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The mitigation of greenhouse gas emissions in sheep farming systems

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The mitigation of greenhouse gas emissions in sheep farming systems

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by

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Summary

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 64 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.

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Abbreviations, acronyms and formulae

AIC	Akaike's information criterion
BCS	Body condition score
BSI	British Standards Institute
BWS	Best-Worst Scaling
CCC	Committee on Climate Change
CF	Carbon footprint
CH_4	Methane
CI	Confidence interval
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
CV	Coefficient of variation
DCD	Dicyandiamide (a nitrification inhibitor)
DECC	Department of Energy and Climate Change
DM	Dry matter
DMI	Dry matter intake
EBLEX	English Beef and Lamb Executive
EBV	Estimated breeding value
EF	Emission factor
FAO	Food and Agriculture Organization
FIT	Full inversion tillage
g	Gram
GEI	Gross energy intake
GHG	Greenhouse gas
GWP	Global warming potential
ha	Hectare
HCC	Hybu Cig Cymru
HSG	High sugar grass
IBERS	Institute of Biological, Environmental and Rural Studies
IGER	Institute of Grassland and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
kg	Kilogram
kPa	Kilopascal
LCA	Life cycle assessment
LCTP	Low Carbon Transition Plan
LFA	Less favoured area
LSU	Livestock units
LW	Live weight
LWG	Live weight gain
m	Metre
MACC	Marginal abatement cost curve
MC	Monte Carlo
MM	Mitigation measure
MNL	Multinomial logit
Mt	Million tonnes
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide

NH_3	Ammonia
NH_4^+	Ammonium
NI	Nitrification inhibitor
NO_2^-	Nitrite
NO_3^-	Nitrate
P	Phosphorous
PAS	Publically Available Specification
RFI	Residual feed intake
t	Tonne
UI	Urease inhibitor
VIF	Variance inflation factor
WAG	Welsh Assembly Government
WFPS	Water-filled pore space
WSC	Water soluble carbohydrate

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). Williams et al. (2006) modelled the GHG emissions of agricultural commodities produced in England and Wales, and estimated emissions of 17.4 kg CO_2 equivalents (CO_2e) per kg sheep meat and 15.8 kg CO_2e per kg for beef, compared to just 6.35 kg CO_2e/kg for pig meat and 4.58 kg CO_2e/kg for poultry.

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). Thirty five percent of English and 63% of Welsh CH_4 emissions arise from agricultural sources, primarily enteric fermentation, with sheep accounting for 15% of total agricultural CH_4 emissions in England and 37% in Wales. Agriculture is also responsible for 83% of English and 88% of Welsh total N_2O emissions (Salisbury et al., 2013). The primary contributors to this being emissions from soils in response to synthetic fertiliser applications and the excreta of grazing animals.

The majority of UK livestock farmers are beef and / or sheep producers, with the breeding ewe flock estimated to be 15.2 million animals in 2012 (DEFRA et al., 2013). Stock numbers

[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.

have declined over the last two decades and production efficiency has improved, with 5% fewer animals needed to produce each tonne of meat in 2008 than in 1998 (EBLEX, 2009). This is reflected in an overall long-term downwards trend in reported agricultural emissions (Salisbury et al., 2013). Reduced fertiliser use in line with increased prices per tonne, and reduced livestock numbers as a result of the Common Agricultural Policy reform are identified by the Committee on Climate Change (CCC) as the primary causes of long-term emissions decline (CCC, 2010). Whilst past reductions have therefore been a by-product of non-climate policy, it is recognised that achieving the cuts needed to stabilise atmospheric GHG levels will require dedicated policy. The enormity of projected increases in global food demands accentuates the need to regulate agricultural emissions. Furthermore, sheep numbers and agricultural emissions have increased slightly in the UK in the last two years recorded, which does not in itself affect the long-term downwards trends but may be an indication of directional change (DEFRA et al., 2013; Salisbury et al., 2013).

With the Kyoto Protocol having set a global precedent for committing to emission reductions, in 2008 the UK Government passed the Climate Change Act, requiring that national emissions be reduced by 80% by 2050 (from 1990 levels). This is to be achieved through a series of carbon budgets set in law, each restricting emissions over successive five year periods. The Carbon Plan which superseded the UK Low Carbon Transition Plan (LCTP), sets out pathways through which each sector of the economy can contribute to the overall targets of the Climate Change Act (DECC, 2011). Whilst the original LCTP set a target for agricultural emission reductions, its successor did not, stating that the heterogeneity of the industry and subsequent uncertainty associated with estimated emissions meant that the government's focus is on "*research to expand the evidence base*", alongside achieving production efficiencies (DECC, 2011). An industry-led partnership subsequently developed an action plan for reducing agricultural emissions. The industry partnership committed to reducing annual emissions in England by 3 million tonnes (Mt) CO_2e by the third carbon budget period (2018 – 2022) (Joint Agricultural Climate Change Task Force, 2011) (total English agricultural emissions were 31.9 Mt CO_2e in 2011 (Salisbury et al., 2013)). Although not a statutory commitment, the government is supportive of this as a realistic target (DEFRA, 2012). The plan identifies on-farm actions to deliver emissions reductions under the categories of best practice in soil and land management, efficient crop and grassland production, efficient management of livestock systems and efficient use of on-farm energy and fuel (Joint Agricultural Climate Change Task Force, 2011). 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 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 (MACC) 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). Several subsequent studies have built upon and refined the MACC findings. Research topics have included: the mitigation potential of short-listed MMs on different farm types and sizes at a national level for England; the attitudes of farmers grouped by characteristics such as farm size and farmer behavioural type to MMs; the level of current and likely uptake including drivers for and barriers to adoption; policy instruments suited to delivery and an initial assessment of policy costs (Barnes et al., 2010; Harris et al., 2009; Jones et al., 2010). 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 subsequent chapters. The contents of each chapter and connections between them are outlined below, and illustrated in Fig. 1:

Chapter 1 reviews published and industry literature to identify and assess the 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 chapter provides the long-list of MMs to be assessed by experts and farmers in Chapter 3.

The research for Chapters 2 and 3 ran concurrently. In **Chapter 2**, the cradle to farm gate carbon footprints (CFs) of a sample of 64 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 chapter provides the baseline farm data for later MACC construction.

Chapter 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 Chapter 1. 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.

Chapter 4 is the culmination of the study, bringing together baseline emissions data for selected case-study farms from Chapter 2 and the top MMs identified in Chapter 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. Implications for policy development are discussed and further research requirements highlighted.

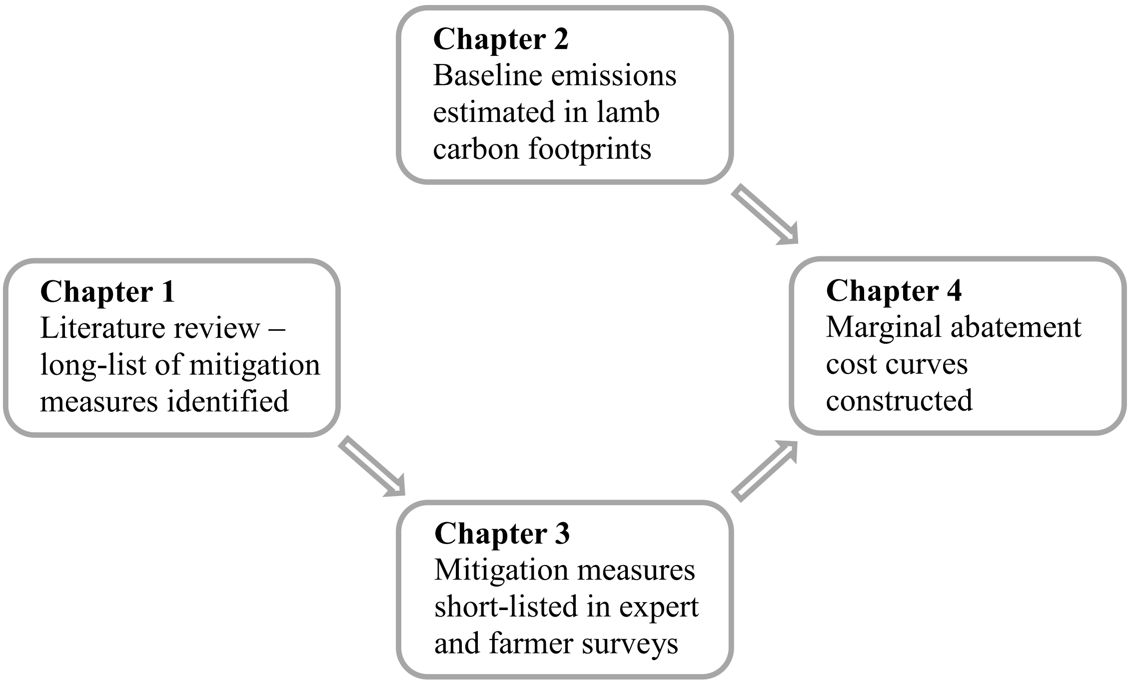

Fig. 1. Schematic of chapter content and connectivity.

Chapter 1

The carbon footprint of UK sheep production: Current knowledge and opportunities for reduction in temperate zones[1]

[1] This chapter was 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.

Abstract

Livestock production is a significant source of methane (CH_4) and nitrous oxide (N_2O) emissions globally. In any sheep-producing nation, an effective agricultural greenhouse gas (GHG) mitigation strategy must include sheep-targeted interventions. The most prominent interventions suited to sheep systems are reviewed in the current paper, with a focus on farm-level enteric CH_4 and soil N_2O emissions. A small number of currently available interventions emerge which have broad consensus on their mitigation potential. These include breeding to increase lambing percentages and diet formulation to minimise nitrogen excretion. The majority of interventions still require significant research and development before deployment. Research into the efficacy of interventions such as incorporation of biochar is in its infancy, while for others such as dietary supplements, successes in isolated studies now need to be replicated in long-term field trials under a range of conditions. Enhancing understanding of underlying biological processes will allow capitalisation of interventions such as vaccination against rumen methanogenesis and pasture drainage. Many interventions cannot be recommended at a regional or national scale because, either, their mitigation potential is inextricably linked to soil and weather conditions in the locality of use, or their use is restricted to more intensive, closely managed systems. Distilling the long-list of interventions to produce an effective farm-level mitigation strategy must involve: accounting for all GHG fluxes and interactions, identifying complimentary sets of additive interventions, and accounting for baseline emissions and current practice. Tools such as whole-farm GHG models and marginal abatement cost curves are crucial in the development of tailored, practical sheep farm GHG mitigation strategies.

1.1. Introduction

The growing demand for food products and an increasing awareness of the impact of unsustainable production methods are of increasing concern to society. Global food requirements are expected to be 70% higher in 2050 than in 2009 (FAO, 2009), placing unprecedented demand on agricultural land and supply chains. Pressures such as soil erosion, reduced numbers of pollinating insects and water stress are of particular concern because they can generate negative feedbacks that may compromise future food production. The contribution of agriculture to global warming through the release of greenhouse gases (GHGs) is another such feedback. Agriculture contributes up to 32% of anthropogenic GHGs when land use change is included (Bellarby et al., 2008). Projected consequences for agriculture in the 21st century include increased crop productivity at mid to high latitudes, decreased crop productivity at lower latitudes, decreased water resources in semi-arid areas and changes in precipitation patterns (Bernstein et al., 2007).

Up to 18% of global GHG emissions are attributed to livestock production when land use change is included (Steinfeld et al., 2006). Of particular concern are the potent GHGs methane (CH_4) and nitrous oxide (N_2O), which have warming potentials of 25 and 298 times that of carbon dioxide (CO_2) per kg over a 100 year period (Forster et al., 2007). The production of CH_4 as a by-product of feed fermentation in the rumen means that red meat has far greater emission intensity than an equivalent quantity of white meat produced from monogastric animals (Bellarby et al., 2008; Gill et al., 2010; Stott et al., 2010). Red meat produced from pasture-based systems can be a significant source of N_2O emissions, particularly direct emissions from soil as a result of fertiliser applications (Edwards-Jones et al., 2009; Schils et al., 2005). This recognition of agriculture's contribution to climate change is manifest in intra and international GHG policy and emission reduction targets for agriculture and the red meat sector. For example, the UK Climate Change Act requires that all emissions be reduced by 34% (from 1990 levels) by 2020 and 80% by 2050. This has shaped sector-specific targets under the low carbon transition plan, including a 10% reduction for the agriculture industry by 2020 (DECC, 2009). A GHG action plan subsequently identified nutrient and livestock management as categories for action, resulting in a red meat GHG reduction strategy (EBLEX, 2012). Literature on mitigating GHG emissions from red meat production at a farm-scale level typically focuses on cattle to the exclusion of sheep. The current paper presents an overview of the most prominent mitigation options suited to sheep farm systems, and focuses primarily on options aimed at reducing enteric CH_4 and soil N_2O emissions, as the dominant forms of sheep farm emissions.

1.2. Sheep farm emissions

On-farm emissions dominate the sheep supply chain carbon footprint up to the point of sale (EBLEX, 2012) and even after-export and consumer-stage emissions such as cooking are accounted for (Ledgard et al., 2010). Enteric fermentation CH_4 emissions constitute the largest component of on-farm emissions from sheep production (e.g. 57-58%), followed by N_2O arising directly from soils in response to nitrogen application as fertiliser or animal waste (e.g. 15%) (Ledgard et al., 2010; Taylor et al., 2010).

Emissions associated with sheep meat production are linked strongly to farm type. In the UK, for example, sheep produced in lowland systems typically have lower emissions per kg than their upland and hill counterparts (EBLEX, 2012; Wiltshire et al., 2009). Better pasture and subsequent silage quality and a milder climate favour faster growth rates and quicker sales in lowland environments. Recent data place the average carbon footprint of lowland lamb produced in England at 10.98 kg carbon dioxide equivalents (CO_2e) per kg live weight (LW) and at 14.42 kg CO_2e/kg LW for hill production (EBLEX, 2012). Substantially lower emissions have been reported elsewhere, e.g. 7.2–8.3 kg CO_2e/kg of hot carcase produced in Western Australia (Peters et al., 2010). However, differences in calculation and reporting methods make comparisons problematic (Edwards-Jones et al., 2009; Schils et al., 2007). Carbon footprinting practitioners advocate that carbon footprints should be used as a starting point to steer the process of emission reduction and not to identify poor performers. Some production systems will inevitably have a higher footprint than others, for example those with a significant area of organic soil may have high N_2O emissions, as highlighted by Edwards-Jones et al. (2009). Mitigation options tailored to the requirements of specific systems are therefore required.

Much of the scope for reducing GHG emissions from sheep farms lies in improved productivity and system efficiencies. Enhancing productivity maximises output per unit of input, reducing emissions per kg of product. Tackling system inefficiencies reduces waste such as feed energy lost as CH_4 and fertiliser nitrogen lost directly or indirectly as N_2O. Other mitigation options target emissions that cannot be avoided directly through system optimisation, for example vaccination against methanogens and addition of nitrification inhibitors to pastures. There have been a number of reviews of livestock-related mitigation options (Eckard et al., 2010; EC Agri Directorate-General, 2002; Gill et al., 2010; Johnson et al., 2007; Moorby et al., 2007; Shibata and Terada, 2010; Smith et al., 2008; Weiske, 2005).

The sheep farm-relevant mitigation options reviewed in the current paper are outlined in Fig. 1.1 under the headings of enhancing productivity, animal management, and soil and pasture management.

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. It should also be noted that a proportion of the studies were published as industry or project reports, and therefore not all the literature cited has been subject to rigorous peer-review.

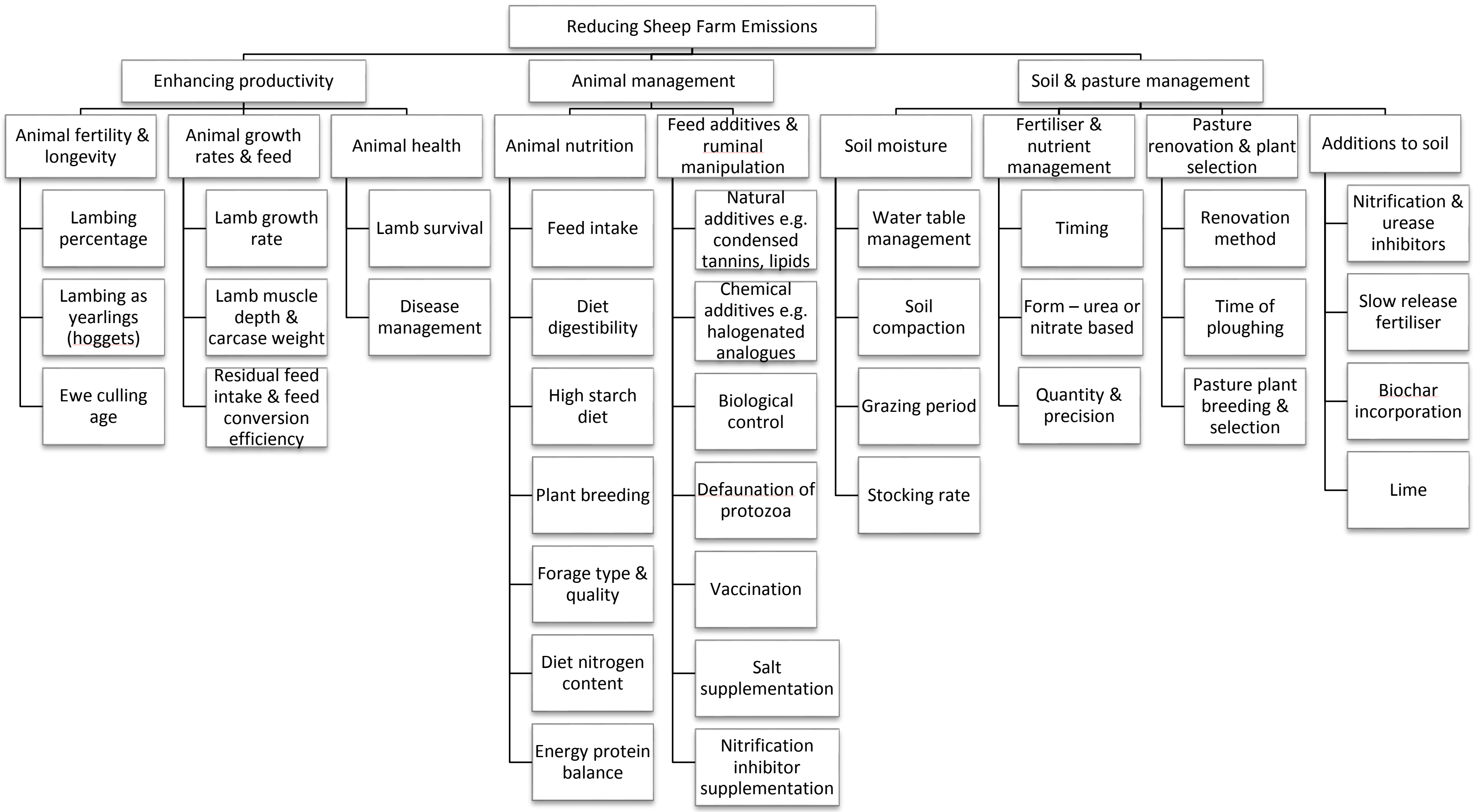

Fig. 1.1. Schematic representation of the opportunities for reducing CH_4 and / or N_2O emissions on sheep farms. The headings 'enhancing productivity', 'animal management' and 'soil & pasture management' corresponded to subsections within the text.

1.3. Enhancing productivity

Despite conflicting results in the scientific literature regarding the efficacy of many mitigation options, there is a general consensus amongst scientists and in the industry that increased productivity is a priority mitigation option (EBLEX, 2010; Gill et al., 2010; Shibata and Terada, 2010). The underpinning notion is that maximised lamb production from the flock's maintenance feed provision will lead to a reduction in emissions per kg of produce (Buddle et al., 2011; Smith et al., 2008). The productivity of sheep systems can be boosted through a range of strategies targeting growth, fertility, longevity and feed efficiency of the animals (Gill et al., 2010; Hegarty et al., 2010). Relevant strategies include increases in lamb growth rate to reduce time on-farm; increases in lamb muscle depth and carcase weight to increase saleable product; increases in lamb births and survivals to increase product output; lambing as yearlings to maximise the ewe's lifetime production capability which in turn decreases the proportion of unproductive time on-farm; increases in ewe culling age to increase lifetime lamb output and reduce the need for replacements; reductions in incidences of disease and reducing residual feed intake (RFI) or improving feed conversion efficiency (Alcock and Hegarty, 2011; Amer et al., unpublished; Genesis Faraday, 2008; Hegarty, 2009; Hegarty and McEwan, 2010; Hegarty et al., 2010).

These strategies can be delivered through genetic improvement, i.e. livestock selection and breeding, and improved animal husbandry, i.e. animal feeding and health management (Gill et al., 2010; Hegarty et al., 2010). Desirable productivity traits can also be attained through changing breeds stocked (Allard, 2009; IBERS et al., 2011a). Some sectors of the UK livestock industry have achieved significant GHG reductions as a by-product of genetic selection for productivity, for example emissions per kg of product from the pig and dairy industries decreased by 0.8% per annum in the 20 years prior to 2008 (Genesis Faraday, 2008). Breeding improvements in the UK sheep industry lag behind those made for other livestock (Gill et al., 2010; Moorby et al., 2007), and as a result emissions per kg of product have decreased by just 0.5% in total over the same 20 year period. Studies in other countries suggest that breeding for improved productivity in the sheep industry may further reduce emissions. For example, Amer et al. (unpublished) estimated that a 10% increase in ewe-litter size in New Zealand between 1994 and 2006 resulted in a 6% reduction in emissions per kg of lamb carcase produced. The Institute of Biological, Environmental and Rural Studies (IBERS) et al. (2011a) suggested that genetic improvement for productivity based on existing breeding indices could decrease annual CH_4 emissions by 0.03% per tonne of carcase produced in Wales.

There is a growing body of research using emissions modelling to estimate the mitigation potential of productivity improvements in defined flocks. The results of a number of recent studies are summarized in Table 1.1 and are discussed in the sections that follow.

1.3.1. Animal fertility and longevity

In a self-replacing New Zealand flock of 1000 ewes, Cruickshank et al. (2008) found that lambing replacements as yearlings (hoggets) instead of waiting to lamb them later (as two-tooth ewes) had the greatest potential for reducing enteric CH_4 emissions (Table 1.1). This strategy maximised lamb output from the maintenance costs of the existing ewes. Similar findings in the direction and magnitude of change were modelled in a study by ADAS (2010a), suggesting that lambing at 12 months rather than 2 years could reduce CH_4 and N_2O emissions by 9.4 kg CO_2e per kg of carcase meat. In the self-replacing Australian flocks modelled by Alcock and Hegarty (2011), mating replacements at 7 months was estimated to reduce enteric CH_4 emissions by 12% per kg of LW lamb produced. However, in their second and third sheep enterprise types, replacements were not home-reared but brought in 2 weeks before mating. Consequently, mating at 7 months increased enteric CH_4 emissions between 3 and 9% per kg LW lamb produced. In these scenarios there was no unproductive young stock on-farm and mating at an earlier age only served to reduce lambing percentages and growth rates.

The Institute of Biological, Environmental and Rural Studies et al. (2011b) found selection for ewe-litter size to be the genetic trait with the greatest stand-alone potential for emission reduction in Welsh flocks over a 10 year period. Similar strategies of increasing scanning percentage and the number of lambs weaned per ewe resulted in substantial enteric CH_4 savings of 3–4% and 7.8%, respectively (Alcock and Hegarty, 2011; Cruickshank et al., 2008). Increasing ewe longevity and decreasing lamb mortality also have potential to reduce lamb production emissions.

Table 1.1. Summary of greenhouse gas (GHG) reductions achieved through improvements in productivity. Data were taken from studies modelling GHG mitigation potential in defined flocks. The greatest reductions modelled in each study are highlighted in bold text.

Study	GHGs included	Strategy	% Change in emissions
Cruickshank et al. (2008)*	Enteric CH_4 only	Decrease ewe live weight 10%	-3.9
		Increase lamb growth rate 10%	-2.6
		Reduce ewe mortality 10%	-0.04
		Increase ewe culling age from 5 to 6	-6.4
		Reduce lamb mortality 10%	-1.3
		Reduce proportion of barren ewes 8 to 6%	-2.7
		Increase scanning % of mixed age ewes from 160 to 180%	-7.8
		Lamb as hoggets	**-13.6**
Alcock and Hegarty (2011)†	Enteric CH_4 only	Mate lambs at 7 months	-12 (enterprise 1) +3 to 9 (enterprises 2 & 3)
		Feed to finish lambs earlier	**-16 to 24**
		Increase lambs weaned per ewe mated 10% (genetics)	-3 to 4
		Increase lamb growth rate 10% (genetics)	-2.7 (enterprise 1) +3.8 to 4.9 (enterprises 2& 3)
		Select for lower CH_4 output per unit dry matter intake or lower residual feed intake (genetics)	-8.7 to -10.3
IBERS et al. (2011a; 2011b)‡	Enteric CH_4 only	**Selection for ewe litter size**	**-8.8 (hill flock, over 10 years)** **-5.3 (lowland flock, over 10 years)**
		Selection for ewe longevity	-3.8 (hill flock, over 10 years) -1.3 (lowland flock, over 10 years)
		Selection for lamb muscle depth and carcase weight	-2.5 (hill flock, over 10 years) -2.7 (lowland flock, over 10 years)
		Selection for lamb growth (no change in ewe weight)	-1.3 (hill flock, over 10 years) -2.3 (lowland flock, over 10 years)
		Selection for lamb survival	-0.3 (hill flock, over 10 years) -0.6 (lowland flock, over 10 years)
		Selection for lamb growth (with increase in ewe weight)	+0.4 (hill flock, over 10 years) -0.7 (lowland flock, over 10 years)
ADAS (2010a)§	N_2O and CH_4	**Lamb at 12 months not 2 years**	**-9.4**

* New Zealand based study which modelled the emission reductions possible through individual management strategies against a baseline flock of 1000 ewes. Baseline emissions were 15.99 kg CH_4 per lamb sold. Percentage reductions are a percentage change from the base flock in terms of CH_4 emissions per net lamb sold.

† An Australian study which modelled management options to reduce CH_4 output on a range of simulated sheep enterprises. Three common Australian production systems were characterised: (1) merino ewe flock – all replacements from progeny and surplus sold as weaners or hoggets; (2) dual purpose merinos – merino ewes mated to Poll Dorset and all progeny sold as stores or to slaughter; (3) prime lamb enterprise where Border Leicester X Merino ewes are mated with Poll Dorset rams and all progeny sold as stores or slaughter. Percentage reductions are in emissions intensity reported as kg CO_2e/kg live weight sold.

‡ A Welsh study which modelled the enteric CH_4 emission reductions possible through selection for single genetic traits to improve productivity in hill, upland and lowland flocks. Reductions are a percentage change in CH_4 emissions over 10 years and per tonne of carcase produced.

§ An English study which calculated the GHG emissions reductions possible per kg of carcase meat produced from a lowland spring lambing flock that breeds its own replacements or buys in ewe lambs.

1.3.2. Animal growth rates and feed

In each of their three modelled enterprise types (Table 1.1), Alcock and Hegarty (2011) found that production and creep feeding to finish lambs earlier had the greatest potential to reduce enteric CH_4 per kg of LW lamb produced. However, their study only considered enteric CH_4 emissions and did not consider the emissions burden of grain production. The effect on emissions of genetic selection for faster growth rate in lambs is dependent on whether or not this also results in a correlated increase in ewe mature weight. The Institute of Biological, Environmental and Rural Studies et al. (2011b) estimated that selection for lamb growth over 10 years in Welsh hill flocks would decrease enteric CH_4 emissions by 1.3% with no change in ewe weight, and increase them by 0.4% if ewe weight increased in synchrony. It is reported that improvements in lamb growth rates were behind most of the genetic-related reduction in GHG emissions in the UK sheep industry in the last 20 years (Genesis Faraday, 2008). However, the net benefit was constrained by the increased emissions associated with the higher mature weights of the ewes. Net N_2O emissions demonstrated a marginal increase over time as a result of faster lamb growth rates, underlining the importance of incorporating all GHGs in any emissions calculation.

