes, we see even few people motivated to purchase food according to sustainability criteria (Dixon and Isaacs 2013). For example Salonen et al. (2013) investigated attitudes of 198 participants from the Helsinki Metropolitan area, and asked them to assess 36 elements of sustainability. The most significant barrier to a sustainable diet was assessed to be cost; participants also expressed a feeling that they had limited power to have an effect. The analysis suggested that 66.5% of barriers expressed were contextual and 33.5% personal. The authors suggest therefore that interventions in the social context would be an effective way to achieve behaviour change.

7.3.1.3 *Examples on sustainable consumer behaviour from other sectors*

There have been a number of reviews of sustainable consumer behaviour in areas not relating to diet. The most relevant are summarised here, as well as by Garnett et al. (2015). These studies can help us understand consumer behaviour and interventions which might shift behaviour in desirable directions. Abrahamse and Steg's (2013) meta-analysis of social influence interventions relating to resource conservation including recycling, grass cycling, composting, nature conservation, gas and electricity conservation, petrol conservation, and water conservation. They included 42 studies into their meta-analysis. They recognised six types of social influence intervention: the use of social norms in information and feedback provision, block leaders and social networks (volunteers who help inform other people about issues), public commitment making, modelling (the use of a confederate to demonstrate a behaviour), the use of social comparison in feedback provision, and feedback about group performance. In their analysis, they found that compared to the control, the block leader approach was most effective, followed by public commitment, modelling, group feedback, and the use of social norms. The authors emphasise that social influence interventions are effective against control groups, but that we must also consider that effectiveness may be different for subgroups.

Momsen and Stoerk (2014) conducted a controlled experiment investigating the effect of a range of 'nudge' techniques relating to the purchase of renewable energy. The experiment was computer based and simulated purchasing an energy contract. The 475 participants were German and International students. The control group were asked to choose between purchasing a conventional energy contract or a 50%/50% conventional/renewable energy contract at a higher cost. The experimental groups were testing the following nudge methods: priming (before the decision, participants were asked whether they intended to by renewable energy, or were told that a related ethical NGO has gone out of business); framing (participants were given information about the additional carbon emissions associated with the conventional contract); decoy (offering a third contract that is equal to the 50%/50% contract but no environmentally beneficial); social norms (adding a statement to say that the majority of your neighbours use a certain energy mix); and finally the default nudge (participants informed that the default contract is the 50%/50% contract). Statistical analysis found that in this experiment on the default nudge had a significant effect compared to the control group.

7.3.1.4 *Labelling and its effects on consumer choices*

Labelling can include labelling for heath, or labelling for production characteristics such as organic, sustainable production practices, or Fairtrade. Garnett et al. (2015) discuss the evidence relating to health based labelling as well as sustainability standards and concludes that the evidence in relation to sustainable based labelling indicates that while consumer awareness of certain labels (Fairtrade, Marine Stewardship Council, Organic for example) is growing, the information presented by these labels is rarely used to make a purchasing decision (Garnett *et al.* 2015).

In relation to producers, these labels are however of concern, as often their business to business function is more significant that retailer to consumer. Examples of retailers changing purchasing policies to favour a particular label include four large UK supermarkets only purchasing Fairtrade certified Bananas (Fairtrade 2014).

Specifically considering carbon labelling, a number of studies, again reviewed in Garnett et al (2015) investigating consumer attitudes and behaviours towards carbon labelling indicate that these are viewed favourably by consumers. However, they also indicate that knowledge and understanding is low, and that as we have seen in relation to sustainable diets, other factors are more significant when making a purchase, such as price.

For producers, labels are important mechanisms to enter certain markets, but they are also costly, and so can have disproportionately negative impacts on small producers and companies. If consumers do not respond to them, this can limit their effectiveness to direct change. Conversely, consumers build up an understanding of what a label purports to achieve, and if this is not demonstrated this can erode the reputation of the label.

7.3.2 Regulation

There are a number of examples where fiscal measures have been introduced in order to try to shift food consumption patterns. These are frequently implemented for public health reasons and focus on food items associated with non-communicable diseases. Examples for taxed food items are sugar and fat. The most common food items which are subsidised for consumers are fruit and vegetables. The Danish 'fat tax' and the Hungarian 'junk food tax' are two examples. From the health literature, a systematic review by Thow et al. (2014) noted that while much of the work done in this area relies on modelling, and is so based on assumptions, there is empirical evidence to suggest that taxation especially of noncore foods such as sugary drinks and unhealthy food according to nutrient profile, does offer an important regulatory mechanism to improve health (Biro 2015, Ecorys *et al.* 2014, Garnett *et al.* 2015).

Again, the literature highlights the importance of identifying unintended consequences. If taxes on certain food items are not designed in conjunction with other unhealthy food items, consumption could shift from one unhealthy pattern to another (substitution) – from foods high in fat, to foods high in sugar for example. Similarly, from unprocessed high fat foods, to heavily processed low fat foods which may have significant environmental impacts (Ecorys *et al.* 2014, Garnett *et al.* 2015).

7.4 Summary

Southerton et al. (2011) in their case studies of behaviour change relating to climate change make it clear in their findings that targeting multiple contexts is key, this is reflected in other work summarised here (Garnett *et al.* 2015) – action is needed from government, industry and the NGO sector to encourage and support consumer changes which will reduce the GHG emissions associated with the agri-food sector.

The modelling work summarised here suggests that there is real potential to reduce agri-food associated GHG emissions by addressing consumption, there are other environmental benefits as well such as water efficiency, and land use. Wide knowledge of social and other environmental impacts such as biodiversity must also be considered.

The need to work across sectors and the supply chain is especially apparent when considering the link between producers and consumers, where shifts in consumption have diluted effects on producers due to international markets (Ecorys *et al.* 2014, Tukker *et al.* 2011). The relationship between consumer attitudes and behaviour are not always straightforward, with cost acting as a significant determinant to purchasing behaviour.

Consumer attitudes and behaviour is heterogeneous, with cultural and socio-economic factors influencing consumers in complex ways, these must be considered when attempting to engender change.

Studies used in this review such as Garnett et al. (2015), indicate a number of areas where empirical evidence would be useful. These include populations of consumers which are underrepresented in the existing literature such as the elderly, particular socio economic groups, and populations in emerging economies, particularly those with large middle classes likely to have a significant contribution to GHG associated with food - such as India and China.

Another area relevant to producers is to understand the response of producers to changes in consumers' consumption. Empirical evidence here would help to place models of GHG reduction for reducing meat and dairy consumption into the context of regional and global production systems.

Reducing GHG emissions from the food system requires a variety of actions to be instigated across the supply chain, there is a need to establish economic and mitigation capacities from different options in order to locate those with the greatest potential both for GHG savings, as well as those which are likely to work. Much of the literature indicates that changing consumer behaviour is complex, requires multiple approaches from government, industry and individuals. Studies comparing these approaches would help to target action.

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Appendix A

Selection of mitigation measures

Table 150 Mitigation measures considered for shortlisting, based on Frelih-Larsen et al. (2014)

Category	Sub-category	Mitigation measure	NOTES
Cropland management	Agronomy	Use improved crop varieties	
		Extend the perennial phase of crop rotations	
		Use cover/catch crops and reduce bare fallow	
		Agroforestry (with low tree density)	
		Plant hedges	
	Nutrient management	Analyse manure prior to application	
		Do not apply fertiliser at high-risk areas	
		Nitrification inhibitors	
		Urease inhibitors	Added to the MACC medium list (it was merged with 'Nitrification inhibitors' in the EU RDP list)
		Place N precisely in soil	Added to the MACC medium list (it was not included into the EU RDP list because commercial information is not available for easy implementation in the RDP)
		Legumes in rotations	
		Legume-grass mixtures	Added to the MACC medium list
		Plant varieties with improved N-use efficiency	Added to the MACC medium list
		Decrease the amount of N in fertiliser recommendations	
	Soil/residue management	Reduced tillage	Added to the MACC medium list (it was not included into the EU RDP list because the lack of robust GHG effect, but was retained in this project because of savings in fuel use and strong positive effects on soil quality)
		No-till	Added to the MACC medium list (it was not included into the EU RDP list because the lack of robust GHG effect, but was retained in this project because of savings in fuel use and strong positive effects on soil quality)
		Retain crop residues	
			Excluded from the MACC medium list (not relevant in the UK)
		Land drainage	

Category	Sub-category	Mitigation measure	NOTES
		Loosen compacted soils / Prevent soil compaction	
		Prevent soil erosion	
			Excluded from the MACC medium list (not relevant in the UK)
			Excluded from the MACC medium list (not relevant in the UK)
			Excluded from the MACC medium list (not relevant in the UK)
			Excluded from the MACC medium list (not relevant in the UK)
			Excluded from the MACC medium list (not relevant in the UK)
			Excluded from the MACC medium list (not relevant in the UK)
Grazing land management	Grazing management	Take stock off from wet ground	
		Pasture renovation	Added to the MACC medium list (this measure was disaggregated in the EU RDP list)
		Higher sugar content grasses	
Management of organic soils	Avoid drainage of wetlands / conversion of peatlands		
Restoration of degraded lands			
Livestock management	Feeding	High fat diet (dietary lipids)	
		High starch diet	
		High concentrate diet	Added to the MACC medium list (it was merged with 'High starch diet' in the EU RDP list)
		Reduce protein intake and provide AA supplementation	
		Chemical treatment of low quality feedstuffs	
		Feeding total mixed ration	
		Precision and multi-phase feeding	
	Dietary additives		Excluded from the MACC medium list (illegal in the EU)
		Nitrate	
		Proprionate precursors	Added to the MACC medium list (it was not included into the EU RDP list because it is not readily available)
		Naked oats to cattle	Added to the MACC medium list (it was not included into the EU RDP list because the lack of robust GHG effect, but was retained in this project to further investigation)
		Essential oils	Added to the MACC medium list (it was not included into the EU RDP list because the lack of long-term GHG effect, but was retained in this project to further investigation)

