The implications of farm-scale methane mitigation measures for long-term national methane emissions

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Executive Summary

Methane (CH_4) is the second most important greenhouse gas after carbon dioxide (CO_2), contributing 20% to global warming. Agriculture (particularly dairy farming) contributes 43% to the UK's emissions of CH_4 and under the Kyoto Protocol there is a target to reduce greenhouse gas emissions by 12.5% of the 1990 levels by the year 2008-2012, although this target is now under re-negotiation. A number of CH_4 mitigation measures have been suggested and identified, but there is a need to know whether these would be effective over broad spatial scales and under future scenarios. Additionally, it is necessary to ascertain whether widespread implementation of these mitigations would have other consequences, e. g. for levels of production and emissions of other pollutants. In this project we have identified a number of potentially effective measures for reducing CH_4 emissions from ruminant livestock farming in England, Wales and Scotland.

Those methods include:

- Increased productivity, i.e. increased milk production per kg CH_4 produced
- Increased fertility, i.e. reducing the number of followers required
- Improved forage composition and balanced energy/protein feeds
- Feed additives – to reduce rumen hydrogen production
- Vaccination – to reduce the methanogens in the rumen

The effectiveness of each of these methods was quantified at the farm and national scales through concerted spatial scenario exploration with a new modelling framework which linked four existing models. The models are the Reading rumen model, the IGER field/farm models NGAUGE and $SIMS_{DAIRY}$ and the CEH AENEID countrywide spatial model.

The models required modifications to enable suitable interfacing and time-step compatibilities. The Reading rumen model generated methane emissions for dairy cattle, beef and sheep under a range of intensities, driven by energy, forage quality, and animal fertility. Further developments to this model allowed herd management decisions and fertility factors affecting replacement rate to be incorporated into the model at a herd level, in order to predict productivity and methane and nitrogen emissions in dairy cows. The IGER $SIMS_{DAIRY}$ and NGAUGE models were then used to simulate emissions of methane from manure managements as well as emissions of ammonia, nitrous oxide and nitrate, according to site soil and weather factors and farm managements.

In order to take into account the national variation in dairy, beef and sheep systems, we defined three typologies for dairy farms (extended grazing, conventional intensive and fully-housed intensive) and two typologies each for beef and sheep farming (upland and lowland) in terms of stocking densities, fertiliser inputs, conception rates etc.

Although emissions of methane were not assumed to be influenced by soil or climate, it was necessary to generate a map of soil/climate zones and take these key controls into account when modelling ammonia and nitrous oxide emissions and nitrate leaching as a result of methane mitigation methods at the farm and national scale.

The emission estimates from the IGER $SIMS_{DAIRY}$ and NGAUGE models were then passed on to the AENEID model to assess the impacts of methane mitigation methods against baseline emissions, by scaling up by farm typology within soil/climatic regions to the national level. We also determined the impact of projections in animal numbers for the year 2015.

This modelling framework provided a detailed assessment and quantification of the effectiveness of methane mitigation strategies that could be applied to dairy farms, and the impacts of these on other forms of atmospheric (ammonia and nitrous oxide) and water pollution (nitrate leaching) at the farm scale, as well as nationally. A less detailed assessment of the effects of methane mitigation measure was also carried out for beef cattle and sheep

Key results

For dairy cattle, an increase in milk yield per cow (by 30% in the modelled scenario), coupled with a reduction in dairy cow numbers, i.e. maintaining current national milk production levels, resulted in the largest reduction in methane emissions at the national level (-24%). The next most effective mitigation strategy was a high fat diet, which provides a 14% saving in methane emissions, followed by increased heat detection rate (HDR) at 7% and a high starch diet at 5%. Changes in diet to high quality forage did not appear to result in large differences in the national emission of methane (-3%), whereas scenarios modelling an increase in low quality forage or decreased HDR resulted in marginal increases in methane emissions. A reduction in the milk yield per dairy cow by 30%, coupled with an increase in the number of dairy cows required to maintain national milk production, resulted in an increase in methane emissions by almost 15%.

The most effective methane mitigation measure for beef cattle and sheep was vaccination (-10%), while a diet high in starch also appeared effective at reducing emissions from beef cattle at the national level (-5%). Diets high in water soluble carbohydrates (WSC) appeared to be counter-productive and actually increased modelled national methane emission estimates slightly.

The effectiveness of increasing milk yield per cow as a measure to decrease methane emissions was matched by similar decreases in emissions of ammonia, nitrous oxide and nitrate leaching. While high fat diets for dairy cows appeared to decrease methane emissions by 14%, emissions of ammonia and nitric oxide were only slightly decreased by applying this mitigation measure, but nitrous oxide emissions and nitrate leaching showed a slight increase compared with the base scenario. Small decreases in methane emissions through the introduction of high starch diets or high quality forage were not matched by similar decreases for the N compounds under investigation, which showed very marginal decreases following the implementation of these measures.