While the efficiency of feed use is widely used for selective breeding in other livestock species, limited use has been made of traits such as RFI in the ruminant industry (Genesis Faraday, 2008; Wall et al., 2010). Studies have demonstrated that cattle with lower RFI have reduced dry matter intake (DMI) and may also have lower daily rates of CH_4 production (Hegarty et al., 2007; Nkrumah et al., 2006). The modelled sheep flock scenarios of Alcock and Hegarty (2011) found selection of sheep for lower RFI to be the most promising genetic improvement option for reducing enteric CH_4 emissions. If achieved, low RFI animals will provide a mitigation option suited to both intensive and extensive systems (Waghorn and Hegarty, 2011).

There is increasing interest in breeding directly for CH_4 reducing traits and feed nitrogen conversion efficiency (Hegarty and McEwan, 2010; Keogh and Cottle, 2009; Wall et al., 2008). Inter-sheep variation was estimated to be responsible for 70–80% of the differences in CH_4 emissions per unit of feed intake recorded from livestock fed the same diet in large scale experiments (O'Hara et al., 2003). Persistent variation in CH_4 emissions between sheep has been recorded under grazing conditions (Pinares-Patino et al., 2003). Making use of this variation in breeding schemes is contingent upon the heritability of CH_4 traits, and the repeatability of this variation for different age classes and diets (Hegarty and McEwan, 2010).

1.3.3. Animal health

Improvements to animal health present opportunities to improve productivity and fertility by reducing culling rates and the subsequent number of replacements needed to maintain maternal flock size (Wall et al., 2010). Stott et al. (2010) estimated that prophylactic disease treatment in a hypothetical extensive sheep farm would reduce overall CH_4 emissions by 28%.

1.4. Animal management

Mitigation measures that target direct emissions from livestock and their excreta dominate the ruminant GHG mitigation debate. These measures fall into two principal categories: nutritional management and dietary and ruminal manipulation. Unlike cattle, there is little scope for reducing sheep farm emissions through manure management because the majority is excreted in the field (Smith et al., 2008).

1.4.1. Animal nutrition

Nutritional strategies for reducing emissions from sheep target the inefficient use of dietary nitrogen and the loss of feed energy as CH_4. Between 75 and 95% of ingested nitrogen is excreted (Eckard et al., 2010), and gross feed energy intake lost as CH_4 ranges from 2 to 15% (Eckard et al., 2010; Hopkins and Lobley, 2009; Lassey, 2007; Weiske, 2005).

1.4.1.1. Enteric methanogenesis

The volume of CH_4 produced during digestion depends upon intake levels, diet composition and the rate and extent of digestion by microflora (Pastoral Greenhouse Gas Research Consortium, 2007; Weiske, 2005). Typically, forages of high fibre or low digestibility that have a long residence time in the rumen will tend to produce high levels of CH_4 (Pastoral Greenhouse Gas Research Consortium, 2007). Models suggest that as sheep DMI increases, live weight gain (LWG) and daily CH_4 also increase, the overall result of which is a decrease in CH_4 production per kg LWG (Fig. 1.2) (Hegarty et al., 2010). As diet digestibility increases, CH_4/kg LWG decreases because of an underlying increase in LWG (Fig. 1.2) (Hegarty et al., 2010).

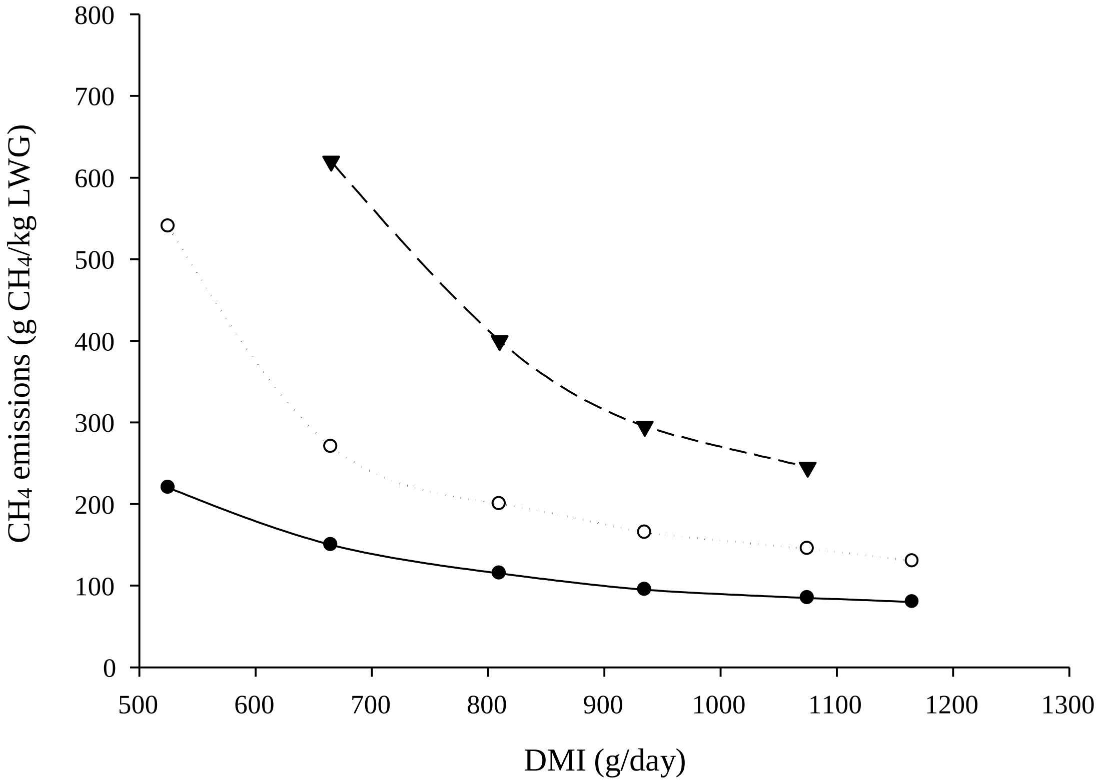

Fig. 1.2. The modelled relationship between dry matter intake (DMI) and CH_4 production per kg of live weight gain (LWG) at three different levels of diet digestibility (▼65%, ○75%, ● 85%) for a 30 kg Border Leicester x Merino wether offered *ad libitum* access to roughage (adapted from Hegarty et al. (2010)).

Increasing feed intake and digestibility can be achieved through replacing structural carbohydrates (cellulose and hemicelluloses) in the diet with non-structural carbohydrates (starch and sugars) (O'Mara et al., 2008), or through altering forage type. Feeding higher starch, such as grain-based diets, not only increases diet digestibility and feed intake but also favours propionate production in the rumen providing an alternative pathway to methanogenesis for hydrogen use (Eckard et al., 2010; Martin et al., 2010). Benchaar et al. (2001) estimated that increasing the proportion of concentrates in the diet from 0 to 20% would reduce CH_4 production in ruminants as a proportion of gross energy intake (GEI) by 3%. However, in a meta-analysis of 87 studies, Sauvant and Giger-Reverdin (2007) found CH_4 losses as a proportion of GEI to be relatively constant for diets containing 30 to 40% concentrate, suggesting higher proportions of concentrates are needed to gain any mitigation benefit. Dragosits et al. (2008) suggested that feeding a high starch diet nationally to sheep flocks would only reduce CH_4 emissions by 1%. Production emissions associated with the grain and the baseline productivity and emissions of the farming system will determine the net GHG impacts of increasing the quantity of grain fed. The applicability of feeding high-concentrates diets is restricted to more intensive production systems.

In other research areas, the breeding of grasses and legumes with high carbohydrate (WSC) content may potentially reduce direct CH_4 emissions from both intensive and extensive farming systems. For instance, IBERS (2010) found that lambs reared on a mix of three high WSC grasses produced up to 25% less CH_4/kg LWG compared to the control diet of conventional (normal WSC) grass. This was possibly due to increased ruminal bacterial numbers in lambs on the high WSC diet, leading to greater capture of metabolic hydrogen and reducing availability for methanogenic archaea. Other forage-based options include grazing animals on less mature herbages (Deighton et al., 2010) and feeding ensiled forages (Lima et al., 2011). Results from studies investigating the emission reduction benefits of feeding or grazing leguminous forages and pastures have been inconclusive. It is thought that legumes have a faster rate of ruminal breakdown than grasses and consequently a higher voluntary intake, lowering CH_4 yields/kg of DMI (Hammond et al., 2011; Rochon et al., 2004). Waghorn et al. (2002) found significant promise for mitigating emissions through changing forage type with a doubling of CH_4 emissions/kg DMI over a range of fresh forage diets, ranging from 11.5 g CH_4/kg on a ryegrass and white clover pasture to 25.7 g CH_4/kg on a diet of lotus forage. Knight et al. (2007) also found significant differences in CH_4 yield/kg DMI through varying legume species and proportion in the diet. In contrast, two separate feeding trials concluded that CH_4 yield is not influenced by forage species or maturity and that '*there are no simple relationships between chemical components of fresh forages and CH_4 yield*' (Hammond et al., 2011; Sun et al., 2012).

1.4.1.2. Nitrogen conversion efficiency

Low efficiency of dietary nitrogen use in ruminants and subsequent high urea nitrogen losses are primarily attributed to imbalances in dietary protein and energy (non-structural carbohydrates), and feeding regimes that contain nitrogen in excess of dietary requirements (Moorby et al., 2007; O'Hara et al., 2003; Prosser et al., 2008). Decreasing the quantity of nitrogen excreted would be expected to reduce N_2O losses, both directly from soils and indirectly when leached nitrate (NO_3^-) is converted to N_2O in water bodies or when volatilised ammonia (NH_3) is deposited on the land.

Increasing the efficiency of nutrient use entails correctly formulating animal diets, matching feed provision more closely to animal nutrient requirement, which requires characterisation of feed composition and nutritional advice (Moorby et al., 2007; Prosser et al., 2008). This can be achieved by avoiding excess nitrogen diets and by increasing the proportion of dietary nitrogen utilised through feeding a diet balanced in energy and protein. Pastures and fresh forages typically contain high levels of protein, in excess of available energy, resulting in the excretion of ammonia (Abberton et al., 2008; Eckard et al., 2010; Luo et al., 2010). Lowering the crude protein content of the diet is known to reduce dietary nitrogen losses (Schils et al., 2013), although careful management is required to ensure maintenance of yield (Nielsen et al., 2003). For example, Seip et al. (2011) showed that supplementing grass and legume silage of adult sheep with barley reduced urinary nitrogen excretion in an unfertilised grassland system. Numerous examples exist of the efficacy of this strategy in dairy systems (Luo et al., 2010; Schils et al., 2013). Increasing the carbohydrate content of the diet is the alternative option for balancing energy and protein, e.g. balancing high protein forages with high energy supplements (Eckard et al., 2010; O'Hara et al., 2003) or through feeding high WSC grasses (Merry et al., 2006). Feeding trials have shown that high WSC grasses can reduce nitrogen excretion by up to 24% whilst also increasing DMI and improving LWG (IGER, 2005).

1.4.2. Feed additives and ruminal manipulation

Many studies have tested the effects of a range of dietary additives and alternative methods of rumen manipulation on enteric CH_4 and dietary nitrogen losses (Table 1.2). The rumen-based CH_4 mitigation strategies listed in Table 1.2 have several different modes of action. Feed additives such as condensed tannins and bacteriocins directly inhibit methanogenesis (Kreuzer et al., 1986; O'Mara et al., 2008). Others, such as organic acids and probiotics, provide an alternative sink or pathway for H_2 use in the rumen, displacing CH_4 production (Martin et al., 2010; O'Mara et al., 2008); while plant saponins and ionophores eliminate rumen protozoa that are thought to have a symbiotic relationship with some methanogenic archaea (Eckard et al., 2010; Kreuzer et al., 1986; Kumar et al., 2009). A number of the strategies act to reduce emissions in multiple ways. For example, ionophores are known to improve feed conversion efficiency (Grainger and Beauchemin, 2011). Fat supplementation may reduce nitrogen losses and CH_4 emissions concomitantly (Machmüller et al., 2006). Oil supplementation may improve digestibility and energy use efficiency (Klevenhusen et al., 2011).

Research interest appears to be focusing upon the use of natural feed additives such as tannins, essential oils and lipids and on the novel approaches of vaccination and defaunation. Supplementation with lipids is one strategy at the forefront of dietary mitigation research. Martin et al. (2010) recently reviewed the results of 67 dietary supplementation experiments from the literature, concluding that overall, for sheep and cattle combined, with every 1% addition of fat, mean CH_4 emissions decreased by 3.8%. Martin et al. (2010) also found that medium chain fatty acids (most frequently coconut oil) showed the greatest mitigation potential. In a similar study, a meta-analysis of studies limiting supplementation within the practical range of feeding, Grainger and Beauchemin (2011) found a slightly greater decrease in cattle CH_4 emissions/g of fat added to the diet. In contrast to Martin et al. (2010), Grainger and Beauchemin (2011) found that fatty acid type had no effect on CH_4 yield. Nor did the form of fat added (oil *vs* oilseed), or fat source (e.g. coconut *vs* sunflower). Grainger and Beauchemin (2011) suggested that their results were more robust than those of Martin et al. (2010) because they were based on a covariance analysis of CH_4 yield data as opposed to average data, and also because their dataset was restricted to practical dietary fat levels. Grainger and Beauchemin (2011) also highlighted a significant difference in the relationship between dietary fat and CH_4 yield between beef, dairy and sheep, finding that more data is needed to give an accurate assessment of the effect of fat supplementation in sheep. In a recent study in Wales, IBERS (2010) measured CH_4 production and nitrogen retention in store lambs fed diets supplemented with linseed oil or a novel high fat naked oat. Linseed oil supplementation reduced CH_4 emissions by 22% and the naked oats by 33% compared to the control diet. Neither supplements affected nitrogen retention significantly.

Table 1.2. Dietary and ruminal manipulation strategies for emissions mitigation.

Dietary additive / ruminal manipulation strategy	Evidence of CH_4 abatement?	Evidence of N_2O abatement?	Successful experimental example(s)	Useful review papers
Condensed tannins (plant extract)	✓	✓	Carulla et al. (2005), Liu et al. (2011)	Patra and Saxena (2011)
Plant saponins (plant extract)	✓	✓	Santoso et al. (2004), Wang et al. (2009)	Patra and Saxena (2010), Wina et al. (2005)
Essential oils (plant extract) e.g. from thyme, oregano, garlic	✓		IBERS (2010), Sallam et al. (2011)	Benchaar and Greathead (2011)
Lipids (fatty acids and oils) e.g. coconut oil, linseed oil	✓	✓	IBERS (2010), Liu et al. (2011), Machmüller et al. (2006)	Grainger and Beauchemin (2011)
Probiotics e.g. acetogens, yeast	✓		Chaucheyras et al. (1995)	Martin et al. (2010)
Organic acids e.g. fumarate, malate	✓		Baraka and Abdl-Rahman (2012), Wood et al. (2009)	Kumar et al. (2009)
Ionophores e.g. monoesin, lasalocid	✓		García et al. (2000)	Grainger and Beauchemin (2011)
Chemical additives e.g. halogenated analogues	✓		Denman et al. (2007)	Kumar et al. (2009)
Biological control e.g. bacteriophages and bacteriocins	✓		Santoso et al. (2004)	Buddle et al. (2011), Kumar et al. (2009)
Defaunation of protozoa	✓		Kreuzer et al. (1986)	Buddle et al. (2011)
Vaccination against rumen methanogens	✓		Wright et al. (2004)	Buddle et al. (2011)
Salt supplementation		✓	Ledgard et al. (2007)	Luo et al. (2010)
Supplementation with nitrification inhibitor		✓	Kool et al. (2006), Ledgard et al. (2008)	Luo et al. (2010)

Lipid supplementation research highlights the uncertainties that persist in the application of many dietary mitigation strategies, e.g. optimal lipid source, dosage level, dependence on diet type, transfer to animal products and possible human health impacts and limited sheep specific data (Hook et al., 2010; Martin et al., 2010). Despite these uncertainties, implementation is beginning to be considered including using drinking water to administer supplements in extensive grazing systems and the identification of high fatty acid content grasses (Grainger and Beauchemin, 2011).

1.5. Soil and pasture management

Soil and pasture-based mitigation options aim to limit direct and indirect N_2O emissions. Nitrogen enters the soil through animal excretion in the field, manure and fertiliser application, crop residues, fixation by leguminous crops and atmospheric deposition (Schils et al., 2013). Losses from the system can occur directly as gas (dinitrogen (N_2) or N_2O) or indirectly through leaching (nitrate (NO_3^-); dissolved organic N), runoff (NO_3^- and ammonium (NH_4^+)) or volatilisation (ammonia (NH_3)). Skiba et al. (1998) estimated that 1.7% of the nitrogen input from mineral fertiliser and animal excreta applied to a sheep grazed pasture in Scotland was emitted as N_2O.

There are multiple pathways through which N_2O is produced in soils (Fig. 1.3), not all of which have been fully characterised. Denitrification (the anaerobic reduction of NO_3^- or nitrite (NO_2^-) to N_2) is thought to be the primary source of N_2O in soils. However, nitrification (the oxidation of ammonia (NH_3) $\rightarrow NO_2^-$) is now known to be a significant source of N_2O in some situations (Baggs and Philippot, 2010). The importance of other N_2O production pathways such as nitrifier denitrification and aerobic denitrification are also now being recognised (Baggs and Philippot, 2010; Wrage et al., 2001). Soil conditions regulate the activity and relative importance of microbial pathways. Understanding the conditions favoured by each is crucial when targeting mitigation strategies to ensure net N_2O reductions (Baggs and Philippot, 2010; Richardson et al., 2009).

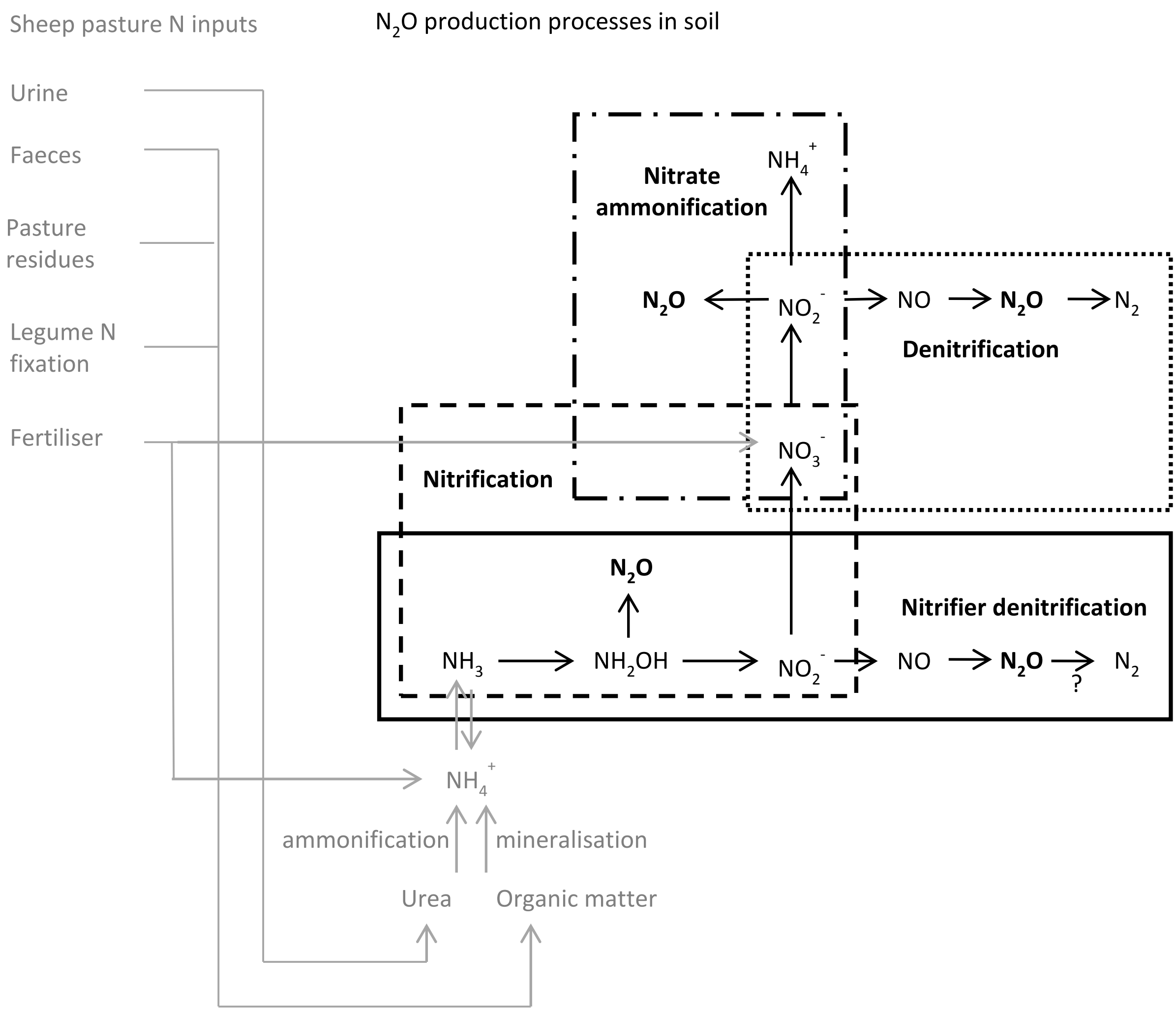

Fig. 1.3. Soil microbial pathways of N_2O production within sheep pasture systems (adapted from Baggs (2008)).

1.5.1. Soil moisture

Several studies have demonstrated that N_2O emissions and overall nitrogen losses are accentuated in high moisture conditions. For example, Chambers et al. (2000) showed that NO_3^- leaching from the application of organic manure to grassland sites was greatest when applied in the autumn and winter. Cardenas et al. (2010) reported far higher N_2O emissions from fertilised grazed grasslands in the West of the UK compared to the East, which they attributed to the wetter conditions in the West. Frequently, N_2O emissions positively correlate with soil water-filled pore space (WFPS), with maximum emissions occurring at between 0.60–80 m^3 water/m^3 pore space (Fig. 1.4) (Clayton et al., 1997; Jones et al., 2007; Rafique et al., 2011). In poorly aerated soils (WFPS >0.60 m^3/m^3) denitrification becomes dominant, and >0.80 m^3/m^3 N_2 becomes the dominant product of denitrification (Dalal et al., 2003). Flechard et al. (2007) found that N_2O emission factors from European grassland sites were highest for soils where WFPS mostly remained in what they called the '*optimum range for N_2O emissions of 60 to 90%*'.

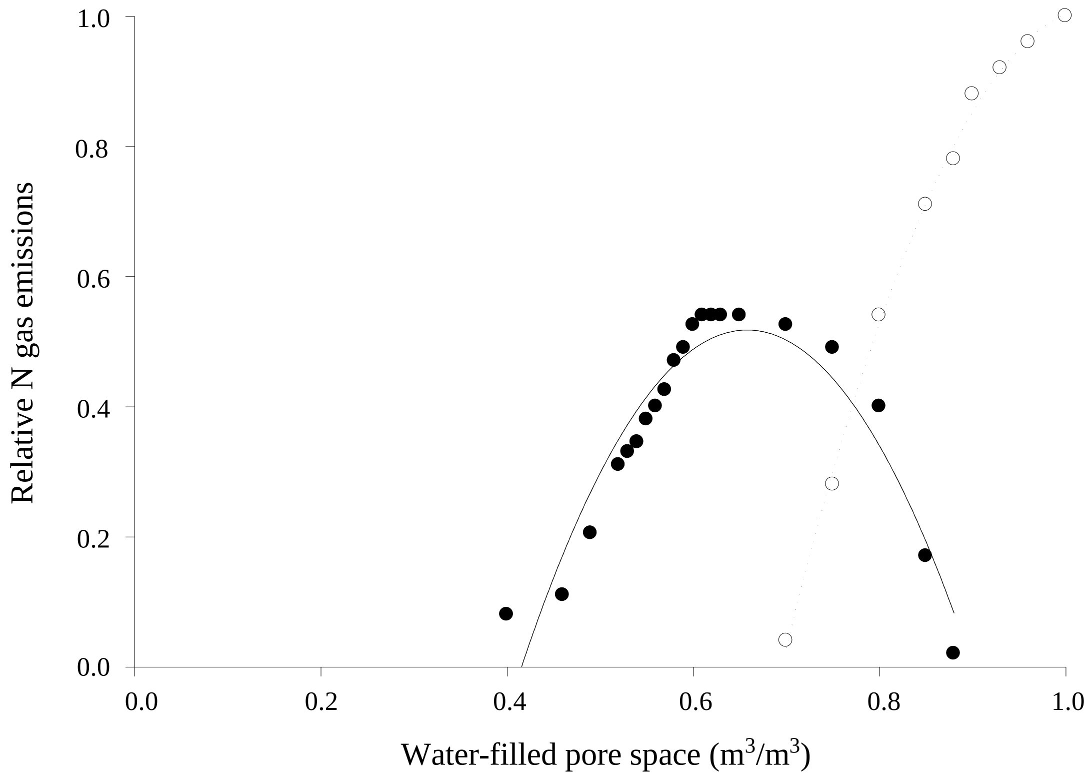

Fig. 1.4. Relationship between water-filled pore space in soil and the relative fluxes of N_2O (●) and N_2 (○) from both nitrification and denitrification within sheep pasture systems (adapted from Dalal et al. (2003)).

1.5.1.1. Water table management

In many northern European countries, water table manipulation through soil drainage presents a practical option for controlling WFPS in sheep-grazed grasslands (Dobbie and Smith, 2006). A small number of studies have investigated the relationship between water table level and N_2O emissions in the field (Table 1.3). Dobbie and Smith (2006) and Kamman et al. (1998) demonstrated a significant decrease in N_2O emissions as water table depth below the soil surface increased. As the water table falls, WFPS and soil moisture decrease, leading to an increase in aeration in the upper soil, which in turn reduces the presence of anaerobic zones for denitrification and enhances root growth leading to better fertiliser N use efficiency. Dobbie and Smith (2006) concluded that draining grasslands to keep the water table more than 350 mm below the surface when nitrogen is available for denitrification could cut N_2O emissions by 50% during the growing season. However, mitigation through water table management is complex (Fig. 1.4). If for example, soil is drained below saturation but WFPS remains above 0.40 m^3/m^3, N_2O emissions could potentially increase (Eckard et al., 2010). The WFPS values at which nitrification and denitrification dominate N_2O production are site- and soil-specific (Müller and Sherlock, 2004). While drainage can effectively reduce CH_4 and N_2O emissions from mineral soils, the case for GHG is more complicated for organic (peat) soils. Draining peat soils may reduce CH_4 and N_2O; however, this can be negatively offset by increased CO_2 emissions as the increased oxygenation stimulates aerobic mineralisation of soil organic matter (e.g. van Beek et al., 2010; Table 1.3). The overall GHG balance of improved drainage is also uncertain due to the increased potential for nitrate leaching (and increased indirect N_2O emissions) (Eckard et al., 2010; Smith et al., 2008).

Table 1.3. The influence of water table depth on N_2O emissions from grassland soils in Western Europe.