Category	Sub-category	Mitigation measure	NOTES
	Animal health	Better health planning	
		Improve hygiene & supervision at parturition	
		Improve maternal nutrition in late gestation to increase offspring survival	
		Vaccination - specify disease	
		Anti-parasitics	
	Herd and breeding management	Improved fertility management	
		Artificial insemination	
		Sexed semen	
		Improved genetic potential in general	
			Added to the MACC medium list as a general measure
			Added to the MACC medium list as a general measure
			Added to the MACC medium list as a general measure
		Improved genetic potential for lower emission intensity	Added to MACC medium list (it was added to distinguish it from breeding for better economic return (including traits like fertility, productivity, etc.))
		Reduced replacement rate	Added to MACC medium list (it was missing from the EU RDP long list)
		Lower age at first calving	Added to MACC medium list (it was missing from the EU RDP long list)
		Reduce the length of the grazing day/season	Added to MACC medium list (it was missing from the EU RDP long list)
		Switching breeds	
		Develop mixed breeds or industrial cross-breeding	
Manure management	Housing	New low-emission housing systems (low NH3)	
		Cages and aviaries instead of floor systems for layer hens	
		Keeping surfaces, manure and animals dry	
		Partly or fully slatted floors	
	Storage	Cooling of manure	
		Covering slurry and farm-yard manure	
		Separating solids from slurry	
		Composting solid manure (also after slurry separation)	
		Manure acidification	
		Combustion of poultry litter	

Category	Sub-category	Mitigation measure	NOTES
		In-house poultry manure drying	
	Anaerobic digestion and CH4 capture	AD	
		Methane capture and combustion	
Land use change	Woodlands	Conversion of low productivity land to woodlands	
Energy, Fuel, Waste	Transport	Capital investment in fuel efficiency	
		Behavioural change towards better fuel efficiency	
	Electricity use	Capital investment in energy efficiency	
		Behavioural change towards better energy efficiency	
	Waste	Reduce on-farm waste	
	Electricity generation	Solar energy	
		Wind power	
		Solar water heating	
		Small-scale hydro-electric power	
		Ground-source or air-source heat pumps	

Table 151 Draft short list developed during the project

Mitigation measures	Notes
Mitigation measures suggested for quantitative analysis	
Improved synthetic N use	Still scope for improving N use. Do not include N placement techniques, and require farmers to do the rest as a bundle.
Improved organic N use	Still scope for improving N use. Do not include N placement techniques, and require farmers to do the rest as a bundle.
Catch/cover crops	Abatement potential of soil N_2O, with additional benefits on soil C
Nitrification inhibitors	Significant abatement potential
Plant varieties with improved N-use efficiency	More theoretic as of today, but potential for the 4th-5th C budget period
Legumes in rotations	Good abatement potential; differentiate between grain legumes and legume-grass mixtures
Legume-grass mixtures	Good abatement potential; differentiate between grain legumes and legume-grass mixtures
Land drainage	Don't include: Drainage systems are likely to continue deteriorating, but there is no robust evidence on this measure
Reduced tillage	Don't include: No robust impact on soil C
Precision farming (crops)	Already feasible, potentially high abatement
Loosen compacted soils / Prevent soil compaction	N_2O emissions can be reduced and yield increased
	Not much scope in the UK
High concentrate diet	Good abatement and feasibility
Naked oats to cattle	Don't include: partly overlapping with 'High concentrate diet' as increased starch content
Chemical treatment of low quality feedstuffs	
Feeding total mixed ration	
Precision and multi-phase feeding	Brought in from qualitative analysis list as technology exists
Probiotics	Good abatement
Nitrate as feed additive	Robust abatement potential
High fat diet	Robust abatement potential
Treatment and prevention of Johne's disease	One of the most important health improvement measure
Treatment and prevention of liver fluke	One of the most important health improvement measure
Sexed semen	Abatement at the national cattle production level
Reducing breeding overhead via reduced replacement rates or lower age at first parturition	Don't include: More likely to be a by-product of other actions on farm (not much direct evidence), e.g. improved nutrition and health; a too strong push for this can have negative consequences on health
Selection for balanced breeding goals	Rephrased to reflect that these breeding goals include productive and non-productive traits
Covering slurry and farm-yard manure	Don't include: Low abatement (indirect GHG effect from NH_3 mitigation)
Slurry acidification	Significant potential abatement of manure $_{CH4}$
Anaerobic digesters	Significant potential abatement of manure CH_4 and energy use
Conversion of low productivity land to woodlands	High C sequestration potential
Climate-proofing investments	Don't include: Difficult to quantify (very broad), but would be important both for mitigation and adaptation, and has a long lead-in time - discuss qualitatively

Mitigation measures	Notes
Behavioural change in fuel efficiency of mobile machinery	Mobile machinery is an important source of on-farm CO_2 emissions, this is a low-cost measure; other behavioural changes can be promoted to improve energy efficiency in other activities on farm, these will be discussed qualitatively
Capital investment in more fuel efficient mobile machinery	Don't include: High interaction with behavioural change
Waste reduction	
Mitigation measures suggested for qualitative analysis	
Controlled release fertilisers	
Adopting systems less reliant on inputs	
Ionophores	Don't include: Not legal in the EU
Propionate precursors	Don't include: Low acceptability
GM livestock	
Transgenics	Don't include: Overlapping with GM livestock
Novel crops	
Essential oils	Don't include: Not proven long-term effects, high potential interaction with other nutritional measures
Agroforestry (with low tree density)	C sequestration potential

Appendix B

Mitigation formulas and technical cost inventory

Table 152 Emission related parameters/variables identified to be potentially relevant to describe the abatement of the mitigation measures

	Crop areas	FSN	EF1	EF4	EF5	FracLeach	FracGASF	FracGASM	Soil C flux	Crop yield	Energy use	Livestock numbers	VS	MCF	Nex	EF3	FracGasMS	Ym	DE%	GE	WG	Milk yield
Emissions	All crop GHG	Soil N_2O	Soil N_2O	Soil N_2O	Soil N_2O	Soil N_2O	Soil N_2O	Soil N_2O	Soil C	Soil N_2O	Energy CO_2	All livestock GHG	Manure CH_4	Manure CH_4	Manure N_2O	Manure N_2O	Manure N_2O	Enteric CH_4	Enteric CH_4	Enteric CH_4	Enteric CH_4	Enteric CH_4
Reference[1]	-	eq 11.1, p11.6	eq 11.1, p11.6	eq 11.9, p11.21	eq 11.10, p11.21	eq 11.10, p11.21	eq 11.11, p11.22	eq 11.11, p11.22	-	-	-	-	eq 10.23, p10.41	eq 10.23, p10.41	eq 10.25, p10.54	eq 10.25, p10.54	eq 10.26, p10.54	eq 10.21, p10.31	eq 10.14-15, p10.20	eq 10.16, p10.21	eq 10.6-7, p10.17	eq 10.9, p10.18
MM1	N	Yes	Yes	N	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM2	N	Yes	Yes	N	N	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM3	N	Yes	N	N	N	Yes	N	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N
MM4	N	Yes	N	N	N	Yes	N	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N
MM5	N	Yes	N	N	N	Yes	N	N	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N
MM6	N	Yes	Yes	N	N	Yes	Yes	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N
MM7	N	Yes	N	N	N	Yes	N	N	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N
MM8	Yes	Yes	N	N	N	N	N	N	Yes	Yes	N	N	N	N	N	N	N	N	N	N	N	N
MM9	Yes	Yes	N	N	N	N	N	N	Yes	Yes	N	N	N	N	N	N	N	N	N	N	N	N
MM10	N	Yes	Yes	N	N	Yes	N	N	N	Yes	Yes	N	N	N	N	N	N	N	N	N	N	N
MM11	N	Yes	Yes	N	N	Yes	N	N	N	Yes	Yes	N	N	N	N	N	N	N	N	N	N	N
MM12	N	N	N	N	N	N	N	N	N	N	N	N	Yes	N	N	N	N	N	Yes	N	Yes	Yes
MM13	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Yes	N	N	Yes	Yes

	Crop areas	FSN	EF1	EF4	EF5	FracLeach	FracGASF	FracGASM	Soil C flux	Crop yield	Energy use	Livestock numbers	VS	MCF	Nex	EF3	FracGasMS	Ym	DE%	GE	WG	Milk yield
MM14	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	Yes	N	N	Yes	N	N	Yes	Yes
MM15	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Yes	Yes	N	Yes	Yes
MM16	N	N	N	N	N	N	N	N	N	N	N	Yes	Yes	N	Yes	N	N	N	Yes	Yes	Yes	Yes
MM17	N	N	N	N	N	N	N	N	N	N	N	Yes	Yes	N	Yes	N	N	N	Yes	Yes	Yes	Yes
MM18	N	N	N	N	N	N	N	N	N	N	N	Yes	Yes	N	Yes	N	N	N	Yes	Yes	Yes	Yes
MM19	N	Yes	N	N	N	N	N	Yes	N	N	Yes	N	N	Yes	N	N	Yes	N	N	N	N	N
MM20	Yes	N	N	N	N	N	N	Yes	N	N	Yes	N	N	Yes	N	N	Yes	N	N	N	N	N
MM21	Yes	N	N	N	N	N	N	Yes	N	N	Yes	N	N	Yes	N	N	Yes	N	N	N	N	N
MM22	Yes	N	N	N	N	N	N	Yes	N	N	Yes	N	N	Yes	N	N	Yes	N	N	N	N	N
MM23	Yes	N	N	N	N	N	N	N	N	N	Yes	Yes	N	N	N	N	N	N	N	N	N	N
MM24	N	N	N	N	N	N	N	N	N	N	Yes	N	N	N	N	N	N	N	N	N	N	N

Notes:
[1] Reference to the IPCC 2006 guidance (IPCC 2006)

Table 153.a Financial costs/benefits considered identified to be potentially relevant to the mitigation measures

