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The mitigation of greenhouse gas emissions in sheep farming systems

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EBLEX is the beef and lamb division of the Agriculture and Horticulture Development Board for levy payers in England.
Hybu Cig Cymru - Meat Promotion Wales (HCC) is the Welsh red meat organisation for levy payers in Wales.

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1. Abstract

Multiple opportunities exist for mitigating greenhouse gas emissions on livestock farms. However, prioritising mitigation measures in policy is problematic because of the fragmentary nature of the evidence-base on abatement potentials and the heterogeneous nature of the industry. Limited literature exists on the abatement potential of sheep farm-specific mitigation measures and livestock measures applied in a sheep farm setting. This study augments the evidence-base on mitigation opportunities for sheep systems in England and Wales through: estimating the cradle to farm gate greenhouse gas emissions of 60 sheep farms and assessing the relationship between farm variables and carbon footprint at the multi-farm level; producing a short-list of practical and effective mitigation measures based on the opinions of experts and farmers derived through Best-Worst Scaling surveys; developing marginal abatement cost curves for a case-study lowland, upland and hill sheep farm, indicating the abatement potentials and cost-effectiveness of short-listed mitigation measures. The results convey two primary messages for industry and policy decision-makers: firstly the importance of productivity and efficiency as influential drivers of emissions' abatement in the sector, particularly the cost-effective measures improving ewe nutrition to increase lamb survival and lambing as yearlings; and secondly, the need for policy instruments to acknowledge and account for heterogeneity within the industry. Instances of heterogeneity include variation in farmer perceptions of the practicality of sheep breeding measures according to farm size and type, and differences in the abatement potential of individual measures linked to current farm management. It is suggested that productivity and efficiency targets could be communicated to farmers through the use of productivity benchmarks, and that the construction of further case-study farm marginal abatement cost curves could allow guidelines to be developed which define the management scenarios and conditions in which each measure is most effective. Case-study farm-level marginal abatement cost curves are advocated as a potential tool to inform farm-level mitigation strategy in addition to refining higher-level policy.

2. Introduction

Global anthropogenic greenhouse gas emissions (GHGs) increased by 70% between 1970 and 2004, and continue to rise, despite consistent evidence that this increase has caused discernible changes in the global climate since the mid-20th century (Bernstein et al., 2007; Cubasch et al., 2013). Agriculture is one sector contributing significantly to anthropogenic GHG emissions, with estimates ranging from 10% of total global emissions (excluding land use change and energy emissions) (Smith et al., 2014), up to a maximum of 32% when land use change is also considered (Bellarby et al., 2008). Agriculture is the primary source of nitrous oxide (N_2O) and methane (CH_4) emissions globally. Both are potent GHGs with global warming potentials of 298 and 25 times that of carbon dioxide (CO_2) per kg over a 100 year period, respectively (Forster et al., 2007)[1]. These headline figures mean that the agriculture industry has not escaped the notice of governments in the development of GHG mitigation strategies, alongside more polluting sectors such as energy supply. The livestock industry has come under particular scrutiny with its total contribution to global emissions estimated to be up to 18% including land use change impacts (Steinfeld et al., 2006). Red meat is frequently identified as being the most emissions-intensive of all livestock products, primarily due to CH_4 emitted through enteric fermentation (Bellarby et al., 2008; Gill et al., 2010; Stott et al., 2010).

In England and Wales, agricultural emissions (excluding land use change) account for 7.6% and 12.9% of national GHG inventories, respectively (Salisbury et al., 2013). An industry-led partnership has developed an action plan for reducing emissions in the sector. The industry partnership has committed to reducing annual emissions in England by 3 million tonnes (Mt) CO_2 equivalents (CO_2e) by 2018 (Joint Agricultural Climate Change Task Force, 2011) (total English agricultural emissions were 31.9 Mt CO_2e in 2011 (Salisbury et al., 2013)). The power to mitigate agricultural emissions is devolved in Wales, where government has set a target of reducing emissions by 3% annually from 2011 against a baseline of average emissions from 2006 to 2010 (WAG, 2010) (the agricultural baseline is approximately 5.8 Mt CO_2e/year (Salisbury et al., 2013)). In both England and Wales, agricultural emission reduction targets are further underpinned in the livestock sector by red meat roadmaps developed by the levy boards, the English Beef and Lamb Executive (EBLEX) and Hybu Cig Cymru (HCC). The roadmaps benchmark production emissions of beef and lamb and outline opportunities for emissions reductions.

Multiple possible opportunities exist for mitigating emissions on livestock farms. However, selection of mitigation measures (MM) for recommendation and implementation is challenging, and often avoided. Government emphasis is on the prioritisation of economically efficient MMs, requiring

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[1] The global warming potential values of methane and nitrous oxide were recently revised to 28 and 265 respectively (Myhre et al., 2013). This reference has not been updated for consistency with the values used in the remainder of the study, particularly the emissions modelling work which predates the revision.

evidence on both abatement potentials (against a quantified baseline) and the cost of measures per unit of carbon abated (Moran et al., 2011). Furthermore, development of effective policy instruments which can promote on-farm adoption of measures relies upon understanding farmer perceptions of, and motivations for, implementing MMs. Multiple sector-specific issues complicate the decision-making process of policy-makers, industry and individual farmers when selecting MMs: notably that heterogeneity in biophysical and management conditions between farms and over time mean that the abatement potentials of MMs may vary; and that implementing MMs alone or in combination with others causes complex interactions amongst multiple GHGs, which may not be fully accounted for in GHG models (MacLeod et al., 2010a).

The UK has developed a stronger evidence-base than many countries to facilitate decision-making in agricultural GHG mitigation (Norse, 2012). National marginal abatement cost curves (MACCs) have been developed based upon average sized cereal, mixed and dairy farms, reporting the abatement potentials and cost-effectiveness of short-listed crop and livestock MMs (Moran et al., 2008). Although the original MACCs included livestock-specific measures, they did not assess abatement potential for grazing livestock farms. Limited literature exists on the abatement potential of sheep farm-specific MMs and livestock measures applied in a sheep farm setting. Similarly, very little literature exploring the heterogeneity of MM abatement potential exists despite recognition of the potential merits of regional and farm-specific MACCs in refining agricultural mitigation budgets (Moran et al., 2011).

This study was jointly funded by both EBLEX and HCC, to augment the evidence-base on sheep farm system GHG emissions and abatement potentials. The overall aim of the study was to produce a series of case-study farm MACCs, identifying cost-effective and practical MMs suited to the main sheep farm types found in England and Wales. The study was undertaken with the specific objectives of:

1) Identifying practical activities that sheep farmers can undertake to reduce farm GHG emissions.
2) Estimating the GHGs emitted from a large sample of farms using a whole-farm GHG model and empirical data.
3) Short-listing potential MMs by assessing expert opinion on effectiveness and farmer opinion on practicality.
4) Selecting a representative lowland, upland and hill case-study farm and modelling the emissions abatement possible on each through implementing short-listed MMs.
5) Calculating the private cost of implementing each MM to the farm business.
6) Constructing MACCs for each case-study farm.

These objectives are met in the course of four separate but interdependent studies:

2.1. Study 1

Study 1 reviews published and industry literature to identify and assess MMs applicable to UK sheep farm systems. Currently available MMs which achieve broad consensus on their mitigation potential are identified, and the unfulfilled research requirements of others discussed. Crucial considerations and tools needed to develop practical sheep farm mitigation strategies are identified. This study provides the long-list of MMs to be assessed by experts and farmers in study 3.

2.2. Study 2

In study 2, the cradle to farm gate carbon footprints (CFs) of a sample of 60 sheep farms across England and Wales are estimated using empirical farm data. This large dataset is used to explore differences in CFs between farms categorised by variables including land classification and breeding ewe flock size. Farm management variables that significantly impact the size of the CF across all farms are also identified. This study provides the baseline farm data for later MACC construction.

2.3. Study 3

Study 3 reports the results of a two-round Best-Worst Scaling survey eliciting expert and famer opinion on the relative effectiveness and practicality of the sheep farm MMs long-listed in study1. Farmer perceptions are compared and contrasted with expert opinion for individual MMs, and implications for policy development discussed. Sources of heterogeneity in farmer opinion for individual MMs are also explored. Mitigation measures identified as possessing the combined qualities of above average effectiveness and practicality are taken forward for emission modelling in MACC construction.

2.4. Study 4

Study 4 is the culmination of the project, bringing together baseline emissions data for selected case-study farms from study 2 and the top MMs identified in study 3, in the construction of MACCs. The stand-alone abatement potentials and costs of the MMs are modelled for each farm, based on assumptions from the published literature, against the real farm baseline. Marginal abatement cost curves are constructed for each farm, reporting the abatement potential of MMs per unit of produce and their cost-effectiveness in £ per unit of CO_2e abated. Costs and abatement potentials are compared between land classification categories and based on individual farm management.

The methods and results sections of this report are structured to reflect these four separate studies.

3. Materials and methods

3.1. Study 1: Identifying practical activities that sheep farmers can undertake to reduce farm GHG emissions[2]

A comprehensive review of published and industry literature was undertaken to identify and assess MMs suited to sheep farm systems. The review provided an overview of the most prominent mitigation options, focusing primarily on options aimed at reducing enteric CH_4 and soil N_2O emissions, as the dominant forms of sheep farm emissions. For a number of the mitigation options, research on mitigation potential originated in cattle-only studies. If there were no equivalent sheep system studies available it was necessary to supplement the sheep system-related literature with examples from cattle-based systems, with the understanding that the mitigation options are generic across ruminant systems. Mitigation options were reviewed under the headings of enhancing productivity, animal management, and soil and pasture management.

3.2. Study 2: Estimating the carbon footprint of lamb[3]

3.2.1. Footprint calculation

Empirical farm data were used to estimate the GHG emissions associated with sheep production on farms in England and Wales. Carbon footprints were calculated for 60 farms, based on data provided by a random sample of farmers in face-to-face interviews. The CFs were calculated within a cradle to farm gate system boundary following LCA principles (BSI, 2011). The CFs accounted for all major sources of CH_4, N_2O and CO_2, encompassing both direct and indirect emissions. Direct emissions are those which occur on-farm (e.g. enteric CH_4) whilst indirect emissions can be attributed to the farm, but occur elsewhere (e.g. those emissions arising from the manufacture of farm inputs and emissions resulting from nitrate leached and ammonia volatilised) (Foley et al., 2011). Emissions were shared between categories of sheep produce (finished lambs, live lambs, culls sold for meat, breeding sheep and wool) using economic allocation, based on prices provided by the farmers. The functional unit used for reporting emissions was 1 kg of live weight (LW) finished lamb.

All CH_4 and N_2O emissions were estimated using standard equations from the Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories (IPCC, 2006). This national reporting approach was refined to the farm scale by estimating animal and excreta

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[2] Published as Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of UK sheep production: current knowledge and opportunities for reduction in temperate zones. *Journal of Agricultural Science*, 152, 288-308.

[3] Published as Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of lamb: Sources of variation and opportunities for mitigation. *Agricultural Systems*, 123, 97-107.

emissions on a monthly time-step to accurately reflect fluctuations in sheep numbers. Each month, the numbers and mean LWs of sheep in each category (and cohorts within this) were adjusted according to births, deaths, purchases, sales and growth rates, as specified by the farmer. Full details of the whole-farm GHG model used including all activity data and emission factors (EFs) are given in Jones et al. (2014).

3.2.2. Assessing variation

Underlying drivers of variation were assessed using multiple linear regression models to explore the relationship between the dependent variable, the CF of finished lamb, and selected farm management variables across the sample of 60 farms. Ten important management variables were selected based upon our understanding of the role of farm characteristics in determining footprint size. Common industry metrics relevant to farmers were targeted. The selected variables reflected efficiency of input use, intensity of farming and productivity, normalised by farm size or livestock numbers. The 10 selected farm variables (all per year) were:

1) Fuel use (litres/hectare).
2) Inorganic fertiliser use (kg nitrogen/hectare).
3) Concentrate use (kg/livestock unit (LSU)).
4) Area of managed peat soil (% of farm).
5) Stocking density (LSU/hectare).
6) Number of lambs reared per ewe (head/ewe).
7) Lamb growth rate (grams/day).
8) Breeding ewe replacement rate (%).
9) Percentage of finished lambs purchased as stores (%).
10) Percentage of ewe and replacement ewe lamb flock not mated (%).

Stepwise regression based on Akaike's information criterion was conducted to identify significant variables (Burnham and Anderson, 2002). The model (i.e. the combination of variables) with the smallest AIC score was selected as the best model. The relative importance of each variable in the final model was assessed by dominance analysis (Tonidandel and LeBreton, 2011). This approach was implemented in the statistical software R using the "lmg" metric in the package "relaimpo" (Grömping, 2006). Bootstrap resampling was used to estimate the probability distribution of each variable's contribution to R^2 and calculate 95% confidence intervals (Grömping, 2006).

3.3. Study 3: Shortlisting mitigation measures[4]

3.3.1. Best-Worst Scaling surveys

We utilised Best-Worst Scaling (BWS), a discrete choice survey method, to elicit expert and farmer opinion on the relative effectiveness and practicality of MMs to reduce GHG emissions from sheep production systems. Eighty candidate MMs were initially identified through a search of the relevant academic peer-reviewed and grey literature in study 1. A preliminary expert panel was presented with the task of reducing this list of 80 MMs to a more manageable shortlist. The top 26 scoring MMs were subsequently used to populate the BWS survey (Table 1).