Soil type (under grassland)	Location	Water table depth (cm below soil surface)	Average N_2O-N emissions (defined time period)	Overall impact of deeper water table on N_2O emissions	Reference
Drained peat soil (fertilised and grazed)	Netherlands	40cm	11.6 kg N_2O-N/ha/yr	+	van Beek et al. (2010)
		55cm	29.5 kg N_2O-N/ha/yr		
Imperfectly drained gleysol with a sandy loam topsoil and underlain by clay loam (fertilised and previously grazed)	Scotland	Variation between 0 and 60 cm over the growing season	13.9 kg N_2O-N/ha (Apr to Nov)	-	Dobbie and Smith (2006)
		Kept below 35cm over the growing season	7.0 kg N_2O-N/ha (Apr to Nov)		
		Kept below 45cm over the growing season	2.7 kg N_2O-N/ha (Apr to Nov)		
Stagnofluvic gleysol on sandy loam sediments over clay (non-grazed, fertilised extensive grassland)	Germany	Below 70 cm	Approx. 0.8 kg N_2O-N/ha/yr	-	Kammann et al. (1998)
		Below 120 cm	Approx. 0.4 kg N_2O-N/ha/yr		

1.5.1.2. Soil compaction

The deposition of excreta on waterlogged soils increases nitrogen supply for denitrification and subsequent emissions may be exacerbated by soil compaction through animal trafficking. The likelihood and severity of compaction increases at elevated soil moisture content, creating anaerobic sites in the soil (Rafique et al., 2011). In separate field experiments, Sitaula et al. (2000), van Groenigen et al. (2005) and Bhandral et al. (2007) demonstrated that soil compaction increased average N_2O emissions from agricultural soils receiving urine and / or fertiliser by a factor of 1.7, 2.2 and 7 respectively compared to no compaction. On an intra-farm scale, Matthews et al. (2010) showed that poached land surrounding water troughs on beef and sheep farms can have significantly higher N_2O emissions rates than surrounding managed pasture. Information on the impact of sheep grazing on soil compaction and subsequent N_2O emissions is scarce (Saggar et al., 2007). While the hoof pressures of sheep are lower than those of cows (83 kPa compared to 192 kPa), there is evidence that infiltration in soil decreases with increased sheep-stocking rate (Willatt and Pullar, 1984). Decreased infiltration indicates that soil is compacted. Betteridge et al. (1999) found that the effect of a severe short-term treading event on wet hill soils was greater for cattle than sheep stocked at the same metabolic LW/ha, but they also indicated that at soil water contents above the critical water content for compaction the ratio of soil compaction to deformation may be greater for sheep than for cattle. Many opportunities to reduce soil compaction on pastures are already well established as best practice for limiting poaching, water-pollution and safeguarding animal welfare when out-wintering stock. These include sale of barren ewes to reduce stocking rates in winter, and the use of electric fences to control access to forage crops and boggy areas.

There has been little follow-through research on the impact of these measures on N_2O emissions. Restricted grazing on wet pastures (e.g. through housing animals) may reduce N_2O emissions provided that collected excreta is spread uniformly (Hopkins and Lobley, 2009). The extent to which this mitigation measure is relevant to sheep farms will depend upon the stocking rate and current winter housing and grazing practice. Schils et al. (2005) modelled the GHG budget of reducing grazing time on a case-study dairy farm. Reduced N_2O emissions from excreta were offset by an increase in CH_4 emissions from manure storage, suggesting that restricted grazing may not offer mitigation potential at a whole-farm level. Luo et al. (2010) suggested that for grazed winter forage crops, the method of tillage used to establish the crop will impact upon the subsequent soil compaction by grazing animals and therefore N_2O emission. Direct drilling to establish forage crops was suggested as a means of emissions reduction.

Reducing stocking rates also holds potential for emissions reduction. Howden et al. (1996) found that CO_2e emissions/ha grassland increased linearly with stocking rate at low to moderate stocking rates (from 2 to 8 or 9 ewes/ha), but remained constant at higher stocking rates from 10–14 ewes /ha, although the causality of this relationship was not explored. Rafique et al. (2011) found that intensively grazed grasslands produced N_2O fluxes up to three times higher per hour than their extensive counterparts, which they attributed to greater urine and dung excretion and soil compaction on intensive sites.

1.5.2. Fertiliser and nutrient management

Soil moisture should also be taken into account when planning fertiliser applications. High WFPS, low oxygen conditions promote denitrification when carbon and NO_3^- supplies are non-limiting, indicating that fertiliser applications should be avoided in late autumn and winter and early spring. In conditions where denitrification predominates, such as during cool, wet months, N_2O emissions may be lower from the application of a urea-based fertiliser than a NO_3^- based fertiliser. Conversely, emissions may be expected to be higher from ammonium rather than NO_3^- based fertilisers in drier soil conditions favouring nitrification (Eckard et al., 2006).

Other fertiliser management opportunities for emissions reduction limit the supply of nitrogen feedstock for N_2O-producing soil microbes. When fertiliser applications exceed pasture or forage requirements the nitrogen surplus can be immobilised, becoming part of the organic nitrogen pool or lost through the pathways previously defined. As nitrogen supply exceeds the requirements of the pasture the efficiency of use for growth declines (Eckard et al., 2006). Pasture-derived emissions of N_2O are positively correlated with nitrogen input (Cardenas et al., 2010; Jones et al., 2007; Rafique et al., 2011). Adoption of a fertiliser recommendation system which includes a soil and plant nutrient analysis would ensure optimisation of nutrient supply (Moorby et al., 2007; O'Hara et al., 2003). This would also account for the nitrogen content of the soil and any applied manure (as many farmers fail to account for the nutrient content of organic manures when applying fertilisers (Jones et al., 2007)). Proper maintenance and calibration of spreader equipment will improve targeting of nutrients to crop needs. Precision in fertiliser timing can also reduce nitrogen losses. These are simple approaches including ensuring application coincides with periods of rapid crop growth; minimising delays between application and crop uptake and splitting applications into several smaller applications to improve efficiency of nitrogen uptake (Eckard et al., 2006; Jones et al., 2007).

1.5.3. Pasture renovation and plant selection

Temporary pastures on sheep farms are periodically ploughed and either reseeded to grass to improve sward productivity or planted with a forage crop. Pasture renovation has been associated with temporary, but significant, increases in soil N_2O emissions (Davies et al., 2001; Estavillo et al., 2002; Vellinga et al., 2004). Velthof et al. (2010) found that renovation of intensively managed fertilised grasslands increased N_2O emissions by an average of 1.8–3 times compared to non-reseeded control grasslands. Possible explanations include increased mineral nitrogen content of soil through the incorporation of crop residues, mineralisation of N from soil organic matter, and limited uptake of nitrogen by crops post-ploughing. Careful management of pasture ploughing (i.e. method and timing) may reduce emissions, although the number of studies supporting this is limited. Contrary to what might be expected, MacDonald et al. (2011) showed that full inversion tillage (FIT) reduced N_2O emissions relative to soil NO_3^- levels by two or three times compared to a no-till/glyphosate (chemical fallow) regime on poorly drained grassland soils. They suggested that FIT may reduce N_2O emissions in a wet year by placing the most nutrient-rich soil surface at depth where lower oxygen levels lead to the complete reduction of NO_3^- to N_2. In the case of chemical fallow, carbon and nitrogen remain available close to the surface, where higher oxygen concentrations may hinder the full conversion of N_2O to N_2. Similarly, Velthof et al. (2010) reported lower N_2O emissions from ploughed grassland than grassland renovated through chemical destruction of the sward, perhaps due to increased aeration of soils through ploughing. Grassland renovation in spring as opposed to autumn may reduce total nitrogen losses from soil because the new sward has a higher capacity to take up nitrogen during the growing season (Vellinga et al., 2004; Velthof et al., 2010). Davies et al. (2001) have also suggested that avoiding grazing and fertiliser application on pastures prior to ploughing can reduce emissions, however, further work is needed to quantify the overall benefits of this.

Pasture renovation provides an opportunity to select plant varieties that may reduce nitrogen losses over the long-term. Mixed pastures of legumes and grass typically fix between 100 and 250 kg/N/ha/yr, reducing the need for mineral fertiliser use (Rochon et al., 2004). In a life-cycle analysis model of lowland and upland sheep production systems in England, lamb production emissions from fertilised grasslands has been estimated to be 14.6 kg CO_2e/kg of meat compared to 13.1 kg CO_2e/kg produced from an unfertilised grass-clover sward (EBLEX, 2009). However, some uncertainty relating to the mitigation potential of clover arises from the possibility that NO_3^- and dissolved organic nitrogen leaching may increase with the legume content of the sward and the level of nitrogen fixation (Rochon et al., 2004). Possible explanations include low soil nitrogen immobilisation and high mineralisation due to the low carbon-to-nitrogen ratio of clover litter; and improved soil structure (Loiseau et al., 2001; Rochon et al., 2004). Forage legumes also represent a small source of N_2O, directly from the process of biological fixation, but primarily as a result of the release of root exudates in the growing season and the decomposition of crop residues post-harvest (Rochon et al., 2004). Few studies have compared the overall nitrogen balance of grazed unfertilised grass-clover pastures with grazed fertilised pure grass pastures. In a review of available data, Ledgard et al. (2009) found total nitrogen leaching losses and N_2O emissions from nitrogen cycling of excreta to be similar in both pasture types with comparable total nitrogen inputs.

However, due to fertiliser-specific CO_2 and N_2O emissions (such as increased denitrification losses) whole system GHG emissions were typically lower per unit of produce in grass-clover systems. Research on the comparative nitrogen balance of pure legume pastures is more limited. There is some evidence that nitrogen leaching from pure white clover pasture may be considerably higher than grass-white clover pasture, possibly as a result of high nitrogen concentrations in the clover leading to greater nitrogen excretion which the pasture is unable to take up (Loiseau et al., 2001).

Plant breeding to improve the efficiency of nitrogen use holds promise for future mitigation through pasture plant and forage crop selection. One area of current research interest is ryegrass breeding for improved fertiliser recovery (Abberton et al., 2008). Some species hold interest for future breeding strategies because of features such as improved rooting depths that enable nitrogen uptake from deep in the soil profile; the production of natural nitrification inhibitors in the roots; and greater nitrogen immobilisation in soil associated with the quality of the crop residues (Luo et al., 2010; Schils et al., 2013). Richardson et al. (2009) suggested that plant breeding to control exudates to the soil could be a means of manipulating denitrification to increase the ratio of N_2 to N_2O production. Although these rhizosphere strategies involving manipulation of the soil microbial community hold strong promise it is likely that this technology will not be readily transferable between soil types, making its widespread adoption difficult.

1.5.4. Additions to soil

Nitrification inhibitors (NIs), urease inhibitors (UIs) and slow-release fertilisers influence the rate at which fertiliser or urine nitrogen is supplied to plants (Shaviv and Mikkelsen, 1993). They provide a steadier supply of nutrients to pasture and forage crops and minimise losses of excess nutrients. Slow release fertilisers such as those coated to reduce solubility have been shown to reduce losses of applied nitrogen, avoiding large fluxes of N_2O after rainfall (following a fertiliser application), whilst maintaining yields (Ball et al., 2004). Despite confidence in their mitigation potential, the cost of slow release fertilisers in terms of substitution for a conventional fertiliser and in terms of the cost per tonne of carbon abated is currently prohibitive (Ball et al., 2004; Moran et al., 2008). Although outreach programmes are increasing farmer awareness of GHG issues, overcoming the barriers to technology adoption will remain difficult without farm subsidies.

Nitrification inhibitors and/or UIs can be applied directly to the crop (e.g. as a spray), incorporated into fertilisers or even infused into the gastrointestinal tract of livestock for excretion onto pasture (Ledgard et al., 2008). Nitrification inhibitors reduce the rate of conversion of NH_4^+ to NO_3^- in the soil (Di et al., 2007), releasing NO_3^- at a rate which better matches crop uptake. Urease inhibitors slow the conversion of urea to NH_4^+, reducing the potential for NH_3 volatilisation (Watson and Akhonzada, 2005). Numerous studies have demonstrated the efficacy of NIs (Di et al., 2007; Hoogendoorn et al., 2008; Ledgard et al., 2008) and UIs (Dawar et al., 2011; Watson and Akhonzada, 2005) in reducing nitrogen losses from pastures and forage crops receiving urine and / or urea. A recent review of studies on the NI Dicyandiamide (DCD) found that, when applied above the recommended minimum rate of 10 kg/ha, it reduced N_2O emissions from urine by an average 57% (compared to controls receiving no DCD) (de Klein et al., 2011). However, emission reduction potential varies depending on site-specific factors such as soil type, soil moisture, urine nitrogen application rate and whether or not urea fertiliser is also applied (de Klein et al., 2011; Luo et al., 2010).

Critical knowledge gaps remain for NIs, including their efficacy over the long-term and under non ideal conditions (Suter et al., 2007). The validity of extrapolating data from small-scale experiments to whole-farm potentials is also problematic (Suter et al., 2007). Most studies to date have been based in New Zealand, therefore efficacy under other climatic conditions is less certain. The UK, for example, has predominantly heavy texture soils and short growing seasons in comparison to the free draining soils and longer growing seasons in New Zealand (Moorby et al., 2007). In contrast, one UI (n-butyl thiophosphoric triamide (NBTPT)) is already available commercially in the UK. When applied with urea to four contrasting soil types (two arable, two grassland), it inhibited NH_3 loss on average across all soils, temperatures and formulations by 61.2–79.8% (Watson and Akhonzada, 2005).

The effect of biochar incorporation on soil nitrogen cycling is an emerging area of research. In addition to the primary objective of sequestering carbon, biochar incorporation in soil may also increase biological nitrogen fixation, reduce N_2O emissions and NO_3^- leaching and increase nitrogen retention as NH_3 and NH_4^+ (Clough and Condron, 2010). In the only field-based study to date on the effect of biochar incorporation on emissions from ruminant urine patches on pasture, Taghizadeh-Toosi et al. (2011) incorporated biochar into a renovated perennial ryegrass pasture. The grass was fertilised with urea after emergence, cut to simulate grazing and received an application of urine. Biochar addition at a rate of 30 t/ha was found to reduce cumulative N_2O emissions over a 65 day period by *c*. 50% compared to a urine-only treatment. This biochar treatment also had the lowest soil NO_3^- concentrations and the highest soil NH_4^+ concentrations. Taghizadeh-Toosi et al. (2011) proposed that the biochar functioned as a sink for urinary NH_3, reducing the inorganic nitrogen pool available to nitrifiers, therefore reducing N_2O emissions and the subsequent formation of NO_3^-. Work on forage crops and grassland destined for silage has also indicated increased N use efficiency in the presence of biochar; however, the effects were not consistent over a 3 year period, suggesting that it does not offer a reliable strategy for GHG emission reduction (Jones et al., 2012). In addition, the high production and transport cost of biochar, competition from other sectors for biochar feedstock (e.g. biomass energy), risks to humans and the environment from pollutants contained within the biochar (e.g. dioxins, PAHs), negative interactions with pesticides and current legislative barriers all limit its use in sheep-based agricultural systems (Jones et al., 2011). Further work is certainly needed to understand the mechanisms through which biochar affects soil nitrogen cycling, the soil conditions which favour these mechanisms and cost-effective strategies for implementation.

The addition of lime to soil has been suggested as a mitigation option with small potential for reducing N_2O losses (Luo et al., 2010). The rates of both nitrification and denitrification are sensitive to soil pH (Dalal et al., 2003; Kemmitt et al., 2006). Bouwman et al. (2002) modelled the relationship between N_2O emissions and controlling environmental and management factors such as climate, soil type and fertiliser type based on 846 published N_2O emission measurements. Soil pH was a significant determinant of N_2O emissions, which were lowest in alkaline conditions. Recent studies by Zaman and Nguyen (2010) and Galbally et al. (2010) found that liming pasture soils with and without the addition of urine or nitrate fertiliser has no significant effect on N_2O emissions, demonstrating that understanding of the impacts of liming under different field conditions restricts its viability as an on-farm mitigation option at present. It must also be remembered that lime itself has a high intrinsic GHG cost associated with production, transport and its subsequent decarbonation in soil (Brock et al., 2012). As with any GHG intervention, it is therefore important that a full life-cycle assessment (LCA) is performed to evaluate the net GHG balance of the mitigation strategy in a truly holistic sense before blanket policy recommendations are made.

1.6. Current and future mitigation options

The present review has highlighted the current research and development status of mitigation options applicable to sheep farms. A number of interventions have 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 WSC 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 RFI is at an early stage and longer-term trials are required urgently.

1.7. Developing a mitigation strategy

Distilling the long-list of mitigation options to produce a farm-specific short-list is challenging. Mitigation strategies must be developed based upon a whole-farm approach to GHG accounting, i.e. ensuring all CO_2, N_2O and CH_4 fluxes and the effect of mitigation measures on interactions between fluxes are accounted for (Eckard et al., 2010; Schils et al., 2005; Schils et al., 2007; Smith et al., 2008; Stewart et al., 2009). Often only the most evident of interactions are accounted for (Schils et al., 2005) and in reality the full effect of numerous mitigation practices on the GHG budget are still to be explored. The GHG balance of buying in additional concentrates to creep-feed lambs for faster growth is one example of this.

Another crucial consideration is that mitigation strategies must be constructed using additive measures that act upon different elements of the production system. Putting together complimentary sets of interventions is challenging given that the effectiveness of an abatement measure may be diminished depending upon the measures applied before or after it. A very limited number of studies touch upon interactions between interventions.

In any farm system, abatement potential is contingent upon current baseline emissions and the extent to which good practice, such as optimal fertiliser management, have already been adopted. Lambing replacements at a younger age has been shown to be an effective mitigation option in self-replacing flocks. However, in flocks where replacements are purchased, lambing earlier can decrease lambing percentages and growth rates and subsequently increase emissions. This example affirms that the effect of any intervention is highly dependent on the baseline flock management scenario. Many interventions such as pasture drainage and selection of fertiliser form cannot be recommended at a regional or national scale because their mitigation potential is inextricably linked to soil and weather conditions in the locality of use.

Other considerations when designing a mitigation strategy include ease of adoption, financial commitment and the permanence of the effect of the interventions (Smith et al., 2008), for example, the long-term efficacy of nitrification inhibitors is unknown. It has also been argued that the uncertainty surrounding the calculated abatement potential figure of a mitigation measure should itself be used as a selection criterion in mitigation strategies (Schils et al., 2005).

A number of tools are now available which help with bringing together some of these selection criteria:

1) Whole-farm GHG models quantifying all direct, indirect, upstream and on-farm GHG emissions are a crucial tool for developing emissions baselines and exploring the abatement potential of farm-level mitigation options. As a result of increased model sensitivity at a farm-level (e.g. estimation of enteric CH_4 emissions based upon diet composition), the GHG reduction potential of mitigation measures is continuously being refined.
2) Some emissions mitigation studies have refined their strategies by farm type and locality. For example: MacLeod et al. (2010b) assessed the applicability of a short-list of mitigation measures to specific farm types, sizes and locations using a qualitative scoring system and found that, across all regions, mitigation measures were typically most applicable to larger farms. Sintori and Tsiboukas (2010) grouped dairy farms through cluster analysis based upon size, intensity and production orientation. This identified four farm types for which they were able to estimate the effects of varying levels of emissions reductions on the gross margin under optimal management. Applying this type of analysis to sheep farms will identify the mitigation options most suited to different production systems in different countries, for example, lowland, upland and hill farms in the UK.
3) Final selection and implementation of mitigation measures relies upon the incorporation of a financial component into whole-farm models (Schils et al., 2005; Schils et al., 2007; Weiske, 2005). Gibbons et al. (2006) used a whole-farm model which maximised farm net margin by optimising the crop, animal and labour mix over a year, and linked this with emissions data to determine the most cost-effective measures for reducing farm emissions. Marginal abatement cost curves plot the relationship between the cost per tonne of carbon abated against the abatement potential for individual mitigation measures. They provide a decision-making tool for selecting cost and emissions saving measures, or for selecting options that reduce emissions below a selected cost threshold.

Applying these tools which have primarily been developed and adopted in relation to beef and dairy systems to sheep farms is a critical next step in sheep farm-specific GHG mitigation research.

1.8. Conclusions

Incorporation of the most promising mitigation options into sensitive and holistic farm models is needed to develop robust sheep farm GHG mitigation strategies. Refining the full set of mitigation options is a function of each individual measure's estimated abatement potential, whole system effects and interactions, deployment stage, ease of adoption and cost to the farm business. One significant hurdle to overcome is accounting for the effect of interactions between interventions on the overall carbon footprint. This will enable complimentary sets of interventions to be developed. Modelling mitigation potential against baseline emissions specific to farm typology will ensure that interventions with the maximum mitigation benefit in those conditions can be selected. Costed mitigation strategies tailored to sheep farm typology will be a critical stage in the translation of research based advice to farm-level action, and in the realisation of agricultural emissions targets.

Chapter 2

The carbon footprint of lamb: Sources of variation and opportunities for mitigation[1]

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Abstract

Carbon footprinting can be used to characterise the greenhouse gas emissions profile of agricultural products, providing a baseline against which mitigation targets can be set and progress measured. Farm-level emissions vary in relation to local conditions and management choices. Carbon footprinting models can be used to assess the impact of farm characteristics on emissions; however, the benefits of such models have been underexploited thus far for sheep production. This study estimated the cradle to farm-gate carbon footprints of 64 sheep farms across England and Wales using empirical farm data. This large dataset enabled an assessment of the relationship between farm variables and carbon footprint at a multi-farm level. Mean carbon footprints of 10.85, 12.85 and 17.86 kg CO_2e/kg live weight finished lamb were recorded for lowland, upland and hill farms respectively, from samples with coefficients of variation of 33%, 23% and 34%. Multiple linear regression models indicated that four farm management variables had a significant impact on the size of the carbon footprint of finished lamb. Irrespective of farm category, these were the number of lambs reared per ewe (head/ewe), lamb growth rate (grams/day), the percentage of ewe and replacement ewe lamb flock not mated (%), and concentrate use (kg/livestock unit). Dominance analysis indicated that, of these, the number of lambs reared per ewe mated and lamb growth rate were the most influential. Productivity improvements are arguably most problematic for extensive hill farms; however, the top performing hill farms in this study outperformed the mean lowland and upland farms. The results suggest that, at a national level, the emphasis for reducing the carbon footprint of lamb should be on closing the productivity gap between poor and top performing farms.

2.1. Introduction

Agriculture is responsible for approximately 10% of global anthropogenic greenhouse gas (GHG) emissions (excluding land use change) (Smith et al., 2007a). Effective mitigation of such emissions is of increasing concern in research and policy (Garnett, 2009). In order to meet growing global food demands, agricultural intensification and expansion are needed (Foresight, 2011). The successful management of agricultural GHG emissions therefore presents a substantial challenge to the scientific, commercial and policy communities.

Robust and reliable methodologies for estimating and monitoring changes in emission levels are needed to inform the development and delivery of effective agricultural emissions' mitigation strategies (Norse, 2012; Smith et al., 2007a). Life cycle assessment (LCA) is an internationally accepted, standardised methodology for quantifying the environmental impact of a product (ISO, 2006a; ISO, 2006b). The ISO 14040/44 standards provide a framework for assessing the global warming potential (GWP) of GHG emissions, forming the basis of the carbon footprinting approach. A carbon footprint (CF) provides an estimate of total GHGs emitted during part or all of the life of a good or service (BSI, 2011), expressed as carbon dioxide equivalents (CO_2e). Carbon footprinting is increasingly used in the food supply chain to determine the quantity of GHG emitted at each stage of the production process, and may extend to the distribution and use phases. Recent examples include estimates of the CF of American milk up to the farm gate (Rotz et al., 2010), Australian beef and sheep meat to the point of exiting the meat processing plant (Peters et al., 2010) and exported New Zealand lamb up to and including the consumer use phase (Ledgard et al., 2011).

Carbon footprinting enables carbon labelling of food products to inform sustainable consumer purchasing decisions, and provides an emissions' benchmark against which mitigation targets can be set and progress measured (Edwards-Jones et al., 2009; Plassmann et al., 2010). Such emissions data are reported per unit of produce. Conceptually, this should enable comparisons of the GWP of different food groups, producers and supply chains for the same product. Unfortunately, divergence in methodological approaches between studies often hinders meaningful comparison of calculated CFs (Flysjö et al., 2011). To tackle this issue and provide a consistent methodology for assessing the CF of products, the British Standards Institute (BSI) developed the Publically Available Specification 2050:2008 (PAS 2050) for assessment of the life cycle GHG emissions of goods and services, which was updated in 2011 (BSI, 2011). More recently, international product CF standards have been developed by both ISO (ISO 14067) and the Greenhouse Gas Protocol (Product Life Cycle Accounting and Reporting Standard) (ISO, 2013; World Resources Institute and World Business Council for Sustainable Development, 2011). Whether the development of multiple standards will improve methodological consistency remains to be seen.

Studies estimating the CFs of multiple food groups have shown that red meats are amongst the most emission-intensive food products (Williams et al., 2006). Whilst beef and milk have received considerable research interest, the CF of sheep meat has been less well reported in the scientific literature. However, global sheep numbers are expected to increase 60% by 2050 (Foresight, 2011).

The largest sheep farm CF study undertaken in England and Wales estimated the mean CF of sheep production in England only to be 11.86 kg CO_2e / kg live weight (LW) lamb. Typically, the CF of an average or representative system is used to advise decision-makers on the environmental impact of a product (Basset-Mens et al., 2009). However, there is increasing recognition that variation between and within farm types should be considered in the development of effective mitigation strategies (Jones et al., 2013).

Two sources of variation in estimates of farm-level CFs have been characterised. These are: (1) variation arising from uncertainties in the data and models employed to calculate the CFs, and (2) natural variation relating to differences in environmental conditions and management practices between farms (Basset-Mens et al., 2009; Henriksson et al., 2011). The former results from imprecise data and uncertainty when modelling the biological processes associated with nitrous oxide (N_2O) and methane (CH_4) emissions, and the latter from variability between farm characteristics and management practices. By refining input data and emission factors (EF), the precision of CF models can be improved both spatially and temporally and uncertainty in the CF estimate reduced (Basset-Mens et al., 2009; Karimi-Zindashty et al., 2012; Payraudeau et al., 2007). Variation between farm CFs may reveal opportunities to reduce emissions through improved management.

A small number of studies have explored how differences in farm variables (particularly in relation to management) can impact the CF of livestock products. One approach is to estimate the CF of a single farm based on empirical or modelled data, and to use sensitivity analyses to determine the impact of changing one or more farm variables (Cruickshank et al., 2008; Taylor et al., 2010). Variability in dairy and beef farm emissions is typically explored by calculating the CF of an average farm (constructed from national datasets) and using Monte

Carlo (MC) simulations to vary farm parameters within known limits (Flysjö et al., 2011; Henriksson et al., 2011). For example, Basset-Mens et al. (2009) calculated the average CF per kg of New Zealand milk and used MC simulations to vary the values of key production variables, including milk output and fertiliser application rates, within the range specified in national industry databases. An alternative approach is to analyse the relationship between CF and farm variables across a large sample of farms, based on empirical farm data (Kristensen et al., 2011). This approach captures the true co-variation of farm parameters. No analysis of the relationship between farm variables and sheep farm CFs at a multi-farm or national level appears to have been reported in the scientific literature.

Given the diversity of systems within the English and Welsh sheep industry, a corresponding variation in footprint is to be expected. Farm holdings operate a range of production systems, often dictated by geography and climate. The industry is characterised by interdependent lowland, upland and hill farm systems, differentiated by harsher climates, poorer quality grazing and lower productivity with increasing altitude (Croston and Pollott, 1985; Goodwin, 1979). The main product of the industry is meat i.e. fat lamb and mutton (Goodwin, 1979). Output varies significantly between average and top producers (Brown and Meadowcroft, 1990). Wool is now a secondary product in the industry, with the income obtained from wool often insufficient to cover the cost of shearing.