ID	Crops																			
	Change in land use	Seed purchase	Synth N purchase	Fertiliser additives	Other fertiliser costs	Machinery hire	Machinery use	Infrastructure maintenance	Energy purchase	Other inputs	Crop protection	Crop drying	Crop insurance	Labour: in field	Labour: management	External expertise	Other expense changes	Machinery capital cost	Infrastructure capital cost	Other capital costs
MM1	N	N	Yes	N	N	N	N	N	N	N	N	N	N	Yes	Yes	Yes	Yes	N	N	N
MM2	N	N	Yes	N	Yes	N	N	N	N	N	N	N	N	Yes	Yes	Yes	Yes	N	N	N
MM3	N	N	Yes	N	Yes	Yes	Yes	N	Yes	N	N	N	N	Yes	Yes	N	N	Yes	N	N
MM4	N	N	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	Yes	N
MM5	N	Yes	Yes	N	N	N	Yes	N	Yes	Yes	N	N	N	Yes	Yes	N	N	N	N	N
MM6	N	N	Yes	Yes	N	N	Yes	N	Yes	N	N	N	N	Yes	N	N	N	N	N	N
MM7	N	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM8	Yes	Yes	Yes	N	Yes	Yes	Yes	Yes	Yes	N	Yes	Yes	Yes	Yes	Yes	N	N	Yes	Yes	N
MM9	N	Yes	Yes	N	N	N	Yes	N	Yes	N	N	N	N	Yes	N	N	N	N	N	N
MM10	N	N	Yes	N	Yes	Yes	Yes	N	Yes	N	Yes	N	N	Yes	Yes	Yes	Yes	Yes	Yes	N
MM11	N	N	Yes	N	N	Yes	Yes	N	Yes	N	N	N	N	Yes	Yes	Yes	N	N	N	N
MM12	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM13	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM14	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM15	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM16	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM17	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM18	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM19	N	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Yes	N	N
MM20	N	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM21	N	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM22	N	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM23	Yes	Yes	Yes	N	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N	N	N	N	Yes
MM24	N	N	N	N	N	N	Yes	N	Yes	N	N	N	N	N	N	N	Yes	N	N	N

Table 153.b Financial costs/benefits considered identified to be potentially relevant to the mitigation measures

ID	Crops				Livestock														
	Change in yield per ha	Reduced losses on farm	Change in output quality/value	Other income changes	Change in herd structure / animal numbers	Insemination costs	Feed composition: cost per kg	Feed additives	Amount of feed per head	Machinery hire	Machinery maintenance	Infrastructure maintenance	Energy purchase	Other inputs	Livestock insurance	Labour: in field	Labour: management	External expertise	Other expense changes
MM1	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM2	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM3	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM4	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM5	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM6	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM7	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM8	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM9	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	Yes	N	N
MM10	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM11	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM12	N	N	N	N	N	N	Yes	N	Yes	N	N	N	N	N	N	Yes	Yes	Yes	Yes
MM13	N	N	N	N	N	N	N	Yes	N	N	N	N	N	N	N	Yes	N	N	N
MM14	N	N	N	N	N	N	Yes	Yes	N	N	N	N	N	N	N	N	Yes	N	N
MM15	N	N	N	N	N	N	Yes	N	N	N	N	N	N	N	N	N	Yes	N	N
MM16	N	N	N	N	Yes	N	N	N	Yes	N	N	N	N	N	Yes	Yes	Yes	Yes	N
MM17	N	N	N	N	Yes	N	N	N	Yes	N	N	N	N	N	Yes	Yes	Yes	Yes	N
MM18	N	N	N	N	Yes	Yes	Yes	N	Yes	N	N	N	N	N	N	Yes	Yes	Yes	N
MM19	N	N	N	N	N	N	N	N	N	N	Yes	Yes	Yes	N	N	N	Yes	N	N
MM20	N	N	N	N	N	N	N	N	N	N	N	Yes	Yes	N	N	Yes	Yes	Yes	Yes
MM21	N	N	N	N	N	N	N	N	N	N	N	Yes	Yes	N	N	Yes	Yes	Yes	Yes
MM22	N	N	N	N	N	N	N	N	N	N	N	Yes	Yes	N	N	Yes	Yes	Yes	Yes
MM23	Yes	N	Yes	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
MM24	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

Table 153.c Financial costs/benefits considered identified to be potentially relevant to the mitigation measures

ID	Livestock							Crops/livestock			
	Machinery capital cost	Infrastructure capital cost	Other capital costs	Change in yield per animal	Reduced losses on farm	Change in output quality/value	Other income changes	Capital costs arising from admin	Labour: learning	Labour: keeping records	Other admin time
MM1	N	N	N	N	N	N	N	Yes	Yes	Yes	N
MM2	N	N	N	N	N	N	N	Yes	Yes	Yes	N
MM3	N	N	N	N	N	N	N	N	Yes	N	N
MM4	N	N	N	N	N	N	N	N	Yes	N	N
MM5	N	N	N	N	N	N	N	N	Yes	N	N
MM6	N	N	N	N	N	N	N	N	Yes	N	N
MM7	N	N	N	N	N	N	N	N	N	N	N
MM8	N	N	N	N	N	N	N	N	Yes	N	Yes
MM9	N	N	N	N	N	N	N	N	Yes	N	N
MM10	N	N	N	N	N	N	N	Yes	Yes	Yes	N
MM11	N	N	N	N	N	N	N	N	Yes	N	N
MM12	N	N	N	Yes	N	Yes	N	N	Yes	Yes	N
MM13	N	N	N	Yes	N	N	N	N	Yes	N	N
MM14	Yes	Yes	N	Yes	N	N	N	N	Yes	Yes	N
MM15	Yes	Yes	N	Yes	N	N	N	N	Yes	Yes	N
MM16	N	Yes	N	Yes	Yes	N	N	N	Yes	Yes	N
MM17	N	Yes	N	Yes	Yes	N	N	N	Yes	Yes	N
MM18	N	N	N	Yes	N	N	N	N	Yes	Yes	N
MM19	Yes	Yes	N	N	N	N	N	N	Yes	Yes	N
MM20	N	Yes	N	N	N	N	N	N	Yes	Yes	N
MM21	N	Yes	N	N	N	N	N	N	Yes	Yes	N
MM22	N	Yes	N	N	N	N	N	N	Yes	Yes	N
MM23	N	N	N	N	N	N	N	N	Yes	Yes	N
MM24	N	N	N	N	N	N	N	N	Yes	Yes	N

Appendix C

Notes of the Expert Workshop ''Mitigation options in the UK agriculture: abatement, cost and uptake in 15 years' time"

The Workshop was held on 5th June 2015, in Edinburgh. The attendee list and the agenda are presented in Table 154 and in

Table 155. Following these tables are the notes of the Workshop.

Table 154 Attendee list

Name	Organisation
Julian Bell	SAC Consulting
Irene Cabeza	SRUC
Dave Chadwick	Bangor University
Mizeck Chagunda	SRUC
Simon Draper	Indagronomy
John Elliott	ADAS
Vera Eory	SRUC
Naomi Fox	SRUC
Michael MacLeod	SRUC
Hugh Martineau	Ricardo-AEA
Cath Milne	SRUC
Christine Moeller	Directorate-General for Climate Action
Kirsty Moore	SRUC
Colin Morgan	SAC Consulting
Bob Rees	SRUC
Gareth Salmon	SRUC
Rogier Schulte	Teagasc
Ute Skiba	Centre of Ecology and Hydrology
Philip Skuce	Moredun Research institute
Pat Snowdon	Forestry Commission
Indra Thillainathan	Committee on Climate Change
Kairsty Topp	SRUC
Eileen Wall	SRUC
Tony Waterhouse	SRUC
J Webb	Ricardo-AEA
Lyn White	Soil Association
John Williams	ADAS

Table 155 Agenda of the workshop

Timing	Sessions	
9.00-9.30	**Introduction**	
9.30-11.00	**Session 1**	
	Crops-soils working group	*Livestock working group*
	Improved synthetic N use	Sexed semen
	Improved organic N use	Selection for balanced breeding goals
	Legumes in rotations	
	Legume-grass mixtures	
11.30-13.00	**Session 2**	
	Crops-soils working group	*Livestock working group*
	Plant varieties with improved N-use efficiency	Improvement of cattle health
	Precision farming (crops)	Improvement of sheep health
	Soil compaction	
14.00-15.30	**Session 3**	
	Crops-soils working group	*Livestock working group*
	Conversion of low productivity land to woodlands	High concentrate diet
	Slurry acidification	Probiotics
	Behavioural change in fuel efficiency	Nitrate as feed additive
		High fat diet (dietary lipids)
15.30-16.00	**Wrap-up**	

MM1: Improved synthetic N use

Short description of measure

Carrying out soil analysis for pH, soil liming (if required), using an N planning tool, decreasing the error of margin on application and not applying the fertiliser in very wet/waterlogged conditions.

Discussion

	Assumption	Question	Notes
Abatement	Better information on soil nutrient content and higher awareness on weather-related timing of fertilisation will reduce N use. N reduction: 5 kg/ha N on the fields where the measure is implemented	How actual N fertiliser applications compare with best practice: on those fields where there is overuse, what is the overuse in % N (or kg N) for the main crops?	Is N used efficiently? The question is not just about how much N. Emissions intensity is not the focus, we must use the inventory basis of calculation. If more N is applied, generally more N_2O is emitted; this is different to leaching, which is more closely related to any excess of N applied, and is from N not taken up, in the following winter. Used the example of oilseed rape with and without applied S – more N with S emits less N_2O than less N without S. Most N_2O emissions in 1st 48h, so application rate important for direct N_2O; indirect N_2O emission is similar to leaching in that it is related to N quantity not taken up.
Abatement	The improved synthetic N use will not impact on the proportion of N applied to be emitted as N_2O/NH_3 or leached from the soil.	Is the assumption that the emission/leaching proportions don't change realistic?	No Abatement potential – use gap between best farmers and worst?
Abatement			Use gap between best farmers and worst?
Applicability			There is less potential now than 5 years ago. 80-90% of arable fields have specific N fertiliser recommendation, but only 20% of grassland fields. There is more scope for improvement on grass; arable 10%, grass 50%, but not all grass has N applied, so this is not applicable across the whole area. There is not much excess applied N, perhaps there is an underuse, the overall national excess is perhaps 1% UK average. [Estimated from Farmscoper results]

	Assumption	Question	Notes
Current and future uptake	Potential additional maximum uptake in the 2030's: 10% of farms	What % of farmland will still get too much N in the 2030's (either because of lack of soil analysis, N planning or poor timing regarding weather)?	
Costs		Is there additional learning (e.g. understanding recommendations, weather-related information, using software) required?	The main barriers are knowledge and education.
Costs		Is there additional on-field or management time required to implement the measure?	
Costs		What are the costs of additional soil analysis, liming, etc.?	