Table 1. Short-listed mitigation measures used in the expert effectiveness and farmer practicality Best-Worst Scaling surveys.

Number	Mitigation Measure
1	Use a fertiliser recommendation system
2	Improve timing of fertiliser applications
3	Improve precision of fertiliser applications in soil
4	Avoid feeding excess nitrogen to minimise nitrogen losses in excreta
5	Analyse manure prior to application
6	Calibrate & maintain spreader equipment
7	Include legumes in pasture reseed mix e.g. clover
8	Increase lamb growth rates for earlier finishing
9	Feed a diet balanced in energy & protein
10	Increase the number of lambs born per ewe
11	Increase pasture productivity to enhance carbon storage
12	Performance recording & selective breeding for improved feed conversion efficiency
13	Increase ewe longevity
14	Improve ewe nutrition in late gestation to increase lamb survival
15	Increase diet digestibility
16	Reduce mineral fertiliser use
17	Split fertiliser applications
18	Improve drainage (non-organic soils only)
19	Lamb as yearlings
20	Performance recording & selective breeding for reduced enteric CH_4/kg dry matter intake
21	Improve hygiene & supervision at lambing
22	Avoid conversion of peatlands
23	Select pasture plants bred for improved nitrogen conversion efficiency
24	Avoid fertiliser applications prior to pasture renovation
25	Avoid conversion of woodlands to pasture / crops
26	Select pasture plants bred to minimise dietary nitrogen losses e.g. high sugar grasses

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[4] Published as Jones, A.K., Jones, D.L., Edwards-Jones, G., Cross, P., 2013. Informing decision making in agricultural greenhouse gas mitigation policy: A Best-Worst Scaling survey of expert and farmer opinion in the sheep industry. *Environmental Science and Policy*, 29, 46-56.

BWS is an extension of the method of paired comparisons. Respondents are shown a predefined number of sets of candidate items (in the case of this study items are individual MMs), and are asked to choose the two items within each set that they consider the 'best' and 'worst' (Finn and Louviere, 1992). Within each set, respondents select the pair of items which they feel "exhibit the largest perceptual difference on an underlying continuum of interest" (Finn and Louviere, 1992). In the case of our expert survey, the continuum of interest is the degree of effectiveness in reducing GHG emissions, and in our farmer survey the practicality of MM implementation. In a set of five items (A to E) selection of a best and worst provides preference information on seven out of ten possible pairs. If A is chosen as best and E as worst we know that: A>B, A>C, A>D, A>E, B>E, C>E, D>E, where ">" indicates "is preferable to" (Sawtooth Software, 2007). This choice task is repeated over a number of sets containing different combinations of items. Analysis of the responses provides a mean preference score across the sample of respondents for each item on an interval scale (Finn and Louviere, 1992; Marti, 2012). In the expert survey, MMs were scored on a scale of effectiveness; and in the farmer survey, on a scale of practicality. This is a relative approach i.e. all effectiveness and practicality scores are relative to each other on an arbitrary scale (Cross et al., 2012).

Experts in agricultural land management or livestock management with knowledge of GHG mitigation were drawn from academia, government and industry. Expert surveys were completed on-line at the beginning of 2012. Farmer practicality surveys were completed face to face with an interviewer. Data were collected at agricultural shows across England and Wales between May and August 2012.

BWS respondents were presented with 13 sets of five MMs and asked to select the best and worst measure in each set, i.e. the most and least effective for reducing emissions in the case of experts and the most and least practical to implement in the case of farmers. Both BWS surveys were designed and analysed using the software Sawtooth SSI Web. Effectiveness and practicality scores were estimated using a choice model based on random utility theory which treats best and worst choices as utility maximising and minimising decisions. The model defines the probability of a respondent choosing a pair of MMs as most and least effective as the probability that the difference between them on the underlying effectiveness scale (plus their error terms) is greater than the difference between any other possible pair of combinations in the set. It is assumed here that the error term has a Gumbel distribution. Incorporating this into the described probability calculation creates a multinomial logit model which returns estimates of effectiveness scores that are a maximum likelihood fit to the actual choices made by respondents. Individual level effectiveness and practicality scores were also calculated under the logit rule using hierarchical bayes which borrows information across the distribution of responses to stabilise and calculate each respondent's score for each MM. Full details of the analyses are given in Jones et al. (2013).

Farmer demographic data, collected as part of the survey, were used to assess whether the distribution of individual respondent practicality scores differed significantly between subgroups of respondents and farm types. For the top MMs with high mean practicality and effectiveness scores we used non-parametric Mann-Whitney and Kruskal-Wallis tests to compare the distribution of individual respondent scores between subgroups of interest, for example lowland, upland and hill farms. Dunn-Bonferroni post hoc tests were used following significant Kruskal-Wallis results.

3.4. Study 4: Developing marginal abatement cost curves

Marginal abatement cost curves provide a simple graphical representation of the abatement potential and cost-effectiveness of mitigation measures, offering a useful tool for decision-making in GHG policy. Following the construction of the national agricultural MACCs for the UK, Moran et al. (2011) stated that "there is merit in deriving more regional and farm specific MACCs", in order to reflect heterogeneity in abatement potential and costs. With this in mind, and given that no sheep farm focussed MACCs have been constructed to date, this study was undertaken with the aim of constructing farm-level MAC curves for a lowland, upland and hill sheep farm, indicating the most cost-effective MMs for each farm type.

3.4.1. Mitigation measure and case study farm selection

The top six MMs from study 3, considered to be both practical to implement by farmers and effective in reducing emissions by agricultural GHG experts, were selected for modelling on case study farms. The measures were aimed at reducing emissions per kg of meat produced, reflecting the importance of expressing emissions per unit of output as opposed to at a whole-farm level (Franks and Hadingham, 2012). The MMs, listed below, are numbered here and throughout for consistency with study 3:

- Include legumes in pasture reseed mix (7)
- Increase lamb growth rates for earlier finishing (8)
- Improve ewe nutrition in gestation to increase lamb survival (14)
- Reduce mineral fertiliser use (16)
- Lamb as yearlings (19)
- Select pasture plants bred to minimise dietary nitrogen (N) losses e.g. high sugar grass (26)

For the purposes of this study, three case-study farms were selected from the sample footprinted in study 2 to assess the potential for MMs to reduce the mean CF. A single lowland, upland and hill farm were selected, each of which had a CF close to the mean for their category. These three case-study farms provided the 2010/2011 baseline against which the abatement potentials of MMs were modelled (Table 2).

Table 2. Characteristics of the three case-study farms (baseline scenarios).

	Lowland	Upland	Hill
Farm area (ha)	48.8	115.0	71.7
Stocking density (LSU/ha)*	1.3	1.1	0.6
Grassland			
Improved grass area (ha)	48.8	80.0	38.0
Fertiliser nitrogen (kg/ha/year)	92	42	33
Area of improved grass with clover in the ley (%)	51	32	32
Area of improved grass ploughed (%/year)	20	6	8
Flock			
Breeding ewe flock size (head)	412	350	258
Ewe mature weight (kg)	80	80	45
Ram mature weight (kg)	100	100	60
Unmated first year ewe lambs (head)	90	51	73
Mean lamb growth rate (g/day)	313	242	179
Mean concentrates fed to ewes (kg/head/year)	17	66	85
Feed types:	Unspecified Homegrown silage	Ewe nuts Molassed sugar beet Homegrown cereal Homegrown silage	Ewe nuts Molassed sugar beet Homegrown silage
Mean creep fed to lambs (kg/head/year)	67	28	12
Produce			
Mean finished lamb sale weight (kg LW)	42	40	36
Number of finished lambs sold per year (head)	338	425	197
Other categories of stock sold	Ewe lambs Ram lambs Cull ewes	Cull ewes	Cull ewes Cull rams

* LSU are livestock units calculated according to the values given in Nix (2013).

3.4.2. Modelling mitigation potential

The whole-farm livestock CF model described by Jones et al. (2014) (study 2) was adopted and developed in this study to enable the impact of MMs to be modelled on the case-study farms. Both the baseline and mitigation scenarios were calculated as cradle to farm gate CFs per kg of LW finished lamb, accounting for all major sources of CH_4, N_2O and CO_2, encompassing both direct and indirect emissions (see Jones et al. (2014) for a schematic of the system boundary and further details on EFs and allocation approach).

To ensure that the impacts of MMs were accurately reflected within the calculated CFs, the sensitivity and accuracy of the baseline CF model was improved from the study of Jones et al. (2014) by:

1) Estimating animal and excreta emissions on a daily, as opposed to monthly time-step;
2) Updating enteric CH_4 and N excretion calculations from the IPCC Tier 1 approach to the more detailed and sensitive Tier 2;

3) Reviewing soil N_2O EFs for a UK specific setting.

As a result of these changes, the model is now sensitive to impacts of MMs such as changes in live weight gain and feed intake and improved efficiency of dietary N use. All modifications to the model are detailed in Appendix A, including Tier 2 equations, underlying assumptions and updated N_2O EFs.

The individual, stand-alone abatement potentials of the six MMs were calculated by comparing the post-implementation CFs of each of the three farms to their 2010/2011 CF baselines. Each MM was modelled according to the general consensus in the peer-reviewed and industry literature on method of implementation, impacts on CO_2, N_2O and CH_4 emissions and effects on productivity. Mitigation measures were modelled as being applied at a whole-farm level, across sheep enterprises. Modelled impacts included: changes to the level of farm inputs e.g. fertilisers and feeds; on-farm operational changes in grass yield and quality, stock carrying capacity, lamb survival and growth; changes in the level of outputs and wastes.

Only the direct impact of each MM was modelled, with no prediction of the farmer's resultant change in management. For example, if a measure increased productivity then farm output was increased, it was not assumed that stock would be sold to maintain constant production. To enable comparison of MMs implemented over different timescales, the abatement potentials for each measure were estimated for ten years and reported as a mean annual reduction against the fixed 2010/2011 baselines. Other overarching assumptions applied to all measures are detailed in Appendix B.1. Calculated abatement potentials for each MM on each farm are contingent upon a range of assumptions relating to implementation and emissions and productivity impacts. A brief description of each MM, relevant background literature, ensuing modelling approach and all assumptions are detailed in Appendix B.2.

3.4.3. Cost calculations and marginal abatement cost curve construction

The calculated stand-alone cost of each MM is a net cost incorporating capital expenditure and changes in variable costs and revenue as a result of changes in farm productivity. Farmer time is also accounted for. All costs are private costs to the farmer, reflecting a departure from the baseline scenario, and relate specifically to the application of each MM on each case-study farm. For example, fertiliser savings calculated as a result of the inclusion of legumes in pasture reseed mixes are farm-specific, based upon the reduction of fertiliser from their baseline application multiplied by the average cost of fertiliser per kg from Nix (2013). All cost calculations were based on the MM's specific assumptions on changes in inputs and outputs, as detailed in Appendix B.2. All costs and underlying assumptions are detailed in Appendix C. Costs and benefits occurring from year two to ten were discounted using a 7% private discount rate to provide a net present value. The final farm-level costs used in cost-effectiveness calculations were mean annual net present values across the ten years of implementation.

Individual farm MACCs were constructed using an engineering approach indicating the stand-alone mitigation potential of each MM. The MMs modelled targeted emissions' reductions per kg of meat produced and to reflect this MACCs were constructed with abatement potential on the x axis expressed per kg of lamb produced (i.e. the change in the lamb CF). To ensure that the results of the MACCs could be scaled to other farms without impacting upon national production or displacing emissions, a system expansion approach to MACC construction was adopted, enabling the abatement potential for each MM to be reported at the same baseline level of production. Cost-effectiveness reported on the y axis was calculated as the total cost of implementing the MM divided by total emissions savings.

4. Results

4.1. Study 1

A number of interventions emerged which are available for current application, which have broad agreement on their mitigation potential and are likely to be widely applicable across sheep farms. These are: increasing lambing percentages, lamb survival and ewe longevity; increasing diet digestibility and formulating diets to minimise nitrogen excretion; avoiding exceeding pasture and forage crop nitrogen requirements particular in wet conditions. Other more novel interventions are also becoming commercially available such as high water soluble carbohydrate grasses, a urease inhibitor and lipid supplemented feed (currently only available for dairy cows).

Many more interventions require significant research and development before deployment or need technological enhancement or farm payment subsidies to become cost-effective. Long-term field trials under a range of conditions are clearly needed for interventions such as dietary additives and NIs. An assessment of net impact on all GHGs is required for interventions such as the inclusion of legumes in pasture and faster growth rates in lambs. Furthering understanding of underlying biological processes will enable exploitation of the mitigation potential of interventions such as pasture drainage and vaccination against rumen methanogenesis. Research into the efficacy of interventions such as the incorporation of biochar and breeding for lower residual feed intake is at an early stage and longer-term trials are required urgently.

4.2. Study 2

Completed datasets were collected and analysed for 60 footprinted farms (27 lowland sheep farms and 33 LFA sheep farms: 12 upland and 21 hill). The mean CF of finished lamb produced in England and Wales was estimated to be 10.85 kg CO_2e/kg LW for lowland farms, 12.85 kg CO_2e/kg LW for upland and 17.86 kg CO_2e/kg LW for hill farms (Table 3). Enteric CH_4 emissions represented the largest component of the CF for each farm category (Table 3). Direct N_2O emissions arising from soils as a result of excreta and manure deposition were the second largest component of the footprint for all farm systems.