Limited data on the CF of sheep production have been published in the scientific literature. Reported results typically lack depth in terms of the characteristics of the farms footprinted and analyses of the influence of farm variables on the CF. The aim of this study was to calculate the CF of lamb produced on a range of farm types, using empirical data collected from sheep farms across England and Wales. The calculated CFs were then analysed with the objectives of:

1) Providing an emissions breakdown, detailing the greatest sources of emissions.
2) Reporting variation in farm characteristics and analysing the impact of farm category on the CF.
3) Identifying key farm management variables as drivers of footprint size at a national level, and evaluating their potential for mitigation.

2.2. Methods

2.2.1. Footprint calculation

Empirical farm data were used to estimate the GHG emissions associated with sheep production on farms in England and Wales. The CFs were calculated using an updated version of the livestock model used by Edwards-Jones et al. (2009) and Taylor et al. (2010), as detailed below. The global warming potentials of emissions were reported relative to CO_2 over a 100 year time horizon, where 1 kg CH_4 = 25 kg CO_2e and 1 kg N_2O = 298 kg CO_2e (Forster et al., 2007). The functional unit used for reporting emissions was 1 kg of LW finished lamb.

2.2.1.1. Farm-level production data

Sheep farmers were randomly sampled within the categories of lowland and less favoured area (LFA). LFA is a European Union designation for land disadvantaged by its natural characteristics (e.g. by altitude or climate), and is therefore often restricted to extensive livestock production (European Council, 1999). In the UK, LFA land is subdivided into disadvantaged and severely disadvantaged land (DEFRA, 2010a), which is used synonymously in this study with upland and hill land, respectively. Lowland, non LFA farms typically have the best physical conditions for farming and are consequently the most productive. Respondents were drawn randomly from two lists, one of Welsh farmers held by Bangor University and one of English farmers held by EBLEX. Carbon footprints were calculated for 64 farms, based on data provided by farmers in face-to-face interviews. However, only 60 datasets were used in the final analyses, as explained in section 2.2.2.1.

Farmers provided information on important aspects of their production system including inputs (for example feed, fertiliser and bedding use); stock movements (including purchases, births and housing); outputs (including number and weight of sheep sold) and farm characteristics (including area and soil types). Data were provided for a single year between 2010 and 2011, which the farmer considered representative of a typical production year. The quality of farm-level data is sometimes questioned (e.g. Crosson et al., 2011) therefore written farm records such as stock movement books were used to verify important data elements.

2.2.1.2. System boundary

The CFs were calculated within a cradle to farm gate system boundary following LCA principles (BSI, 2011). The system boundary adopted is represented schematically in Fig. 2.1. 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). The footprints did not include emissions resulting from land use change and because of this exclusion are not PAS 2050 compliant (BSI, 2011). Emissions associated with the manufacture of capital goods such as farm buildings and machinery were not included in the footprint as is consistent with the PAS 2050 methodology (BSI, 2011). Due to limitations in the availability of emissions data, emissions associated with veterinary visits and supplies were excluded. Minor emissions' sources were also excluded as is consistent with the PAS 2050 CF methodology (BSI, 2011) e.g. infrequently used consumables such as plastic fertiliser bags.

2.2.1.3. Allocation

Some of the footprinted farm businesses operated multiple enterprises, producing other livestock and / or crops in addition to sheep. Where possible, farmers provided data restricted to the sheep enterprise, avoiding the need for allocation of inputs and emissions. Shared inputs, such as fertilisers applied to fields used for both sheep and cattle, were allocated between enterprises based on total grazing livestock units (LSU), calculated using the ratios in Nix (2010). 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. Based on these prices, the average income, and therefore allocation of emissions, was 72.7% to finished lamb, 4.6% to live lamb, 10.6% to cull sheep, 9.8% to breeding sheep and 2.3% to wool. This approach reflects the value of the products to society (Rotz et al., 2010), and the driving forces for production. The impact of allocation choices on the CF result are discussed in section 2.4.2.1. Although the focus of this study is on emissions per kg of finished lamb, the CF of the other sheep products sold from each farm were also reported.

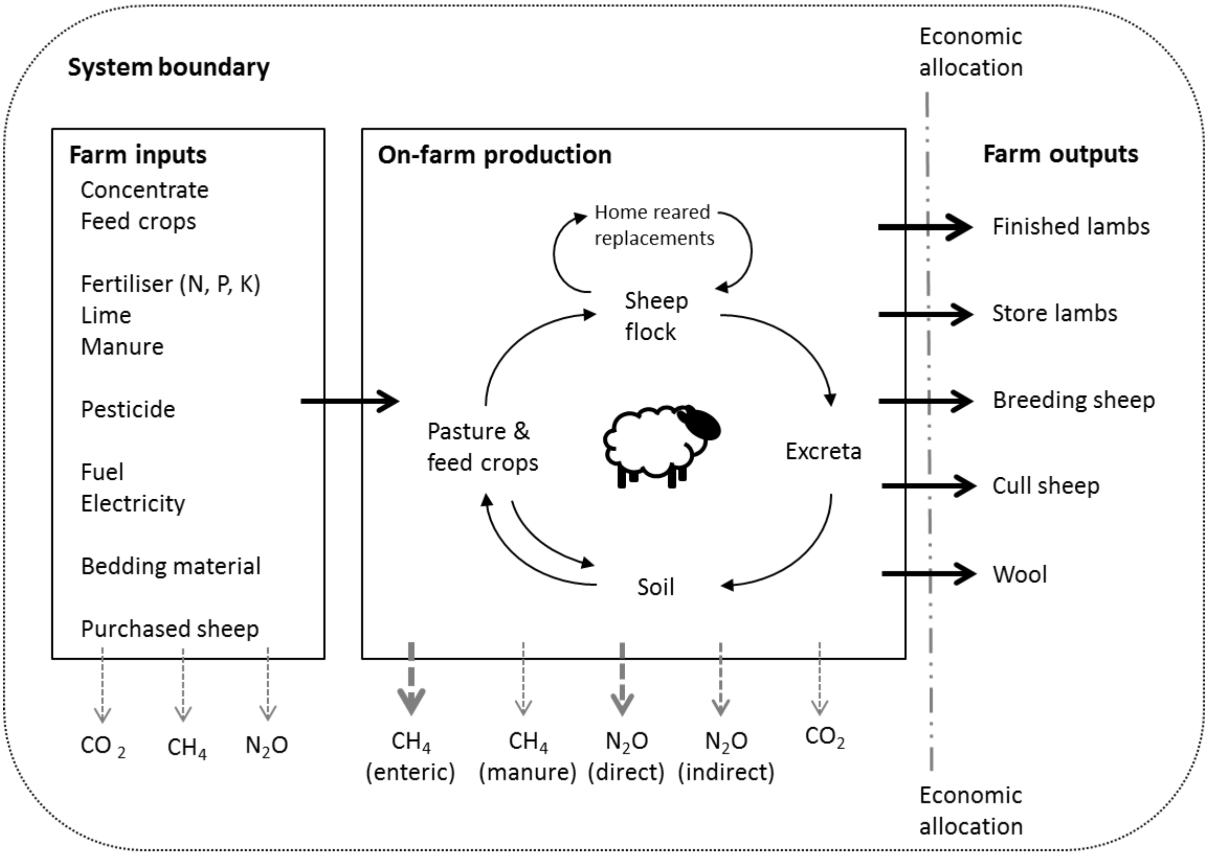

Fig. 2.1. Schematic representation of sheep farming systems and the cradle to farm gate carbon footprint method adopted in this study.

2.2.1.4. Emissions data

The activity data and emission factors used to estimate the primary emissions of CH_4 and N_2O are detailed in Table 2.1. 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 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.

Table 2.1. Activity data and emission factors used to estimate the primary emissions of methane and nitrous oxide from sheep production systems.

Gas and source	Activity data used for calculation	Reference	Emission factor	Reference
CH_4				
Enteric fermentation (sheep > 1 year)	Monthly sheep numbers	Farm stock diary	$^1/_{12}$ × 8 kg/head/year	IPCC (2006)
Enteric fermentation (lambs < 1 year)	Monthly sheep numbers	Farm stock diary	$^1/_{12}$ × 3.2 kg/head/year	Webb et al. (2013)
Excreta & managed manure (sheep > 1 year)	Monthly sheep numbers	Farm stock diary	$^1/_{12}$ × 0.19 kg/head/year	Webb et al. (2013)
Excreta & managed manure (lambs < 1 year)	Monthly sheep numbers	Farm stock diary	$^1/_{12}$ × 0.08 kg/head/year	Webb et al. (2013)
N_2O (direct)				
N additions to soil:				
Mineral fertiliser	N applied in fertiliser	Farm records	0.01 kg N_2O-N/kg N	IPCC (2006)
Manure	Monthly sheep numbers housed & live weights	Farmer	0.01 kg N_2O-N/kg N	IPCC (2006)
	N excretion rate	IPCC (2006)		
	Fraction of N lost in manure management	IPCC (2006)		
Crop residues	Crop yield & fraction of residues removed	Farm records	0.01 kg N_2O-N/kg N	IPCC (2006)
	N content of above & below ground residues	IPCC (2006)		
Drained or managed peat soil	Area of managed peat soil	Farm records	0.25 kg N_2O-N/ha	Scottish Executive (2007)
Excreta deposited on pasture	Monthly sheep numbers grazing & live weights	Farmer	0.01 kg N_2O-N/kg N	IPCC (2006)
	N excretion rate	IPCC (2006)		
Managed manure	Monthly sheep numbers housed & live weights	Farmer	0.005 kg N_2O-N/kg N excreted (solid storage)	IPCC (2006)
	N excretion rate	IPCC (2006)	0.01 kg N_2O-N/kg N excreted (deep bedding)	IPCC (2006)
N_2O (indirect)				
N volatilised from soil & re-deposited	N applied in fertiliser, manure & excreta	As above	0.01 kg N_2O-N/kg NH_3-N + NO_x-N volatilised	IPCC (2006)
	Fraction of applied synthetic & organic N volatilised	IPCC (2006)		
N leaching & runoff from managed soil	N applied in fertiliser, manure, excreta & crop residues	As above	0.0075 kg N_2O-N/kg N leaching & runoff	IPCC (2006)
	Fraction of applied N lost through leaching & runoff	IPCC (2006)		
Managed manure	Monthly sheep numbers housed & live weights	Farmer	0.01 kg N_2O-N/kg NH_3-N + NO_x-N volatilised	IPCC (2006)
	N excretion rate	IPCC (2006)		
	Fraction of N volatilised in manure management	IPCC (2006)		

Default IPCC Tier 1 EFs and equations were used, as this was the procedure for reporting agricultural emissions in the UK GHG inventory at the time of calculation (Webb et al., 2013). Following the UK GHG inventory procedure, it was assumed that enteric and manure management CH_4 emissions for lambs under one year old are equivalent to 40% of those of adult sheep (Webb et al., 2013). The EFs used for lambs were therefore 3.2 kg CH_4 per lamb per year from enteric fermentation and 0.076 kg CH_4 from manure management per lamb per year, both adjusted for the number of months the lambs were on-farm or housed. The only other deviation from the IPCC defaults was the use of an EF derived from a UK study for direct N_2O emissions from managed organic soils (i.e. peat soils). Mean emissions from UK peat soils over a range of grazed grassland habitats were estimated to be 0.25 kg N_2O-N per hectare per year (Scottish Executive, 2007). This EF was adopted in place of the IPCC default of 8 kg N_2O-N/ha/yr for temperate organic crop and grassland soils (IPCC, 2006) because it is arguably more representative of local conditions in the UK (Taylor et al., 2010).

The EFs used for inputs including fertilisers, diesel, agrochemicals, bedding and compound feeds were mid-range values from the published literature given in Edwards-Jones et al. (2009). Additional EFs used in this study were for the production of individual non-blended feed crops (straights) purchased by the farm and for the rearing of purchased stock. Emission factors for straight feed crops were taken from the Carbon Trust Footprint Expert Database (2010). Indirect emissions associated with the rearing of purchased stock depend upon the production system of the originating farm and age at sale. A single mean EF was used for live purchased sheep of 7.62 kg CO_2e / kg LW based on all previous sheep footprints calculated by Edwards-Jones et al. (2009) and Taylor et al. (2010). This mean value represents a range of production systems and is similar to the approach adopted by Rotz et al. (2010) to determine an EF for purchased heifers in their dairy system CFs.

2.2.2. Assessing variation

Variation in the CFs relating to both system type and management was assessed.

2.2.2.1. Effect of system type on the carbon footprint

Comparisons of the distribution of the CFs of finished lamb were made between sheep farms categorised by system type using the non-parametric Kruskal-Wallis test. The use of a non-parametric test was necessary because the CFs within each farm category were not normally distributed. The dependent variable in each case was the CF of finished lamb and the independent variables were the farm categories. Comparisons were made between the footprints of lowland, upland and hill farms; between farms categorised by breeding ewe flock size; then between farms categorised by area. Significant Kruskal-Wallis results were followed by Dunn-Bonferroni *post-hoc* tests. Four of the 64 farms were excluded from the analysis because they either did not produce any finished lambs or they were store fattening businesses only and had no permanent flock on-farm, making them incomparable with more conventional systems.

2.2.2.2. Effect of management variables on the carbon footprint

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. Ten important management variables were selected based upon our understanding of the role of farm characteristics in determining footprint size. The intention was to identify underlying variables determining footprint size, and not to duplicate the IPCC equations. 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 variables fuel, inorganic fertiliser and concentrate use were included based on their percentage contributions to the mean footprint. Both the variables ‘fuel use’ and ‘inorganic fertiliser use’ were calculated as total usage over the year divided by the area of the farm used for the sheep i.e. they are average areal values across the whole-farm. ‘Concentrate use’ was the annual total usage divided by mean LSU on-farm, where LSU were calculated at the beginning of each month and averaged over the 12 months. The ‘area of managed peat soil’ was included because large areas of managed peat soil can contribute considerably to direct N_2O emissions on Welsh sheep farms (Edwards-Jones et al., 2009). This was calculated as percentage of the managed farm area on peat soil. The intensity of farm management was accounted for in the variable ‘stocking density’, expressed as mean LSU per hectare. Variables that reflected farm productivity were prioritised given that the CF is determined by dividing whole-farm emissions by the weight of produce. The ‘number of lambs reared per ewe’ was included to reflect both lamb birth rate and lamb survival. ‘Lamb growth rate’ was estimated as the weight at sale minus weight at birth, divided by days to sale i.e. overall average growth rate. ‘Breeding ewe replacement rate’ was calculated as the number of ewes and ewe lambs purchased or retained in the year, divided by the size of the breeding ewe flock. This variable was not adjusted for changes in flock size over the year i.e. high replacement rates indicated an increase in breeding ewe flock size from the beginning to the end of the year. The variable was not adjusted to ensure it reflected the purchase of breeding stock in addition to sales and losses. Variables that impacted sheep numbers were also deemed important on the understanding that direct CH_4 and N_2O emissions are the primary contributors to the footprint of lamb. The percentage of 'finished lambs purchased as stores' was estimated by weight at point of sale. The percentage of the 'ewe and replacement ewe lamb flock not mated' was estimated by weight at the date(s) of mating. 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/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 (AIC) 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. Diagnostic plots indicated that the assumptions of linearity of variables, homogeneity of variance, and normality of residuals held for the best identified model. Three possible outliers were identified in diagnostic plots, however they were retained when their removal was not found to alter the selection of variables in the best model. A correlation matrix indicated moderate collinearity of the variable stocking density with area of managed peat soil and inorganic fertiliser use. 'Stocking density' was removed and the regression repeated. Variance inflation factors (VIF) were estimated as a further indicator of multicollinearity. All remaining variables had VIFs below two and were therefore retained.

The relative importance of each variable in the final model was assessed by dominance analysis (Tonidandel and LeBreton, 2011). The variance in the CF data accounted for by each variable in the model was estimated by averaging over all possible orderings of the variables in the model, as recommended by Kruskal (1987). Both the direct effect of an independent variable on the dependent and its effect in combination with other independent variables were taken into account when decomposing R^2. 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). Combinations of both the dependent and independent variables were randomly resampled with replacement from the CF dataset over 1000 bootstrap runs.

2.3. Results

2.3.1. Characteristics of the footprinted farms

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 primary produce of the majority of the farms (generating the largest component of the sheep enterprise's income) was home reared finished lamb (n=55). Other farm specialisms were producing breeding sheep (n=4) and producing store lambs for sale (n=1).

The characteristics of the 60 farms were summarised in Table 2.2. The sample of farms ranged in size from 16 to 518 hectares with breeding ewe flock sizes between 60 and 2280 head. Mean stocking density decreased with declining land quality from 1.2 LSU/ha on lowland farms to 0.6 LSU/ha on hill farms. The mean rate of fuel and nitrogen use per hectare was similar for lowland and upland farms and lowest on hill farms. Some productivity indicators varied with farm category: mean lamb growth rate on lowland farms was 238 g/day compared to 178 and 177 g/day on upland and hill farms respectively; and the mean percentage of the ewe and ewe lamb flock not mated increased from 6.2% on lowland farms to 11.2% on hill farms. Other productivity indicators were relatively static across categories but showed considerable variation within the category: the mean quantity of lamb produced for sale or retention (per ewe mated) was 0.8 or 0.9 kg lamb / kg ewe for lowland, upland and hill farms but varied by 0.8 or 0.9 kg lamb / kg ewe between poor and top performing farms within each category.

2.3.2. Carbon footprint results and contribution analysis

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 2.3). The upland category showed the least variation in footprint size between farms with a coefficient of variation (CV) of 23% relative to the mean, compared to 33% for lowland and 34% for hill farms. There was greater variation in footprint size within each category than between them (lowland, upland and hill farm). The results of the statistical tests comparing the CFs of lowland, upland and hill farms are reported in section 2.3.3.1.

Enteric CH_4 emissions represented the largest component of the CF for each farm category (Table 2.3). The proportion of emissions from this source was greater for hill compared to upland, and upland compared to lowland farms (hill 48.2%, upland 43.5%, lowland 42.6%).

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. These two emissions sources were amongst the least variable within farm systems. Mean total inputs represented 19.4%, 19.7% and 15.3% of the lowland, upland and hill farm finished lamb CFs, respectively. Purchased feed, stock, fuel and fertiliser were the primary contributors to emissions associated with inputs. Emissions associated with inputs showed a high degree of variation between farms. Direct soil N_2O emissions arising from crop residue incorporation and the management of organic (i.e. peat) soils were also highly variable between farms (CVs for lowland farms were 218% and 376% respectively). Indirect soil N_2O emissions arising from nitrogen volatilised, leached or lost in surface run-off represented a large component of the mean CFs (lowland 9.9%, upland 8.9%, hill 8.5%). Agrochemical, bedding, electricity use and emissions associated with manure storage made minimal contributions to the mean CFs in all categories.

Table 2.2. Characteristics of the 60 footprinted farms producing finished lamb. See section 2.2.2.2 for a full description of how variables were calculated.

	Farm classification								
	Lowland (n=27)			Upland (n=12)			Hill (n=21)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Farm and flock structure									
Sheep farm area (ha)[a]	68.9	17.0	227.0	102.3	34.8	307.6	163.4	16.0	518.0
Area of managed peat soil (% of farm)	2.8	0.0	51.6	19.3	0.0	66.7	38.7	0.0	100.0
Breeding ewe flock size (head/farm)	563.5	60.0	2280.0	547.6	96.0	1210.0	649.3	92.0	1700.0
Stocking density (LSU/ha)	1.2	0.2	1.9	0.7	0.4	1.1	0.6	0.1	1.8
Inputs									
Fuel (litres/ha)	41.2	5.7	115.7	48.5	2.7	115.0	26.3	0.1	66.3
Inorganic fertiliser (kg N/ha)	26.8	0.0	118.2	26.3	0.0	72.5	16.9	0.0	103.9
Concentrates (kg/LSU)	577.2	0.0	3720.9	411.2	0.0	1119.3	495.7	0.0	1213.7
Percentage of finished lambs purchased as stores (%)	1.1	0.0	30.2	1.0	0.0	12.2	2.0	0.0	27.5
Outputs									
Lamb sold or retained per ewe mated (kg LW lamb/kg ewe)	0.8	0.5	1.2	0.9	0.6	1.2	0.8	0.4	1.1
Wool (kg/LSU)	19.3	4.1	31.0	20.2	11.1	48.8	18.9	11.4	32.6
Productivity indicators									
Lambs reared per ewe (head/ewe)	1.4	0.8	1.7	1.4	1.0	1.8	1.2	0.7	1.6
Lamb growth rate from birth to finishing (g/day)	238.2	56.9	355.8	178.2	102.6	241.7	176.5	107.3	257.7
Breeding ewe replacement rate (%)[b]	24.5	0.0	54.1	27.3	16.4	69.8	27.0	15.8	67.4
Percentage of ewe and replacement ewe lamb flock not mated (%)	6.2	0.0	25.0	9.6	0.0	19.6	11.2	0.0	22.6

[a] Calculated based on grazing livestock units for shared farms e.g. beef and sheep enterprises.

[b] Breeding ewe replacement rate is unadjusted for changes in flock size over the year i.e. high replacement rates indicate an increase in breeding ewe flock size.

Table 2.3. 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	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

2.3.3. Variation in carbon footprints

2.3.3.1. Comparisons between farm categories

In the 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 (Fig. 2.2). 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 (Fig. 2.2). 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}) ($H(3)=3.76, p=0.289$). Because of the small sample sizes in some categories, comparisons could not be made between the CFs of farms categorised by farm production orientation. The mean CFs of finished lamb, live lamb, breeding sheep and cull sheep from farms categorised by production orientation are reported in Table 2.4.

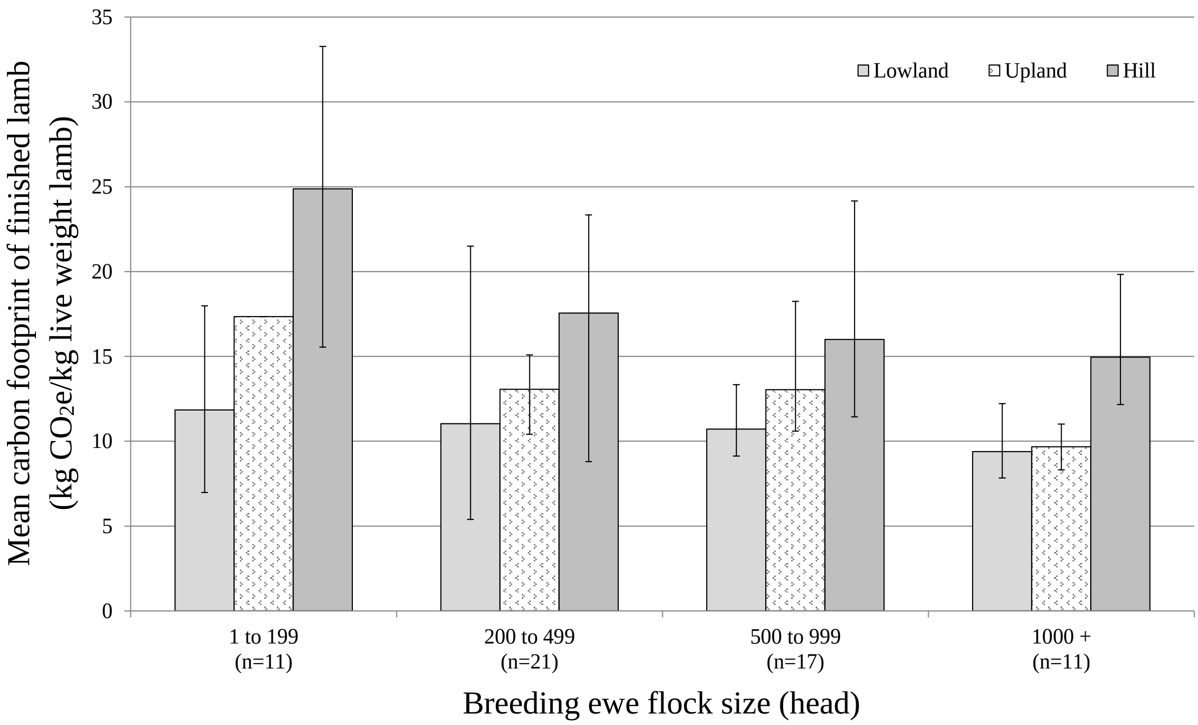

Fig. 2.2. Variation in the carbon footprint of finished lamb between lowland, upland and hill farms of varying flock size. Bars represent minimum and maximum calculated footprints. The number of farms in each flock size group is indicated by n.

Table 2.4. Mean carbon footprint of finished lamb, live lamb, breeding sheep and cull sheep categorised by farm specialism (kg CO_2e/kg LW). The number of farms in each category is indicated by n.

Farm specialism (primary produce)	n	Mean carbon footprint (kg CO_2e/kg LW) Finished lamb	n	Live lamb (stores and couples)	n	Sheep for breeding	n	Cull sheep (sold as meat)	n
Finished lambs (home reared)	55	14.1	55	12.6	18	12.5	18	7.4	54
Sheep for breeding	4	8.1	4	10.4	2	16.4	4	5.5	4
Store lambs	1	17.2	1	16.2	1	22.5	1	12.3	1

2.3.3.2. Variation with management

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 2.5. Both concentrate use and the percentage of ewe and replacement ewe lamb flock not mated had a significant positive relationship with the size of the CF. The number of lambs reared per ewe and lamb growth rate had a significant negative relationship with the size of the CF, i.e. as they increased the CF decreased.

Table 2.5. 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. 2.3. 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%).

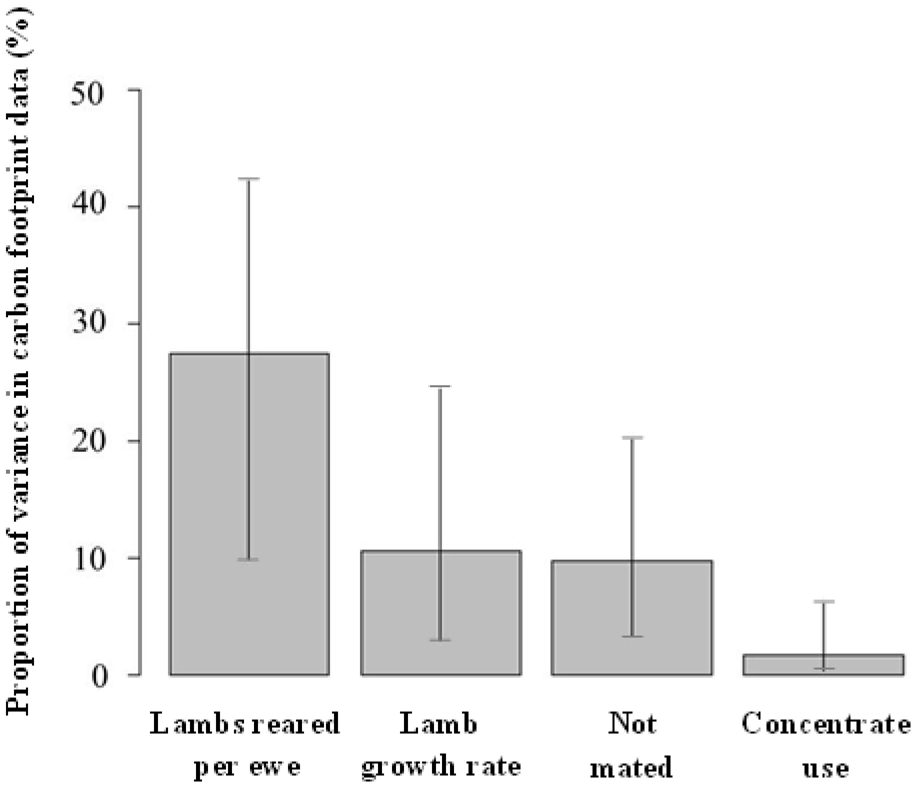

Fig. 2.3. Results of the dominance analysis indicating the percentage of variance in carbon footprint explained by each variable in the final regression model. Values sum to the overall model R^2 = 49.4%. Bars represent 95% bootstrap confidence intervals.