MM2-MM4: Improved organic N use

Short description of measure

Carrying out soil analysis for pH, soil liming (if required), analysing or using a software to calculate the manure's plant-available N content, using an N planning tool (also taking into account manure N applications from previous years), decreasing the error of margin on application both of synthetic and organic N, and not applying the manure in very wet/waterlogged conditions. This measure does not assume a shift between spring/winter cultivars, neither in spring/winter application of organic N.

Discussion

	Assumption	Question	Notes
Abatement	Better information on soil and manure nutrient content, higher awareness on weather-related timing of fertilisation will reduce synthetic N use. N reduction: 5 kg/ha N on the fields where the measure is implemented	How much more N (kg N/ha) would be available for the plants for the main crop types by better information on soil/manure and better weather related timing?	This measure is not about changing the cropping pattern in order to move the timing of application from autumn to spring. There is a need to change the timing to decrease leaching, and need to rapidly incorporate to reduce NH_3 emission. Solid cattle manure does not have much available N compared with slurries and poultry manure. This measure is linked to the previous measure, since making better allowance for organic manures could reduce the amount of synthetic fertiliser N application We need to separate the attribution of emissions to measures. Up to 80kg less N needed if application in spring, and further 10kg for improved application method. Perhaps this estimate is too large? I checked RB209 for the average increase in N available from delaying manure application from early autumn to Spring. The results for sandy soils, based on the maximum permitted application of manure-N (250 kg/ha) are as follows: Cattle slurry, +75 kg; Pig slurry,+100; Cattle FYM, +12.5 kg; Pig FYM, +12.5 kg Layer manure, +62.5; Broiler manure, +50] The increase in available N on heavier soils will be less. A maximum of 62.5 for pig slurry, others will be less. So, for slurries on sandy soils the figure is about right, but will be less for other manures.
Abatement	The improved organic N use will not impact on the proportion of N applied to be emitted as N_2O/NH_3 or leached from the soil.	Is the assumption that the emission/leaching proportions don't change realistic?	No

	Assumption	Question	Notes
Applicability	50% of manure applications could be improved	What % of land will get too much synthetic N on top of the manure N in the 2030's due to not accurate soil/manure information or no proper consideration of soil wetness conditions?	Half N comes from organic manures including from grazed animals. 1/3 gets manure every year 22% gets manure (from Defra statistics). This measure needs investment. The future Irish MACC will split by farm size, because cost and applicability changes. There are BSFP figures on application of manures. 23% tillage land, 35% grass 5 years or more, 47% grass < 5 years.
Costs		Is there additional learning (e.g. understanding recommendations, weather-related information, using software) required?	Transport of water in slurry is a barrier.
Costs		Is there additional on-field or management time required to implement the measure?	
Costs		What are the costs of manure planning software (considering livestock diet, etc.), soil analysis, liming, etc.?	

MM7: Plant varieties with improved N-use efficiency

Short description of measure

Using new crop varieties that either provide at least the same yield as current ones but require less N or give greater yields increased N inputs.

Discussion

	Assumption	Question	Notes
Applicability		What is the baseline expected improvement in NUE and/or yield by crop type and crop quality (incl. grass) by 2030s as these are used on farms?	Cereal crops – other criteria than yield is the focus of breeders Breeders can breed for same yield but less N. Historically in wheat, yield and N requirement have both increased, but in spring barley, yield has increased but not N requirement. For wheat the focus has been on milling wheat, leading to varieties with higher N requirement to support protein requirements.

	Assumption	Question	Notes
Abatement		What will be the further achievable NUE improvement commercially available but not included in the assumed baseline for the 2030's? (By crop type and crop quality, incl. grass.)	
Abatement	Yields will be constant and N use will be reduced by 9% on fields where new varieties are cultivated.	What % change can be achieved with these varieties by the 2030's in yield and N use? (Again, additional to the future baseline which might already be improved NUE.)	Unknown because there is no clear motivation to breed for better NUE. Better disease resistance influences NUE.
Current and future uptake		Would it be agronomically feasible to use improved varieties on all land area under the different crop types and crop qualities and pasture?	Yes Barriers: Breeding programme not in place for cereals, and probably not for grass. Grass for AD may have different criteria – worth checking?
Costs		How much additional time is required to learn about the new varieties and their applicability?	
Costs		How much additional management time is required when using the improved varieties?	
Costs	Won't be more expensive than any new cultivar.	How much more expensive would the seeds be relative to non-improved varieties?	

MM8: Legumes in rotations

Short description of measure

Grain legumes to be grown in rotation with other arable crops. This would involve one year of peas or beans within a 6 year rotation.

Discussion

	Assumption	Question	Notes
Abatement	The average annual N use in the rotation is reduced because no N will be applied to the legume. N reduction: 10% overall, given that the grain legume which represents 1/6 of the arable cropping area would receive no N	What are the crops likely to be replaced by the legumes? In what proportion?	Cereals most likely to be replaced (second wheat).
Abatement	The average annual N use in the rotation is further reduced because of the reduced N need of the subsequent crop (carryover effect). N reduction to subsequent crops: 10%. OR 30 kg N/ha, according to RB209	What is the carryover effect to the subsequent crop (% reduction in N use)?	20-40 kg N per annum carry-over.
Abatement	Substituting for legumes in the rotation will not impact on the proportion of N applied to be emitted as N_2O/NH_3 or leached from the soil.	Is the assumption that the emission/leaching proportions don't change realistic?	
Applicability	Currently 3% of arable land is cultivated for peas and beans - assuming 6 year rotations this means that 18% or arable land has rotations with legumes.	What % of current arable area would be agronomically suitable to rotations with legumes? If not all, what are the main obstacles?	Can be grown 1/5 years. Marketing is a barrier (barriers are the problem, not the mitigation potential), size of contract and price; unstable market.
Applicability		What are the main implications replacing cereal production with legume production in the UK on a larger scale? What is a realistic assumption on the maximum arable area with legume rotations without having a major impact on the UK agricultural production (prices, supply chains)?	The problem is the barriers not the mitigation potential. In favour of implementation – greening rules and grass weed problems (wet autumn conditions so need a spring crop), replacing cereal crops. Feed market price is too low. Beans easier to grow, but feed market and less benefit for blackgrass control. Vining peas mostly grown in Poland (cheaper freezing). 2.5Mt of soya are imported, and some of this could be replaced at 5t/ha yield. Julian Bell can provide more details.

	Assumption	Question	Notes
Current and future uptake		What % of arable area will have legume rotations in the 2030's without any policy interventions beyond current policy (incl. CAP Greening)?	A barrier to growing peas is climate variability associated with wet autumn conditions as peas cannot grow in wet water bogged areas.
Costs		How much additional time is required to learn about the legumes and plan the new rotations and access the market for the products?	
Costs		Are there any costs associated with this measure beyond the change in gross margin due to the change in crop areas? (E.g. additional storage or equipment)	

MM9: Legume-grass mixtures

Short description of measure

Pure grass monocultures replaced by grass clover leys and clover content is increased on mixed swards to be up to 20-30% DM at an annual average.

Discussion

	Assumption	Question	Notes
Abatement	N application (both synthetic and organic) is reduced (in line with RB209), and yield is reduced as well (and yield variability will increase in response to annual weather). A 10% reduction in productivity, but 75% reduction in N application	What is the expected change in N application (% or kg N/ha for synthetic and organic N) and in yield (% or t/ha)?	150kgN/year is fixed. Emissions need to take the whole cycle into account. Higher-N forage goes through animal, increasing urine N concentration. Ireland has used both the inventory and LCA approaches. We must take account of re-seeding more often. The main benefit is less N fertiliser manufacture, but this is in a different sector of the inventory. The emissions comparison between grass and grass/clover roughly balances at a farm level using a LCA approach but not accounting for saving in N fertiliser manufacture.

	Assumption	Question	Notes
Abatement	The clover content will not impact on the proportion of N applied to be emitted as N_2O/NH_3 or leached from the soil.	Is the assumption that the emission/leaching proportions don't change realistic?	Clover increases leaching because it peaks late in the season, providing excess N in forage which is excreted in patches and much of this leaches (some will be emitted as N_2O). Also because of uneven application. There is a benefit in an inventory, but this is false because the late emissions described above are not captured.
Current and future uptake		What proportion of current grassland may be considered as 'clover-rich', i.e. obtaining most of the N supply from clover?	We don’t know. GHG Platform has estimated this from practice survey data, but what does this mean? We don’t know; the survey data do not give a clear answer.
Current and future uptake		What proportion of grassland will be 'clover-rich' in 2030's?	Barriers identified as management time and skill needed to manage weeds which grow as there are fewer options for herbicide use that doesn’t kill off the clover. Irish MACC didn’t consider the clover impact on changes in methane emissions due to enteric fermentation.
Current and future uptake		What are the main barriers to extending grass clover cultivation?	Weed control Slurry in spring Management time
Costs		How much additional time is required to learn about the clover types and their suitability?	
Costs		How much additional time is required to manage the mixed swards?	
Costs		What are the additional seed costs? Is more frequent seeding required?	

MM10: Precision farming (crops)

Short description of measure:

Use an understanding of the spatial variability in SMN and from monitoring crop growth to adjust fertiliser recommendations in line with RB209 guidelines (variable rate technology, VRT). Use yield mapping to identify poorly performing areas and where necessary take corrective action (e.g. improve drainage).