Table 3. Breakdown of the mean carbon footprint of finished lamb produced on lowland, upland and hill farms in England and Wales (kg CO_2e/kg LW finished lamb). Figures in brackets represent the percentage contribution of each emissions source to the mean footprint.

Emissions source	Farm classification											
	Lowland (n=27)				Upland (n=12)				Hill (n=21)			
	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
CO_2 from manufacture of inputs												
Fuel	0.29 (2.7)	108	0.1	1.4	0.85 (6.6)	197	0.0	6.1	0.35 (2.0)	70	0.0	0.8
Electricity	0.02 (0.2)	171	0.0	0.2	0.11 (0.9)	261	0.0	1.1	0.03 (0.2)	163	0.0	0.2
Fertilisers	0.34 (3.2)	107	0.0	0.9	0.54 (4.2)	72	0.0	1.1	0.46 (2.6)	85	0.0	0.9
Lime	0.07 (0.6)	210	0.0	0.6	0.19 (1.5)	135	0.0	0.7	0.33 (1.9)	238	0.0	3.7
Agrochemicals	0.01 (0.1)	140	0.0	0.1	0.00 (0.0)	95	0.0	0.0	0.01 (0.0)	151	0.0	0.0
Bedding materials	0.03 (0.3)	142	0.0	0.2	0.01 (0.1)	93	0.0	0.0	0.01 (0.1)	126	0.0	0.1
Mixed GHGs from growth of inputs												
Concentrates and other feeds	0.81 (7.4)	124	0.0	4.0	0.49 (3.8)	93	0.0	1.7	1.08 (6.0)	97	0.0	4.5
Purchased stock	0.52 (4.8)	194	0.0	5.1	0.34 (2.7)	117	0.0	1.1	0.46 (2.6)	125	0.0	2.0
Inputs total	**2.10 (19.4)**	**81**	**0.2**	**6.6**	**2.53 (19.7)**	**75**	**1.0**	**8.1**	**2.73 (15.3)**	**47**	**0.9**	**4.6**
N_2O emissions from soils												
Direct - fertiliser (organic and artificial)	0.36 (3.3)	128	0.0	2.0	0.37 (2.9)	73	0.0	0.7	0.31 (1.7)	86	0.0	0.9
Direct - excreta and manure	2.31 (21.3)	38	1.2	5.5	2.49 (19.4)	24	1.4	3.4	3.37 (18.9)	39	0.7	5.8
Direct - crop residues	0.05 (0.4)	218	0.0	0.4	0.03 (0.2)	226	0.0	0.2	0.01 (0.1)	236	0.0	0.1
Direct - peat soil	0.00 (0.0)	376	0.0	0.1	0.17 (1.3)	165	0.0	0.8	0.70 (3.9)	176	0.0	5.3
Indirect - volatilised	0.48 (4.5)	38	0.3	1.1	0.51 (3.9)	23	0.3	0.7	0.69 (3.9)	36	0.4	1.2
Indirect - leaching and run off	0.59 (5.4)	36	0.3	1.2	0.64 (5.0)	22	0.4	0.8	0.83 (4.6)	37	0.2	1.3
N_2O emissions from manure storage												
Direct	0.10 (0.9)	104	0.0	0.4	0.18 (1.4)	92	0.0	0.4	0.11 (0.6)	146	0.0	0.5
Indirect	0.04 (0.3)	107	0.0	0.1	0.05 (0.4)	91	0.0	0.1	0.05 (0.3)	172	0.0	0.4
N_2O total	**3.94 (36.3)**	**38**	**2.2**	**8.1**	**4.43 (34.5)**	**23**	**2.8**	**6.0**	**6.07 (34.0)**	**44**	**1.4**	**13.6**
CH_4 emissions												
Enteric fermentation	4.62 (42.6)	48	2.4	11.9	5.59 (43.5)	26	3.7	8.9	8.61 (48.2)	42	4.1	17.9
Excreta	0.11 (1.0)	48	0.1	0.3	0.13 (1.0)	26	0.1	0.2	0.20 (1.1)	42	0.1	0.4
CH_4 total	**4.73 (43.6)**	**48**	**2.4**	**12.2**	**5.72 (44.5)**	**26**	**3.4**	**9.1**	**8.81 (49.3)**	**42**	**4.2**	**18.4**
CO_2 from lime breakdown	0.08 (0.7)	210	0.0	0.6	0.17 (1.3)	136	0.0	0.7	0.25 (1.4)	160	0.0	1.7
Total mean carbon footprint	**10.85**	33	5.4	21.5	**12.85**	23	8.3	18.3	**17.86**	34	8.8	33.3

In an initial analysis of the impact of farm and flock structure on the CF of finished lamb, the CF decreased as the size of the breeding ewe flock increased across all farms. However, differences in the CFs of farms categorised by flock size were not found to be significant (H(3)=4.54, p=0.209). The CF of finished lamb increased from lowland to upland to hill farms. A Kruskal-Wallis test revealed a significant effect of land classification on the CF (H(2)=19.84, p<0.001). Post-hoc pairwise comparisons showed that the CFs of lowland and hill farms were significantly different (p<0.001). There were no significant differences between the CFs of farms categorised by farm area (ha^{-1}) (H(3)=3.76,p=0.289).

The final model obtained through stepwise regression contained four of the initial 10 independent variables: concentrate use (kg/LSU), number of lambs reared per ewe (head/ewe), lamb growth rate (grams/day) and the percentage of ewe and replacement ewe lamb flock not mated (%). The model was statistically significant (F(4,55)=13.4, p<0.001)) and explained approximately 49% of the variance in CF (R^2=.494, adjusted R^2=.457). The regression coefficients and associated significance of the independent variables in the final model are reported in Table 4.

Table 4. Summary of the final linear model obtained through stepwise regression for the dependent variable, the carbon footprint of finished lamb. Unadjusted model R^2=.494, adjusted model R^2 = .457, $F_{4,55}$ = 13.4, p<0.001.

Variable	Unstandardised coefficient	Standard error	t value	p
Concentrate use	1.70×10^{-3}	8.43×10^{-4}	2.02	0.049
Lambs reared per ewe	-1.09×10^{1}	2.25	-4.82	<0.001
Lamb growth rate	-2.12×10^{-2}	8.47×10^{-3}	-2.50	0.016
Not mated	2.13×10^{-1}	7.59×10^{-2}	2.81	0.007
Intercept	2.96×10^{1}	3.12	9.45	<0.001

The results of the dominance analysis indicating the percentage of variance in CF explained by each variable in the final regression model are given in Fig. 1. The number of lambs reared per ewe was found to be the most important predictor of CF (explaining 27.4% of the variance in CF), followed by lamb growth rate (10.6%), the percentage of ewe and replacement ewe lamb flock not mated (9.8%) and concentrate use (1.7%).

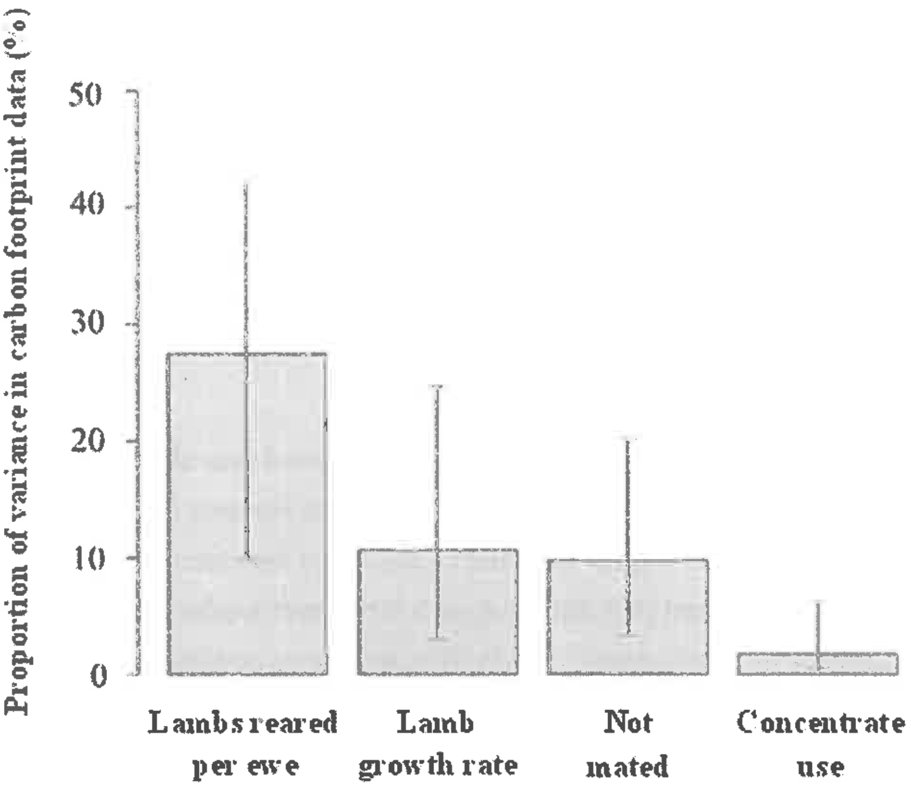


Fig. 1. Results of the dominance analysis indicating the percentage of variance in carbon footprint explained by each variable in the final regression model. Values sum to the overall model R^2 = 49.4%. Bars represent 95% bootstrap confidence intervals.

4.3. Study 3

Responses from 55 expert and 225 farmer surveys were analysed. The estimated mean expert scores for the 26 MMs obtained via the choice model were ranked on a scale of effectiveness, and the farmer scores ranked on a scale of practicality. Both the mean expert effectiveness and farmer practicality scores were zero-centred and plotted in an effectiveness and practicality 2 x 2 space (Fig. 2). The axes (zero) represent the average effectiveness and practicality scores of all 26 MMs. Measures in the upper right quadrant scored highly for both effectiveness and practicality whereas those MMs located in the lower left-hand quadrant were low scoring for both criteria. Practical and effective MMs included three targeting flock productivity (*increasing lamb growth rates for earlier finishing* (8), *improving ewe nutrition in late gestation to increase lamb survival* (14) and *lambing as yearlings* (19)); two relating to pasture management (*inclusion of legumes in pasture reseed mixes* (7) and *selecting pasture plants to minimise dietary nitrogen losses e.g. high sugar grasses* (26)); and one relating to fertiliser management (*reducing mineral fertiliser use* (16)).

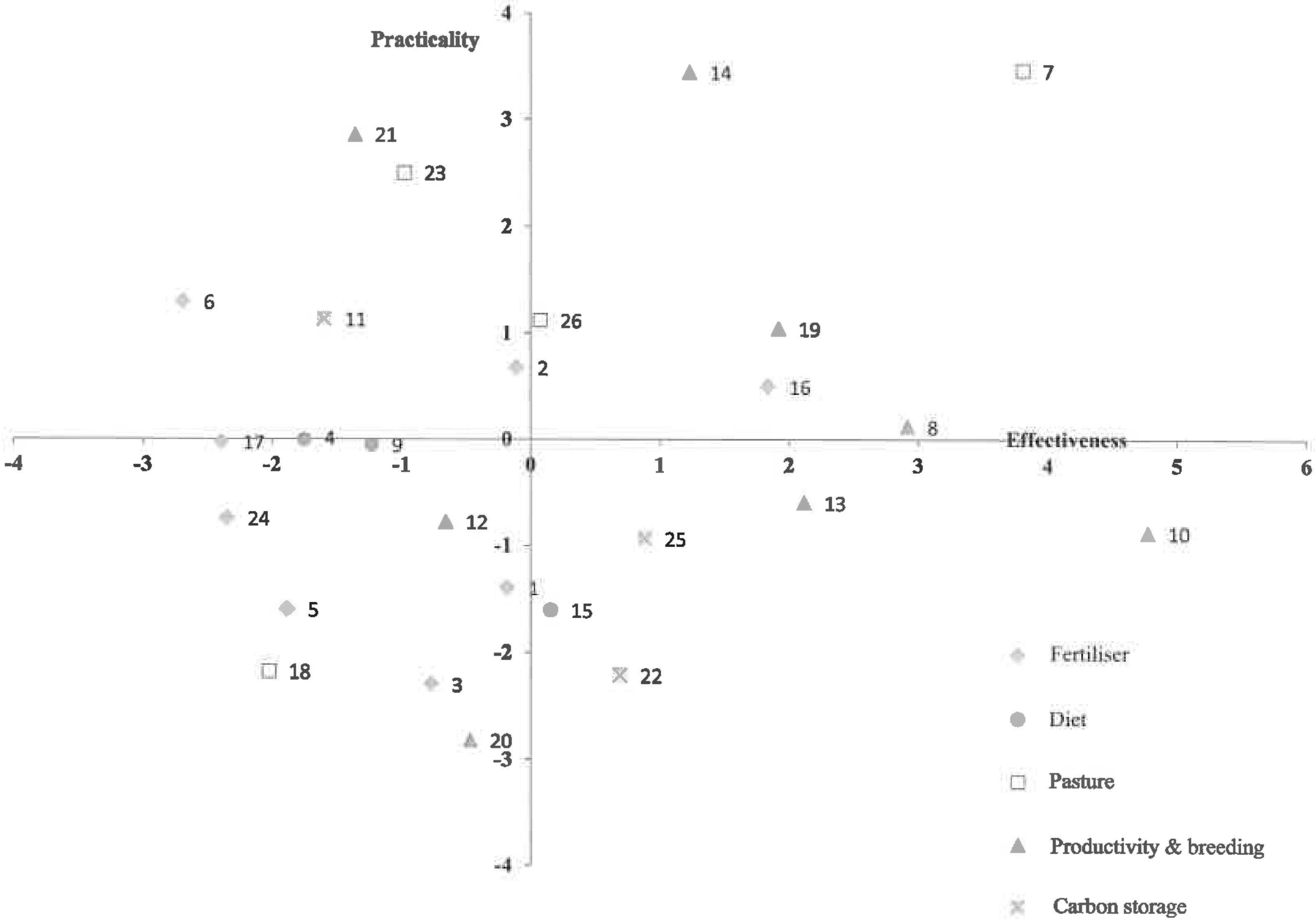


Fig. 2. Zero-centred scatter plot of mean effectiveness and practicality for the 26 mitigation measures, categorised by mitigation type.