The effect of future agricultural projections of livestock numbers to 2015 were estimated using the modelling approach. Emissions of methane from beef cattle were modelled to decline by approx. 18% compared with the current beef cattle population. These reductions were estimated to result in decreases in emissions of N gases and nitrate leaching of approx. 16%. For sheep, reductions in the national flock were estimated to result in reductions in methane emissions of approx. 4%, compared with current sheep populations, and similar reductions in N pollutants. Emissions from the national dairy herd were estimated to decrease by 25% due to reductions in animal numbers according to future projections in decreasing animal numbers.

Introduction

Whilst agriculture contributes only 7% of the UK's total greenhouse gas (GHG) emissions, it accounts for around 40% of methane (CH_4) emissions. The IPCC inventory considers CH_4 to be derived from two sources - enteric fermentation and manure management, the former accounting for *ca* 85% of the total CH_4 produced by agricultural sources. Within this context, dairy production accounts for some 30% of CH_4 emissions from UK agriculture and provides a major target for mitigation policies. Beef and sheep production account for *ca* 65% of the total UK agricultural CH_4 emission, but there is less scope for mitigation in these more extensive systems. Both we and others have reviewed possible strategies to decrease methane production from ruminants[1]. Much of this work was summarised in a DEFRA workshop (project CC0260), and at that time six strategies were selected as best options for further consideration. These are:

- increased productivity per head, to reduce the number of animals required for a given milk yield;
- dietary formulation to optimise carbohydrate utilisation and microbial growth in the rumen;
- improving the nutrition value or restricting use of poor quality forages;
- strategic use of dietary oil supplements;
- exploitation of the role of naturally occurring supplements
- immunisation to reduce CH_4 production.

The performance-lifetime of a dairy cow is presently *ca* 3.1-3.4 lactations or 36-40 months, and this must be set against a period of *ca* 30 months from birth to first calving. Increasing the number of lactations for which the average cow remains economically productive would therefore significantly reduce CH_4 emissions from the UK dairy industry. Similarly increasing the rate of productivity per head, possible by feeding a more concentrated diet or by improving the nutritional value of the forage offered to the cattle, would decrease CH_4 production per unit of production and, importantly, within the framework of milk production quotas, decrease CH_4 emissions from the dairy industry.

The type of feed offered to a ruminant can have a major effect on CH_4 production. The forage to concentrate ratio (F:C ratio) of the ration has an impact on the rumen fermentation and hence the acetate : propionate ratio (which declines with F:C ratio). It would therefore be expected that CH_4 production would be less when high concentrate diets are fed (Moss, 1993). Johnson and Johnson (1995) reported a CH_4 energy loss of 6% to 7% of gross energy intake when forages were fed at the maintenance plane of nutrition, and this reduced to 2-3% when high grain concentrates (>90%) were offered at near *ad libitum* intake levels. Van Soest (1982) indicated that a high grain diet and/or the addition of soluble carbohydrates gave a shift in fermentation pattern in the rumen which gave rise to a more hostile environment for the methanogenic bacteria where passage rates are increased, ruminal pH is lowered and certain populations of protozoa, ruminal ciliates and methanogenic bacteria may be eliminated or inhibited. The work of Lana *et al.* (1998) supports this theory by confirming that low rumen pH regulates methane production.

Lipid inclusion in the diet causes a marked decrease in CH_4 production by rumen fluid, with the effect being at least partly governed by the fat source used (Dong et al., 1997; Macmuller et al., 1998). This effect is partially but not fully mediated by the depression of protozoal numbers in the rumen due to the inclusion of fat (Machmuller et al., 2001, 2003). Rumen protozoa have been shown to harbour approximately 25% of the methanogens in the rumen (Newbold et al., 1996) and lipids appear to represent one of the few practical methods of controlling protozoa *in vivo* (Newbold and Chamberlain, 1998). However, the effects of fat on CH_4 production are not limited to those mediated via the rumen protozoa, and lipids have been shown to inhibit methanogenesis even in the absence of rumen protozoa (Broudiscou et al., 1990; Dohme et al., 1999) possibly due to the toxicity of long chain fatty acids to methanogenic bacteria (Prins et al., 1972; Hendersen, 1973). However, as with defaunation, the effect of fat supplementation cannot be viewed in isolation. Fat inclusion in the diet (particularly at levels above 5 g kg^{-1} DM) can significantly inhibit fibre breakdown in the rumen (Kowalcyk et al., 1977; Machmuller and Kreuzer, 1997) and again the severity of the effect varies with the fat used (Machmuller et al., 1998).