Discussion

	Assumption	Question	Notes
Abatement	Fertiliser use can be reduced with maintaining or improving yields	How much N applied can be reduced and/or yields improved with VRT?	Better application technology will decrease overlaps, saving application quantity. 20% of grassland has over-application for this reason. GPS is needed to avoid this (but is this precision farming?) K, P, lime are main applications. Discussion about what precision farming is. Spatially-variable application driven by a computer map, not different treatment of large blocks. Should this be a means of achieving other measures? There is a lot of overlap.
Abatement	VRT will not impact on the proportion of N applied to be emitted as N_2O/NH_3 or leached from the soil.	Is the assumption that the emission/leaching proportions don't change realistic?	
Applicability		Is precision farming potentially applicable (and effective) on all arable land and grassland? If not, on that % it is applicable and effective?	
Applicability		What could be a farm size threshold (if any) below which implementation is very unlikely?	
Current and future uptake		On what proportion of arable land and grassland will VRT be applied in the 2030's without additional policies?	
Costs		How much additional time is required to gather information for decision about investing in VRT and then acquire the know-how?	£40/ha cost.

	Assumption	Question	Notes
Costs	Capital investment (machinery, hardware, software): low-cost system (±10 m precision and manual speed change) £4,500, fully integrated system (DGPS, removable control system) £12,000 – £16,000. One-off training: £500. Annual maintenance 3.5-8% of the capital costs. Annual soil sampling and crop monitoring £10/ha.	What are the costs of implementing precision farming? (Either in terms of capital costs or as annual costs from hiring contractors.)	Costs need to be reviewed, they are too low.

MM11: Loosen compacted soils

Short description of measure

Surface and subsoil compaction reduced by surface and subsoil cultivations.

Discussion

	Assumption	Question	Notes
Abatement	Alleviating compaction reduces N_2O emissions EF1 from 1.00 to 0.98 (arable land) and to 0.40 (grassland)	How much higher are N_2O emissions (kg N/ha or %) in compacted soils compared to non-compacted soils on grassland and arable land?	There is very little work on this. Norwegian work? (Ball *et al.* 1999a, Hansen 1996, Yamulki and Jarvis 2002) Loosen soil under maize: 40kg less N is applied. Must apply this measure together with drainage assessment and improvement. 2% crops, 60% grass: decreases in N_2O emissions, but poor evidence (for % tillage land area that is compacted). Recent Defra project (BD2304) gives a good estimate of the proportion of grassland compacted (and this was used in our work).
Abatement		Do the higher emissions result from an increase in % N emitted as N_2O, or an increase in leaching?	
Abatement		What would be the expected increase in productivity and/or an expected decrease in N applied?	

	Assumption	Question	Notes
Applicability	Currently, 20% of arable and 16% of grassland soils would benefit from action to reduce compaction in any given year.	What % or arable land and grassland will benefit from compaction alleviation in any given year in the 2030's without additional policy intervention?	These estimates are the best available.
Costs		How much additional learning or management time is required?	Barriers: understanding and diagnosing the problem
Costs	Cost of loosening compaction: £4/ha	What are the costs involved in reducing the compaction?	

MM11: Prevent soil compaction

Short description of measure

Compaction prevented where there is a risk of it.

Discussion

	Assumption	Question	Notes
Abatement		What is the avoided % increase in N_2O emissions for grassland and arable land on areas where compaction is prevented?	Caused by travelling on wet soil. 10 October is cut-off date. Larger tractors, more weight, but possible to travel/cultivate when soil is too wet.
Abatement		What is the avoided % decrease in yield for grass and arable crops where compaction is prevented?	
Applicability	On 40% of arable land compaction can become an issue.	What will be the % of arable land and grassland where compaction could become an issue, i.e. where prevention is important in the 2030's?	
Current and future uptake		What will be the % of arable land and grassland where compaction prevention will be carried out by the farmers without further policy intervention?	

	Assumption	Question	Notes
Costs		What are the additional expenses and time requirements associated prevention measures?	

General livestock feeding questions

	Assumption	Question	Notes
Annual average dairy cow diet	Proportion of concentrates: 28%		
	in the remaining 72%: Fresh grass : grass silage : maize silage = 4 : 5 : 1	What proportion of the dairy cows is permanently housed and what is the proportion of fresh cut grass in their diet?	
	Concentrates : grazing : silage = 28% : 28.8% : 43.2%	Is the proportion of concentrate likely to change by 2030's in the dairy cow average ration?	Scotland 31:33:36 dairy might change, beef and sheep less likely
	Soya bean meal: 5% annually, i.e. 17.8% in the concentrate (=9.3% CP in the concentrate)	Is soya use likely to change by 2030's in the dairy cow average ration?	
	Concentrate average price: £320/t fresh (£360/t DM)	Is this a good assumption?	
Annual average beef cow diet		What is the average annual beef cow diet (concentrates : grazing : silage)?	
		Is this diet likely to change by 2030's?	
Annual average growing beef diet		What is the average annual growing beef diet (concentrates : grazing : silage)?	Scotland 21:52:27
		Is this diet likely to change by 2030's?	
Annual average sheep diet		What is the average annual sheep diet (concentrates : grazing : silage)?	Scotland 3.4:80:17.6
		Is this diet likely to change by 2030's?	
Feed mixers		What proportion of dairy/beef farmers have feed mixer? Do they mix in silage as well?	dairy herds with 80+ cows get total mixed ration, ~20% of beef herd (increasing proportion of feedlots, and they have feed mixers)

	Assumption	Question	Notes
		For the permanently housed dairy do farmers make total mixed ration using cut and carry grass? Or is the cut and carry grass fed separately?	
		How much does a feed mixer cost? And what investment is needed for additional feed storage?	£15-40k, additional feed storage might be needed, though usually farmers would have that
		How many months a year eat the dairy/beef cows/sheep enough concentrate to feasibly mix in additives/oil?	
		How many months a year eat the dairy/beef cows/sheep enough concentrate+silage to feasibly mix in additives/oils?	

Additional points

Recognise that animals are often fed sub-efficiently, improving the diet for higher efficiency could be part of the feeding mitigation. Fixing this needs spending money on feed advisors (1-2x year, £100-150/occasion for a large dairy farm + forage analysis min. once a year, £20-30/analysis).

Other alternative to define the nutritional improvement measure is to look at the top 20% performance and assume that 50% of the rest could be improved to that level, and this gives the abatement.

Io to a higher level, and group all feeding options into one, thus there will be fewer assumptions and transparency will increase (that's how it's done in the Irish MACC). Though individual actions are not prescribed with this approach, this gives the flexibility at policy and farm level as well to choose options which fit best.

High concentrate diet

Short description of measure

Increasing the starch content of the diet by increasing the amount of starchy concentrates in the ration. The total CP content of the diet doesn't change.

Discussion

	Assumption	Question	Notes
Abatement	Each 1% additional starch reduces enteric CH_4 emission by 0.78% for	Are these mitigation and yield assumptions realistic?	Good forage quality can make the same effect as increasing concentrates

	ruminants. Yield increases by 5%.		Would farmers improve forage quality?
Abatement		What is the starch content of the baseline diet (dairy cows/beef cows/growing beef/sheep)?	
Abatement		What would be a realistic maximum increase in the starch content (without the risk of acidosis)?	For dairy starch should not be increased further, for beef yes
			Land-use related GHG emissions is a problem, can offset GHG gains Full LCA is needed Also making use of available resources (i.e. grass), and not increasing competition for grain
Applicability	Applicable to dairy cows, beef cows, growing beef and sheep.	Is this assumption realistic?	
Current and future uptake		Is the starch content of the diet going to change by the 2030's without policy intervention?	Big dairy farms (high yielding cows) might shift towards increased concentrate content Starch content of the diet highly dependent on grain prices
Costs		Is there a change in the average price of concentrates to be fed, given that the protein content of the concentrate will be lower?	
Costs		How much additional learning or management time is required?	

MM13: Probiotics

Short description of measure

Adding probiotics (also been referred to as directly fed microbes, e.g. *Saccharomyces cerevisiae* and *Aspergillus oryzae*) to the ruminant diet. The probiotics are top-dressed or mixed into the ration.

Discussion

	Assumption	Question	Notes

Abatement	Enteric CH_4 is reduced by 3% (95% CI: -1% - 7%), yield is increased by 3%.	Are these mitigation and yield assumptions realistic?	Low impact on yield Long-term effect on GHG, as long as it is kept fed Effect diminishing with increasing yield Apply it only to the lower yielding part of the national herd
Abatement		What is the required dose?	
Abatement		Are specific strains required? If yes, are these already commercially available, or will they be by the 2030's?	
Applicability	Applicable to dairy, beef and sheep, in any growth stage.	Is this assumption realistic?	
Current and future uptake		What proportion of dairy/beef/sheep is already supplemented with probioitics? Is this value likely increase by 2030's without policy intervention?	Only tactical use in the UK to treat acidosis
Costs		What is the cost of supplementing probiotics?	
Costs		How much additional learning or management time is required?	

MM14: Nitrate as feed additive

Short description of measure

Adding 1.5% NO_3^- in the ruminant diet, e.g. in the form of $Ca(NO_3)_2$ (e.g. Bolifor CNF). The $Ca(NO_3)_2$ would (partially) replace non-protein N (NPN) sources (e.g. urea), or high protein content components, like soya. It would also (partially) replace limestone as calcium source. As there is a risk of poisoning from overdose, the nitrate has to be mixed homogeneously in the feed.

Discussion

	Assumption	Question	Notes
Abatement	Assumption 1: nitrate will only be mixed in the concentrate		
Abatement	Assumption 2: nitrate will be mixed in the concentrate+silage (feed mixers)		

Abatement	At 15 g nitrate / kg DM feed dose the enteric CH_4 reduced by 17.3% (SE ±80%) (this dose equals 0.37% N, which is 2.31% CP)	Is the mitigation assumption realistic?	
Abatement	No difference in the nitrate content between dry period and lactating period	Should the nitrate concentrate be lower in the dry period?	
Abatement	Other protein source to be replaced: soya bean meal (2.31% CP equivalent)	Is urea fed to dairy/beef cows in the UK? Is it realistic to replace some/most of the soya bean meal with the nitrate?	Urea is commonly used in beef compound feed
Applicability	Applicable to dairy cows, beef cows and growing beef.	Is this assumption realistic?	
Uptake			Risk of low uptake if additive is considered "unnatural" Nitrate is natural; a lot depends on marketing/message
Costs	Nitrate price: £630/t NO_3^- (Bolifor, 63% $NO3^-$ content, EUR 550/t in the Netherlands)	Any UK data on this?	
Costs	Soya bean meal price: £340/t DM (without VAT) (£300/t FM, 89% DM)	Is this a good assumption?	
Costs		Is limestone used as Ca source? What is the price of limestone?	