In the lower right quadrant are MMs judged to be effective by experts but impractical by farmers. These included two of the highest scoring productivity enhancing MMs from the expert survey: *increasing the number of lambs born per ewe* (10) and *increasing ewe longevity* (13). In contrast, *improving hygiene and supervision at lambing* (21), and *selecting pasture plant for improved nitrogen conversion efficiency* (23) were perceived as practical by farmers but ineffective by experts.

To assess variation in farmers' perceptions of practicality for each top rated MM featured in the upper right quadrant of the effectiveness-practicality space, we plotted the number of respondents against the practicality score they ascribed to the MM (Fig. 3 a-f). The profile of the frequency distributions of individual level practicality scores for each MM reveal the degree of agreement amongst farmers. Although there was a wide spread of scores for MMs 7 and 14, both distributions were skewed towards high scores indicating overall agreement on their above average practicality (Fig 3a and 3c). For MMs 8, 16 and 19 opinion was divided (Fig 3b, 3d and 3e). Their modal scores were low but numerous respondents also scored them moderately or highly. As a result, the mean scores of these MMs were above the overall mean for the 26 MMs. This divide in opinion was particularly marked for MM 19.

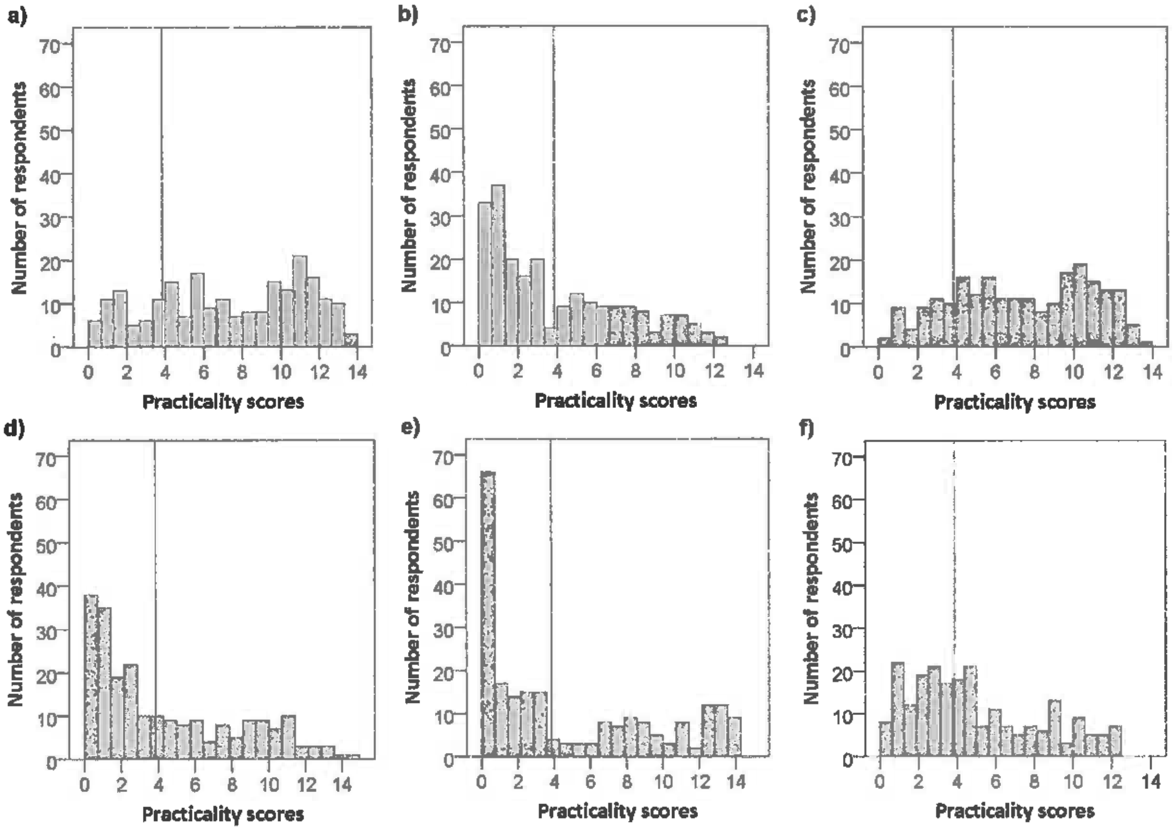
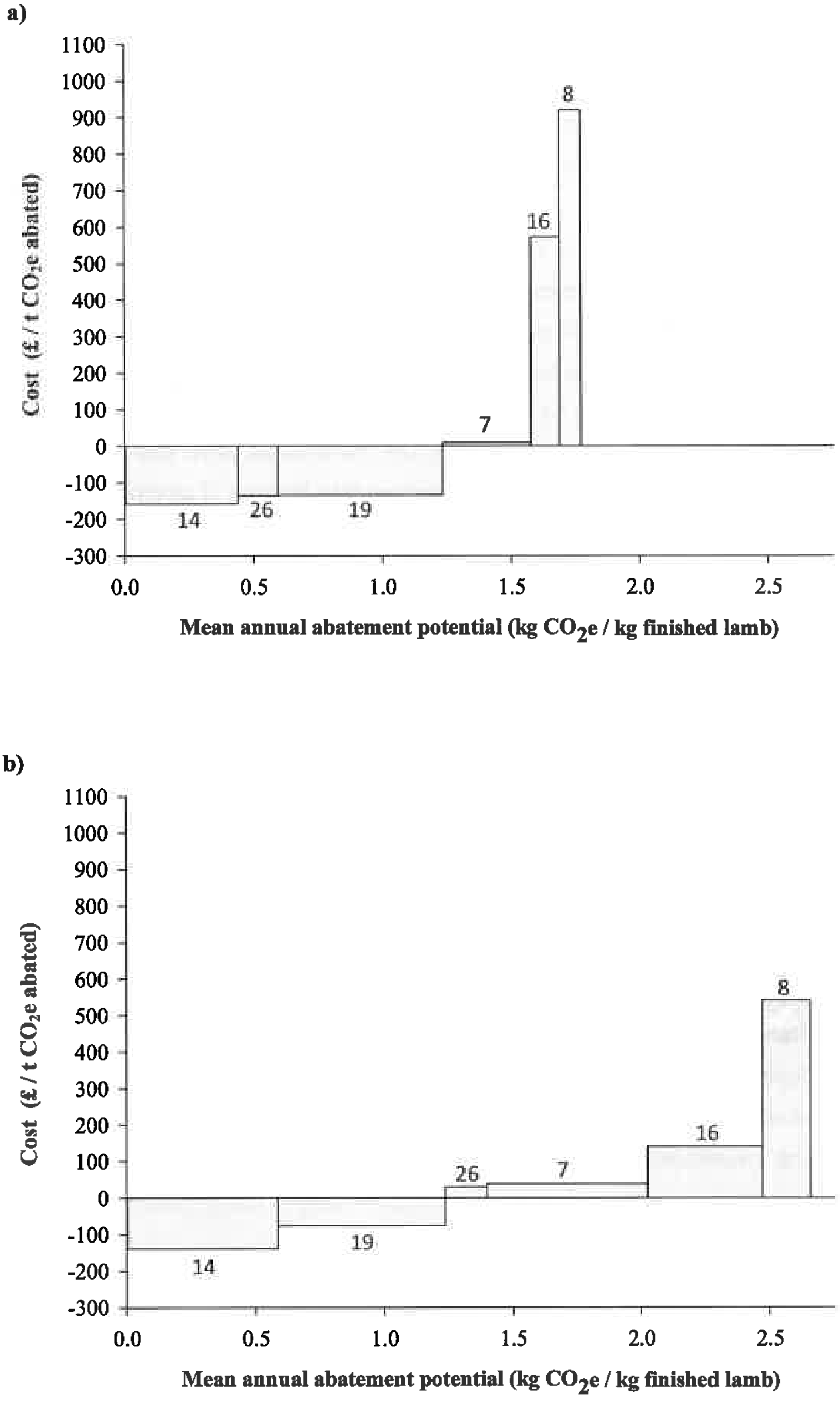


Fig. 3. Distributions of individual level farmer practicality scores for the top mitigation measures: (a) Include legumes in pasture reseed mix (7), (b) Increase lamb growth rates for earlier finishing (8), (c) Improve ewe nutrition in late gestation (14), (d) Reduce mineral fertiliser use (16), (e) Lamb as yearlings (19), and (f) Select pasture plants bred to minimise dietary nitrogen losses (26). The solid vertical line in all panels represents the average score across all mitigation measures.

In a further assessment of heterogeneity in farmer perceptions of practicality, for top rated MMs, we compared the distribution of scores between subgroups of the sheep industry based upon demographic data. Both breeding ewe flock size and farm type influenced perception of the practicality of *increasing lamb growth rates for earlier finishing* (8). Farmers with between 1 and 49 breeding ewes perceived this measure to be less practical than those with between 100 and 199 ($p=0.049$). Although not significantly different, farmers with the smallest flock size of between 1 and 49 breeding ewes perceived this MM to be less practical than farmers of all other flock sizes, according to mean and median scores. Farms with an arable enterprise considered this MM less practical than farms specialising in ruminant livestock ($p=0.024$ and $p=0.043$ for sheep and cattle, and specialist sheep farms respectively).

4.4. Study 4

The three case-study farm MACCs are presented in Fig. 4a-c. Each bar represents an individual MM, ordered from left to right based on cost-effectiveness, with the least cost-effective measures on the right. The width of each bar indicates its abatement potential and the height of the bar its cost-effectiveness. The abetment potentials of the MMs are not necessarily additive because they were modelled on a stand-alone basis. The MACCs show that if the individual MMs were compatible, cumulative total abatement potentials of 1.77, 2.66 and 2.04 kg CO_2e/kg lamb are the maximum that could be achieved through implementing the six measures on the lowland, upland and hill case-study farms respectively. On all three case-study farms, MMs were identified that could reduce emissions at negative cost to the farmer (cost saving measures below the x axis). The CF of lamb produced on the lowland, upland and hill farm could be reduced by 1.24, 1.24 and 1.68 kg CO_2e/kg lamb respectively at a negative cost to the farmer, if the abatement potentials were cumulative.


a)
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
Cost (£ / t CO₂e abated)
8
16
7
14
26
19
0.0
0.5
1.0
1.5
2.0
2.5
Mean annual abatement potential (kg CO₂e / kg finished lamb)
b)
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
Cost (£ / t CO₂e abated)
8
16
26
7
19
14
0.0
0.5
1.0
1.5
2.0
2.5
Mean annual abatement potential (kg CO₂e / kg finished lamb)

c)

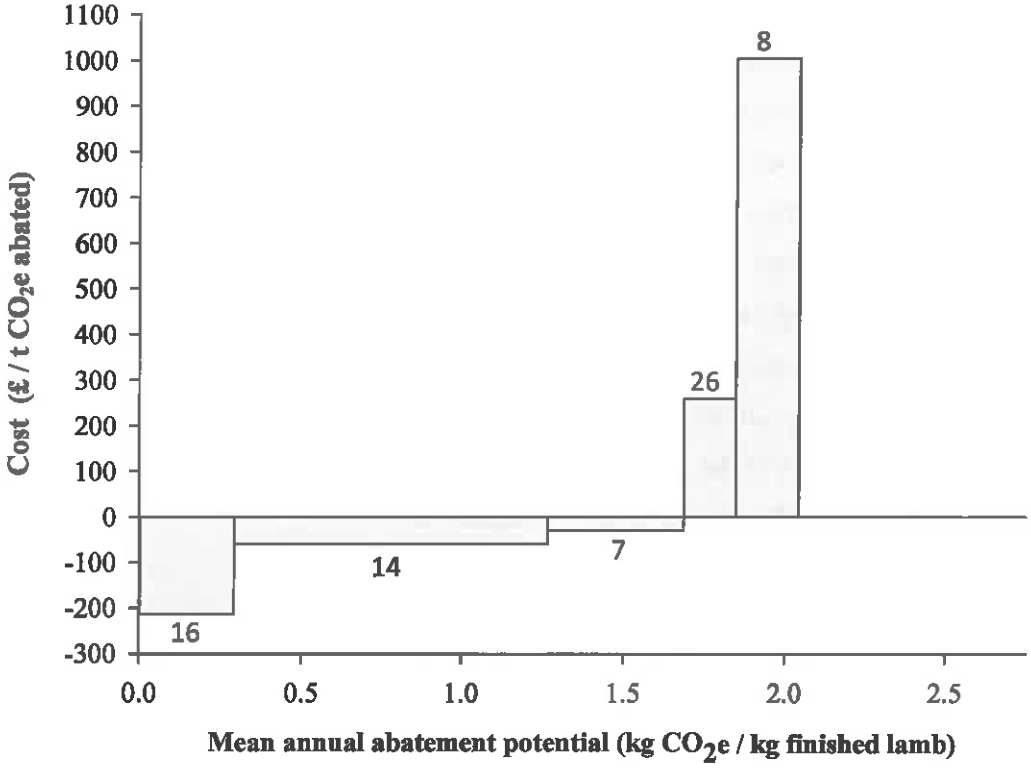


Fig. 4. Marginal abatement cost curves for a) lowland sheep farm, b) upland sheep farm and c) hill sheep farm. The numbered mitigation measures are: include legumes in pasture reseed mix (clover) (7); increase lamb growth rates for earlier finishing (selective breeding) (8); improve ewe nutrition to increase lamb survival (14); reduce mineral fertiliser use (16); lamb as yearlings (19) and select pasture plants bred to minimise dietary nitrogen losses (high sugar grass) (26).