2.4. Discussion

2.4.1. Variation in carbon footprints and opportunities for mitigation

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 for productivity (Henriksson et al., 2011). In our sample, lowland sheep farms had significantly lower CFs than hill farms. This difference reflects the impact of harsher climates and poorer quality grazing on the productivity of hill flocks. Variation driven by local conditions was evidenced by the recorded characteristics and emissions' contributions of hill compared to lowland farms, including: slower mean lamb growth rates; increased direct N_2O emissions from managed peat soils; increased lime related emissions, and an increase in the percentage of the unmated ewe flock. Other studies have also reported an increase in lamb CF from lowland intensive flocks to more extensive flocks in the uplands and hills. In England, EBLEX (2012) estimated the mean CF of lamb produced in lowland, upland and hill flocks to be 10.98, 10.86 and 14.42 kg CO_2e/kg LW respectively. Their results are comparable to those reported here; although their mean hill lamb CF is slightly lower, perhaps reflecting the inclusion of Welsh farms in this study. Elsewhere, Ripoll-Bosch et al. (2013) reported CFs of 19.5, 24.0 and 25.9 kg CO_2e/kg LW for Spanish lamb produced in high intensity zero-grazing, mid altitude and extensive LFA pasture systems, respectively. The differences in size of CF to those reported here are likely to be a reflection of methodological divergence (they allocated all GHG emissions to the lamb product), differences in climate and production methods (e.g. lower slaughtering weights in Spain compared to the UK). Despite being disadvantaged by local conditions, the top performing hill farms in this study had lower CFs than the lowland and upland mean CFs. This overlap in the range of CFs between categories and the considerable variation within categories suggests opportunities for improved management choices to mitigate emissions on the poorest performing farms.

Four farm management variables were found to have a significant impact on the size of the CF of finished lamb, and present targets for emissions mitigation efforts. Irrespective of farm category, these four underlying drivers of footprint variation were: number of lambs reared per ewe (head/ewe), lamb growth rate (grams/day), the percentage of ewe and replacement ewe lamb flock not mated (%), and concentrate use (kg/LSU). The first three of which indicate the importance of flock productivity in managing the CF. Farms with higher productivity are maximising their output from the resources and emissions invested in the adult stock, therefore reducing their CF per kg of lamb. A productivity target of one kg of lamb sold or retained per kg of ewe mated is aspired to in sheep industry literature to improve farm performance and profitability (e.g. Vipond et al., 2010). Our study suggests that the number of lambs reared per ewe and lamb growth rate are the variables that most significantly impact the size of the CF are therefore compatible with this existing industry target. Within the study sample of farms, the number of lambs reared per ewe varied between 0.7 and 1.8; and lamb growth rate between 57 g/day and 356 g/day, demonstrating considerable potential for improvement on the poorest performing farms.

Improved lamb output per ewe can be achieved through a range of interventions including selective breeding for ewe productivity, increased lamb survival through better hygiene and management at birth, and nutritional management. Improving lamb growth rates can be achieved through feeding or selective breeding. Selection for growth rates in maternal lines may lead to a correlated increase in mature ewe requirements (Wall et al., 2010). In both scenarios at an individual farm-level, it is critical that the emission reductions of finishing lambs earlier is not negated by either a corresponding increase in additional feed requirement emissions, or an increase in fertiliser requirements to improve pasture productivity. Although increasing lamb output and improving growth rates are arguably most problematic for hill farms, it should be noted that the top performing hill farms in this study achieved higher lamb outputs and growth rates than the mean lowland and upland farms. This indicates strong potential for improvement in some instances.

The percentage of ewe and replacement ewe lamb flock not mated also explained a significant proportion of the variance in CF. This reflects the unproductive emissions burden associated with unmated ewe lambs and suggests that ewe lambs should be mated in their first year where possible. However, it is recognised that lambing as yearlings is not implementable on some farms due to limitations in ewe lamb size and live weight (Jones et al., 2013). ADAS (2010a) estimated that 45% or more of English lowland flock replacement females could not be lambed as yearlings. It is also apparent that lambing yearlings may reduce the overall flock ratio of the number of lambs reared per ewe mated. Despite a reduction in that variable, an overall increase in lamb output from stock already on-farm would reduce the CF per unit of lamb produced. This indicates the complexity of the relationships between management variables, and the importance of exploring the whole-farm GHG impacts of mitigation strategies. Similarly, although the rate of concentrate use was found to have a lesser but still significant impact on the size of the CF, reducing concentrate use may reduce growth rates or increase pasture dependence and possibly fertiliser requirements. Therefore, the management focus should be on the efficiency of concentrate use, within the context of overall farm efficiency.

A number of studies have recently modelled the impact of improved productivity on CH_4 emissions from scenario flocks. The most promising improvements in each study respectively were: creep feeding to finish lambs earlier, lambing ewes at a younger age (as yearlings) and selectively breeding ewes to increase litter size (Alcock and Hegarty, 2011; Cruickshank et al., 2008; IBERS, 2011a). Alongside this study's findings, these interventions indicate the importance of lamb growth rates and the lifetime productivity of the ewe in determining CF size. EBLEX (2012) and Foley et al. (2011) also highlighted faster growth rates as a characteristic of low carbon livestock farms. In a recent survey of expert and farmer opinion, both increasing lamb growth rates and improving ewe nutrition in gestation to increase lamb survival were considered effective and practical measures for mitigating emissions on sheep farms (Jones et al., 2013). However, farmer opinions on the practicality of lambing as yearlings were highly polarised (Jones et al., 2013).

It is clear from our findings that at a national level, emphasis for reducing the CF of lamb should be on closing the gap in productivity between poor performing and top performing farms. However, in some farm settings, potential increases in productivity may be inhibited by local conditions or farm priorities. For example, farmers selling lamb directly to the customer may value slower growth because it is perceived to produce better quality meat (Bruce, 2012). Although not considered in this study, an alternative emissions mitigation strategy would be to manage farm grasslands and trees to enhance carbon sequestration. Soussana et al. (2010) found that grassland carbon sequestration could offset a significant proportion of emissions associated with ruminant production systems. Sequestration potential may be limited in older permanent pastures, as it is suggested that soil carbon storage capacity is finite, reaching an equilibrium within 10 to 100 years (Freibauer et al., 2004; Soussana et al., 2010). However, Janssens et al. (2005) estimated that UK grasslands are net carbon sinks, gaining an estimated 0.24 t carbon/ha/yr. Soil carbon stock change should be taken into account in future CF methodologies to recognise emissions mitigated or arising through means other than productivity and efficiency improvements. It should also be considered, that alternative productivity metrics reflecting both food production and environmental priorities, may favour production in extensive systems, e.g. kg of edible output produced per quantity of ecosystem services provided on-farm (Garnett, 2011; Ripoll-Bosch et al., 2013).

2.4.2. Carbon footprint calculation method

2.4.2.1. Co-product allocation

Sheep farms typically produce multiple saleable outputs, necessitating allocation of whole-farm emissions amongst products. In this study, economic allocation was adopted to apportion emissions between co-products including finished lamb, unfinished lambs, cull sheep, breeding sheep and wool. Arguably, allocation by economic value reflects the driving forces for production; however it must be acknowledged that both ISO 14044 and PAS 2050 recommend alternative approaches over economic allocation. Both standards give preference to avoiding allocation by collecting data separately for farm sub-processes, and if this is not possible, by allocating emissions based upon an underlying physical relationship (BSI, 2011; ISO, 2006b). One criticism of economic allocation is that it is contingent upon time and place (Kristensen et al., 2011). In this study, prices for a single year were adopted for economic allocation. An alternative would be to use a long-term average to account for annual variability in prices. However, due to the demands of data collection, obtaining prices for multiple years from farmers was not possible. In practice, economic allocation is the most commonly used approach in CF studies (Nguyen et al., 2013).

Allocation approach is known to have considerable impact on the apportionment of emissions to farm co-products (Crosson et al., 2011). In this study, a number of the farms produced breeding sheep in addition to meat, which because of their economic premium may have skewed the proportion of emissions allocated to finished lamb. In this case, separate sub-process data collection or physical allocation may be preferable, although potentially problematic in data collection terms because these sub-processes typically operate on-farm as a single flock. The impact of farm production orientation on the CF, and the calculation of separate CFs for sheep categories other than finished lamb such as breeding sheep and stores are important areas for future CF research.

2.4.2.2. Purchased sheep

Emissions associated with purchased stock are typically omitted from CF calculations. However, emissions associated with the rearing of purchased rams, ewe replacements and stores should arguably be accounted for within a cradle to farm gate system boundary, in the same way that Rotz et al. (2010) included emissions associated with purchased heifers in their dairy CFs. In this study, we adopted a single EF per kg of live sheep purchased from previous CF estimates. The value adopted was low compared to those estimated in this study for live sheep. A consistent approach is needed in agricultural product CF methodology to account for purchased replacement stock. If replacement stock emissions are omitted, flocks purchasing replacements and stores will be at an advantage over those rearing their own in CF calculations. This study has contributed towards the availability of CF data for other sheep categories alongside finished lamb.

2.4.2.3. Uncertainty in carbon footprint estimates

All CFs reported were mid-range emissions estimates. Although touched upon earlier, uncertainty associated with the estimated CFs was not assessed in this study because of a focus on variation resulting from local conditions and management choices. By using empirical farm data, uncertainty around the input data for individual farms has been reduced, and variation at a multi-farm level captured. The impact of uncertainty in EFs on the CF of lamb warrants a separate study e.g. as conducted by Flysjö et al. (2011) for milk production. Owing to the size of the dataset analysed and the limitations of available emissions data, it was not possible to use EFs specific to each farm type and situation in the CF estimates. The emphasis of this study was on applying an established standard CF model to a large sample of real farms. It is acknowledged that the IPCC Tier 1 methodology adopted represents a generalised approach, which does not account for the impact of localised factors, such as soil type and water content on N_2O emissions. Improving the calculation methodology from IPCC Tier 1 to the IPCC Tier 2 method would be expected to provide a more refined representation of farm systems and emissions. This may allow a more detailed assessment of underlying causes of variation in emissions such as the impact of diet on enteric CH_4 production. Enteric CH_4 and N_2O arising from soil following manure or excreta application are consistently the largest component of the CF and are therefore foci for efforts to refine emissions' models. As EFs and calculation methodologies are refined spatially and temporally, ensuing assessments of the characteristics of a low carbon sheep farm would also be expected to improve.

2.5. Conclusions

Limited research relating to the CF of lamb production has been reported in the scientific literature. This study has provided baseline data on which future lamb CF research can build, including sheep farm characteristics, the breakdown of farm emissions and identification of farm variables that significantly influence the size of the CF. The CF of English and Welsh lamb was highly variable within and across farm categories, suggesting opportunities for improved management choices to mitigate emissions on the poorest performing farms. Lowland sheep farms and those that are highly productive were found to have the lowest CFs per kg of lamb produced. Four farm management variables had a significant impact on the size of the CF across all farms sampled. Of these, the number of lambs reared per ewe mated and lamb growth rate were the most influential. The results suggest that, at a national level the emphasis for reducing the CF of lamb should be on closing the gap in productivity between poor and top performing farms. This study also highlighted the difficulty of striking a balance between data collection effort requirements and subsequent refinement in the CF model.

Chapter 3

Informing decision-making in agricultural greenhouse gas mitigation policy: A Best-Worst Scaling survey of expert and farmer opinion in the sheep industry[1]

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Abstract

Policy decision-making for agricultural greenhouse gas mitigation is hindered by scientific uncertainty regarding the effectiveness of mitigation measures. Successful on-farm adoption of measures is contingent upon farmer perception of the relative practicality of implementing the measure and associated incentives and advice. In the absence of a comprehensive evidence-base, we utilised Best-Worst Scaling, a discrete choice survey method, to elicit expert and farmer opinion on the relative effectiveness and practicality of mitigation measures to reduce greenhouse gas emissions from sheep production systems. The method enabled individual mitigation measures to be ranked on a ratio scale of effectiveness (expert opinion) and practicality (farmer opinion). Six measures were identified as possessing the combined qualities of effectiveness and practicality and are considered priority candidates for policy promotion. The overall preferred measure was the *use of legumes in pasture reseed mixes*. Estimation and analysis of the distribution of individual respondent scores revealed heterogeneity in farmers' perceptions of practicality, suggesting that flexible policies are required to enable farmers to select mitigation measures most suited to their farm type and locality. Practical measures with below average effectiveness may be widely adopted with limited regulation, incentivisation or advice, whilst some highly effective measures with lower practicality are likely to present greater obstacles to adoption.

3.1. Introduction

Increasing numbers of governments throughout the world are committing to reducing greenhouse gas (GHG) emissions across all economic sectors. In the UK, the Climate Change Act 2008 requires a 34% reduction in all GHG emissions by 2020 (from 1990 levels). This has generated agricultural emission reduction targets of 10% by 2020 under the low carbon transition plan in England, and by 3% annually in Wales under the "One Wales" agreement (DECC, 2009; WAG, 2010). Meeting these targets requires reductions in all agricultural sectors including the emissions-intensive red meat industry.

Rearing sheep produces the potent GHGs methane (CH_4) and nitrous oxide (N_2O) which have global warming potentials of 25 and 298 times that of carbon dioxide (CO_2) per kg over a 100 year period (Forster et al., 2007). CH_4 is emitted largely as a by-product of feed fermentation in the animal's rumen; and N_2O is primarily produced from soils in response to fertiliser application and excreta deposition (Edwards-Jones et al., 2009). Multiple, well documented, opportunities exist for reducing and offsetting ruminant emissions on-farm (Eckard et al., 2010; Garnett, 2009; Gill et al., 2010). However, the uptake of mitigation measures (MMs) lags far behind technical potential (Smith et al., 2007a). Effective policy decision-making is therefore needed to prioritise MMs and assess how best to promote their adoption.

Field trials have evaluated the efficacy of individual MMs in localised experiments such as, nitrification inhibitors to reduce N_2O emissions from animal urine patches (Di et al., 2007) and natural dietary supplements to reduce ruminal CH_4 production (Santoso et al., 2004). However, the evidence-base for the relative efficacy of many MMs remains incomplete, lacking the scientific rigour normally associated with randomised control trial settings. Emission values and mitigation potentials are frequently founded upon a number of assumptions, extrapolated data and employed beyond the limited range of conditions in which they have been measured (Lassey, 2007). Considerable uncertainty exists regarding the potential of many MMs due to limitations in the scientific community's understanding of underlying biological processes, and temporal and geographical variation in potential across and within agricultural systems (Smith et al., 2007b).

Currently, meaningful assessment of the effectiveness of MMs is problematic due to the level of uncertainty associated with each intervention which in turn hinders efficient policy-making (Smith et al., 2007b). When confronted with an incomplete systematic evidence-base, alternative methods of evidence rationalisation are required. This frequently involves the provision of recommendations to policy-makers based upon best available data, whilst acknowledging any evidence uncertainties. Eliciting expert opinion and evaluating consensus between experts is one such approach that has been shown to lead to balanced informed decisions (Cross et al., 2012).

In addition to identifying the most effective MMs, policy needs to overcome barriers to uptake through regulation, provision of information and financing (Stern et al., 2006). Delivering emission reductions in the agriculture sector is problematic because measures need to be applicable across tens of thousands of farm holdings which may be very different in terms of size, geography and management. Success will ultimately be contingent upon the willingness and ability of farmers to adopt MMs. Information on the extent to which farmers perceive each MM as practicable is required to assess the likely future rate and degree of adoption. This approach recognises the importance of farmer inclusion in rural policy development, and specifically of the inclusion of behavioural science elements into GHG mitigation research (Norse, 2012; Oliver et al., 2012).

Several methods have been used to elicit expert and farmer opinion on environmental issues. Commonly in agricultural GHG mitigation research, a qualitative approach has been followed, using open-ended survey questions or group discussion at workshops and on expert panels to elicit individual or group opinion (Barnes et al., 2010; Moran et al., 2008). Alternative quantitative approaches include the use of Likert and other rating scales (MacLeod et al., 2010b; Sullivan et al., 1996) and discrete choice surveys to analyse choice behaviour and determine preference scores for alternative items. Typically, discrete choice surveys require respondents to make trade-offs between items of interest to reveal their relative preferences for each item. Examples in agricultural research include the use of conjoint analysis to determine farmer and veterinary preferences for animal disease mitigation strategies, and the "potentially all pairwise rankings of all possible alternatives" method to determine expert and farmer preferences for alternative sheep breeding objectives (Byrne et al., 2012; Cross et al., 2009). Best-Worst Scaling (BWS) is an alternative discrete choice technique that enables large numbers of stand-alone items to be ranked (Cross et al., 2012). It is typically employed in health, social science and market research and has recently been successfully used to evaluate MMs at a farm scale in relation to animal and zoonotic disease management (Auger et al., 2007; Cross et al., 2012; Lusk and Briggeman, 2009; Marti, 2012). In this context, we employed BWS to elicit expert and farmer opinion on the effectiveness and practicality of GHG reducing MMs at a sheep farm scale.

3.1.1. Progress in the UK

The UK has developed a stronger evidence-base than many countries for decision-making in agricultural emissions mitigation (Norse, 2012). The marginal abatement costs of a range of measures have been estimated for average sized cereal, mixed and dairy farms (Moran et al., 2008). Sheep were excluded from the analysis but several of the top performing MMs possess the potential to reduce GHGs when evaluated in a sheep farm setting. Using the results of this study, Jones et al. (2010) assessed the cost-effective mitigation potential for a range of farm types and sizes, taking into account current uptake levels. MMs estimated to have the greatest potential for mitigation on beef and sheep farms were ‘optimum diet formulation’, ‘livestock breeding’ and ‘use of clover’; all of which were found to be cost negative (i.e. money saving). Initial assessment of farmers’ attitudes revealed drivers for and barriers to the uptake of MMs including finance, knowledge and understanding of MMs and whether other local farms have successfully adopted the MM (Barnes et al., 2010).

Here we seek to strengthen and refine this body of knowledge from a sheep farm perspective. We assessed the relative effectiveness and practicality of MMs applicable to sheep farms across England and Wales. The study was undertaken with the specific objectives of: (1) identifying the most effective MMs for reducing or offsetting total farm GHG emissions across sheep farms in England and Wales; (2) identifying the most practical MMs for implementation on sheep farms; (3) comparing and contrasting expert opinion on effectiveness and farmer opinion on practicality (4) exploring how variation in effectiveness and practicality scores can help to shape policy and focus advisory and financial resources to aid delivery.

3.2. Methods

3.2.1. Best-Worst Scaling (BWS)

BWS is an extension of the method of paired comparisons. Respondents are shown a predefined number of sets of five 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).

BWS holds a number of advantages over traditional alternatives of rating and ranking scales because it is less cognitively demanding to select extremes on a scale rather than ranking all items simultaneously; it avoids scale bias and provides improved discrimination between items (Cross et al., 2012; Finn and Louviere, 1992; Marti, 2012). Selection of best and worst items also provides sufficient information to calculate the preference scores of each survey respondent, allowing heterogeneity of responses for individual items to be assessed.

3.2.2. Short-listing mitigation measures

Eighty candidate MMs were initially identified through a search of the relevant academic peer-reviewed and grey literature. This list consisted of 17 MMs relating to productivity (breeding, fertility and health); 10 MMs relating to rumen manipulation and dietary additives; five MMs relating to diet quality; 15 MMs relating to pasture, grazing and soil management; seven MMs relating to solid manure storage; nine MMs relating to fertiliser management;

eight MMs relating to energy use on-farm and embedded in farm inputs; and nine MMs relating to carbon storage.

A preliminary expert panel was presented with the task of reducing this list of 80 MMs to a more manageable 26. Experts evaluated each measure in terms of its potential to reduce GHG emissions per kg of sheep meat produced on farms across England and Wales. The classification options were “very effective”, “quite effective”, “ineffective” or “don’t know”. Responses were scored with values of “2”, “1”, “-1” and “0”, respectively, and summed for each MM. The top 26 scoring MMs were subsequently used to populate the BWS survey (Table 3.1).

Table 3.1. 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

3.2.3. Survey design

Respondents were presented with 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. Four or five items per set are regarded as optimal for respondent evaluation, more than this may lead to respondent fatigue (Sawtooth Software, 2007). In order to keep the number of items per set to a manageable five and to ensure each item was shown to each respondent more than twice in a different set, we used 13 choice sets per survey. Both BWS surveys were designed and analysed using the software Sawtooth SSI Web.

One thousand possible survey designs were generated for each survey. Optimal designs were selected based on the primary criterion that each MM appeared an equal number of times. Secondary and tertiary criteria were that each MM was paired with any other MM an equal number of times, and that each MM occurred on the left and right of the page an equal number of times (Sawtooth Software, 2007). We used multiple versions of each survey to increase variation in the position and combination of MMs across respondents, reducing any potential context bias (Sawtooth Software, 2007).

3.2.4. Data collection

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 (see Appendix A for an example of the paper BWS surveys used with farmers). Data were collected at agricultural shows across England and Wales between May and August 2012. Demographic data collected related to the farmer and their land and included farmer age (18-34, 35-44, 45-54, 55-64, 65+); country in which they farm (England, Wales); farm type (specialist sheep, sheep and arable, sheep and cattle, sheep and other livestock, mixed i.e. sheep, livestock and crops); dominant land classification (lowland, upland, hill); breeding ewe flock size (1-49, 50-99, 100-199, 200-499, 500-999, 1000-2000, 2000+); and whether they had already implemented any MMs (yes, no).

3.2.5. Analysis

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 effectiveness score for respondent n and measure A is modelled as:

$$E_{nA} = \delta_A + \varepsilon_{nA}$$

where δ_A is the position of measure A on the underlying effectiveness scale and ε_{nA} is an error term. In a subset of five MMs there are twenty possible best-worst combinations. The model defines the probability of respondent n 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 (MNL) 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. For further details of the workings of the MNL model and individual level score estimation see Cross et al. (2012), Finn and Louviere (1992) and Sawtooth Software (2007). The effectiveness and practicality scores were rescaled to sum to 100 across all MMs, placing the scores on a ratio scale and aiding interpretation.

Based on individual scores we also calculated individual fit statistics which are a measure of internal consistency indicating the reliability of a respondent's answers. Any respondent whose fit statistic was less than 25% was removed from further analysis as their responses were considered unreliable (5 farmers).

Farmer demographic data 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. Effect size indices (eta^2) were calculated for each MM indicating the proportion of variance in scores accounted for by each grouping variable. All statistical tests were performed using SPSS 19 (IBM Corp., Armonk, NY, USA).

3.3. Results

3.3.1. Expert and farmer participation

Responses from 55 expert and 225 farmer surveys were analysed. Two hundred and twenty three farmers provided demographic information. Approximately half of the respondents farmed in England (53.8%) and half in Wales (46.2%). A number of farmers said they had already implemented at least one of the MMs in the survey (43.9%).

3.3.2. Expert effectiveness scores

The estimated mean expert scores for the 26 MMs obtained via the choice model described in section 3.2.5, were ranked on a scale of effectiveness (Fig. 3.1). The scores were zero-centred so that the y-axis represented the overall mean effectiveness score of the 26 MMs. Measures to the left of the x-axis received below average effectiveness scores and measure to the right of the x-axis achieved above average effectiveness scores.

Seven measures received scores that were significantly above the mean (i.e. their confidence intervals (CI) do not overlap the zero-centre (Fig. 3.1)). *Increasing the number of lambs born per ewe* (10) was deemed the most effective MM. Four other MMs aimed at improving productivity were also amongst the most effective. The only non-productivity related measures that achieved scores significantly different from the mean were the *inclusion of legumes in pasture reseed mixes* (7) and *reducing mineral fertiliser use* (16). *Calibrating and maintaining spreader equipment* (6) and *splitting fertiliser applications* (17) were considered the least effective.

The CIs around the mean scores indicate uncertainty and/or disagreement associated with the effectiveness of the MMs. Overall, the width of the CIs increases as the mean score of the measures increase.

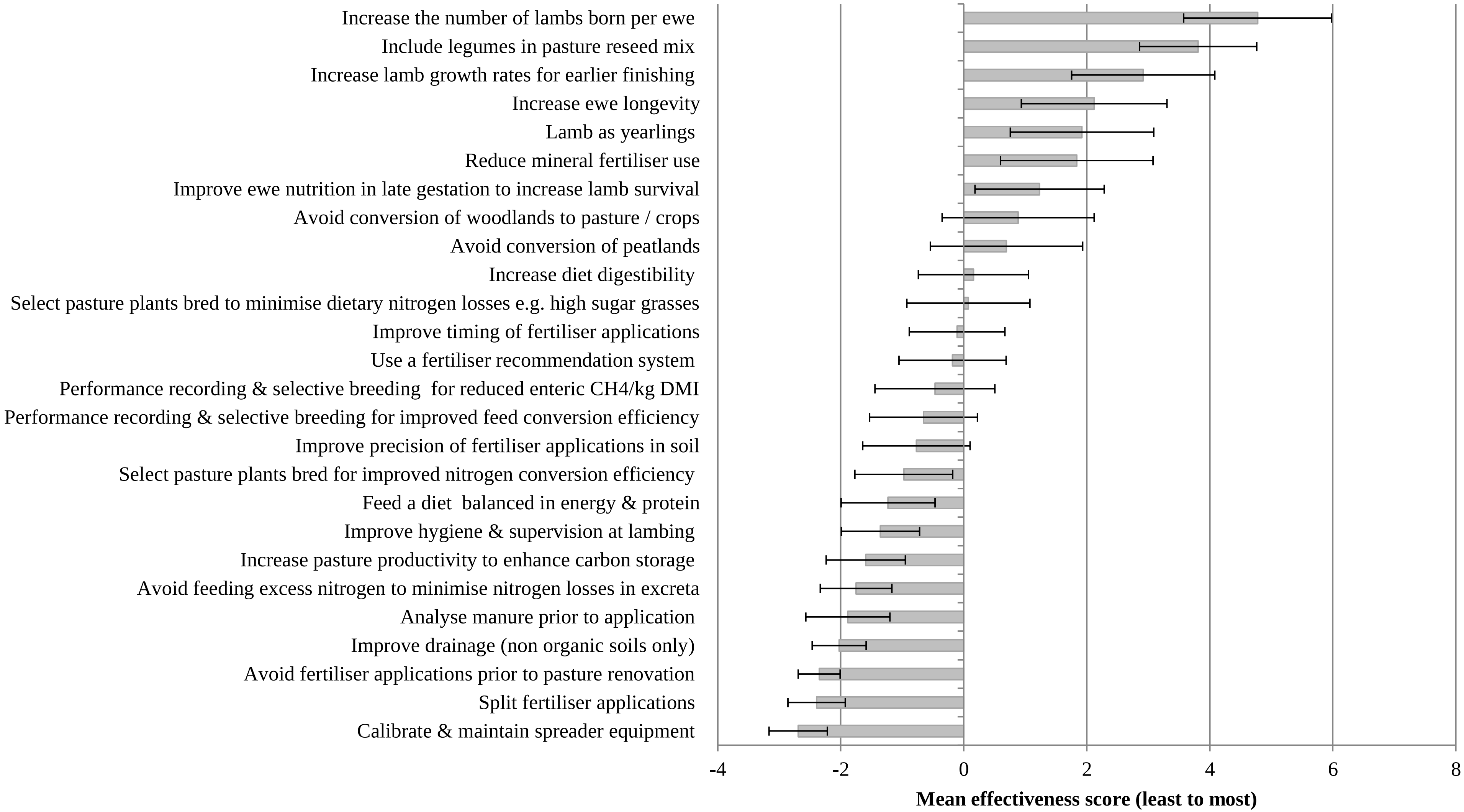


Fig. 3.1. Mean estimates of the effectiveness scores across all experts for the 26 short-listed mitigation measures. The error bars represent 95% confidence intervals of the mean scores.