MM15: High fat diet (dietary lipids)

Short description of measure

This measure is the increase in the fat content of ruminant feed to 5 DM%. Various supplementary fat sources exist, here we suggest using cracked rapeseed.

Discussion

	Assumption	Question	Notes
Abatement	Assumption 1: rapeseed will only be mixed in the concentrate		
Abatement	Assumption 2: rapeseed will be mixed in the concentrate+silage (feed		

	mixers)		
Abatement	Each 1% additional fat reduces enteric CH_4 emission by 3.4%, 2.0% and 6.9% for dairy cows, growing cattle and sheep, respectively	Is this mitigation assumption realistic?	
Abatement	Fat source replaces concentrates (at an equal DM basis). (Cracked rapeseed: CP 20.9%, oil 46%; concentrate: CP 30%, oil 10%.)	Is it realistic to replace concentrates directly with cracked rapeseed?	
Applicability	Applicable to dairy cows, beef cows, growing beef and sheep.	Is this assumption realistic?	
Current and future uptake	Fat content in the baseline diet: 2%, fat added: 3%	Is this assumption realistic? Is the fat content in the diet going to change by 2030?	
Costs		What is the price of cracked rapeseed?	Ask Edinburgh farm about rapeseed price

MM16 and MM17: Improving cattle health and Improving sheep health

Short description of measure

Improving animal health could in principle lead to significant reductions in emissions intensity by, for example, improving the feed conversion ratio of individual animals and reducing the herd breeding overhead (through improved fertility and reduced mortality).

Assumptions and questions

Are there key pieces of evidence on the relationship between ruminant health and GHG emissions not cited in the following table that could be of relevance to the UK?

Disease and treatment	Reference
Preventive program for mastitis in Spanish dairy cows	Hospido and Sonesson (2005)
Increasing routine disease treatment in Scottish sheep	Stott *et al.* (2005)
Eradication programme for BVD in N. Ireland	Guelbenzu and Graham (2013, p27)
Mitigation measures for ten cattle diseases in the UK	ADAS (2014)
Ewe health in Scotland	Skuce *et al.* 2014

The ADAS (2014) report is the most comprehensive analysis of the GHG mitigation benefits of controlling disease in UK cattle currently available. To quantify the mitigation, ADAS (2014) estimated the values for key production parameters (replacement rates, fertility rates, milk yield, mortality etc.) for two situations: baseline (now) and healthy. They also estimated the extent to which the national herd average could be moved form the baseline value to the healthy value under two scenarios: pessimistic (20% movement from baseline to healthy value) and optimistic (50% movement).

The workshop will discuss the method and key assumptions, then apply it to sheep by:

- Defining baseline and healthy values for key parameters (see table below)
- Discussing what improvements could be achieved cost-effectively under optimistic and pessimistic scenarios
- Highlight the main pathways by which these improvements might be achieved (i.e. disease x treatment).
- Categorise the CE of the possible treatments.

	Average ewe	Disease free ewe	Average lamb	Disease free lamb
Fertility rate			na	na
Fecundity			na	na
Age at first parturition				
Age at slaughter				
Replacement rate			na	na
Mortality rate				
Growth rate	na	na		
Weight at slaughter				
Fertility rate			na	na
Food conversion ratio				
Quantity of output				
Quality of output				
Other effects				

If time available, other questions that may be discussed include:

- How might health improvement interact with other measures, such as breeding, sexed semen and feeding?
- To what extent would/could the mitigation be captured in the inventories?
- Do we need to distinguish between private and public costs/benefits to inform policy?

Discussion

John Elliot provided an overview of the approach used in the cattle health MACC project (ADAS (2014).

- ADAS (2014) MACC doesn't take into account interactions, so the abatement of the individual measures cannot be summed.
- Scenario approach was used to estimate the scale of abatement potential (AP) if we moved (a) 20% from current performance to disease-free status and (b) 50% to disease-free status.
- Cost-effectiveness (CE) of AP not estimated in the scenario approach.

The CCC was also interested in measures that reduced EI rather than total emissions, while also noting that total emissions couldn't keep rising.

Difficult to capture some of the less tangible effects of disease (e.g. changed feed intake, energy partitioning, digestive efficiency).

Health will be included in the next Irish MACCs.

Could we make a rough estimate the CE of the scenarios by calculating the weighted average CE of measures below the SCC? While this does not take into account interactions, does this matter if the costs are negative? Potential risk that we are double counting the savings from the efficiency gains.

System	Weighted average CE ($£/tCO_2e$)
Dairy cattle	-35
Suckler beef	-19
Dairy beef	-101
All cattle	-42

Sheep – not good data on (a) prevalence, (b) impact of diseases on animal performance or (c) efficacy of treatments.

MMacL presented baseline values for key parameters that could change when moving from average performance to disease-free status.

	Intensive	Semi intensive	Extensive (~hill)	Source
Ewe replacement rate	0.28	0.28	0.25	b
Mature ewe weight, kg	57.0	53.5	50.0	a
Ewe death + cull rate, %	6.7	8.0	9.0	a
Ewes lambing, %	93.4	91.6	90.4	a
No. lambs per ewe lambing	1.51	1.31	1.11	a
Lamb mortality (% reared)	14.6%	12.2%	11.7%	a
All lambs weaning weight, kg	28.9	27.1	25.7	a
Mean age at weaning, d	119	119	119	a
Post weaning growth rate, g/d	120	120	—	a

Sources: a. Conington et al 2004; b. FMH

Need to add store lambs to the systems.

Hill ewe mortality could be reduced form 9% to 5%. Improved feeding potentially more important than specific disease treatments. Specific health treatments more important in lowground flocks which have better nutrition, higher parasite burdens and more opportunities to intervene with health treatments.

Use the term "reference scenario" of "counterfactual", as business as usual implies continuation of current policies. If possible, predict counterfactual values for parameters with reference to historic trends (as has been done for EBVs).

Ewe mortality figures cited in FMH have increased over time – dodgy data, so need to be careful extrapolating.

Sheep nutrition should improve over time as there is a gradual shift from lower productivity land.

Sheep premium health scheme may keep data on the performance of healthy flocks. Compare farms before and after a health programme?

Lack of before and after (disease or treatment) data. Scab used to be notifiable, treatment collapsed when this was removed.

Jo Conington has data on mastitis and lameness, but may be for pedigree flocks. Cath Milne can supply data on the impact of some diseases from modelling work.

Policy intervention could be used deliver additional health improvements. Could take a wide range of forms, from direct support for health schemes to providing investment that frees up labour enabling farmer to spend more time monitoring flock. Policy to improve data on disease could be useful.

Animal welfare bigger motivation for policy intervention than GHG mitigation.

Proposed approach

Try and estimate mitigation via sheep health improvement in a way that is consistent (if not identical) to the approach used in ADAS (2014), i.e.

- Estimate change in key parameters when moving form average health status to disease-free status.
- Do for four sheep systems.
- Assume that 20% and 50% movement could be achieved under two scenarios.
- Model flocks in GLEAM for baseline, and 2 scenarios for the four systems.
- Compare health-derived mitigation with other mitigations via improved productivity (e.g. Jones et al 2014, Table1).

MM18: Sexed semen

Short description of measure

In dairy systems sexed semen can be used to increase the proportion of pure dairy (i.e. dairy x dairy) calves that are female (and required for replacing cows), thereby reducing the number of (often unwanted) male pure dairy calves and increasing the number of dairy x beef calves (of both sexes) for rearing as beef animals. Increasing the number of dairy x beef calves means that less suckler cows are required to produce the same total beef output, thereby reducing the total emissions and the emissions per kg of beef produced.

Assumptions and questions

What happens to pure dairy male calves at the moment?

Shot at birth	**Exported, culled at ~3 months**	**Reared in UK, less intensive, cull at 6-8 mo**	**Reared as an (inferior?) beef animal**	**Other**

How different is the performance of a pure dairy male animal to a dairy x beef animal (both physically (e.g. in terms of emissions intensity) and economically?

	Assumption	Question
Current use	Used on maiden heifers only. Lack of varieties of SS no longer a significant barrier to uptake.	What % of dairy heifers and cows are currently serviced with sexed semen?
Current use	Conception rates (per attempt) for heifers: 35% (SS) and 45% (unsexed).	Conception rates for cows? Are future conception rates likely to be different?
Future uptake	In theory all maiden heifers and half of cows could be serviced with SS (only want to be breeding replacements form the top 50% of cows. In practice, only a small % of cows would need to be serviced with SS to provide enough replacements (assuming heifers are serviced using SS).	What is the maximum technical possible uptake of SS by 2032? Are there significant barriers to increasing use of SS over next 15 years? If so, what are they?
Future uptake		Which other measures might SS interact with (e.g. assist with improved genetics?)
Costs	Additional cost is the premium for each straw (£10-30?) and the extra number of straws required to achieve pregnancy. No significant additional learning costs or cost of hiring specialist inseminator	What is the premium for SS (per straw)? Are there other significant costs, such as increased calving interval?
Costs	Culling of calf (£6 per calf)	
Costs	Sale value of surplus male dairy calf £0?	

Discussion

MMacL introduced the measure and some estimates of the theoretical mitigation that could be achieved using SS on a dairy farm (see below). This was followed by discussion of: current practice and future potential of SS.