Notable similarities exist between the MACCs for the three farm land classification categories. The ordering of MMs by cost-effectiveness was similar for the lowland and upland farms. For both farm categories the measure *lambing as yearlings* (19) offered the greatest abatement potential (0.64 and 0.65 kg CO$_2$e/kg lamb respectively), and at a negative cost (-£134 and -£76 /t CO$_2$e abated respectively). This MM was not thought to be technically possible on the hill farm, due to the postponement of puberty by slower growth. On all three farms, *improving ewe nutrition to increase lamb survival* (14) had a negative cost (-£158, -£139 and -£59/t CO$_2$e on the lowland, upland and hill farms respectively) and considerable abatement potential. This MM represented the single largest opportunity for abatement on the hill farm of 0.97 kg CO$_2$e/kg lamb (equivalent to 5.17% of the baseline CF). The abatement potential of the *inclusion of legumes* (7) was also relatively high on all farms. On all farms, *increasing lamb growth rates* (8) was the least cost-effective MM, costing in excess of £1000/t CO$_2$e abated on the hill farm. This MM also had a consistently low abatement potential across farms relative to the other measures modelled.

Differences in costs and abatement potential between the farms were also apparent. On the whole, the larger baseline CF of lamb produced on the hill farm appeared to offer greater abatement potential per MM. However, differences in the individual farm baselines meant that this pattern did not always hold: the *inclusion of legumes in pasture the reseed mix* (7) and *reducing mineral fertiliser use* (16) had greater abatement potentials per kg of lamb produced on the upland case-study farm than the hill. The abatement potential of *reducing fertiliser use* (16) was highly variable between the farms. Both the *inclusion of legumes in the pasture reseed mix* (7) and *reducing mineral fertiliser use* (16) had negative costs on the hill farm, however this was not the case on the lowland and upland farms. The cost of *pasture plants bred to minimise dietary N losses* (26) increased from -£136/t CO_2e abated on the lowland farm to £30 on the upland to £259 on the hill farm, however the abatement potential per kg of lamb produced was fairly consistent between farms. To improve understanding of the impact of baseline farm emissions on abatement potentials, a percentage breakdown of the baseline CF by emissions source is presented for each case-study farm in Table 5. This is discussed further in section 5.

Table 5. Baseline carbon footprints of the finished lamb produced on the case-study farms and their percentage breakdowns by emissions source. Emissions sources and percentages in brackets are part of the total emissions percentage associated with farm inputs.

	Lowland	Upland	Hill
Baseline carbon footprint			
Tier 2 finished lamb carbon footprint (kg CO_2e/kg LW lamb)	11.4	14.3	18.8
Baseline carbon footprint breakdown (%)			
Inputs (direct and indirect emissions)	23.7	16.5	19.5
(including N, P, K fertilisers)	*(5.0)*	*(6.3)*	*(3.7)*
(including concentrate feeds)	*(8.5)*	*(4.8)*	*(12.6)*
(including CO_2 from lime application)	*(4.7)*	*(0.3)*	*(0.0)*
Enteric CH_4	51.4	53.5	53.6
Excreta CH_4	1.0	0.9	1.1
N_2O from soils (direct and indirect emissions)	23.6	28.1	25.8
N_2O from manure storage (direct and indirect emissions)	0.4	1.2	0.0
	100.0	100.0	100.0

5. Discussion

The results of all studies convey two primary messages for industry and policy decision-makers: Firstly, the importance of productivity and efficiency as influential drivers of emissions abatement in the sector, particularly the cost-effective measures *improving ewe nutrition to increase lamb survival* and *lambing as yearlings*; and secondly, the need for policy instruments to acknowledge the heterogeneity within the industry. These findings and subsequent recommendations for policy development and further research are discussed in detail in the ensuing sections.

5.1. Mitigation measure analysis and recommendations

5.1.1. Efficiency and productivity

All four studies affirmed the importance of productivity and efficiency in mitigating sheep farm GHG emissions, across all farm categories. The initial literature review in study 1 highlighted that improving productivity is one of the few mitigation approaches achieving general consensus on its efficacy (e.g. Gill et al., 2010; Shibata and Terada, 2010). The underpinning notion of which is to maximise lamb production from the flock's maintenance feed provision, therefore reducing emissions per kg of produce (Buddle et al., 2011; Smith et al., 2008). Study 2 demonstrated that at a national level, productivity characteristics can explain a significant proportion of inter-farm variation in CFs. In the survey of expert opinion in study 3, five out of 11 MMs considered as having above average effectiveness were aimed at enhancing productivity. The filtering of MMs in studies 3 and 4 left two MMs possessing above average practicality, and offering considerable abatement potential per kg of lamb at a negative cost to farmers: *improving ewe nutrition to increase lamb survival* and *lambing as yearlings*.

Improving ewe nutrition to increase lamb survival received an above average practicality score from the majority of farmers surveyed in study 3 and can be confidently recommended for inclusion in sheep farm GHG mitigation strategies. Increasing lamb survival in this way also contributes to maximising the number of lambs reared per ewe, which was the most significant predictor of CFs identified at a national level in study 2. The proportion of the ewe and ewe lamb flock not mated was another significant driver of variation in CFs. This finding is underpinned by the MACC analysis which suggested that *lambing as yearlings* offered considerable abatement potential at a negative cost on the lowland and upland farms modelled. However, this MM was not deemed viable on the hill farm where slower growth rates postponed puberty. Farmer opinion on the practicality of implementing this measure is highly polarised. Study 2 demonstrated that lamb growth rates represent a significant source of variation in the CF between farms. However, the MACC analysis showed that achieving this through active participation in selective breeding programmes was not competitive in terms of abatement potential or cost when compared to the other modelled MMs. In part this was due to the application of the MM to both slaughter and replacement lambs. Abatement potential per unit of produce may have been greater if the result of faster growth had been modelled as lambs being sold at a heavier weight on the same date as opposed to being sold earlier at the same weight. It must also be considered that the abatement potentials and costs of genetic improvement measures are contingent upon whether they are achieved through performance recording alone or in combination with other traits as part of a breeding index, or through cross breeding to exploit hybrid vigour (Boon, 2013; IBERS, 2011). Ewe fertility and longevity can be significantly improved through capitalising on hybrid vigour (Boon, 2013). The measures *selective breeding to increase the number of lambs born per ewe* and *selective breeding to increase ewe longevity* were considered to be highly effective in reducing emissions in the expert survey, however due to below average practicality they were not explored further in the MACCs. The abatement potential and cost-effectiveness of these measures may warrant further research if it is thought that policy instruments could alter farmer perception in their favour.

These overall findings in favour of increasing productivity and efficiency are consistent and compatible with the current approach of both the UK government's Carbon Plan for the sector, and with the agriculture industry GHG Action Plan which is focused on achieving "*emissions reductions through increasing the production efficiency of each farming system…. decreasing emissions per unit of production*" (DECC, 2011; Joint Agricultural Climate Change Task Force, 2011). Although this study does not explicitly consider the level of uptake possible for MMs nationally, Study 2 recorded considerable variability in productivity indicators such as number of lambs reared per ewe and lamb growth rates between farms, demonstrating the potential for improvement on the worst performing farms. Some hill farms were competitive in productivity terms with lowland and upland farms despite climatic and geographical disadvantages, demonstrating the potential for shrewd management to at least partially local overcome environmental impediments. It was estimated that 41% of the maximum possible annual abatement potential achievable through livestock breeding in beef, dairy and sheep sectors in England had been achieved by 2013 (DEFRA, 2013). The use of high estimated breeding value sires was less widespread when breeding lambs compared to calves, suggesting potential for widespread improvement in the sheep sector (DEFRA, 2013). In addition to technical potential for the uptake of productivity enhancing measures, a study of farmer attitudes by Barnes et al. (2010) found that there is strong support for improving productivity in sheep as a means of mitigating emissions. This support was consistent across farm types and sizes, and between farmers grouped by behavioural types. Policy instruments are now needed that can convert this general receptiveness into further action.

As a result of these findings, it is recommended that industry and policy decision-makers promote farm productivity and efficiency nationally. This could potentially be enacted immediately and by communicating to farmers through the use of productivity indicators. Benchmarks could be developed for productivity related characteristics including the proportion of the ewe and ewe lamb flock mated, the number of lambs reared per ewe, lamb growth rates, concentrate use per unit of produce (all for different farm systems and breeds). The data collected and reported in study 2 could inform the development and definition of such benchmarks. A productivity target of one kg of lamb sold or retained per kg of ewe mated is already aspired to in the sheep industry literature to improve farm performance and profitability (e.g. Vipond et al., 2010). It is this productivity indicator approach that is being suggested here for a broader range of productivity characteristics. Developing a small set of productivity benchmarks should improve the specificity of mitigation strategies promoting productivity improvements, and better define the standards required on-farm.

Alongside the productivity measures, the mitigation *including legumes (clover) in pasture reseed mixes* can also be recommended across farm categories. After accounting for grass yield reduction and reduced stock carrying capacity, reseeding with legumes still achieved considerable abatement potential per kg of lamb produced on all farms modelled, at either a negative or slight cost to the farmer. This measure achieved general consensus on its above average practicality in the farmer survey. Use of clover is included in a list of on-farm mitigation actions encouraged by the GHG Action Plan (Joint Agricultural Climate Change Task Force, 2011) and is mentioned as a means of improving sustainability in the Welsh Red Meat Road Map (HCC, 2011). In 2013, 39% of farms with livestock in England were sowing 80% or more of their temporary grassland with a clover mix, leaving considerable remaining potential for uptake (DEFRA, 2013). However, assumed impacts on stock carrying capacity limit the practical extent of this measure.

5.1.2. Farm heterogeneity

A recurring finding throughout this study was the importance of the characteristics of individual farms in determining baseline emissions and subsequent abatement potentials and costs. Variability in emissions between farms can be attributed to differences in local conditions such as quality of grazing and climate, and management choices such as efficiency of fertiliser use and selective breeding (Henriksson et al., 2011). This was evidenced in study 2 by the considerable differences in emissions and farm characteristics recorded both within and between the categories of lowland, upland and hill farms. The influence of farm heterogeneity was evident throughout, from the choice of EF in the initial CF model e.g. a higher EF for N_2O arising from soil as a result of fertiliser application in the wetter West; to calculated differences in abatement potentials and costs in the final MACCs.

This heterogeneity, inherent in farming, can limit the usefulness of sector level MACCs in farmer decision-making (Franks and Hadingham, 2012). More tailored approaches to MACC construction are therefore recommended to help overcome this issue and refine mitigation strategies. Grouping farms for analysis by characteristics such as region, elevation, enterprise mix and economic size has been shown to reveal heterogeneity in abatement potential and cost-effectiveness (De Cara and Jayet, 2006). Grouping farms by multiple targeted characteristics in this way is suggested as a means of enabling more category specific MM recommendations than were possible in this study for farms categorised by land classification alone. Few concrete differences in abatement potentials could be attributed to land classification in the present study. These were limited to: a significant difference in the CFs of lowland and hill farms in study 2; an indication in studies 2 and 4 that lowland and upland farms may be similar enough to negate the need to assess MMs separately for these land classes; an assumption that *lambing as yearlings* may not be technically possible on hill farms due to lower growth rates; the possible distortion of the estimated cost-effectiveness of measures applied to hill farms by low profits or losses. Although MACC construction for a larger sample of case-study farms may have resulted in firmer conclusions on the impacts of land classification, differences in the abatement potentials of MMs between farms appeared to be a result of individual farm management more often than land classification. Categorising by land classification alone therefore seems insufficient to develop more tailored mitigation strategies. Further research is clearly needed to better understand the impact of farm category on abatement potentials. Characteristics suggested as a result of this study that could be considered for farm categorisation include breeding ewe flock size, farm production orientation / enterprise mix and farm profitability.

Case-study farm-level MACCs can highlight the role that differences in farm management and baseline emissions can play in determining the abatement potential of a MM. The abatement potentials and cost-effectiveness of MMs modelled in this study were frequently dependent upon farm-level differences such as: the breakdown of the baseline CF (particularly the division of emissions between inputs and emissions directly associated with stock); baseline management choices e.g. the area of grassland currently ploughed; and the farm's profit margin. The development of case-study MACCs based on empirical data in this study has improved understanding of the conditions in which some MMs are likely to be most effective. For example, it is suggested that: *improving lamb growth rates* offers greatest abatement potential for farms breeding slaughter lambs and replacement lamb flocks separately; the *use of clover* and *reducing mineral fertiliser use* hold greatest abatement potential on farms with a large proportion of the CF from mineral fertiliser; *reseeding with clover or high sugar grasses* is most cost-effective on farms already reseeding to grass. The generation of further case-study farm-level MACCs based on empirical data is suggested as a means of informing the development of guidelines on the farm and baseline CF conditions to which each MM is best suited. When used in this way MACCs have the potential to inform both farm-level mitigation strategies and higher-level policy. Alongside case-study farm-level MACCs, sensitivity analyses could be used to reveal the farm management changes which have the greatest impact on the estimated abatement potentials and costs of individual MMs.