3.3.3. Farmer practicality scores

The estimated mean farmer scores for the 26 MMs were ranked on a scale of practicality (Fig. 3.2). Again the scores have been zero-centred so that the y-axis represents the mean practicality score of the 26. Nine measures had practicality scores significantly different to the overall mean. The top four MMs received practicality scores which were significantly higher than all other MMs. These were the *inclusion of legumes in pasture reseed mixes* (7), *improving ewe nutrition in late gestation to increase lamb survival* (14), *improving hygiene and supervision at lambing* (21) and *selection of pasture plants bred for improved nitrogen conversion efficiency* (23). The least practical MM was *selective breeding for reduced enteric CH_4 production* (20).

The CIs associated with the mean practicality scores were smaller than those associated with the mean expert effectiveness scores, indicating a higher-level of agreement and certainty relating to practicality overall. In general, variation around the mean increased with practicality score. *Lambing as yearlings* (19) exhibited the greatest heterogeneity of responses.

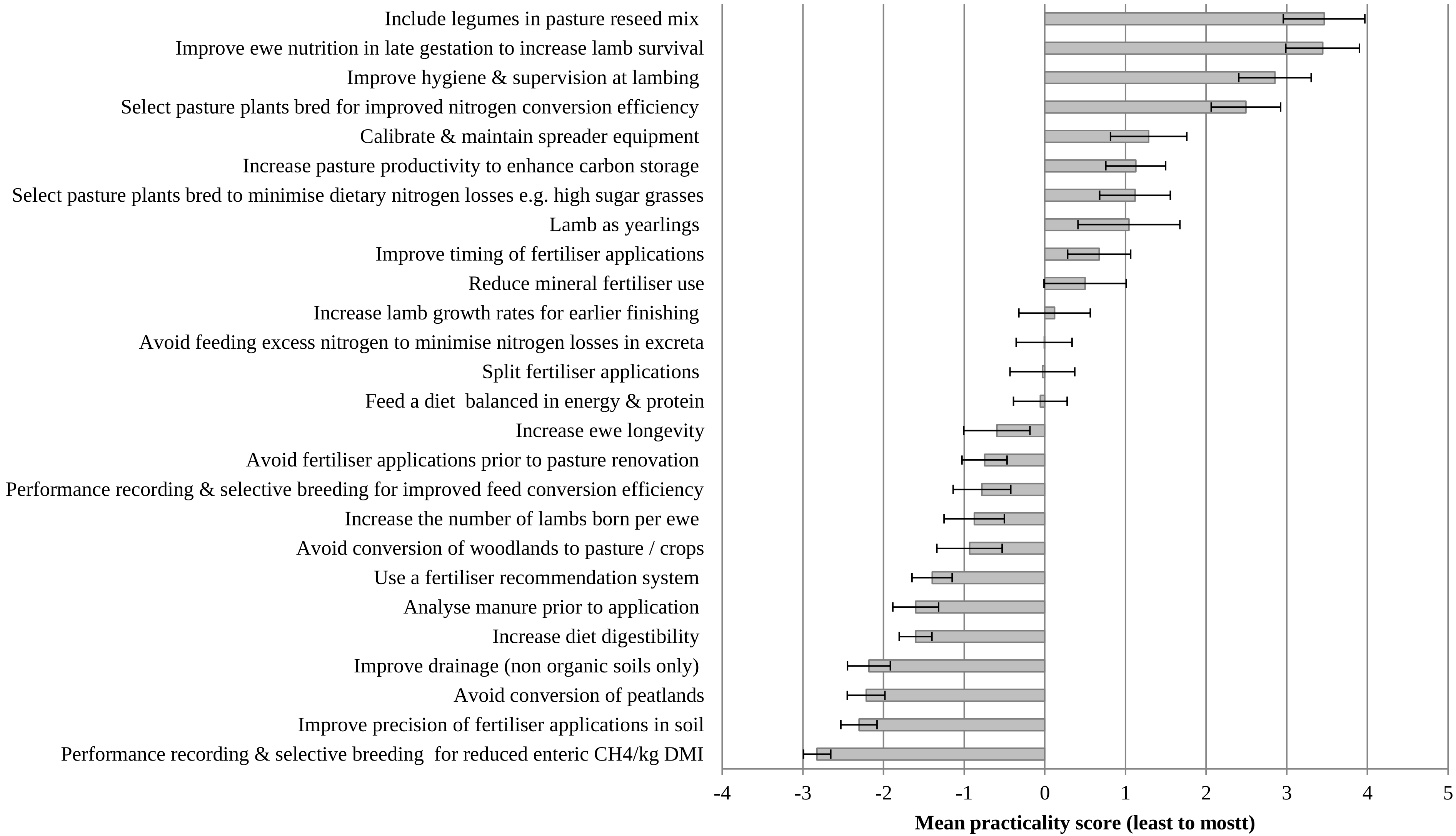


Fig. 3.2. Mean estimates of the practicality scores across all farmers for the 26 short-listed mitigation measures. The error bars represent 95% confidence intervals of the mean scores.

3.3.4. Effectiveness and practicality combined

Both the mean expert effectiveness and farmer practicality scores were zero-centred and plotted in an effectiveness and practicality 2 x 2 space (Fig. 3.3). 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)).

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.

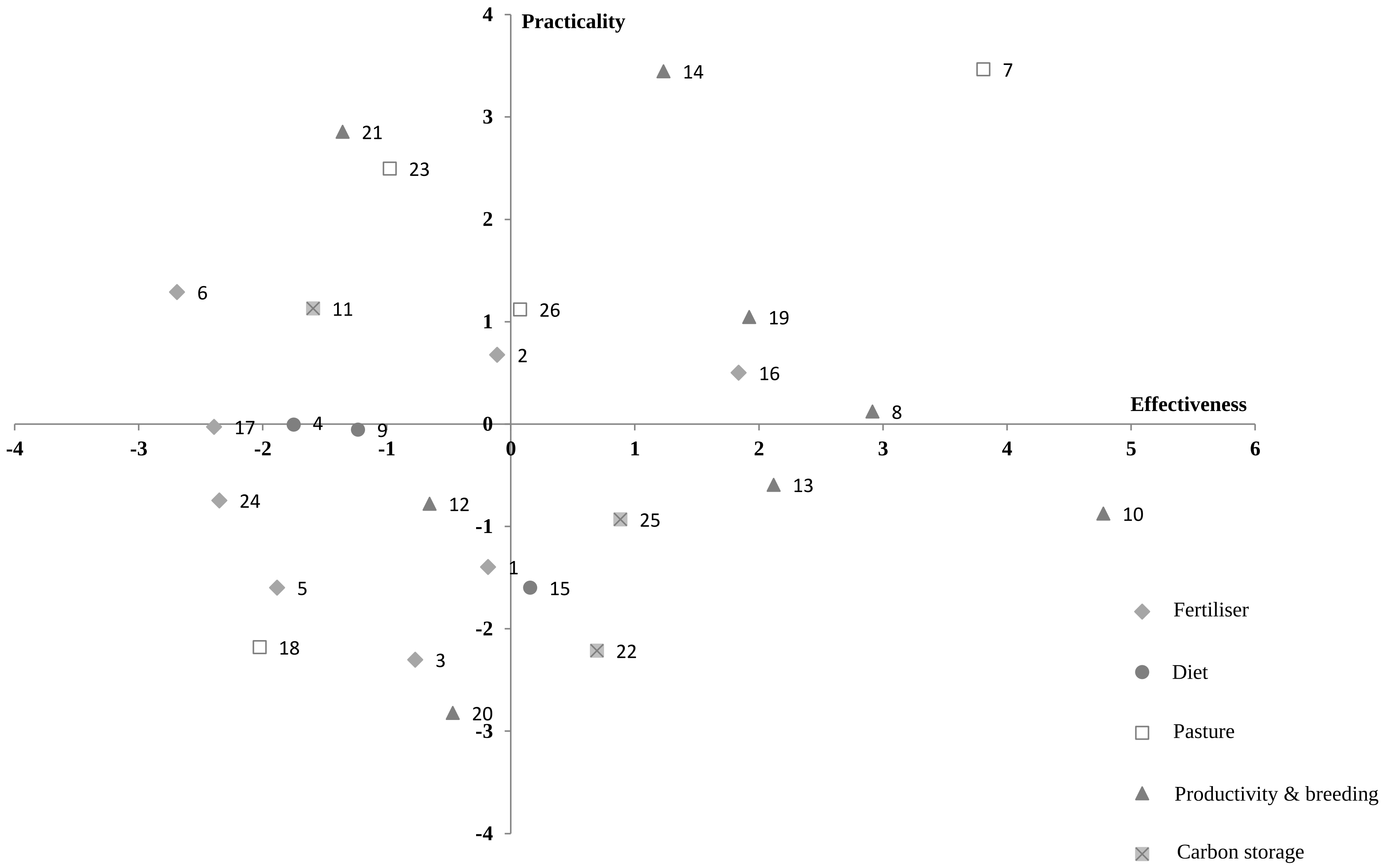


Fig. 3.3. Zero-centred scatter plot of mean effectiveness and practicality for the 26 mitigation measures, categorised by mitigation type.

3.3.5. Heterogeneity in farmer responses

The practicality scores from the multinomial logit model reported in sections 3.3.3 and 3.3.4 reflect the mean preference for MMs across all respondents. Although we are primarily interested in identifying consensus, mean scores across all respondents can mask potentially informative heterogeneity in preference between respondents.

3.3.5.1. Frequency distributions of respondent scores

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. 3.4 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 3.4a and 3.4c). For MMs 8, 16 and 19 opinion was divided (Fig 3.4b, 3.4d and 3.4e). 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.

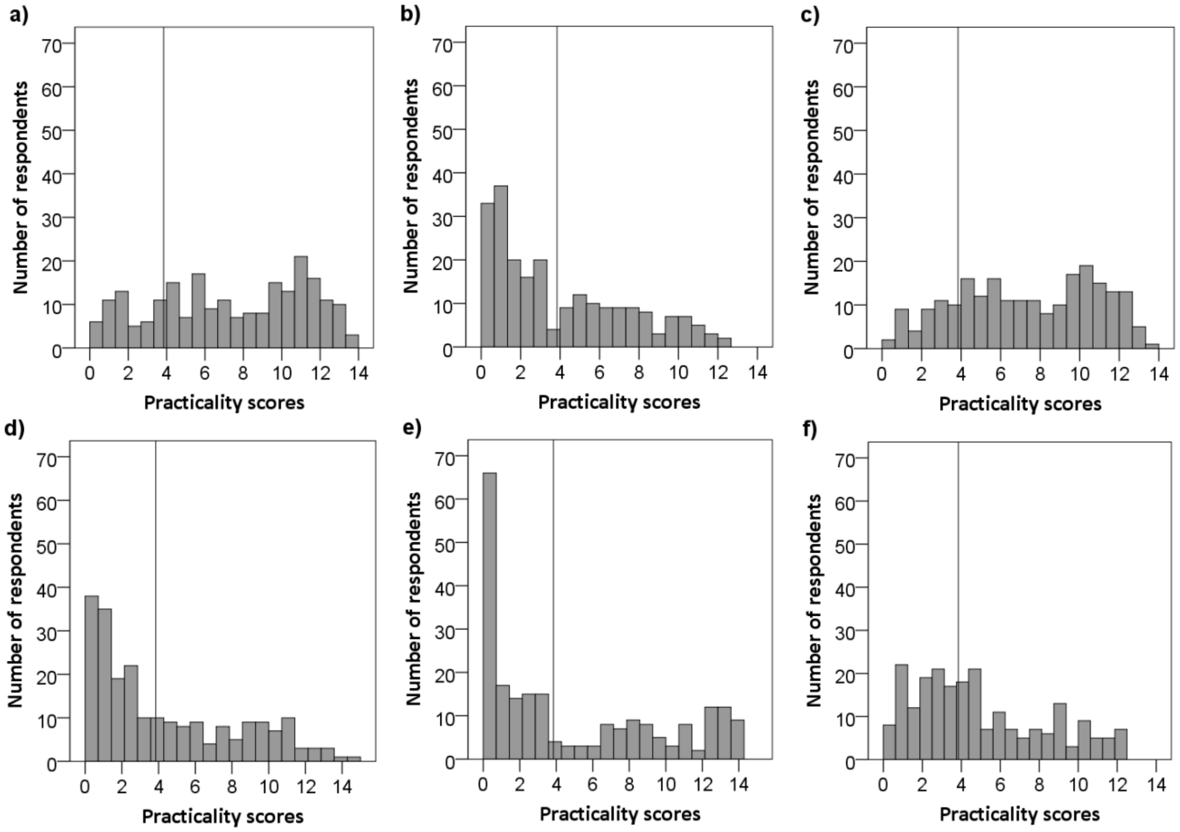


Fig. 3.4. Distributions of individual level farmer practicality scores for the top mitigation measures: (a) Include legumes in pasture reseed mix (7), (b) Increase lamb growth rates for earlier finishing (8), (c) Improve ewe nutrition in late gestation (14), (d) Reduce mineral fertiliser use (16), (e) 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.

3.3.5.2. Comparison of scores between subgroups

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 (Table 3.2). The results suggest that farmers who have already implemented at least one MM perceived the *inclusion of legumes in pasture reseed mixes* (7) to be more practical than farmers who had not implemented any MMs (p=0.004). 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. The effect-size index for this test showed that flock size accounted for 6.0% of the variation in practicality scores for this MM. 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). *Reducing fertiliser use* (16) was perceived more practical by English farmers compared to their Welsh counterparts (p=0.007), and by specialist sheep farmers compared to sheep and cattle farmers (p=0.032).

The indices of effect-size revealed that the six grouping variables combined explained an average 10.8% of the variation in practicality scores for the six MMs. These relatively low effect-sizes indicate that there are other unidentified factors driving heterogeneity in practicality scores.

Table 3.2. Mean (and median) farmer practicality scores for the top rated mitigation measures by subgroup of respondents. Scores are on a ratio scale of 1 to 100. Mitigation measures 14, 19 and 26 are not shown because there were no significant differences between any compared categories. The grouping variables age and land classification are also omitted because there were no significant differences between categories for any of the mitigation measures.

		Mitigation Measure Number		
Grouping Variable	Category	7	8	16
Country	England	7.04 (7.30)	3.90 (2.65)	4.81 (3.63)^{a}
	Wales	7.64 (8.64)	4.09 (2.99)	3.79 (1.90)^{b}
Farm type	Specialist sheep	7.07 (6.69)	4.12 (2.77)^{a}	5.26 (3.70)^{a}
	Sheep & arable	6.80 (6.53)	1.87 (0.75)^{b}	5.46 (4.41)
	Sheep & cattle	7.66 (8.30)	4.10 (3.00)^{a}	3.77 (2.22)^{b}
	Sheep & other livestock	6.62 (6.81)	4.76 (4.28)	4.67 (3.70)
	Mixed	5.67 (5.16)	3.00 (1.14)	2.70 (2.50)
Breeding ewe flock size	1-49	5.96 (5.72)	2.38 (1.31)^{a}	5.59 (4.48)
	50-99	6.72 (5.58)	4.77 (4.57)	4.75 (3.54)
	100-199	7.57 (8.49)	4.80 (3.89)^{b}	4.16 (1.80)
	200-499	7.50 (8.00)	4.08 (3.05)	3.90 (2.74)
	500-999	7.63 (8.66)	4.19 (2.89)	3.55 (2.06)
	1000-2000	8.52 (9.36)	3.49 (2.63)	4.77 (4.98)
	2000+	6.97 (7.21)	5.21 (6.09)	4.47 (3.49)
Already implemented a MM?	Yes	8.19 (9.03)^{a}	4.31 (2.99)	4.15 (2.75)
	No	6.64 (5.98)^{b}	3.73 (2.63)	4.49 (2.77)
Overall Mean		7.31 (7.39)	3.97 (2.87)	4.35 (2.77)

Different superscript letters indicate statistically significant differences between categories within a grouping variable for a particular mitigation measure (p<0.05, adjusted for multiple comparisons).

3.4. Discussion

This study was undertaken with the objective of refining the knowledge base for decision-making in GHG mitigation strategies and policy relevant to sheep farms. In decision-making situations where not all influential variables are known or quantified, multiple experts' opinions are essential for the development of effective solutions (Vrana, 2008). BWS provides a means of consolidating expert opinion on GHG MMs, enabling ranking on a single scale of effectiveness. Consideration of farmer perception of practicality has added another crucial dimension to inform the decision-making process, with perceived practicality serving as an indicator of future likely levels of adoption.

Typically, GHG mitigation action plans and roadmaps incorporate numerous MMs with no clear means of prioritisation. Our preliminary expert survey short-listed 26 MMs. No MMs relating to manure storage or energy use were short-listed, reflecting the limited contribution of these elements to the carbon footprint of sheep meat production. No MMs involving dietary additives or rumen manipulation were short-listed (for example plant extracts, probiotics and vaccination against rumen methanogenesis). Our surveys revealed a higher degree of certainty and agreement on which measures are ineffective and impractical, but less certainty and agreement on which measures are the most effective and most practical, demonstrating the difficulty associated with achieving consensus in this field.

Using the mean scores of the short-listed MMs, we identified six which were considered both effective by experts and practical by sheep farmers. These six (located in the upper right quadrant of Fig. 3.3) can be considered priority candidates for inclusion in sheep industry mitigation strategies. Although there are no previous sheep-only studies explicitly evaluating the relative effectiveness and practicality of MMs, some studies, focusing on livestock and / or crops, have also short-listed or prioritised measures to enhance productivity and fertility, the introduction of new seed mixes and fertiliser reduction (Jones et al., 2010; Moran et al., 2008). Measures targeting livestock productivity and breeding have been estimated to have negative marginal costs per tonne of carbon dioxide equivalents (CO_2e) abated when assessed for other livestock (Jones et al., 2010; Moran et al., 2008). The marginal abatement costs associated with reseeding and the reduction of fertiliser use are dependent upon the yield impact of the MMs (Moran et al., 2008). Assuming no reduction in yield and a 50% reduction in nitrogen use, Jones et al. (2010) estimated that the use of clover would save over £100 per tonne of CO_2e abated, even on less favoured area beef and sheep farms. Ensuring the adoption of MMs will require dedicated policies or incentives to help farmers overcome barriers to uptake, particularly when the measures are unprofitable (Smith et al., 2007b). Even cost-negative (money saving) MMs may require information campaigns to improve farmer perception and encourage implementation (Barnes et al., 2010). Focussing policy instruments on the implementation of these top six MMs could be considered an effective use of resources.

Analysis of the distribution of individual level scores for the top-rated measures indicated that the level of regulation, financial and/or advisory support required to ensure successful implementation may vary between segments of the sheep farming community. *Inclusion of legumes* (7) and *improving ewe nutrition in late gestation* (14) received above average scores from the majority of farmers and consequently could be recommended for implementation across all sheep farm types. Consultation with farmers suggests 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). Farmer opinion was divided on the practicality of *increasing lamb growth rates* (8), *reducing fertiliser use* (16) and *lambing as yearlings* (19). Consequently, there is no one set of "*universally applicable*" mitigations applicable to all UK sheep flocks (Stewart et al., 2009). *Lambing as yearlings* (19) was scored very low by the majority of respondents but very high by a small subset as it is not implementable on some farms due to limitations in ewe lamb size and live weight. It is estimated that up to 55% of English lowland flock replacement females could be lambed as yearlings (ADAS, 2010a). These differences in potential across the UK flock suggest that a combination of approaches may be better suited to the effective mitigation of emissions. Flexible policy should allow farmers to select the MMs that are most suited to their own situation. Where a priority MM is not possible on a particular farm, policy instruments ideally need to facilitate the selection of alternative MMs.

Differences in the distributions of individual level scores between pre-defined sub-groups of the sheep industry also affirmed the importance of flexible policy instruments, and indicated that tiered levels of support may be needed for some MMs. *Increasing lamb growth rates for earlier finishing* (8) is one such MM. Farms with very small sheep flocks (1 to 49 breeding ewes) and farms that produce arable crops in addition to livestock (i.e. not ruminant specialist farms) may need a higher-level of support than larger and specialist livestock farms to implement this, and possibly other breeding related MMs. Taking steps to ensure adoption in smaller flocks is important because approximately 36% of UK farm holdings with sheep have flock sizes between 1 and 49 breeding ewes (DEFRA et al., 2012). The effect-size indices calculated indicated that substantial variation remains unexplained for farmer scores. Further work is needed to identify sub-groups of sheep farmers for each MM to ensure well targeted policy instruments.

MMs that fall outside the upper right quadrant of the effectiveness-practicality plot pose interesting trade-offs and considerations for decision-makers. Measures in the upper left quadrant with below average effectiveness scores may achieve wider adoption than measures in the lower right quadrant with above average effectiveness due to their greater practicality. These upper left MMs may also require lower levels of regulation or support to ensure their implementation than the lower right MMs. The most effective measures according to expert consensus are *increasing the number of lambs born per ewe* (10) and *increasing ewe longevity* (13). These MMs feature in the national red meat emission reduction roadmaps of England and Wales (EBLEX, 2009; HCC, 2011). Overall, farmers perceived these measures to have slightly below average practicality. A greater level of advisory support or improved communication of the cost-benefits of these measures in terms of productivity may help to improve perception of practicality and implementation. Further research on farmer attitudes is needed to discover what mechanisms could improve likely uptake of these MMs.

One crucial consideration in the development of mitigation strategies, not touched upon here, is the need for additive MMs at a farm-level. Several of the top six MMs are compatible. The productivity measures *increasing lamb growth rate* (8), *improving ewe nutrition in late gestation* (14) and *lambing as yearlings* (19) are potentially complementary, if practical on-farm. Faster growth rates in replacement lambs in addition to slaughter lambs could make lambing as yearlings more feasible. This set of productivity MMs could also be combined with a pasture based MM such as *inclusion of legumes* (7). *Reduction of fertiliser use* (16) should occur as a direct result of the *inclusion of legumes* (7) therefore the abatement potential of these MMs is not additive. *Inclusion of legumes* (7) and *selection of pasture plants bred to minimise dietary nitrogen losses* (26) may not be possible in combination nor have additive abatement potentials. Alongside flexibility in the selection of MMs, farmers will need advice on successful combinations suited to their locality and farm type.

A complete systematic evidence-base for sheep farm GHG mitigation would include life cycle assessment data and marginal abatement costs for all MMs, alone and in combination with other MMs against a range of farm baselines and conditions. Here, we have provided a brief overview of current expert opinion on the effectiveness of MMs at a single point in time based upon current scientific understanding. We have not explicitly considered costs or uptake potential; however farmer practicality scores are inevitably influenced by their perception of these factors. A natural extension of this research would be to model the GHG abatement potential and costs of the top rated MMs on a range of sheep farm types.

3.5. Conclusions

The absence of a systematic evidence-base can hinder the decision-making process in the development of agricultural GHG mitigation strategies. Best-Worst Scaling represents a unique tool for eliciting expert opinion and drawing consensus on a range of potential mitigation options. Eliciting farmer opinion on the same set of MMs is a crucial step in bridging the gap between strategy and implementation. Twenty-six short-listed MMs have been ranked on a single scale of expert effectiveness and separately on a scale of farmer practicality. Six MMs were considered both effective by experts and practical by farmers and are priority candidates for inclusion in mitigation strategies and for promotion in policy. Practical MMs with below average effectiveness may be widely adopted with limited regulation, incentivisation or advice whilst some highly effective measures with lower practicality are likely to have more limited adoption and require greater regulation, incentivisation or advice. Estimation and analysis of the distribution of individual respondent scores has provided invaluable insights into heterogeneity in farmers' perceptions, supporting more targeted use of financial and advisory resources. Even MMs achieving high mean practicality scores divide farmer opinion. Some MMs are not possible for particular sheep farm types or locations. Flexible policies are needed to enable farmers to select the MMs that are most suited to their own situation. Significant advice and support will be needed to enable farmers to adopt combinations of MMs with additive abatement potential suited to their farm type and locality.

Chapter 4

Developing marginal abatement cost curves: Cost-effective mitigation opportunities for sheep farming systems

Abstract

Marginal abatement cost curves (MACCs) provide a simple graphical representation of the abatement potential and cost-effectiveness of mitigation measures, offering a useful tool for decision-making in greenhouse gas policy. A suitably robust evidence-base to enable MACC development is currently lacking for mitigation measures appropriate to sheep systems. This study constructed farm-level MACCs for a lowland, upland and hill sheep farm in the UK, indicating the most cost-effective mitigation measures for each farm type. The stand-alone mitigation potential of six measures was modelled on a farm-by-farm basis, against the real farm baselines, according to assumed impacts on emissions and productivity detailed in published literature. Estimated abatement potentials were reported per kg of lamb produced and cost-effectiveness was reported in £ per tonne of carbon dioxide equivalents abated. As in other agricultural sectors, the MACCs revealed the potential for negative cost emissions' abatement in the sheep industry. Across all farms, the measure *improving ewe nutrition to increase lamb survival* offered considerable abatement potential at a negative cost to the farmers. *Lambing as yearlings* also offered competitive abatement potential at a negative cost on lowland and upland farms but was not considered technically possible on the hill farm. The results broadly advocate maximising lamb output from existing inputs on all farm types, and highlight the importance of productivity and efficiency as influential drivers of emissions abatement in the sector. The abatement potentials and costs of other measures were more varied, and demonstrated the importance of accounting for differences in farm management between baseline scenarios. Identified heterogeneity in the abatement potential and marginal cost of mitigation measures appeared to be a result of differences in individual farm management more often than land classification. The construction of further case-study farm MACCs is recommended to define the management scenarios and conditions in which each measure is most effective, enabling guidelines to be developed. Case-study farm-level MACCs have been demonstrated to be an important tool for refining agricultural GHG mitigation priorities, with the potential to inform both farm-level mitigation strategies and higher-level policy.

4.1. Introduction

It is estimated that agriculture produces approximately 10-12% of global anthropogenic greenhouse gas (GHG) emissions (Smith et al., 2014). Corresponding figures for England and Wales are 7.6% and 12.9% of GHG emissions, respectively (Salisbury et al., 2013). As an important source of emissions, the agricultural sectors in England and Wales are required to contribute to the UK commitment of reducing total national GHG emissions by 80% by 2050 (from 1990 levels) under the Climate Change Act 2008 (DECC, 2011). Agricultural emissions are dominated by methane (CH_4), emitted largely as a by-product of feed fermentation in ruminant animals, and nitrous oxide (N_2O), primarily produced from soils in response to fertiliser application and excreta deposition (Edwards-Jones et al., 2009; Salisbury et al., 2013). The first and last of these can be primarily attributed to ruminant livestock production.