Medium UK dairy herd, 149 cows, replacement rate 0.33 (Own calculations, using GLEAM)

	Unsexed	Sexed
No of cows replaced	49	49
Female calves required to provide 49 replacements	62	62
Heifers giving birth	49	49
Surviving female dairy calves from heifers	23	41
Surviving male dairy calves from heifers	23	5
Female dairy calves from cows	39	21
Male dairy calves from cows	39	21
Dairy x beef calves	31	68

AF replacement rate	0.33	0.33	0.25	0.25	0.2	0.2	0.167	0.167
Sexed semen	NO	YES	NO	YES	NO	YES	NO	YES
% of male dairy calves culled at birth	0	0	0	0	0	0	0	0
female dairy calves (#)	62	62	47	47	37	37	31	31
male dairy calves (#)	62	26	47	19	37	15	31	13
dairy x beef calves (#)	31	68	50	78	62	84	70	88
Meat, (t LW/year)	49	67	51	64	51	62	52	61
Milk sold standard (t/year)	894	894	894	894	894	894	894	894
Dairy male calves culled	0	0	0	0	0	0	0	0
Dairy male calves sold	62	26	47	19	37	15	31	13
Total emissions (tCO2e/year)	2226	2423	2210	2359	2200	2320	2194	2293
Beef emissions avoided	765	1056	795	1015	814	990	827	974
Veal calf emissions avoided	45	19	34	14	28	11	23	10
Milk emissions (total GHG - avoided GHG)	1416	1348	1381	1330	1359	1318	1344	1310
EI of milk (kgCO2e/kg milk)	1.58	1.51	1.54	1.49	1.52	1.47	1.50	1.47

What is happening to surplus male dairy calves?

- Less being shot, tend to be reared.
- Specialist companies rear them (uncastrated) and slaughter them at 14-16 months, (b) reared as less intensive (rose) veal.
- BCMS should be able to provide data on the types of animals slaughtered.

Current practice with SS

- Mainly used with maiden heifers.
- Uptake is increasing as technology improves. Estimated that 5-10% of dairy semen sold is sexed. Limited uptake for beef.
- People may use it as a means of speeding up genetic gain (i.e. it means that more of your replacements are coming from heifers, speeding up the rate of turnover).
- Keeping cows longer is another way of reducing emissions (by reducing the breeding overhead) - but there may be a trade-off between mitigation via increased longevity and via genetic improvement. Cows with increased longevity tend to have better carcass quality.
- Without SS, the optimal no of lactations is 3.5 – SS would change that.
- Male and female dairy x beef similar value, but production costs could be quite different
- Use of SS likely to lead to increased beef production, rather than less suckler cows.
- Beef subsidies keeping a lid on dairy.
- In 15 years' time SS will be 100% female (currently ~95%, with 90% guaranteed)

Policies to support SS

- Policy to support SS would be flawed.
- EU policy on breeds/genetics may act as a barrier, so not so much a question of having a policy to promote SS, but may be scope for reducing policies that act as disincentives and lead to underinvestment.

Conclusions

- Mitigation potential may be overestimated if most male dairy calves are being reared (relatively efficiently) for meat.
- Use of SS unlikely to lead to a reduction in suckler cows, and therefore may have limited impact on the cattle emissions recorded in the GHG inventory (though EI could still be reduced).
- Uptake of SS is likely to be driven by market forces (primarily as a means of increasing the rate of genetic improvement in the dairy herd).
- There is limited scope for direct policy support for SS, though it could be integrated into wider policy to support genetic improvement. There may also be scope for increasing uptake by removing existing (EU) policy barriers.

Proposed approach

- Assume that there is no additional mitigation in the 4th or 5th budget period from policies to support SS.
- If appropriate, include SS as part of the mitigation via breeding measure.

MM19: Selection for balanced breeding goals

Short description of measure

Improving breeding so that breeding indices involve more environmental goals, i.e. shift from economic breeding indices to a balance of economic-environmental breeding goals. Applicable for ruminants and monogastrics alike.

Main assumptions and related questions

	Question
Abatement	Improvements via breeding are reported as changes per annum – though these are cumulative, they might show a diminishing trend. For how many years can we add up the annual trend so that not to overestimate the effect?
Abatement	How are the economic breeding goals expected to change the parameters listed below by 2030? (See next table)
Abatement	How could the balanced breeding goals expected to change the parameters listed below by 2030? (See next table)
Current and future uptake	What proportion of the national herd is using economic breeding indices currently? Can we assume that in the rest of the herds no changes are happening?
Current and future uptake	What proportion of the national herd is going to use economic breeding indices in the 2030's without any additional policies?
Current and future uptake	What proportion of the national herd would use balanced breeding indices in the 2030's without any additional policies?
Current and future uptake	What proportion of the national herd is using AI?
Current and future uptake	With maximum speed of uptake, theoretically how long would it take for a trait to penetrate the national herd? I.e. how to calculate the accumulation of changes via time and across the national herd?
Current and future uptake	What are the main barriers of uptake for the economic breeding indices?
Current and future uptake	What are the main barriers of uptake for the balanced breeding indices?
Costs	What would be the costs for the farmers of using balanced indices compared to economic indices?
Costs	Are there any costs to the industry and research?

Discussion

Short introduction by VE.

2 routes are possible:

- Increased uptake of improved genetics as resulted from current breeding goals.
- Changing the breeding goals to include GHG effects.

Data are available in the Defra report "The potential for reducing greenhouse gas emissions for sheep and cattle in the UK using genetic selection" and in the Sustainable intensification project.

Dairy uptake of current breeding goals is good, but could be made higher (80% more improvement could be achieved). Uptake in the beef sector is still very low, but has started changing rapidly in the past few years (still under 10%). Uptake in the sheep sector is very low, not much improvement is expected in the coming few years without policy intervention, but change might come by 2030. In the beef sector farmers didn't believe in EBV some years ago, now they are using it more and more, and the sheep sector by now they believe in technology, but there are some concerns about validity and trust.

Overall, dairy seems to be able to sort itself out by the market, but policy intervention might be needed for beef and sheep.

For beef the main changes by wider uptake of current breeding goals would be improvement in fertility. For sheep higher fertility is not necessarily the key, more focus should be on lamb performance (faster growth).

Farmers tend to keep beef to long on pastures, well beyond the optimum point in the weight gain curve – changing this would also provide mitigation.

In the Scottish RDP the beef scheme is being developed, rolling it out to the rest of the UK could be a policy instrument (beef scheme: farmers get payment for recording data). For sheep payments could be offered for publishing EBV.

Improved infrastructure (e.g. e-tags) could be a way to promote more attention on breeding (and also nutrition, health). The key is reducing labour (handling time).

By 2030 more specialisation can be expected in the sheep sector.

Breeding for low enteric CH_4 has not got to a breakthrough point (some research in Denmark and New Zealand might show some potential). Better to increase the uptake of current breeding goals.

Theoretically, if breeding goals to change, then it takes 5 years to generate the breeding tool (for all ruminant species), and another 5 and 10 years for turnover for dairy/sheep and beef, respectively.

Better extension is important.

MM20: Slurry acidification

Discussion

Adopted elsewhere, but not in UK.

Research at Bangor (DC), but kills grass.

Smell might be an issue.

The UNECE Guidance Document on ammonia abatement cites the additional costs of acidification as 5 euros per animal place.

MM22: Conversion of low productivity land to woodlands

Notes:

- GHG benefits less in short term (2030), better in long term (2200).
- High growth rates give better removal and retention of C.
- Economic balance between sheep farming and forestry has been changing in favour of forestry.
- Other benefits? Out of scope.
- Leakage/indirect emissions? No, not accounted for.

MMacL presented some results from (Crabtree 2014)

2027/2032

"woodland creation could make no useful contribution to meeting short-term policy targets" (i.e. to 2030) (Crabtree 2014, p1) "Carbon emissions from soil - when planted on organo-mineral soils - and low rates of sequestration in early life limit the short-term abatement (to 2030) achieved by many forest systems." (Crabtree 2014, p6).

2050

"With some notable exceptions, the forest systems delivered limited retention to 2050 and many were characterised by negative emissions. The highest short-term retentions occurred where growth rates were high and soil emissions low – e.g. lowland conifers and continuous cover forestry in some English regions." (Crabtree 2014, p46).

2200

Significant net retention over a range of systems.

While acknowledging that forestry performed better as a mitigation option in the medium to long-term, Pat Snowdon (FC) questioned Crabtree's (2014) conclusion that "woodland creation could make no useful contribution to meeting short-term policy targets " (i.e. to 2030) (Crabtree 2014, p1). He thought that FC's recent submission to DECC had indicated significant mitigation during the 5th budget period. He also noted that planting also helps to achieve other policy goals (e.g. biodiversity, flooding, air pollution etc).

Discussion of how to deal with displacement of production (and the induced LUC that arises from it)

MMacL proposed 3 ways of approaching indirect LUC:

- Assume that displacing production does not lead to land use change elsewhere, and that the production induced outwith the UK occurs with a similar carbon footprint to the displaced production (Crabtree 2014, p22).
- Assume that trees are only planted in ways that do not reduce production (e.g. on fallow, buffer strips, possibly agroforestry?) What fraction of the aspirational rates could be achieved without reducing production?
- Try and identify areas where the net retention per kg of lost output is higher than the emissions arising from the displaced production, e.g. map the (potential) net retention and the current production, calculate the retention/production and identify areas above a threshold of, e.g. 100 t CO_2e (kg CW)$^{-1}$

Proposed approach

In order to be consistent with FC submission to DECC:

- For 5th budget period, use the FC DECC submission estimate – aggregate by the 8 forest systems?
- If FC estimates are not available for 2050, calculate based on (Crabtree 2014)) data and the following approach: (a) Identify cost-effective measures, i.e. those mitigating at <SCC in 2050; (b) For each cost-effective measure, multiply the net retention by the estimated total planting rates to 2050;(c) Calculate the weighted average UK CE for the 8 forest systems.
- Do not include emissions arising from indirect LUC.

MM23: Behavioural change in fuel efficiency of mobile machinery

Discussion

Less opportunity with new machines, which are, in effect, implementing this measure, and by 2030 all machines will be efficient and prevent inefficient operation.