5.2. Policy considerations

Policy and industry decision-makers are tasked with interpreting often incomplete and disparate evidence on abatement potentials, to develop instruments which will enable farmers to implement suitable MMs. Policy instruments must aid farmers in overcoming barriers to uptake, particularly when measures are unprofitable (Smith et al., 2007). The present study has suggested that the level of regulation, financial or advisory support needed to ensure implementation may vary between MMs and different segments of the farming community. For example, a spread of opinions on the practicality of productivity measures was recorded, both within and between measures. Measures perceived to have below average practicality are likely to require greater support and advice through policy instruments to ensure delivery (e.g. *selective breeding to increase the number of lambs born per ewe* and *selective breeding to increase ewe longevity*). Study 3 also demonstrated the need for policy instruments that are flexible enough to account for differences in farm type. For example, *improving lamb growth rates through selective breeding* was perceived to be significantly less practical to both farmers of very small flocks and those with an arable enterprise. Therefore, policy instruments may need to account for the potentially greater support requirements of very small and mixed farms in improving productivity. Developing effective policy instruments relies upon understanding farmer perceptions of and motivations for implementing MMs, however causes of variation in farmer opinion on the practicality of MMs in this study are largely unexplained and unexplored. The six grouping variables used to compare differences in farmer opinion explained an average of 10.8% of variation in the practicality scores for the top six MMs. These were farm type, breeding ewe flock size, whether or not they had already implemented a MM, country (England or Wales), farmer age and land classification (lowland, upland, hill). Additional grouping variables such as farmer behavioural type may explain further variation in farmer perceptions of the practicality of MMs (Barnes et al., 2010). The UK Department for Environment, Food and Rural Affairs (DEFRA) has defined five farmer types, characterised by general attitudes and motivations, to account for diversity in farmer behavioural responses to agricultural policy (Pike, 2008). This segmentation approach may further explain variation in farmer perceptions of the practicality of MMs, and could inform targeted policy communication to appeal to different groups of the farming community.

Policy instruments must encourage farmers to deviate from their current habitual management, enabling them to overcome any perceived risks or preconceptions associated with investing time and money in MMs. Whilst a private discount rate of 7% was adopted to calculate the net present value of costs and benefits to the farmer in the present study, farmer discount rates may be far higher in reality, reflecting the higher rate of return needed to overcome perceived risks associated with MM adoption (Duquette et al., 2012; Kesicki and Ekins, 2012). Farm-level heterogeneity complicates the recommendation of MMs, and the subsequent lack of conviction in mitigation strategies is unlikely to promote farmer confidence in implementation. Even cost-negative measures (such as *lambing as yearlings*) may require information campaigns to change farmer perception and encourage implementation (Barnes et al., 2010). Policy-makers must decide which barriers to the uptake of MMs can and cannot be overcome (Kesicki and Ekins, 2012). Whilst barriers such as information failures and inertia can be overcome, the same may not be possible for high adoption costs (Kesicki and Ekins, 2012). Jones et al. (2010) explored barriers to the uptake of individual MMs in a farmer telephone survey. Barriers to the uptake of beef breeding measures included costs; lack of evidence that animals with a high estimated breeding value sell; lack of evidence that productivity is improved and small farm size. Policy instruments that can overcome such barriers include making additional allowances for small farms in technical support and advisory schemes; offering small grants for measures with a net cost or upfront investment; capitalising on demonstrations and peer influence to improve knowledge of economic and environmental benefits (Barnes et al., 2010). Consultation with farmers suggested that improved advice, incentives and inclusion in environmental stewardship schemes are all potential drivers for increasing the uptake of clover inclusion in the sward (Jones et al., 2010; Moran et al., 2008). Choice of policy instrument can influence MM selection, resultant abatement potential, private and policy costs (Bakam et al., 2012). Harris et al. (2009) assessed current and potential voluntary, economic and regulatory policy instruments to reduce agricultural GHG emissions in England. In the long-term it was thought that modification of Cross Compliance to include GHG abatement within existing or new standards offered greatest abatement potential due to its significant coverage, and at a limited public policy cost. The costs of modifying existing policy instruments and developing new ones are still to be fully explored, and may alter perspectives on the cost-effectiveness of some MMs when social costs are considered in addition to private costs. It remains to be seen whether abatement potential in the sheep and wider livestock sector is competitive with other sectors when the social costs of policy delivery are accounted for.

5.3. Research and methodology considerations

This study has highlighted the usefulness of whole-farm GHG models and MACCs as a means of quantifying and reporting baseline emissions, abatement potential and costs. Several methodological caveats associated with these tools have been highlighted throughout the study, and should, where possible, be improved upon in future MACC development. Considerable uncertainties exist in the EFs used to estimate farm CFs and in the emissions and productivity impacts of MMs. Long-term field trials under a range of conditions are needed to enable selection of EFs, emissions and productivity impact figures that are most suited to individual farm conditions; increasing the accuracy of modelled CFs and abatement potentials. A series of government funded projects are currently underway to improve the accuracy and resolution of UK agricultural GHG reporting (ADAS, 2010). Through literature reviews, emissions modelling and experimental work, livestock system EFs for CH_4 and N_2O are being refined to reflect differences between breeds, local conditions and farming systems (ADAS, 2010). The projects which are due to be completed this year should improve the accuracy of estimated baseline emissions and abatement potentials. Furthermore, the Intergovernmental Panel on Climate Change is currently in the process of publishing its fifth assessment report which will update current global thinking on emissions sources, mitigation options and related policies. This is a fast moving research area and future MACCs can take advantage of this progress to produce more accurate and informed estimates of abatement potentials and cost-effectiveness.

The multiple assumptions necessary to enable abatement potentials to be modelled in the present study means that the MACCs produced are inevitably scenario specific. Sensitivity analyses could be used to pinpoint the assumptions that have the greatest impact on MACC results. Future research could then focus on improving the certainty of these assumptions or identifying values tailored to specific farm situations. It was originally hoped that this study would produce a wider range of case-study farm MACCs for farms of varying size in addition to land classes. However, the time demands of modelling individual abatement potentials meant that this was not possible. The process of producing the current MACCs has indicated that there is merit in producing further MACCs for farm types in addition to individual case-study farms, particularly when using empirical data sets rather than cross-sector modelled mean values.

A limitation of this study, and significant challenge still to be tackled for sheep industry MMs, is the impact of interactions between multiple measures on abatement potentials and costs. The impacts of MM interactions on abatement potentials were accounted for in the UK MACCs developed by Moran et al. (2008) and were later revised by MacLeod et al. (2010b). For crop and soil measures, the former used expert derived interaction factors for all possible two way combinations of MMs to reduce abatement potentials when applied together. For livestock measures, interactions were dealt with more simply: either MMs could or could not be applied simultaneously. In the latter study, the interaction factors were weighted by the geographic area to which the MM could be applied in combination with another MM to reflect the impact of interactions on national abatement potential. Following this revised approach, MacLeod et al. (2010b) stated that there are significant improvements to be made to interaction calculations, including the need for field trials to estimate interactions between pairs and packages of MMs. At the individual farm-level the order and combination of MMs implemented will differ, making accounting for the impact of interactions on abatement potentials highly problematic.

Future MACC research and improvements recommended as a result of this study will take time to achieve; therefore this should run concurrently with work to encourage productivity and efficiency which can deliver more immediate results.

5.4. Broader considerations

Marginal abatement cost curves, as constructed in this study, fail to account for broader environmental, animal welfare and food production priorities. The emphasis of the constructed MACCs was on abatement potential reported in emissions per unit of produce, as is consistent with most CF approaches. No measures associated with protecting or enhancing carbon stores were modelled. However, the imminent reform of farmer payments under the Common Agricultural Policy highlights a shift in emphasis at the European Union level to greener farming, promoting farm carbon sequestration and biodiversity. Alternative production metrics reflecting both food production and environmental priorities may favour production in less productive systems e.g. kg edible output produced per quantity of ecosystem services provided on-farm (Garnett, 2011; Ripoll-Bosch et al., 2013). In this case, MMs that enhance carbon sequestration or deliver ancillary environmental benefits may be favoured over those offering GHG abatement potential alone. Moran et al. (2012) assessed the wider impact of GHG MMs in English agriculture: potential benefits included improvements in field level biodiversity associated with measures that reduce fertiliser use; potential issues included negative impacts on fitness traits in beef cattle as a result of genetic improvement measures and a reduction in food production associated with clover pastures. It was suggested that the agriculture industry's GHG Action Plan should be aligned with DEFRA's ecosystem services approach (Moran et al., 2012). The Farmscoper decision support tool developed by ADAS (2013) could be used to provide an indication of the impact of some of the MMs prioritised in the present study on other agricultural pollutants, biodiversity and water use. The time and resource demands of CF and MACC studies, particularly at the case-study farm-level, mean that ensuring recommendations are compatible with the wider research and policy landscape is, unfortunately, almost invariably beyond the scope of individual studies.

Arguably, supply side MMs alone will be insufficient to meet agricultural emission reduction targets and reductions in meat and dairy consumption are also advocated (Franks and Hadingham, 2012; Garnett, 2009). Scaling the results of MACCs to the national level is a crucial step in comparing the abatement potential, private and policy costs of supply side livestock mitigation strategies to alternative demand side strategies in agriculture, and beyond this to strategies proposed in other sectors. This process has in part been implemented in the UK with the existence of carbon budgets and sectorial plans within this based, in the agricultural sector, on national MACCs for averaged modelled farms. Studies such as this are now providing the finer detail needed to confidently recommend and promote MMs suited to farm categories and crucially, individual farm scenarios.

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Appendix A: Details of improvements made to the whole-farm carbon footprint model

To ensure that the impacts of mitigation measures were accurately reflected within the calculated carbon footprints (CFs), the sensitivity and accuracy of the baseline CF model was improved from the study of Jones et al. (2014) by: estimating animal and excreta emissions on a daily, as opposed to monthly time-step; updating enteric methane (CH_4) and nitrogen (N) excretion calculations from the IPCC Tier 1 approach to the more detailed and sensitive Tier 2; reviewing soil nitrous oxide (N_2O) emissions factors (EFs) for a UK specific setting.

Manure storage related emission calculations were not updated to Tier 2 given that they represent a small percentage of the overall mean CF. All other calculations and EFs were unchanged from Jones et al. (2014).

A.1. Updating enteric methane and nitrogen excretion to the Tier 2 approach

Whilst the Tier 1 methodology uses rigid EFs per head for enteric CH_4 and N excretion calculations, the Tier 2 methodology takes a stock category specific approach, linking emissions to animal performance based on energy intake (IBERS, 2011; Lassey, 2007). Gross energy (GE) intake was calculated daily for each cohort of sheep on farm using default Intergovernmental Panel on Climate Change (IPCC) equations (2006). The net energy demands of maintaining body condition, grazing activity, growth (including wool), sustaining pregnancy and producing milk were all accounted for (where relevant); through combining live weight and gain data provided by the farmer with standard coefficients from IPCC (2006). Gross energy intake was subsequently estimated taking into account inefficiency of feed use and feed digestibility. The full list of equations and coefficients used and underlying assumptions are detailed in Table A.1. Using assumed values for the proportion of GE lost as CH_4 and for dietary N retention, enteric CH_4 emissions and N excretion were estimated, as detailed in Table A.2.

A.2. Revising soil nitrous oxide emission factors

Given that N_2O emissions can represent a substantial component of the CF of lamb, N_2O EFs were reviewed for the UK setting to improve the accuracy of the CFs.

The IPCC Tier 1 methodology uses a single EF for direct N_2O emissions arising from managed soils as a result of the application of mineral fertilisers, organic fertilisers and crop residues (EF1) (IPCC, 2006). However, a wealth of N_2O studies have shown that fertiliser induced emission rates vary in relation to rainfall, time and rate of application, fertiliser, soil and crop type (Skiba et al., 2013). In the UK a number of studies have reported greater N_2O

emissions per kg of N applied in the West than the East, and the use of region specific EFs based on climatic conditions has been suggested as a means of reducing uncertainty in N_2O emission calculations (Cardenas et al., 2010; Dobbie and Smith, 2003; Lesschen et al., 2011). Based on the geographic division in Lesschen et al. (2011) separate EFs were adopted in this study for N_2O emissions arising from mineral fertiliser applications to grasslands in the West and East of the UK. The adopted EFs for the percentage of mineral N applied emitted as N_2O are 2.42% in the West and 1.12% in the East. These are mean values calculated from a range in the published literature (Cardenas et al., 2010; Dobbie and Smith, 2003; Jones et al., 2005; Ryden, 1981; Skiba et al., 2013; Smith et al., 1998). Emission factors from potato and leafy vegetable studies were also included within the mean grassland values based on the recommendations of Dobbie and Smith (2003) and Flynn et al. (2005). A separate, country wide EF of 0.51% was adopted for cereals, which do not exhibit a response to rainfall (Dobbie et al., 1999; Dobbie and Smith, 2003). A single, country wide EF of 0.5% was adopted for organic N applications to all crop types as in Flynn et al. (2005). Very little UK data exist on the influence of crop residues on N_2O emissions from soils therefore the default IPCC (2006) value of 1% was unchanged.