Mitigation measures (MMs) with potential to abate emissions from ruminant farm systems are well documented (e.g. Eckard et al., 2010; Gill et al., 2010; Jones et al., 2014a), and conceptually, the research and policy drivers needed to deliver emissions' abatement at the farm-level are well understood. Such drivers are founded upon an evidence-base that enables the selection of effective MMs based upon their lifecycle GHG impacts and costs, alone and in combination with other MMs, for a range of farm baselines and conditions (Jones et al., 2013). Beyond the selection of effective MMs, policy must promote implementation through regulation, provision of information and financing (Stern et al., 2006). Despite this conceptual understanding, evidence on abatement potentials, costs and policy mechanisms for implementation remains fragmentary. The challenge of reducing emissions from this sector is compounded by its heterogeneous nature. Farm productivity, emissions and abatement potential vary spatially and temporally in relation to biophysical and management conditions (Beach et al., 2008). Furthermore, calculations of abatement potential must account for all carbon dioxide (CO_2), CH_4 and N_2O fluxes and the interactions between them (Schils et al., 2005; Stewart et al., 2009).

Whole-farm GHG models provide a representation of complex farm systems, their material and nutrient flows and related GHG emissions, which allow exploration of the abatement potential of farm-level MMs (Jones et al., 2014a; Schils et al., 2007). A number of studies have used whole-farm models to determine the abatement potential of single or multiple measures applied to case-study or modelled average farms (e.g. del Prado et al., 2010; Schils et al., 2005; Stewart et al., 2009). Consideration of the costs and benefits of MMs assessed in whole-farm models is necessary to facilitate final selection and implementation (e.g. del Prado et al., 2010; Gibbons et al., 2006). Such MMs can be cost-effective per tonne (t) of CO_2 abated in the context of both abatement from other sectors e.g. power and manufacturing (Norse, 2012), and when compared to the damage costs of carbon emissions (Moran et al., 2011).

In the UK, the evidence-base for cost-effective MMs is more developed than in many other countries (Norse, 2012). Moran et al. (2008) constructed marginal abatement cost curves (MACCs) for average sized cereal, mixed and dairy farms in the UK and scaled their results to the national level to inform the development of carbon budgets in climate mitigation policy. They estimated that approximately 17.3% of the UK's agricultural GHG emissions (in 2005) could be abated at a cost of less than £100/t CO_2 equivalents (CO_2e) in 2022, in their central feasible abatement scenario. Sheep farms were excluded from the analysis but several of the top performing MMs possess the potential to reduce GHGs when evaluated in a sheep farm setting. Using the results of this study, Jones et al. (2010) assessed the cost-effective mitigation potential for a range of farm types and sizes, taking into account current uptake levels. Mitigation measures possessing the greatest potential to reduce emissions on beef and sheep farms were: optimum diet formulation, livestock breeding and use of clover; all of which were found to be cost negative (money saving). Marginal abatement cost curves such as those constructed by Moran et al. (2008) are now a commonly used tool in the assessment of MMs for climate policy development (Kesicki and Strachan, 2011).

4.1.1. Marginal abatement cost curves

The first MAC curves, originally called supply curves, were developed by Meier (1982) to assess the cost-effectiveness of residential energy conservation measures. This approach was subsequently adopted to identify cost-effective abatement measures in the fields of air and water pollution (e.g. Braden et al., 1989; Silverman, 1985), and later GHGs (e.g. Nordhaus, 1991). The first agricultural GHG MACCs appeared in around 2000 (e.g. McCarl and Schneider, 2000). Many more have since been constructed; ranging from the farm-level nutrition-focussed MACCs of the Institute of Biological, Environmental and Rural Studies (IBERS) (2010) to whole agricultural sector MACCs at a regional, European and global level (Beach et al., 2008; De Cara et al., 2005). An array of methodological approaches exist in the MACC literature, variations include: the system boundary used for GHG modelling; the nature and extent of costs and benefits accounted for and associated choice of discount rate; the treatment of interactions between MMs; and the timescale over which MMs have been applied. Despite these differences in approach, providing assumptions are clear and limitations are communicated, MACCs enable simple interpretation of cost-effectiveness data for the multiple stakeholders involved in climate change policy (Kesicki and Ekins, 2012; Kesicki and Strachan, 2011).

Marginal abatement cost curves provide a graphical representation of the relationship between abatement potential and costs. They can be constructed using either, an "engineering" approach based on modelled abatement potentials and costs for individual MMs, or derived using energy models at the systems level where the introduction of a constraint such as a CO_2 tax leads to emissions' abatement (Kesicki and Strachan, 2011; Vermont and De Cara, 2010). In an engineered MACC, each bar on the graph represents an individual MM. The width of the bars on the x axis indicates abatement potential, whilst the height of the bar on the y axis indicates the marginal cost of emissions' abatement (e.g. in £/t CO_2e) (Kesicki and Strachan, 2011).

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. This study builds on the previous sheep farm emissions abatement work of Jones et al. (2013; 2014b) (Chapters 2 and 3) which estimated the mean carbon footprint (CF) of finished lamb produced in England and Wales, and identified practical and effective MMs for lamb-producing farms based on expert and farmer opinions. The specific objectives of this study were to:

1) Use a whole-farm model to estimate the abatement potential of pre-selected MMs on case-study lowland, upland and hill sheep farms in England and Wales.
2) Calculate the private costs and benefits of the MMs to the farmers.
3) Construct a lowland, upland and hill MAC curve that enables the results to be scaled to other farms.
4) Augment the evidence-base on cost-effective MMs applicable to sheep farms.

4.2. Methods

4.2.1. Mitigation measure selection

Modelled MMs were based on the selection criteria of Jones et al. (2013) (Chapter 3). They identified a subset of six, considered to be both practical to implement by farmers and effective in reducing emissions by agricultural GHG experts. 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). This approach allows consideration of MMs that increase farm productivity and possibly total farm emissions, but crucially reduce emissions per kg of product. The MMs, listed below, are numbered here and throughout for consistency with the original study (Jones et al., 2013) (Chapter 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 (HSG) (26)

4.2.2. Case-study farm selection

Jones et al. (2014b) estimated the CFs of finished lamb produced on a random sample of 64 sheep farms in England and Wales, based on empirical data provided the farmers (Chapter 2). For the purposes of this study, three case-study farms were selected from the sample 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. Whilst the results relate specifically to the baseline of the case-study farms they are also indicative of the emissions savings possible against the mean CF of lowland, upland and hill farms. The baseline characteristics of the three case-study farms are detailed in Table 4.1. Because these are real farms, although they have close to the mean CF for their category, individual farm characteristics are not necessarily representative of mean values, reflecting inter-farm variation in management and conditions.

Table 4.1. 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)

4.2.3. Modelling mitigation potential

4.2.3.1. Whole-farm model

The whole-farm livestock CF model described by Jones et al. (2014b) (Chapter 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 live weight (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. (2014b) (Chapter 2) for a schematic of the system boundary and further details on emission factors (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 by: estimating animal and excreta emissions on a daily, as opposed to monthly time-step; updating enteric CH_4 and N excretion calculations from the Intergovernmental Panel on Climate Change (IPCC) Tier 1 approach used by Jones et al. (2014b) (Chapter 2) to the more detailed and sensitive Tier 2; 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 (LWG), and feed intake and improved efficiency of dietary N use. All modifications to the model from the version described by Jones et al. (2014b) (Chapter 2) are detailed in Appendix B, including Tier 2 equations, underlying assumptions and updated N_2O EFs.

4.2.3.2. General approach

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. Similarly, if a grassland measure decreased stock carrying capacity then a corresponding reduction in stock was modelled, not a reactive compensatory increase in land area or purchased feed. Consequently, the farm areas were constant in all MM scenarios and farm-level production was allowed to vary with MM. However, to ensure that MMs would not alter national production levels or cause emissions displacement when applied at the multi-farm level, a system expansion approach to MACC construction was adopted (see section 4.2.5 on MACC construction for details). This enabled the abatement potential of each MM to be reported in the MACCs at the farm baseline level of production.

Some of the MMs (clover and HSG leys) have emissions abatement time profiles which extend beyond a year, and the impacts of selective breeding on lamb growth are temporally cumulative; therefore, modelling abatement potentials and costs for a single year would not be fully representative of the impacts of these MMs. For this reason, and to enable MMs implemented over different timescales to be compared, abatement potentials for each measure were estimated for 10 years and reported as a mean annual reduction against the fixed 2010/2011 baselines. This is similar to the approach taken by Moran et al. (2008). Other overarching assumptions applied to all measures were:

- 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 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 CFs, therefore an increase in ploughing emissions associated with crop residues was calculated in relation to the area increase when the grassland 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 N use was altered according to the fertiliser / grass yield relationship assumed for MM 16 (see section 4.2.3.3). 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.

4.2.3.3. Mitigation measure specific approach

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, 2010b).
- 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 N_2O emissions from N cycling of excreta were similar in both pasture types with comparable total N inputs. On this basis, the same 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 LWG (e.g. Vipond et al., 1997).
- No change in the percentage of gross energy intake (GEI) lost as 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. (2011a) 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 overfeeding 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 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, 2010a; Jones et al., 2014a).

- 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, 2010a). 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, 2010a).
- 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 (2010a), as listed in Table 4.2.
- 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, 2010a).
- To ensure that ewe lambs can reach optimum BCS for their second mating they should only rear one lamb as yearlings (ADAS, 2010a). 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 4.2. Assumptions for the mitigation measure *lamb as yearlings* (19) all from ADAS (2010a).

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.

4.2.4. Cost calculations

The calculated stand-alone cost of each MM is a net cost incorporating capital expenditure, 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 section 4.2.3.3. Cost data were derived from several sources: rye grass seed, feed, fertiliser and labour costs form Nix (2013); clover and HSG seed mixes from online distributors, performance recording costs from the Signet website (Signet Breeding Services, 2013) or attained through direct correspondence with a Signet representative (Boon, pers. comm.). Where stock carrying capacity or lamb output increased or decreased as a result of a MM, cost or sale prices used were provided by the farmers. All costs and underlying assumptions are detailed in Appendix C.

The majority of the costs reflected the most up to date information available i.e. they were £ 2013 values. Older cost data were inflated to £ 2013 using UK agricultural price indices (DEFRA, 2013a). Veterinary and stock-related costs were inflated using category specific percentage increases in price from 2010 to 2013, the overall increase for inputs was used for all other costs. Limited information is available for cost variations in lowland, upland and hill settings, therefore in most cases one typical value was used for all farms. Costs and benefits occurring from year two to 10 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 10 years of implementation.

4.2.5. Marginal abatement cost curve approach

Individual farm MACCs were constructed using an engineering approach indicating the stand-alone mitigation potential of each MM. The MMs modelled were aimed at reducing emissions 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). This approach is consistent with typical carbon accounting approaches and with the CFs baselines used in this study. Reductions in emissions intensity indicated by the x axis represent savings in the lamb allocated proportion of the farm's CF. This atypical representation of abatement potential as emissions intensity as opposed to whole-farm emissions means that the MACCs do not display the typical properties of the integral of the curve being equal to the total cost and abatement potential. However, MACCs constructed in this way allow results to be scaled to other farms by multiplying the measures' abatement potentials by quantity of lamb produced (IBERS, 2010).

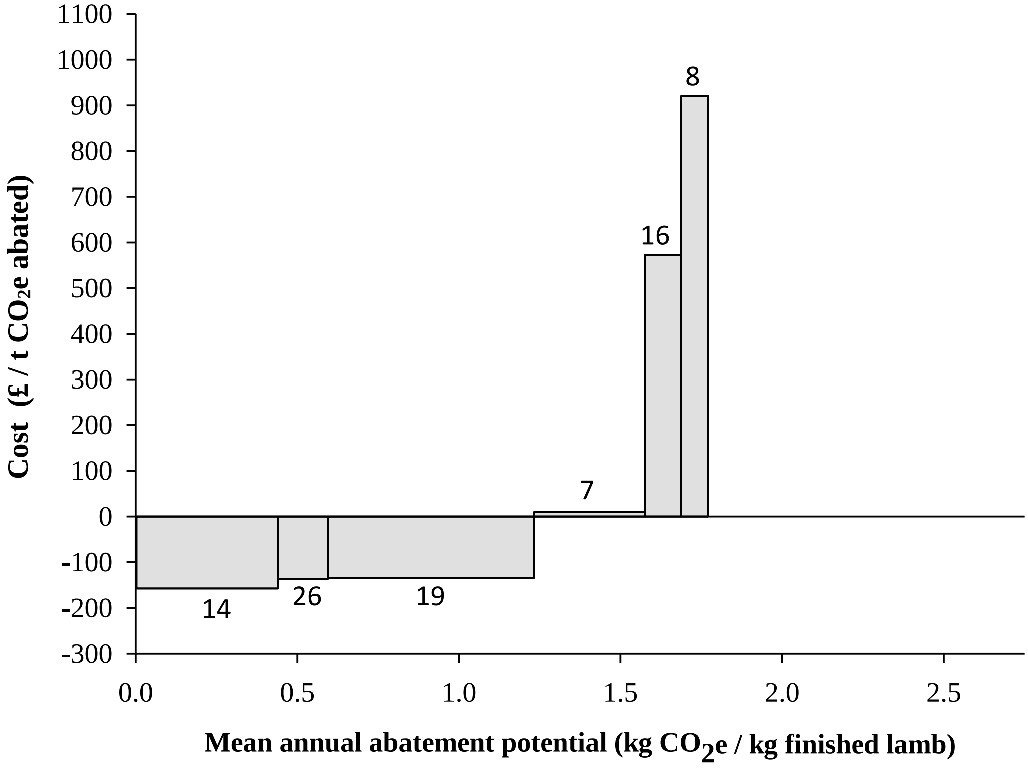
To ensure that the results of the MACCs could be scaled to other farms without impacting upon national production or displacing emissions, a system expansion approach to MACC construction was adopted, enabling the abatement potential for each MM to be reported at the same baseline level of production. Some of the modelled MMs decreased farm production, requiring more lamb to be produced elsewhere to maintain national production levels. Other modelled MMs increased farm production, replacing production elsewhere. The system expansion approach adopted involved: calculating the increase or decrease in production from the baseline after applying the MM, multiplying this quantity by the mean CF of lamb produced elsewhere, subtracting or adding this value from/to farm emissions depending on whether the MM replaced or required an increase in production elsewhere, dividing this adjusted total emissions figure by the baseline quantity of lamb produced to give the MM scenario CF. By taking this approach, the abatement potential of each MM reported in the MACCs corresponds to the same farm baseline production level, aiding MM comparison and avoiding emissions displacement as a result of production changes. The mean CFs of external produce used in systems expansion were assumed to be the mean values for England and Wales as estimated by Jones et al. (2014b) (Chapter 2).

Cost-effectiveness reported on the y axis was calculated as the total cost of implementing the MM divided by total emissions savings. The cost-effectiveness value for each measure represents the mean annual net present value divided by the mean annual total abatement potential over the 10 years of implementation.

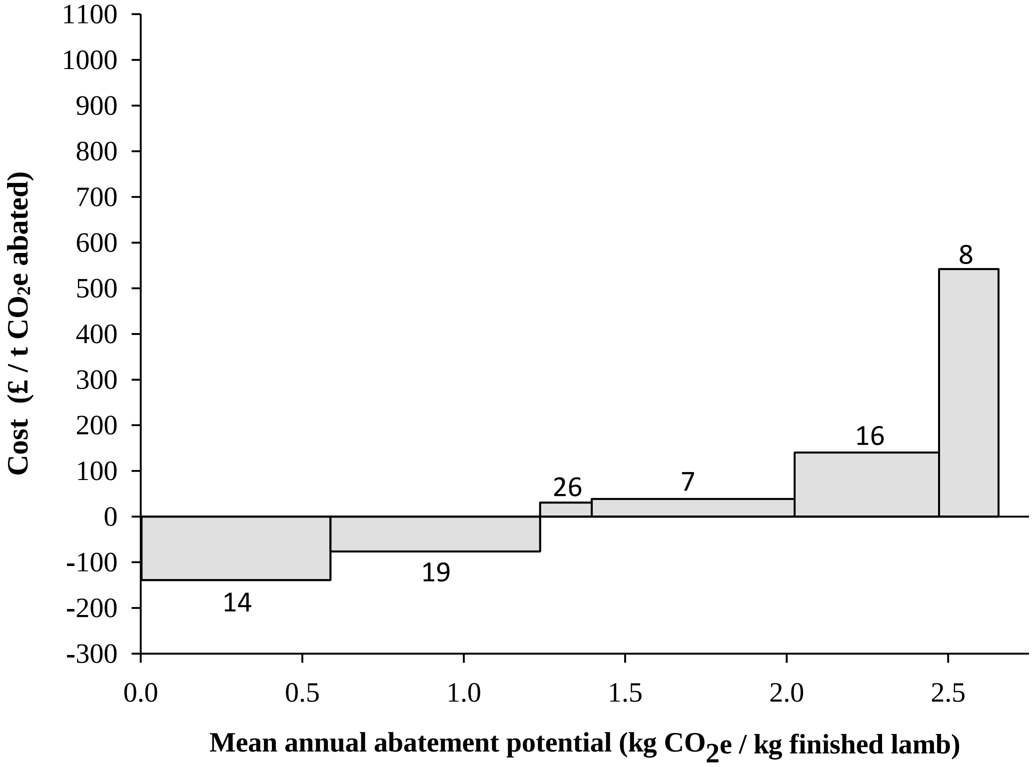
4.3. Results

The three case-study farm MACCs are presented in Fig. 4.1a-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 CO_2e abated)
8
16
7
14
26
19
0.0
0.5
1.0
1.5
2.0
2.5
Mean annual abatement potential (kg CO_2e / kg finished lamb)

b)


1100
1000
900
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700
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500
400
300
200
100
0
-100
-200
-300
Cost (£ / t CO_2e abated)
8
16
26
7
14
19
0.0
0.5
1.0
1.5
2.0
2.5
Mean annual abatement potential (kg CO_2e / kg finished lamb)

c)

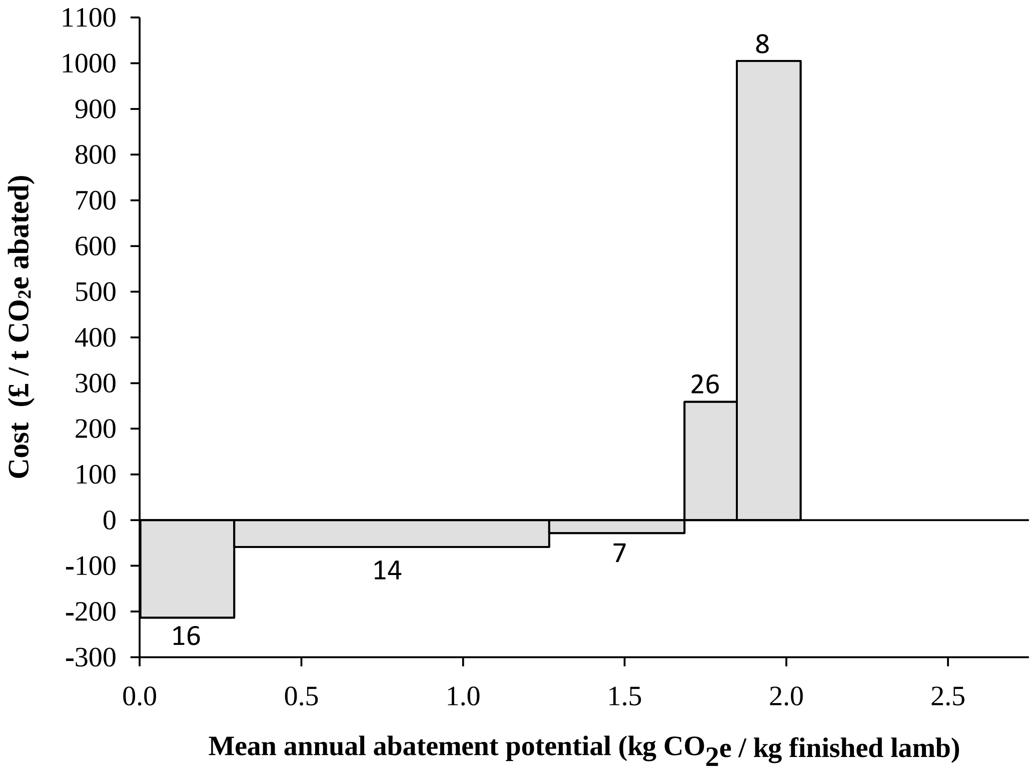

Fig. 4.1. Marginal abatement cost curves for a) lowland sheep farm, b) upland sheep farm and c) hill sheep farm. The numbered mitigation measures are: include legumes in pasture reseed mix (clover) (7); increase lamb growth rates for earlier finishing (selective breeding) (8); improve ewe nutrition to 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).

To aid interpretation of the MACCs, the modelled abatement potential of each MM on each farm is recorded in Table 4.3, alongside the percentage reduction in the baseline CF that this equates to.

Table 4.3. Modelled abatement potential for each mitigation measure on each case-study farm, and the corresponding percentage reduction in the baseline carbon footprint in brackets. Mitigation measure (MM) numbers correspond to those used in Chapter 3, as explained in section 4.2.1 above.

Baseline carbon footprint (kg CO_2e/kg lamb)		Modelled abatement potential (kg CO_2e/kg lamb) MM7	MM8	MM14	MM16	MM19	MM26
Lowland	11.39	0.34 (3.01)	0.08 (0.73)	0.44 (3.86)	0.11 (0.98)	0.64 (5.61)	0.16 (1.36)
Upland	14.26	0.63 (4.40)	0.18 (1.29)	0.59 (4.12)	0.45 (3.14)	0.65 (4.55)	0.16 (1.12)
Hill	18.83	0.42 (2.22)	0.20 (1.05)	0.97 (5.17)	0.29 (1.55)	0.00 (0.00)	0.16 (0.86)

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_2e/kg lamb respectively), and at a negative cost (-£134 and -£76 /t CO_2e 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_2e 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_2e/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_2e 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 4.4. This is discussed further in section 4.4.1.

Table 4.4. 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

The total abatement potential and cost of a MM on any lowland, upland or hill farm with a mean CF could be estimated using the MACCs. If the baseline quantity of lamb produced on a farm is known (kg), it can be multiplied by the abatement potential per kg for the MM on the x axis to give the farm's total abatement potential for lamb. When this value is converted to tonnes it can be multiplied by the cost-effectiveness value on the y axis to give the total cost of the emissions abated to the farm. Used in this way these MACCs can convey the same information as a conventional MACC reporting emissions savings at the whole enterprise or farm-level.

4.4. Discussion

This study was undertaken with the objective of augmenting the evidence-base on cost-effective MMs applicable to sheep farms in UK systems. Achieving agricultural emission reduction targets relies upon the provision of cost-effectiveness data to discriminate between MMs (Franks and Hadingham, 2012). Marginal abatement cost curves provide a simple graphical representation of the abatement potentials and cost-effectiveness of short-listed measures, serving as a useful tool to engage relevant stakeholders in climate change mitigation debate and for policy decision-making (Kesicki and Ekins, 2012).

4.4.1. Abatement potential and cost-effectiveness

The construction of three case-study farm-level MACCs suggests that, where technically possible, two MMs can be widely recommended across sheep farms in the study area. Both *improving ewe nutrition to increase lamb survival* (14) and *lambing as yearlings* (19) offer considerable relative abatement potential per kg of lamb produced whilst providing a financial benefit to the farmer. In each case, the costs of additional inputs and labour associated with the measure were negated by the income from additional lamb sales. Both MMs increase the level of output from existing stock, serving to increase the efficiency of resource use and invested emissions. These measures are suggested as priority candidates for inclusion in sheep farm mitigation strategies and demonstrate that emissions' mitigation in the sheep sector can be delivered at costs competitive with those of other agricultural sectors.

Including legumes in pasture reseed mixes (7) can also be widely advocated across farm categories, offering considerable abatement potential on all farms at negative or low cost. The impact of the measure *increasing lamb growth rates for earlier finishing* (8) through selective breeding was also consistent across farm categories; having relatively low abatement potentials and high costs on all farms. Reduced feed and stock-related emissions following earlier lamb sales were partially negated by the higher feed intakes to necessary to achieve the faster growth rates. Concurrent faster growth and increased intakes in lambs retained for breeding also partially negated the potential of this measure. This was most notable for the lowland farm. Running separate flocks to produce slaughter and replacement lambs and restricting this measure to the slaughter lamb flock would increase its abatement potential. Abatement potential for this measure appears greatest on farms which have a larger proportion of the CF associated directly with stock (i.e. not input related) and when creep feeding to finish lambs e.g. the upland farm. The high cost of this measure reflects the annual fee of belonging to a performance recording service and the labour costs of recording on-farm. Because the net cost of this measure contains a large fixed cost element, cost-effectiveness per tonne of carbon abated is greater for larger farms with higher outputs and greater abatement potentials per kg (e.g. the upland farm). The cost of performance recording associated with this measure would be significantly reduced if the farmer were to breed for a range of traits e.g. as part of an index, therefore sharing the costs across desirable traits.

Whilst the abatement potentials and marginal costs of the aforementioned MMs were relatively consistent across the case-study farms, the results of other MMs proved to be more heterogeneous. Baseline farm management and emissions can have a considerable impact on MM abatement potential and cost-effectiveness. This is particularly evident for the MMs: *include legumes in pasture reseed mix* (7), *reduce mineral fertiliser use* (16) and *select pasture plants bred to minimise dietary N losses e.g. HSG* (26). The measures *include legumes in pasture reseed mix* (7) and *reduce mineral fertiliser use* (16) offered their greatest abatement potential (in absolute and percentage terms) on the upland farm. This can be explained by the contribution of fertiliser related emissions (from manufacture and application) to the baseline CF which was greatest on the upland farm (Table 4.4). Mitigation measures 7 and 16 also led to a reduction in stock carrying capacity and emissions directly related to stock. Of the three farms, the upland case-study also had the largest component of the CF directly from stock emissions (enteric and excreta related) and therefore contributed to the greatest abatement potential. These two MMs were found to be cost-negative on the hill farm but cost-positive on the other farm types. Based upon the stock costs provided by the farmer and the standard cost data used, it appears that the hill farm was operating at a loss. As a result, measures that reduced stock carrying capacity appeared cost favourable. Jones et al. (2010) also reported a distortion in their results due to some farms having "*very low incomes*". Similarly, *reducing mineral fertiliser use* (16) had a high cost on the lowland farm because of the significant foregone income associated with the reduction in stock carrying capacity. Both pasture reseeding measures (7 and 26) were most cost-effective on the lowland farm because unlike the upland and hill farms, no increase in the area ploughed and reseeded from the baseline was needed to meet the assumptions of the mitigation scenario. Identified heterogeneity in the abatement potential and marginal cost of MMs appeared to be a result of differences in individual farm management more often than land classification.

The MACCs demonstrate that where a broad scope of emissions and costs are modelled against real farm baselines, the impacts of MMs are complex and variable. Consequently, recommending effective MMs may be problematic even when considered at the farm category level such as land classification. No single farm represents a "typical" farm, each having features unique and distinct to their baseline management and emissions. The results broadly advocate maximising lamb output from existing inputs i.e. increasing production efficiency, particularly through *improving ewe nutrition to increase lamb survival* (14) and *lambing as yearlings* (19). Further recommendations require an assessment of the individual farm baseline CF. Potential reductions in emissions intensity are dependent upon whether current management is already optimal (Alcock and Hegarty, 2011). Even the construction of more tailored MACCs by region or farm type would fail to account for the nuances of individual farm management. Consequently, two strands of future research are recommended: the construction of tailored MACCs for "mean" farms grouped by a range of pertinent characteristics such as farm type, region and economic size to provide general guidance on the MMs suited to each category (e.g. De Cara and Jayet, 2006); alongside the use of further case-study farm MACCs based on empirical data to develop guidelines or benchmarks on the situations in which each MM may be most effective. For example, the results indicate that selective breeding for lamb growth rate may be most appropriate on farms running separate slaughter and replacement lambs flocks, which have above the mean percentage of their CF directly from stock and are creep feeding to finish lambs. These two strands of research would enable MACCs to be used to inform farm-level mitigation strategies in addition to refining higher-level policy.