Appendix D

MACC tables

Table 156 Abatement potential and cost-effectiveness, with and without interactions (2030, UK, LFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
Probiotics	13	-230	20	-5	20	-230	20
SpringMan	4	-155	11	-2	32	-155	11
ImprovedNUE	7	-139	33	-5	65	-139	33
PF-Crops	10	-109	26	-3	91	-95	29
ManPlanning	2	-110	3	0	94	-26	10
BeefBreeding	18	-52	18	-1	113	-52	18
GrassClover	9	-51	35	-1	147	-20	70
CattleHealth	16	-42	25	-1	173	-42	25
ADMaize	22	-41	10	0	182	-41	10
ImprovedNutr	12	-30	18	-1	200	-26	20
ADPigPoultryMaize	21	-19	11	0	211	-19	11
SoilComp	11	1	26	0	237	1	26
SheepHealth	17	30	12	0	249	30	12
Afforestation	23	37	284	11	534	37	284
NitrateAdd	14	82	51	4	585	62	63
FuelEff	24	90	13	1	598	90	13
SlurryAcid	19	97	19	1	618	45	32
ManSpreader	3	126	12	1	629	110	13
ADCattleMaize	20	186	16	3	645	125	22
CRF	6	190	23	3	669	37	76
HighFat	15	227	28	6	697	171	35
SynthN	1	255	7	1	703	35	29
GrainLegumes	8	400	43	16	747	312	52
CoverCrops	5	6,505	1	2	747	1,226	2

Table 157 Abatement potential and cost-effectiveness, with and without interactions (2030, UK, HFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
Probiotics	13	-230	104	-24	104	-230	104
SpringMan	4	-155	58	-9	162	-155	58
ImprovedNUE	7	-139	169	-24	332	-139	169
PF-Crops	10	-107	334	-36	666	-95	379
ManPlanning	2	-102	15	-1	681	-26	45
BeefBreeding	18	-52	93	-5	775	-52	93
GrassClover	9	-45	158	-7	933	-20	359
CattleHealth	16	-42	663	-28	1,596	-42	663
ADMaize	22	-41	125	-5	1,721	-41	125
ImprovedNutr	12	-29	83	-2	1,805	-26	95
ADPigPoultryMaize	21	-19	144	-3	1,949	-19	144
SoilComp	11	1	318	0	2,267	1	318
SheepHealth	17	30	307	9	2,574	30	307
Afforestation	23	37	3,739	140	6,313	37	3,739
NitrateAdd	14	81	662	51	6,975	62	829
FuelEff	24	90	63	6	7,039	90	63
SlurryAcid	19	95	250	19	7,288	45	424
ManSpreader	3	125	139	17	7,427	110	156
CRF	6	140	227	37	7,654	37	1,003
ADCattleMaize	20	170	194	35	7,848	125	284
SynthN	1	186	24	5	7,872	35	138
HighFat	15	222	333	72	8,205	171	422
GrainLegumes	8	362	555	191	8,760	284	672
CoverCrops	5	6,289	8	31	8,768	1,226	25

Table 158 Abatement potential and cost-effectiveness, with and without interactions (2030, UK, MTP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
Probiotics	13	-230	113	-26	113	-230	113
SpringMan	4	-155	63	-10	177	-155	63
ImprovedNUE	7	-139	184	-26	361	-139	184
PF-Crops	10	-107	362	-39	723	-95	412
ManPlanning	2	-101	18	-1	741	-26	53
BeefBreeding	18	-52	101	-5	842	-52	101
GrassClover	9	-45	170	-8	1,012	-20	390
CattleHealth	16	-42	784	-33	1,796	-42	784
ADMaize	22	-41	136	-6	1,932	-41	136
ImprovedNutr	12	-29	98	-3	2,030	-26	112
ADPigPoultryMaize	21	-19	156	-3	2,186	-19	156
SoilComp	11	1	374	0	2,561	1	374
SheepHealth	17	30	363	11	2,924	30	363
Afforestation	23	37	4,064	152	6,988	37	4,064
NitrateAdd	14	81	719	55	7,706	62	901
FuelEff	24	90	75	7	7,781	90	75
SlurryAcid	19	95	271	21	8,052	45	461
ManSpreader	3	125	163	20	8,215	110	184
CRF	6	135	239	40	8,454	37	1,090
ADCattleMaize	20	169	209	39	8,663	125	309
SynthN	1	174	26	6	8,689	35	163
HighFat	15	221	390	85	9,080	171	497
GrainLegumes	8	358	602	205	9,682	281	730
CoverCrops	5	6,269	8	34	9,690	1,226	27

Table 159 Abatement potential and cost-effectiveness, with and without interactions (2030, England, CFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
Probiotics	13	-232	32	-7	32	-232	32
SpringMan	4	-155	24	-4	55	-155	24
ImprovedNUE	7	-132	67	-9	122	-132	67
PF-Crops	10	-103	134	-14	256	-90	150
ManPlanning	2	-108	6	0	261	-26	16
BeefBreeding	18	-52	19	-1	281	-52	19
GrassClover	9	-50	52	-2	333	-20	110
CattleHealth	16	-42	85	-4	418	-42	85
ADMaize	22	-41	52	-2	470	-41	52
ImprovedNutr	12	-30	21	-1	490	-26	23
ADPigPoultryMaize	21	-19	61	-1	551	-19	61
SoilComp	11	1	135	0	686	1	135
SheepHealth	17	30	35	1	720	30	35
Afforestation	23	39	741	29	1,462	39	741
NitrateAdd	14	82	195	15	1,657	62	243
SlurryAcid	19	94	82	6	1,739	44	139
FuelEff	24	95	25	2	1,764	95	25
ManSpreader	3	124	53	6	1,817	108	59
CRF	6	156	103	14	1,919	36	392
ADCattleMaize	20	179	62	11	1,982	125	87
HighFat	15	222	114	24	2,095	170	143
SynthN	1	230	9	1	2,104	35	43
GrainLegumes	8	366	242	84	2,346	286	292
CoverCrops	5	6,384	3	11	2,349	1,223	9

Table 160 Abatement potential and cost-effectiveness, with and without interactions (2030, Wales, CFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
Probiotics	13	-363	4	-2	4	-363	4
SpringMan	4	-212	1	0	5	-212	1
ImprovedNUE	7	-184	2	0	7	-184	2
PF-Crops	10	-144	5	-1	12	-125	5
ManPlanning	2	-102	1	0	13	-25	4
BeefBreeding	18	-52	5	0	18	-52	5
GrassClover	9	-52	11	-1	29	-22	23
CattleHealth	16	-42	17	-1	46	-42	17
ADMaize	22	-41	1	0	47	-41	1
ImprovedNutr	12	-40	6	0	53	-36	7
ADPigPoultryMaize	21	-19	1	0	54	-19	1
SoilComp	11	1	5	0	59	1	5
SheepHealth	17	30	20	1	79	30	20
FuelEff	24	48	2	0	81	48	2
Afforestation	23	51	709	16	791	51	709
NitrateAdd	14	82	38	3	829	62	47
SlurryAcid	19	104	12	1	840	49	19
ManSpreader	3	135	8	1	848	118	9
ADCattleMaize	20	179	12	2	860	125	16
SynthN	1	194	2	0	862	35	9
CRF	6	204	4	1	866	40	15
HighFat	15	221	17	4	884	166	21
CoverCrops	5	2,422	0	0	884	1,140	0
GrainLegumes	8	3,505	1	2	885	2,551	1

Table 161 Abatement potential and cost-effectiveness, with and without interactions (2030, Scotland, CFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
ImprovedNUE	7	-165	11	-2	11	-165	11
SpringMan	4	-147	4	-1	16	-147	4
PF-Crops	10	-128	23	-3	38	-113	26
Probiotics	13	-108	7	-1	46	-108	7
ManPlanning	2	-107	1	0	47	-26	3
BeefBreeding	18	-52	13	-1	60	-52	13
GrassClover	9	-42	16	-1	76	-17	34
CattleHealth	16	-42	28	-1	105	-42	28
ADMaize	22	-41	8	0	112	-41	8
ImprovedNutr	12	-25	11	0	123	-22	12
ADPigPoultryMaize	21	-19	3	0	127	-19	3
SoilComp	11	1	24	0	151	1	24
SheepHealth	17	30	14	0	165	30	14
Afforestation	23	33	317	24	482	33	317
NitrateAdd	14	80	41	3	523	61	51
FuelEff	24	89	5	0	528	89	5
SlurryAcid	19	103	11	1	539	48	19
ManSpreader	3	124	10	1	549	108	11
ADCattleMaize	20	179	10	2	559	125	14
CRF	6	188	19	3	578	42	71
SynthN	1	215	3	0	581	35	14
HighFat	15	245	24	5	604	186	30
GrainLegumes	8	423	32	13	636	331	38
CoverCrops	5	6,456	1	4	637	1,246	3

Table 162 Abatement potential and cost-effectiveness, with and without interactions (2030, Northern Ireland, CFP, d.r. 3.5%)

Mitigation measure	ID	CE with interactions	AP with interactions	Total annualised cost	Cumulative AP	CE WITHOUT interactions	AP WITHOUT interactions
		£ t CO_2e^{-1}	kt CO_2e y^{-1}	M£ y^{-1}	kt CO_2e y^{-1}	£ t CO_2e^{-1}	kt CO_2e y^{-1}
Probiotics	13	-265	8	-2	8	-265	8
ImprovedNUE	7	-180	2	0	10	-180	2
SpringMan	4	-150	0	0	10	-150	0
PF-Crops	10	-141	4	-1	14	-123	5
ManPlanning	2	-104	1	0	14	-25	1
GrassClover	9	-53	4	0	18	-21	8
BeefBreeding	18	-52	8	0	27	-52	8
CattleHealth	16	-42	28	-1	55	-42	28
ADMaize	22	-41	1	0	56	-41	1
ImprovedNutr	12	-23	7	0	63	-20	8
ADPigPoultryMaize	21	-19	6	0	69	-19	6
SoilComp	11	1	4	0	73	1	4
Afforestation	23	21	61	1	134	21	61
SheepHealth	17	30	4	0	138	30	4
FuelEff	24	58	2	0	140	58	2
NitrateAdd	14	81	52	4	192	62	65
SlurryAcid	19	98	18	1	210	47	30
ManSpreader	3	134	3	0	213	117	4
ADCattleMaize	20	179	16	3	229	125	22
SynthN	1	188	2	0	230	35	7
HighFat	15	216	24	5	254	164	30
CRF	6	230	4	1	258	46	12
CoverCrops	5	2,612	0	0	258	1,229	0
GrainLegumes	8	3,105	0	1	258	2,259	1