The EF for direct N_2O emissions for managed organic soils (peat) (EF2) was unchanged from the UK derived value adopted in Jones et al. (2014).

The EF for direct N_2O emissions as a result of dung and urine deposition on pasture (EF3) was unchanged from the default IPCC value adopted in Jones et al. (2014). Only a limited number of relevant studies exist in UK conditions making reaching a consensus on a representative or mean value for the EF problematic. Most studies report measurements over a short period which cannot be scaled up to a year, report a combined EF for excreta and fertilisers, or are laboratory based studies (Skiba et al., 1998; Williams et al., 1999; Yamulki et al., 1998).

The EF for indirect N_2O emissions as a result of N volatilised from soil and re-deposited (EF4) was unchanged from the default IPCC value adopted in Jones et al. (2014). Whilst UK data exist on ammonia emitted from grazing systems (Misselbrook et al., 2013), no complementary data on conversion to N_2O were found.

The EF for indirect N_2O emissions as a result of N leaching and run-off from managed soils (EF5) was unchanged from the default IPCC value adopted in Jones et al. (2014). The IPCC value was informed by the results of a UK study (Reay et al., 2004) and has since been supported by the results of a further field study (Reay et al., 2009).

Table A.1. Method for estimating gross energy intake

Equation	Underlying assumptions		Reference(s)
Net Energy Requirements			
Net energy for maintenance (NE_m) (MJ/day)			
$NE_m = Cf_i * W^{0.75}$	$Cf_i = 0.236$ MJ/day/kg	female and castrated male lambs to 1 year	IPCC (2006)
Where:	$Cf_i = 0.271$ MJ/day/kg	intact male lambs to 1 year	
Cf_i = coefficient varying with animal category	$Cf_i = 0.217$ MJ/day/kg	ewe or castrated ram older than 1 year	
W = live weight (kg)	$Cf_i = 0.250$ MJ/day/kg	intact ram older than 1 year	
Net energy for activity (NE_a) (MJ/day)			
$NE_a = C_a * LW$	$C_a = 0.0096$ MJ/day/kg	housed lactating ewe	IPCC (2006),
Where:	$C_a = 0.0054$ MJ/day/kg	housed pregnant ewe	AFRC (1993),
C_a = coefficient corresponding to animal's feeding situation	$C_a = 0.0107$ MJ/day/kg	lowland ewe out-of-doors	Baker (2004)
W = live weight (kg)	$C_a = 0.0240$ MJ/day/kg	hill grazing ewe	
	$C_a = 0.0067$ MJ/day/kg	housed fattening lambs	
	$C_a = 0.0086$ MJ/day/kg	lamb out-of-doors	
Net energy for growth (NE_g) (MJ/day)			
$NE_g = EV_g * W_d$	$EV_g = 2.5 + 0.35W$	intact male	IPCC (2006),
Where:	$EV_g = 4.4 + 0.32W$	castrated male	Baker (2004)
EV_g = energy value of the liveweight gain	$EV_g = 2.1 + 0.45W$	female	
W_d = daily weight gain (kg/day)			
Net energy for lactation (NE_l) (MJ/day)			
$NE_l = ((5 * WG_{wean})/365) * EV_{milk}$	$EV_{milk} = 4.6$ MJ/kg		IPCC (2006),
Where:			AFRC (1993)
WG_{wean} = weight gain of lamb between birth and weaning (kg)			
EV_{milk} = energy value of ewe milk (MJ/kg)			
Net energy to produce wool (NE_{wool}) (MJ/day)			
$NE_{wool} = (EV_{wool} * Production_{wool})/365$	$EV_{wool} = 23.7$ MJ/kg		IPCC (2006),
Where:			AFRC (1993)

EV_{wool} = energy value of wool (MJ/kg)			
$Production_{wool}$ = annual wool production per sheep (kg)			
Net energy for pregnancy (NE_p) (MJ/day)			
$NE_p = C_{pregnancy} * NE_m$	$C_{pregnancy} = 0.077$	single birth	IPCC (2006)
Where:	$C_{pregnancy} = 0.126$	double birth (twins)	
$C_{pregnancy}$ = pregnancy coefficient	$C_{pregnancy} = 0.150$	multiple births (triplets or more)	
NE_m = net energy for maintenance (MJ/day)			
Ratio of net energy available in diet for maintenance to digestible energy consumed (REM):			
$REM = 1.123 - (4.092 * 10^{-3} * DE\%) + (1.126 * 10^{-5} * (DE\%)^2) - (25.4/DE\%)$	$DE\% = 73.28$	lowland farm pasture	IPCC (2006),
Where:	$DE\% = 68.16$	lowland farm silage	MAFF (1992)
DE% = digestible energy expressed as a percentage of gross energy	$DE\% = 63.40$	upland farm pasture	
	$DE\% = 62.89$	upland farm silage	
Ratio of net energy available for growth in a diet to digestible energy consumed (REG):	$DE\% = 60.34$	hill farm pasture	
$REG = 1.164 - (5.160 * 10^{-3} * DE\%) + (1.308 * 10^{-5} * (DE\%)^2) - (37.4/DE\%)$	$DE\% = 60.02$	hillfarm silage	
Where:	$DE\% = 83.64$	unspecified concentrate /creep mean	
DE% = digestible energy expressed as a percentage of gross energy	$DE\% = 82.30$	molassed sugar beet mean	
	$DE\% = 82.23$	cereal (wheat, oat and barley grain mean)	
Gross energy intake (GE)			
$GE = (((NE_m + NE_a + NE_l + NE_p) / REM) + ((NE_g + NE_{wool}) / REG)) / (DE\%/100)$			

Table A.2. Method for estimating enteric methane emissions and nitrogen excretion rates

Emission category and equation	Underlying assumptions	Reference(s)
Enteric CH_4 emission factor (kg CH_4/head/day)		
$EF = (GE*(Y_m/100)) / 55.65$	Y_m = 6.5% mature sheep	IPCC (2006)
where:	Y_m = 4.5% lambs under 1 year	
GE = gross energy (MJ/head/day)	Y_m = 0% lambs pre effective weaning at 8 weeks	
Ym = % of gross energy lost as CH_4		
Nitrogen intake (kg N/head/day)		
$N_{intake} = GE/18.45 * (N \% / 100)$	N% = 2.4 mean N% as content of dry matter	IPCC (2006), ADAS (2007)
where:		
GE = gross energy (MJ/head/day)		
N% = % nitrogen in the diet		
Nitrogen excretion (kg N/head/day)		
$N_{ex} = N_{intake} * (1-N_{retention})$	$N_{retention} = 0.0843$	IPCC (2006), ADAS (2007)
where:		
N_{intake} = nitrogen intake (kg N/head/day)		
$N_{retention}$ = fraction of N_{intake} that is retained		

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Appendix B: Modelling approach and assumptions for mitigation measures

B.1. Overarching assumptions applied to all measures

- Each measure was considered extant at the beginning of the footprinted year.
- Each measure was assumed to be fully implementable on each farm based on the baseline farm data, with the exception of lambing as yearlings on the hill farm, for which there was no precedent in the literature.
- Grassland reseeding measures were assumed to be applied to 20% of the improved grassland area (acknowledging that all farms were already reseeding some of the farm area with clover). Grassland clover and high sugar grass (HSG) leys were assumed to have a five year lifespan. Both the upland and hill farms ploughed less than 20% of the improved grassland area in the baseline carbon footprints (CFs), therefore an increase in ploughing emissions associated with crop residues was calculated in relation to the area increase when the grassland mitigation measures (MMs) were applied.
- When a MM improved lamb growth rate, lambs were sold earlier in the model at the sale weight provided by the farmer as opposed to a heavier weight on the same date.
- When a MM increased lamb numbers, ewe numbers were not decreased to maintain constant output.
- Where stock carrying capacity increased or decreased as a result of a MM, ewes were purchased or sold to match the change. All inputs directly related to stock numbers were changed on a pro-rata basis with stock carrying capacity or changes in sale dates e.g. purchased feed and bedding. Applied lime, diesel and electricity use were assumed to remain constant irrespective of changes in stock carrying capacity. Where grass intake increased or decreased as a result of a measure, fertiliser nitrogen (N) use was altered according to the fertiliser / grass yield relationship assumed for MM 4 (see section B.2). For any changes in N application pro-rata changes in phosphorous (P) and potassium (K) application were assumed, except for when N was replaced by clover.

B.2. Mitigation measure specific background information and assumptions

Calculated abatement potentials are contingent upon a range of assumptions. A brief description of the background literature, ensuing modelling approach and assumptions for each MM are given below:

Include legumes in pasture reseed mix (7): Modelled as reseeding 20% of the farms' improved pasture with a white clover / ryegrass mix in years one and six. Atmospheric N biologically fixed by forage legumes is steadily released to grass in the pasture, reducing mineral fertiliser requirements (Rochon et al., 2004).

- It was assumed that no mineral N fertiliser was applied to the clover swards, therefore the calculated reduction in fertiliser use was equal to the fertiliser application rate provided by the farmer, multiplied by 20% of the farm area. No reduction in the quantity of P or K fertiliser applied was assumed based on the lack of differentiation in guidelines for clover/grass and pure grass swards in the UK Fertiliser Manual (DEFRA, 2010).
- There is a range of often conflicting findings in the published literature relating to nitrate leaching losses and excretal N returns from clover-based compared to pure grass pastures (Loiseau et al., 2001; Rochon et al., 2004). In a review of the environmental impacts of grazed clover/grass pastures Ledgard et al. (2009) concluded that total N leaching losses and nitrous oxide (N_2O) emissions from N cycling of excreta were similar in both pasture types with comparable total N inputs. On this basis, the same emission factors (EFs) were adopted to estimate soil leaching and N_2O losses from clover/grass and pure grass swards. Reported differences in study findings may reflect variation in sward clover content and fertiliser application rates.
- Further debate exists on the impact of clover/grass swards on productivity compared to fertilised pure grass swards. For example Orr et al. (1990) reported no significant difference in lamb growth rates between the two treatment types whilst Munro et al. (1992) reported a significant, large advantage to lamb growth rates of grazing clover/grass swards. Rochon et al. (2004) reviewed research on grazing legumes and concluded that performance per head is greater on grass legume mixtures but that overall production per hectare (ha) is decreased on white clover mixes due to decreased stock carrying capacity. Vipond et al. (1993) reported that with 15% white clover content, a clover/grass sward can produce comparable lamb outputs to a moderately fertilised pure grass sward, through a 15-20% reduction in sheep numbers and 20% higher individual performance. Similar figures were reported by Davies et al. (1989) and Vipond et al. (1997). Based on these studies, a 15% reduction in stock carrying capacity was

assumed on the clover/grass swards (both ewes and lambs) and a 20% increase in lamb growth rate to sale (assuming a clover content of 15-20%).

- It was assumed that lamb dry matter intake (DMI) increased to match the increased live weight gain (LWG) (e.g. Vipond et al., 1997).
- No change in the percentage of gross energy intake (GEI) lost as methane (CH_4) was modelled.
- Emissions associated with ploughing in crop residues in years 5 and 10 were calculated using default IPCC (2006) values for the N content of clover/grass residues.

Increase lamb growth rates for earlier finishing (8): Modelled as genetic improvement in average daily LWG achieved through active participation in selective breeding over 10 years. Performance recording services, such as Signet in the UK, use farm-level data to estimate the breeding value of individual animals. Estimated breeding values (EBVs) are used to identify animals with genetic superiority for a trait of interest, which will be passed on to future generations.

- IBERS et al. (2011) used gene flow techniques to estimate the genetic improvement possible in the Welsh sheep industry through performance recording. Through single trait selection for lamb growth rate to 150 days (grams/day) they estimated an annual genetic change of 1.4% from the mean value in hill flocks and 1% in lowland flocks, which is cumulative from year to year. These percentages were used to inflate the growth rate provided by farmers in this study for all lambs to 150 days. A 1.2% annual genetic change was assumed for the upland farm. For the lowland farm this annual improvement equates to 10% over 10 years which is comparable to the percentage improvements in LW and daily gain achieved after nine years of index based selection in the studies of Simm et al. (2002) and Lewis et al. (2004) .
- No correlated changes in other traits or ewe mature weight were modelled as a result of the selective breeding programme.
- It was assumed that lamb DMI increased in response daily to weight gain i.e. no change in feed efficiency was modelled.
- Supplementary feed intake per head per day was assumed to be fixed to the value provided by the farmer; therefore changes in DMI associated with growth were assumed to be from grass.

Improve ewe nutrition (in gestation) to increase lamb survival (14):

Modelled as a 5% increase in lamb survival achieved through ewe body condition scoring (BCS); forage quality assessment; and redistribution of feed by differential feeding to the requirement of ewes grouped by BCS. The importance of managing ewe nutrition to maximise lamb survival is unanimously agreed in the published literature (e.g. Hatcher et al., 2010; Jordan et al., 2006). However, there are few robust figures available in the literature on the potential impact of ewe nutrition on lamb survival because the extent of the impact is farm-specific, dependent upon baseline management conditions and the improvements proposed.