4.4.1.1. Comparison with other studies

Direct comparison of the results of the MACCs with other studies is problematic due to differences in modelling approach and underlying assumptions. However, the modelled abatement potentials appear to be broadly comparable with other studies. Modelled reductions as a result of improving lamb growth rates ranged from 0.7 to 1.3% of the baseline CF which is comparable to the CH_4 only reduction potentials of 1.3 to 2.3% over 10 years with no change in ewe weight modelled by IBERS et al. (2011a). In their study of breeding from ewe lambs ADAS (2010a) estimated a 9.4% reduction in emissions per kg of lamb carcase through lambing at 12 months as opposed to two years. This figure is comparable to, but greater than the abatement potentials estimated here equivalent to 5.6% and 4.6% of the lowland and upland lamb CFs. These differences may relate to modelling approach: ADAS (2010a) modelled emission reductions per kg of lamb produced by a single ewe over 6 years as opposed to annualised whole-farm emissions allocated to lamb; fertiliser emissions were seemingly not accounted for and they did not model an increase in feed related emissions from the baseline. The modelled abatement potential of HSGs in this study was 0.16 kg CO_2e/kg lamb on all farms which is less than the approximate value of 0.6 kg CO_2e/kg livestock product reported by IBERS (2010) who modelled more favourable impacts on productivity, enteric CH_4 emissions and N excretion than those assumed in this study.

Calculated costs also vary with underlying assumptions between studies. Moran et al. (2008) estimated that as a stand-alone measure reseeding with clover would have a slight positive marginal abatement cost, consistent with the lowland and upland results of this study. Jones et al. (2010) however estimated a negative cost to beef and sheep farmers, having not modelled a reduction in yield associated with clover. In stark contrast to the results of this study, Jones et al. (2010) estimated that livestock breeding could abate emissions on beef and sheep farms at a negative cost per tonne of CO_2e. This discrepancy is explained by a difference in costs included – the rental of high EBV males in Jones et al. (2010) as opposed to active participation in performance recording in this study.

4.4.2. Marginal abatement cost curve approach

Marginal abatement cost curves should be used cautiously when informing mitigation policy, allowing for the caveats of the study (Kesicki and Ekins, 2012). Estimated abatement potentials and costs are contingent upon the assumptions made and are specific to the mitigation scenario defined, as highlighted by inter-study comparisons. A further example in this study was modelling *selective breeding for lamb growth* (8) with and without an associated increase in ewe mature weight. Where mature weight was also increased according to the values in IBERS et al. (2011a), emissions per kg/lamb increased on all farms (results not shown). Targeted sensitivity analyses could be used to reveal which assumptions have the greatest impact on estimated abatement potentials and costs.

The construction of MACCs is another potential source of variation in reported abatement potentials and costs (United States Environmental Protection Agency, 2006). Different approaches exist for dealing with changes in the level of total production as a result of the implementation of a MM. Some livestock MMs increase animal productivity and may therefore increase total farm emissions, however they offer abatement potential at the farm-level through either enabling animal numbers to be reduced whilst maintaining the same level of overall production, or through allowing production to increase and reporting emissions per unit of produce. Other MMs decrease animal numbers and total production, therefore reducing total farm emissions but possibly increasing emissions per unit of produce. The US Environmental Protection Agency (2006) reported two MACC approaches, both for total emissions abatement potential: in the first where a MM increased productivity per animal they modelled a reduction in animal numbers to maintain constant production; and in the second they allowed overall production to increase. The first resulted in greater total emissions abatement due to a reduction in animal numbers, whilst in the second some MMs led to an increase in total emissions. The first assumes that farmers will respond to increased production at the farm-level through decreasing animal numbers and the second does not acknowledge the importance of productivity in reducing emissions per quantity of produce. In the current study the abatement potentials of individual MMs were reported as a change in the CF per kg of lamb produced. This approach was adopted for consistency with the CF method used to calculate baseline emissions and in recognition that comparing MMs based on emissions per unit of produce identifies those that result in the highest productivity per unit of GHG emissions (Stewart et al., 2009). One other example of MACCs reporting abatement potential as emissions intensity has been identified in the published literature (IBERS, 2010). In the current study, production output was allowed to vary in farm-level modelling, according to the impact of the MM on animal productivity and/or farm carrying capacity. This initial modelling approach was underpinned by the assumption that farmers would not decrease stock numbers in response to an increase in productivity at the farm-level. However, to enable results to be scaled to other farms, the MACCs were constructed using a system expansion approach to report MM abatement potentials for the baseline level of production. This approach accounts for emissions leakage (where reduced productivity causes production and emissions to be displaced elsewhere) and ensures that national production levels would be maintained if MMs were applied at the multi-farm level. From the perspective of maintaining national production and avoiding emissions displacement, MACC approaches that model constant production may be favourable. However, the approach taken in the current study may be better suited at the farm-level, particularly if farmers are not expected to reduce stock numbers as a result of productivity improvements. Another consideration is that if a MM that reduces production at the farm-level such as *including legumes (clover) in pasture reseed mixes* is implemented simultaneously with another productivity enhancing MM, the latter may compensate for the former and maintain farm-level production. Dealing with changes in production levels in agricultural MACCs is therefore problematic, and at present there is no favoured method of accounting for these changes.

A number of other limitations, common to MACCs (Kesicki and Ekins, 2012), also apply in the current study: namely that no consideration was given to the ancillary costs and benefits of MMs; and that interactions between measures were not accounted for. Although indirect N_2O emissions as a result of nitrate leaching and ammonia volatilisation were considered in this study, other ancillary impacts, for example on water quality and animal welfare, were not. Inclusion of ancillary impacts can affect the cost-effectiveness of agricultural GHG MMs (Eory et al., 2013). Where MMs are assessed on an individual basis overall abatement potential can be overestimated (Kesicki and Ekins, 2012; MacLeod et al., 2010a). Jones et al. (2013) briefly discussed the complementarity of the six short-listed measures modelled in this study (Chapter 3). Whilst some interactions are evident others are far more complex. For example *reducing fertiliser use* (16) should occur as a direct result of *the inclusion of legumes* (7) therefore the abatement potential of these measures is not additive. A more complex interaction example is that *lambing as yearlings* (19) reduces the generation interval accelerating genetic selection progress, for example in *improving lamb growth rates* (8) (Dýrmundsson and Lees, 1972). To date little or no data exist on the interaction of MMs in the field, therefore any attempt at modelling interactions would rely on expert opinion. Eliciting expert opinion on the multiple and complex interactions possible was beyond the scope of the present study.

Despite these caveats the MACCs represent an additional, useful tool for policy-makers. They provide an indication of the mean abatement potentials in emissions' intensity possible on lowland, upland and hill farms; also enabling total abatement potential and costs to be calculated where the level of production is known. Strengths of the current study include: the use of empirical farm data, which enabled an initial analysis of how baseline farm characteristics can influence abatement potential; estimation of mean abatement potential over 10 years of implementation; a relatively broad cost definition; and crucially, calculation of farm-specific abatement rates using a whole-farm model as opposed to adopting a single rate per MM from the literature. This study has also presented a novel approach to accounting for changes in farm-level productivity in MACCs while reporting abatement potential as a reduction in emissions intensity. Case-study farm-level MACCs have been demonstrated to be an important tool for refining agricultural GHG mitigation strategy for sectors such as the sheep industry.

4.4.3. Mitigation measure implementation

The cost of some of the MMs modelled is likely to be prohibitive to farmers in their current form. Moran et al. (2011) adopted a cost threshold of £100/t CO_2e for feasible abatement measures in their UK MACCs. Using that criterion, *selective breeding for lamb growth rates* (8) would be excluded, also *reducing mineral fertiliser use* (16) on the lowland and upland farms due to decreased stock carrying capacity, and *reseeding with HSGs* (26) on the hill farm due to the cost of ploughing and seeding and additional area. Whilst selection of MMs based on farmer opinion and calculated cost-effectiveness in this study may facilitate delivery, the very existence of negative cost abatement potential indicates that modelled financial benefit does not guarantee implementation. Cost negative abatement potential is "*not compatible with an efficient market*" and may be explained by a narrow cost definition in MACC construction, non-financial barriers to implementation or the choice of discount rate (Kesicki and Ekins, 2012). It is understood that farmers' decisions are influenced by multiple factors, not least farming habit (Edwards-Jones, 2006; Lucas et al., 2007). Barriers to the uptake of MMs stated by UK farmers include, *inter alia*, structural barriers such as security of farm tenure and age; educational barriers such as the need for advice and training; administrative barriers including the complexity of the range of policies applicable to farming (Barnes et al., 2010). Consideration of policy implementation costs such as administration and marketing can change the outlook on the cost-effectiveness of MMs from a social perspective (Kesicki and Strachan, 2011), and is therefore likely to be crucial in the development of effective agricultural mitigation policy.

4.5. Conclusions

The construction of MAC curves for case-study sheep farms with mean CFs has provided an indication of the abatement potential possible through implementation of individual MMs on lowland, upland and hill farms. By reporting abatement potential as emissions' intensity, the MACCs can be used to scale results to other farms. As in other agricultural sectors the development of sheep farm-specific MAC curves has demonstrated the potential for negative cost GHG emissions abatement in the industry. Where technically possible, two MMs that increase the efficiency of lamb production can be widely recommended: *improving ewe nutrition to increase lamb survival* (14) and *lambing as yearlings* (19). These results indicate the importance of considering productivity and efficiency maximisation as influential drivers of emissions abatement in the sector. The abatement potential and costs of other measures were more varied and demonstrated the importance of differences in farm management between baseline scenarios. Identified heterogeneity in the abatement potential and marginal cost of MMs appeared to be a result of differences in individual farm management more often than land classification. The construction of further case-study farm MACCs is recommended to define the management scenarios in which each MM is most effective, enabling guidelines to be developed. Case-study farm-level MACCs, based on empirical data, are suggested as an important tool for refining agricultural GHG mitigation strategy in sectors such as the sheep industry.

Construction of agricultural MACCs is problematic due to the heterogonous nature of the industry and the need to account for the complex interactions of multiple GHGs. Consequently, agricultural MACCs are typically constructed with a number of caveats. This study explicitly stated all assumptions and caveats to ensure transparency. Taking heed of these caveats, policy-makers should use MACCs as one tool amongst others in the decision-making process. Information on abatement potentials and cost-effectiveness from the farmer perspective must be supplemented by data on the costs of overcoming barriers to implementation, to ensure effective policy development for agricultural GHG mitigation.

Chapter 5

Discussion

Development of agricultural greenhouse gas (GHG) mitigation policy relies upon quantification of baseline GHG emissions, identification of appropriate mitigation measures (MMs) and selection of MMs based upon cost-effectiveness (Franks and Hadingham, 2012; Norse, 2012). Whilst previous UK studies have explored the abatement potentials and costs of MMs in the context of livestock farms, none have considered sheep farm-specific MMs. This apparent lacuna is typically attributed to the diversity of sheep systems operating in the UK, and the consequent difficulty of identifying and evaluating MMs applicable across the broad spectrum of sheep farm systems. However, a more tailored approach to assessing abatement potentials and costs is increasingly recommended and needed. This study set out to provide an evidence-base to inform the development of sheep farm GHG mitigation strategies, culminating in the development of three case-study farm marginal abatement cost curves (MACCs) for reducing the carbon footprint (CF) of lamb in a lowland, upland and hill farm setting.

The thesis comprises four distinct but interdependent chapters....

5.1. Chapter summaries

Chapter 1 reviewed published and industry literature to identify MMs suited to sheep systems. Multiple, potentially viable MMs were identified, although only a small number were found to be currently available and achieving broad consensus on their abatement potential. These included breeding to increase lambing percentages and diet formulation to minimise nitrogen excretion. Long-term field trials of the MMs, under a range of environmental conditions, were found to be lacking, but necessary to confirm the efficacy of MMs such as dietary supplementation. It was found that many interventions cannot be recommended at a regional or national scale because, either, their abatement potential is inextricably linked to soil and weather conditions in the locality of use, or their use is restricted to more intensive, closely managed systems. It was concluded that the development of tailored, practical sheep farm GHG mitigation strategies relies on tools such as whole-farm GHG modelling and MACCs. This chapter provided the long-list of MMs assessed by experts and farmers in Chapter 3.

Chapter 2 estimated the cradle to farm gate CFs of 64 sheep farms and assessed the relationship between farm variables and CF at the multi-farm level. Farm-level emissions were found to vary in relation to local conditions and management choices. The estimated mean CF of lowland lamb (10.85 kg CO_2e/kg live weight finished lamb) was significantly lower than that of hill lamb (17.86 kg CO_2e/kg live weight finished lamb). Multiple linear regression models across all farms indicated that four farm management variables had a significant impact on the size of the CF of finished lamb. Irrespective of farm category, these were the number of lambs reared per ewe (head/ewe), lamb growth rate (g/day), the percentage of ewe and replacement ewe lamb flock not mated (%), and concentrate use (kg/livestock unit). Dominance analysis indicated that, of these, the number of lambs reared per ewe mated and lamb growth rate were the most influential. The results highlighted the importance of productivity and efficiency of resource use in reducing the CF of lamb. Carbon footprints were advocated as a tool for providing an emissions baseline against which mitigation targets can be set and progress measured. This chapter provided the baseline farm data for MACC construction in Chapter 4.

The research for **Chapter 3** ran concurrently with Chapter 2. Chapter 3 produced a short-list of practical and effective MMs based on the opinions of experts and farmers derived through Best-Worst Scaling surveys. Six measures possessed the dual qualities of effectiveness and practicality, which were suggested as priority candidates for policy promotion, and taken forward for emission modelling in MACC construction in Chapter 4. It was suggested that practical MMs with below average effectiveness may be widely adopted with limited regulation, incentivisation or advice whilst some highly effective measures with lower practicality are likely to have more limited adoption and require greater regulation, incentivisation or advice. The survey revealed heterogeneity in farmers' perceptions of the practicality of MMs, and indicated that the level of regulation, financial and/or advisory support required to ensure successful implementation may vary between segments of the sheep farming community. It was concluded that flexible policies are needed to enable farmers to select the MMs that are most suited to their own situation.

Chapter 4 combined farm baseline emissions data reported in Chapter 2 with the effective and practical MMs identified in Chapter 3 in the construction of MACCs. Three case-study farm-level MACCs were developed, for a lowland, upland and hill sheep farm indicating the abatement potentials and cost-effectiveness of short-listed MMs. Across all farms the measure *improving ewe nutrition to increase lamb survival* offered considerable abatement potential at a negative cost to the farmers. *Lambing as yearlings* also offered competitive abatement potential at a negative cost on lowland and upland farms but was not considered technically possible on the hill farm. The results broadly advocate maximising lamb output from existing inputs on all farm types, and highlight the importance of productivity and efficiency as influential drivers of emissions' abatement in the sector. *Reseeding with legumes* (clover) also offered considerable abatement potential on all three farm types, at a negative or small cost to the farmer. The abatement potentials and costs of other measures were more varied and demonstrated the importance of accounting for differences in farm management between baseline scenarios. The construction of further case-study farm MACCs was recommended to define the management scenarios and conditions in which each measure is most effective.

5.2. Mitigation measure analysis and recommendations

The results of all chapters 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.

5.2.1. Efficiency and productivity

All four chapters of the present study affirmed the importance of productivity and efficiency in mitigating sheep farm GHG emissions, across all farm categories. The initial literature review in Chapter 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). Chapter 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 Chapter 3, five out of 11 MMs considered as having above average effectiveness were aimed at enhancing productivity. The filtering of MMs in Chapters 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 Chapter 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 Chapter 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. Chapter 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, 2011a). 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, Chapter 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, 2013b). 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, 2013b). 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 Chapter 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, 2013b). However, assumed impacts on stock carrying capacity limit the practical extent of this measure.

5.2.2. 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 Chapter 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 emission factors (EF) in the initial CF model e.g. a higher EF for nitrous oxide (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 Chapter 2; an indication in Chapters 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.

5.3. 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., 2007b). 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*). Chapter 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.

5.4. 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, 2010b). 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, 2010b). 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.

5.5. 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.

Appendix A

Example of the paper Best-Worst Scaling surveys used with farmers

Reducing Greenhouse Gas Emissions on Sheep Farms

Thank you for participating in this survey concerning opportunities to reduce greenhouse gas (GHG) emissions on sheep farms.

GHGs emitted as a result of human activity are contributing to global climate change. Around 9% of total UK emissions arise from agricultural sources. The main GHGs emitted from livestock systems are:

- **methane**, directly from livestock as a by-product of feed digestion and also emitted from manure
- **nitrous oxide**, from soils particularly after fertiliser and manure applications, and from manure
- **carbon dioxide**, through the burning of fossil fuels and through the loss of organic carbon from cultivated soils

Reducing emissions now will limit future global warming. This survey is part of a project trying to identify priority measures for reducing emissions on sheep farms. We've created a short-list of twenty six of the most effective measures for preventing or reducing emissions on-farm.

We would like to know your opinion on how practical these measures would be to implement.

Twenty six measures are a lot to evaluate at once, so we are using a method which breaks this task down into manageable sets. Whilst the stages are a little repetitive they are designed to provide as much information as possible. The survey should take about 10 minutes to complete.

On the following pages you will see sets of different combinations of measures for preventing or reducing GHG emissions on sheep farms.

For each set of five measures, we would like you to consider how practical you think they would be to implement.

For each set you are asked to simply select the measure you think would be:

- **Most practical to implement on-farm**

And the measure you think would be:

- **Least practical to implement on-farm**

Example:

Most Practical		Least Practical
○	Measure 1	○
○	Measure 2	○
✓	Measure 3	○
○	Measure 4	✓
○	Measure 5	○

Tick the circle next to the measure you think **most practical**

Tick the circle next to the measure you think **least practical**

When assessing each measure please consider only how practical it would be to implement and ignore other concerns such as cost or potential for emissions reductions.

Please consider the sets of measures below. In each set, thinking about each measure's **practicality** alone, please select:

- The measure you think would be **most practical** to implement, and
- The measure you think would be **least practical** to implement

Most Practical	Set 1	Least Practical
◯	Lamb as yearlings to limit the number of unproductive stock on-farm	◯
◯	Seek advice from an animal nutritionist to avoid feeding excess dietary protein	◯
◯	Reduce total fertiliser use	◯
◯	Carefully manage ewe nutrition in late gestation (based on body condition scoring & scanning results) to increase lamb survival rates	◯
◯	Split fertiliser applications (to improve efficacy of nitrogen uptake)	◯

Please select the measures you think would be **most** and **least practical** to implement from this set:

Most Practical	Set 2	Least Practical
◯	Improve drainage of **non-peat** soils to minimise water logging & compaction	◯
◯	Avoid drainage / conversion of peatlands to pasture to maintain carbon stores	◯
◯	Avoid fertiliser applications prior to pasture renovation (reducing nitrogen available for loss)	◯
◯	Seek advice from an animal nutritionist to ensure complete diets (pasture & additional feed) are balanced in energy & protein	◯
◯	Improve precision of fertiliser placement in soil e.g. injection or incorporation into soil & precision farming (on larger farms)	◯

Please select the measures you think would be **most** and **least practical** to implement from this set:

Most Practical	Set 3	Least Practical
◯	Improve hygiene & supervision at lambing to increase lamb survival rates	◯
◯	Plan fertiliser application rates based on the recommended rates set out in DEFRA fertiliser manual (RB209)	◯
◯	Analyse manure for nitrogen content prior to application to determine supplementary quantity of mineral fertiliser needed	◯
◯	Participate in selective breeding schemes (or change sheep breed) to increase lamb growth rates, for earlier finishing	◯
◯	Reduce total fertiliser use	◯

Please consider the sets of measures below. In each set, thinking about each measure's **practicality** alone, please select:

- The measure you think would be **most practical** to implement, and
- The measure you think would be **least practical** to implement

Most Practical	Set 4	Least Practical
○	When re-seeding pasture select grass varieties with lower fertiliser requirements	○
○	Split fertiliser applications (to improve efficacy of nitrogen uptake)	○
○	Participate in selective breeding schemes for improved feed conversion efficiency	○
○	Improve timing of fertiliser applications, avoiding periods of high soil moisture content & matching to crop demand	○
○	Participate in selective breeding schemes for reduced rumen methane production	○

Please select the measures you think would be **most** and **least practical** to implement from this set:

Most Practical	Set 5	Least Practical
○	Participate in selective breeding schemes (or change sheep breed) to increase lamb growth rates, for earlier finishing	○
○	Improve timing of fertiliser applications, avoiding periods of high soil moisture content & matching to crop demand	○
○	Carefully manage ewe nutrition in late gestation (based on body condition scoring & scanning results) to increase lamb survival rates	○
○	Calibrate & maintain fertiliser spreader equipment	○
○	Participate in selective breeding schemes (or change sheep breed) to increase the number of lambs born per ewe	○

Please select the measures you think would be **most** and **least practical** to implement from this set:

Most Practical	Set 6	Least Practical
○	Participate in selective breeding schemes for improved feed conversion efficiency	○
○	Increase diet digestibility by feeding a high starch diet to increase dry matter intake	○
○	Include legumes (e.g. red & white clover) in pasture re-seed mix for nitrogen fixation to minimise the need for fertiliser applications	○
○	Analyse manure for nitrogen content prior to application to determine supplementary quantity of mineral fertiliser needed	○
○	Plan fertiliser application rates based on the recommended rates set out in DEFRA fertiliser manual (RB209)	○

Please consider the sets of measures below. In each set, thinking about each measure's **practicality** alone, please select:

- The measure you think would be **most practical** to implement, and
- The measure you think would be **least practical** to implement

Most Practical	Set 7	Least Practical
◯	Avoid fertiliser applications prior to pasture renovation (reducing nitrogen available for loss)	◯
◯	Include legumes (e.g. red & white clover) in pasture re-seed mix for nitrogen fixation to minimise the need for fertiliser applications	◯
◯	Increase diet digestibility by feeding a high starch diet to increase dry matter intake	◯
◯	Improve hygiene & supervision at lambing to increase lamb survival rates	◯
◯	Participate in selective breeding schemes (or change sheep breed) to increase lamb growth rates, for earlier finishing	◯

Please select the measures you think would be **most** and **least practical** to implement from this set:

Most Practical	Set 8	Least Practical
◯	When re-seeding pasture select grass varieties bred to minimise dietary nitrogen losses e.g. commercially available high sugar grasses	◯
◯	When re-seeding pasture select grass varieties with lower fertiliser requirements	◯
◯	Split fertiliser applications (to improve efficacy of nitrogen uptake)	◯
◯	Participate in selective breeding schemes (or change sheep breed) to increase ewe reproductive life	◯
◯	Improve hygiene & supervision at lambing to increase lamb survival rates	◯

Please select the measures you think would be **most** and **least practical** to implement from this set:

Most Practical	Set 9	Least Practical
◯	Seek advice from an animal nutritionist to avoid feeding excess dietary protein	◯
◯	Plan fertiliser application rates based on the recommended rates set out in DEFRA fertiliser manual (RB209)	◯
◯	Participate in selective breeding schemes for reduced rumen methane production	◯
◯	Maximise pasture productivity through sward assessment to avoid over grazing & through re-seeding older pastures	◯
◯	Avoid conversion of woodlands to pasture / crops to maintain carbon stores	◯

Please consider the sets of measures below. In each set, thinking about each measure's **practicality** alone, please select:

- The measure you think would be **most practical** to implement, and
- The measure you think would be **least practical** to implement

Most Practical	Set 10	Least Practical
◯	Participate in selective breeding schemes for reduced rumen methane production	◯
◯	Improve drainage of **non-peat** soils to minimise water logging & compaction	◯
◯	When re-seeding pasture select grass varieties with lower fertiliser requirements	◯
◯	Analyse manure for nitrogen content prior to application to determine supplementary quantity of mineral fertiliser needed	◯
◯	Seek advice from an animal nutritionist to ensure complete diets (pasture & additional feed) are balanced in energy & protein	◯

Please select the measures you think would be **most** and **least practical** to implement from this set:

Most Practical	Set 11	Least Practical
◯	Include legumes (e.g. red & white clover) in pasture re-seed mix for nitrogen fixation to minimise the need for fertiliser applications	◯
◯	Seek advice from an animal nutritionist to avoid feeding excess dietary protein	◯
◯	Avoid conversion of woodlands to pasture / crops to maintain carbon stores	◯
◯	Participate in selective breeding schemes (or change sheep breed) to increase the number of lambs born per ewe	◯
◯	Improve drainage of **non-peat** soils to minimise water logging & compaction	◯

Please select the measures you think would be **most** and **least practical** to implement from this set:

Most Practical	Set 12	Least Practical
◯	When re-seeding pasture select grass varieties bred to minimise dietary nitrogen losses e.g. commercially available high sugar grasses	◯
◯	Lamb as yearlings to limit the number of unproductive stock on-farm	◯
◯	Avoid drainage / conversion of peatlands to pasture to maintain carbon stores	◯
◯	Avoid conversion of woodlands to pasture / crops to maintain carbon stores	◯
◯	Calibrate & maintain fertiliser spreader equipment	◯

Please consider the sets of measures below. In each set, thinking about each measure's **practicality** alone, please select:

- The measure you think would be **most practical** to implement, and
- The measure you think would be **least practical** to implement

Most Practical	Set 13	Least Practical
○	Participate in selective breeding schemes (or change sheep breed) to increase ewe reproductive life	○
○	Maximise pasture productivity through sward assessment to avoid over grazing & through re-seeding older pastures	○
○	Participate in selective breeding schemes (or change sheep breed) to increase the number of lambs born per ewe	○
○	Improve precision of fertiliser placement in soil e.g. injection or incorporation into soil & precision farming (on larger farms)	○
○	Plan fertiliser application rates based on the recommended rates set out in DEFRA fertiliser manual (RB209)	○

Thank you for helping us to assess the practicality of measure for reducing GHG emissions on sheep farms.

How confident were you overall in your decisions on which were the most and least practical measures?

Very sure	☐	Unsure	☐
Fairly sure	☐	Very unsure	☐

Have you already implemented any of the measures you have been evaluating?

If yes please tell us which ones and describe what you have done:

Finally, please tell us a little about you and your farm:

Please tell us your gender:

Male	☐	Female	☐

And your age group:

18 – 34	☐	55 - 64	☐
35 – 44	☐	65 +	☐
45 - 54	☐		

What is your farm type?

Sheep only ☐ Sheep and dairy ☐

Sheep and beef cattle ☐ Other ☐

What is the land classification of the majority of your farm?

Upland ☐ Lowland ☐ Hill ☐

Do you produce home grown forage crops for your sheep?

Yes ☐ No ☐

Which sheep breeds do you stock? ....

....

....

What is your breeding ewe flock size?

1 - 49 ☐ 200 - 499 ☐ 2000 + ☐

50 - 99 ☐ 500 – 999 ☐

100 - 199 ☐ 1000 - 2000 ☐

What is your lambing percentage (reared)? ....

Thank you for completing this survey.

The information provided by you and other farmers will be analysed along with information on effectiveness to identify priority measure for reducing emissions on sheep farms.

If you would like to receive the results of the analysis, please provide either an e-mail or postal address.

Appendix B

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 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. (2014b) (Chapter 2).

B1. 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, 2011a; 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 B1. 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 B2.

B2. 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. (2014b).

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. (2014b). 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. (2014b). 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. (2014b). 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 B1. 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 live weight 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 B2. 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),
where:		ADAS (2007)
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),
where:		ADAS (2007)
N_{intake} = nitrogen intake (kg N/head/day)		
$N_{retention}$ = fraction of N_{intake} that is retained		

Appendix C

Cost data and underlying assumptions used for mitigation measure cost calculations

Table C1. 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 (2010a), 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 (2010a)
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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