- Both under-feeding and over-feeding of ewes can be problematic at various stages of reproduction (Robinson et al., 2002). For example, under-nutrition can impair colostrum production which is crucial for developing immunity in lambs (Robinson et al., 2002), whilst over-feeding leading to high daily LWGs in the ewe can compromise the viability of offspring (Vipond et al., 2010). If all ewes are fed equally, mismatches between feed requirement and provision will occur (Beef and Lamb New Zealand, 2013). It is widely agreed that thin and fat ewes should be fed differently (Robinson et al., 2002). A targeted split flock feeding approach is recommended based on the body condition score (BCS) of ewes and litter size (Beef and Lamb New Zealand, 2013; DEFRA, 2004). Body condition score directly affects lamb survival, and it is reported that lamb survival decreases by 5% for every ½ condition score the ewe is below optimum at lambing (Beef and Lamb New Zealand, 2013). In this study it was assumed that ewe nutrition could be improved through redistributing feed from overfed to underfed ewes within the flock (based on a normal distribution of BCSs), however it may even be possible to reduce total feed purchased through targeted feeding (e.g. Jordan et al., 2006).
- It was assumed that a 5% increase in lamb survival could be achieved through regular BCS of ewes and forage quality assessment. Both ensuring that purchased supplements complement forage provision in targeted rations.

Reduce mineral fertiliser use (16): Modelled as a 20% reduction in fertiliser N applied to grass (and pro-rata 20% reductions in P and K applied). The ensuing impact on farm productivity would vary widely depending on baseline conditions such as background soil N supply, stocking rates and climate.

- It was assumed that the baseline fertiliser application rates on the case-study farms did not exceed grass requirements; therefore yield would be forgone with a reduction in the rate applied. A number of studies have reported, or modelled, grass yield and stock carrying capacity decreases equal to approximately half the percentage decrease in fertiliser use (e.g. IGER, 2004; Orr et al., 1995; Stewart et al., 2009). Consequently, it was assumed that yields were reduced by 10% and stock carrying by 10% at a whole-farm level.

- Individual animal performance was unchanged in the model, on the underlying assumption that herbage mass and crude protein content were not limiting factors in the mitigation scenario (see the review of Peyraud and Astigarraga, 1998). Negligible changes in grass digestibility and intake were assumed, with any decrease in crude protein content partially compensated for by a concurrent increase in water soluble carbohydrate (WSC) content (Peyraud and Astigarraga, 1998).
- The N content of grass typically increases with the fertiliser application rate (Whitehead, 1995) increasing excretion of urinary N (Ledgard et al., 2009). Based on the underlying assumptions: that grass crude protein content increases by 50 to 90 g per kg grass dry matter (DM) per 100 kg of N applied per ha (Peyraud and Astigarraga, 1998); and that 1 g of N is equal to 6.25g of protein, it was assumed that the N content of the diet declined by a mean of 0.112 g N/kg DM/kg reduction in N applied. Nitrogen excretion declined in the modelled mitigation scenario based on this decrease in the N content of the diet. No change was modelled in the proportion of dietary N retained.
- The 10% reduction in grass yield was assumed to be constant across the 10 years modelled i.e. no decline in background soil N supply from fertiliser residues and mineralised organic N was assumed.

Lamb as yearlings (19): Modelled as mating all home reared replacement ewe lambs at eight months of age. Lambing ewes for the first time as yearlings reduces the number of unproductive stock on-farm, and maximises lamb output from the maintenance feed cost of existing ewes (ADAS, 2010).

- Puberty in ewe lambs is generally achieved at 50 to 70% of mature body weight (Rosales Nieto et al., 2013). It was assumed here that ewe lambs achieved at least 60% of their mature weight when mated at eight months (ADAS, 2010). Replacement ewe lambs had already achieved the 60% target by eight months in the baseline for the lowland farm, and were close to this on the upland farm, where it was assumed that they were given additional concentrate to reach the growth rate necessary to achieve the target. In the hill farm baseline, replacement ewe lambs had only reached 45% of mature weight by eight months. Based upon this, and the knowledge that ewe lambs reared in unfavourable conditions will normally fail to reach the development necessary for reproduction in the first year of life (Dýrmundsson and Lees, 1972), this MM was not modelled on the case-study hill farm.
- On the lowland and upland farms it was assumed that the ewe lamb conception rate was 80%, with 0.95 lambs born and 0.8 reared per ewe lamb (ADAS, 2010).

- The growth rates and concentrate feed provisions of the ewe lambs and lambs born were modelled according to the detailed example of breeding from ewe lambs given in ADAS (2010), as listed in Table B.1.
- The milk yields of ewe lambs are typically lower than for adult ewes and were assumed to be 80% (Cruickshank et al., 2008).
- Where the concentrate feed provision did not match the GEI needed to achieve the specified growth rates, it was assumed that any energy requirement in addition to the baseline was met by grass.
- It was assumed that 1.5% more ewe lambs died at lambing than ewes (ADAS, 2010).
- To ensure that ewe lambs can reach optimum BCS for their second mating they should only rear one lamb as yearlings (ADAS, 2010). Therefore, after accounting for lamb losses and subsequent fostering, it was assumed that any surplus lambs were hand-reared.
- The purchase of additional rams was not modelled in this mitigation scenario, as it was assumed that the existing rams could be used to mate with ewe lambs.

Table B.1. Assumptions for the mitigation measure *lamb as yearlings* (19) all from ADAS (2010).

Description	Figure Assumed	Units
Prenatal		
Ewe lamb growth rate for 2 months from mating	250	g/day
Ewe lamb growth rate from 2 months to 6 weeks pre lambing	150	g/day
Ewe lamb growth in last 6 weeks of pregnancy	0	g/day
Postnatal		
Additional ewe nuts fed to ewe lambs	30	kg/head
Creep fed to lambs	50	kg/head
Lamb growth rate	330	g/day
Lamb age at weaning	8	weeks
Lamb age at sale	14	weeks

Select pasture plants bred to minimise dietary nitrogen losses e.g. high sugar grasses (26): Modelled as reseeding 20% of the farms' improved pasture with a 100% HSG mix in years one and six. Grasses high in WSC increase energy supply in the rumen, improving the efficiency of dietary protein use and reducing N excretion to the environment (Miller et al., 2001).

- The extent of the impact on N excretion varies. The Institute of Grassland and Environmental Research (IGER) (2005) stated that a reduction of up to 24% in excreted

N is possible. However, not all studies report an impact and a more conservative reduction potential of 10 to 15% is typically assumed in modelling work (IBERS, 2010; IGER, 2004). A 10% reduction in total N excretion was assumed in this study (e.g. Miller et al., 2001).

- High sugar grasses are also associated with improvements in productivity (e.g. Lee et al., 2001; Munro et al., 1992). Estimated impacts on lamb LWG fall within a broad range. Marley et al. (2007) reported no significant difference in LWG between lambs grazing control grass varieties and those grazing HSGs. However, increases of up to 48% in daily LWG post-weaning for lambs grazing HSGs have been recorded (IGER, 2005). In this study a 12% increase in lamb LWG was assumed, based on the results of the UK based sheep grazing study of Lee et al. (2001).
- Using the results of the same study a 14% increase in stock carrying capacity on the HSG was also assumed (Lee et al., 2001). No change in lamb DMI was modelled, assuming that the LWG increase was due to increased digestibility and /or the elevated WSC (Lee et al., 2001). It must be noted that the response of intake to HSGs is inconsistent (Edwards et al., 2007).
- No difference in N intake was modelled (e.g. Miller et al., 2001).
- Limited data exist on the impact of HSGs on CH_4 emissions. One field study reported a decrease in total CH_4 emissions on HSG (IBERS, 2010), whilst a modelling study indicated that CH_4 output would increase with the WSC content of grass (Ellis et al., 2012). No impact of HSG on the proportion of GEI lost as CH_4 was modelled.

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Appendix C: Cost data and underlying assumptions used for mitigation measure cost calculations.

Table C.1. Cost data and underlying assumptions used for net cost calculations.

Item Description	Cost (£ 2013)	Units	Underlying Assumptions / Information	Reference(s)
Inputs				
Fertiliser nitrogen	0.80	£/kg	Based on ammonium nitrate, includes delivery cost	Nix (2013)
Fertiliser phosphate	0.71	£/kg	Based on triple superphosphate, includes delivery cost	Nix (2013)
Fertiliser potassium	0.54	£/kg	Based on muriate of potash, includes delivery cost	Nix (2013)
Grass seed - 4 to 6 year grass ley (assumed baseline)	162.00	£/ha	Seed rate 35 kg/ha	Nix (2013)
Grass seed - white clover / ryegrass long term ley	159.00	£/ha	Seed rate 30 kg/ha	Cotswold Grass Seeds Direct (2013)
Grass seed - 100% high sugar grass long term ley	184.14	£/ha	Seed rate 37 kg/ha	PRAg Ltd. (2013)
Purchased feed - high energy lamb	270.00	£/t		Nix (2013)
Purchased feed - medium energy sheep	260.00	£/t		Nix (2013)
Purchased feed - sheep and lamb cake	260.00	£/t		Nix (2013)
Purchased feed - sugar beet pulp	230.00	£/t		Nix (2013)
Purchased feed - lamb colostrum average	4.87	£/lamb	Based on 3 doses/ lamb	Green's Country Store (2013), Countrywide (2013)
Purchased feed - lamb milk replacer average	22.85	£/lamb	Based on 10 kg/lamb	Green's Country Store (2013), Countrywide (2013)
Purchased stock - lowland farm ewe	76.49	£/ewe	As ewe sale price provided by farmer*	Farmer
Purchased stock - upland farm ewe	71.49	£/ewe	As ewe sale price provided by farmer*	Farmer
Purchased stock - hill farm ewe	44.68	£/ewe	As ewe sale price provided by farmer*	Farmer
Purchased stock - high EBV ram **premium**	200.00	£/ram		Boon (pers. comm.)
Parasite treatment - Clik	36.00	£/ℓ		Green's Country Store (2013)
Parasite treatment - Crovect	18.24	£/ℓ		Green's Country Store (2013)
Bedding - barley, wheat and oat straw average	97.60	£/t	Includes delivery cost*	ADAS and EBLEX (2011)
Labour and farm tasks				
Labour - standard worker hourly rate	7.07	£/hour		Nix (2013)
Labour - requirement per lowland ewe per year	28.28	£/yr	Based on 4 hours/yr, standard worker rate	Nix (2013)
Labour - requirement per upland ewe per year	25.45	£/yr	Based on 3.6 hours/yr, standard worker rate	Nix (2013)
Labour - requirement per hill ewe per year	22.62	£/yr	Based on 3.2 hours/yr, standard worker rate	Nix (2013)
Labour - ewe body condition scoring	0.04	£/ewe	Based on 3 ewes/minute, standard worker rate	Williams (pers. comm.), Nix (2013)
Labour - artificially rearing orphan lambs	10.61	£/lamb	Based on 1.5 hours/lamb, standard worker rate	Frederiksen et al. (1980), Nix (2013)
Labour - ewe lambs at lambing	7.07	£/ewe lamb	Based on 1 hour/ewe lamb, standard worker rate	ADAS (2010), Nix (2013)
Labour - clover additional sward management	5.98	£/ha/yr	*	Jones et al. (2010)

Mechanical operation - fertiliser distribution	9.00	£/ha	Includes farmer labour, fuel, repairs and depreciation	Nix (2013)
Mechanical operation - ploughing (light land assumed)	55.00	£/ha	Includes farmer labour, fuel, repairs and depreciation	Nix (2013)
Performance recording - splitting ewes to single sire mate	113.12	£/yr	Based on 2 days/yr, standard worker rate	Boon (pers. comm.), Nix (2013)
Performance recording - recording sire and dam at birth	3.77	£/ewe	Based on 20 days/yr for 300 ewes, standard worker rate	Boon (pers. comm.), Nix (2013)
Performance recording - weighing lambs at 8 weeks	56.56	£/yr	Based on 1 day per year, standard worker rate	Boon (pers. comm.), Nix (2013)
Services and fees				
Performance recording - annual Signet recording fee	120.00	£/yr		Signet Breeding Services (2013)
Performance recording - additional recording fee per ewe	3.00	£/ewe	Up to an annual total fee cap of £800/breeder	Signet Breeding Services (2013)
Forage quality assessment	0.00	£/sample	Assumed to be offered free by feed company	Williams (pers. comm.)
Pregnancy scanning	0.80	£/ewe		Nix (2013)
Veterinary and medicine for breeding ewe lambs	2.12	£/ewe lamb	*	ADAS (2010)
Outputs				
Produce - lowland farm finished lamb	89.88	£/lamb	Average live weight at sale 42 kg *	Farmer
Produce - upland farm finished lamb	80.00	£/lamb	Average live weight at sale 40 kg *	Farmer
Produce - hill farm finished lamb	45.00	£/lamb	Average live weight at sale 36 kg *	Farmer
Produce - lowland farm ram lamb	217.6	£/ram lamb	Average live weight at sale 80 kg *	Farmer
Produce - lowland farm ewe lamb	149.6	£/ewe lamb	Average live weight at sale 55 kg *	Farmer
Stock sales - lowland farm cull ewe	75.00	£/ewe	*	Farmer
Stock sales - upland farm cull ewe	50.00	£/ewe	*	Farmer
Stock sales - hill farm cull ewe	30.00	£/ewe	*	Farmer
Stock sales - lowland farm ewe	76.49	£/ewe	*	Farmer
Stock sales - upland farm ewe	71.49	£/ewe	*	Farmer
Stock sales - hill farm ewe	44.68	£/ewe	*	Farmer
Dead sheep disposal - lambs	2.00	£/lamb		Williams (pers. comm.)
Dead sheep disposal - ewes	18.00	£/ewe		Williams (pers. comm.)

* cost has been inflated to 2013 values using the Agricultural Price Index

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