Given the forthcoming EU wide ban on the use of sub-therapeutic levels of antibiotics and ionophores as growth promoters in farm livestock, there has been an explosion of interest in other compounds that might modify microbial activity in the gut. With regards to CH_4 production, attention has focussed on plant secondary metabolites, probiotics and propionate precursors. Whilst major EU funded projects on plant materials to decrease CH_4 production are under way (Wallace, 2004), no details of potential candidate compounds are in the public domain. Potential problems with regulation and registration of such products make it unlikely that commercial products will be released in the near future. Similarly, the use of probiotics to decrease ruminal methane production was investigated in the Defra funded project CC0223, and, while development of this approach continues (http://www.rowett.co.uk/Resources/rrsod.pdf), potential problems with regulation and registration of such products make it unlikely that commercial products will be released in the near future. Possibly the most promising approach in the short term is the use of propionate precursors. Both fumarate and malate are key intermediates in the succinate-propionate pathway, in which malate is dehydrated to fumarate and fumarate reduced to succinate which is then decarboxylated to propionate. Reducing equivalents are consumed in the reduction of fumarate to succinate, hence both fumarate and malate have been shown to compete successfully for hydrogen in the rumen with subsequent decreases in methanogenesis both *in vitro* and *in vivo* (Martin, 1998; Asanuma et al., 1999; Lopez et al., 1999; Bayaru et al., 2001; Wallace et al., 2006; Newbold et al., 2005).

Baker (1995) has proposed that it may be possible to immunise ruminants against their own methanogens with associated decreases in CH_4 output. Shu *et al.* (1999) have shown that such an approach can successfully reduce the numbers of *Streptococci* and *Lactobacilli* in the rumen. Recent research has shown an 8% decrease in CH_4 production by sheep immunized against a range of methanogens. However, the vaccine used probably targeted less than 20% of the methanogens in the rumen and a greater efficacy might be achieved by using more targeted vaccine formulations.

However, a uniform critic of all the above methods is that they have largely been evaluated in single animals, or at best in small groups using field based micrometeorological methods (Wright et al., 2004). To date there have been few attempts to assess the consequences of scaling up such mitigation to the national level and to assess their consequences on the emissions of methane and emissions of other pollutants (ammonia, nitrous oxide, nitric oxide and nitrate leaching) from the ruminant agricultural sectors (dairy, beef and sheep). The use of a suite of models at different scales from the rumen via the herd level to the national level allows data to be extrapolated beyond the horizon of the original trial.

Objectives

The overall objective of the project was to investigate the implications of various methane mitigation measures, often investigated at the individual animal- to farm- scale, on long-term national emissions.

The objectives of the work were:

1. To carry out a review of the feasibility, cost and potential benefits and risks of options for methane abatement
2. To feed these data into mechanistic and non-linear models of productivity, methane and nitrogen emissions at an animal and herd level
3. To integrate the outputs of these models into a whole farm model taking into account other sources of methane (manure management) and describing the influence of variables such as climate, soil type, grassland area and farming practice on N_2O and NH_3 emissions and NO_3^- losses
4. To relate whole farm model outputs to a spatially distributed consideration of agricultural practice within the UK using farm typologies, considering the consequences of displaced production and the potential for increased national production
5. To test scenarios over a 1, 3 and 10 year time frame, taking into account impacts of mitigation strategies over the longer term, e.g. predicted trends in UK dairy farm management and rates of replacements at the herd level.

Approaches

Objective 1. Review of options for methane abatement.

The team carried out a review of published information on CH_4 abatement strategies This provided the basis for further impact modelling. This activity was co-ordinated by Prof. Newbold. The full review can be found in Appendix 1. However, the key conclusion was that the CH_4 abatement methods chosen to take forward to the modelling were:

- Increased productivity, i.e. increased milk production per kg CH_4 produced
- Increased fertility, i.e. reducing the number of followers required
- Improved forage composition and balanced energy/protein feeds
- Feed additives – to reduce rumen hydrogen production
- Vaccination – to reduce the methanogens in the rumen

The intention within this review was also to assess the costs of relevant abatement practices. However, the model modifications were more involved than anticipated and resources had to be switched to ensuring the appropriate modelling frameworks were constructed for future scenario testing.

Objective 2. Modelling effects on methane production at an animal and herd level

Method

Information from the review were used to inform the modelling led by Reading University group. They developed the mechanistic and non-linear modelling approach correlating nutrient intake with CH_4 production and productivity at the individual animal scale (Mills et al., 2001, 2003). Further developments to this model have allowed herd management decisions and fertility factors affecting replacement rate to be incorporated into the model at a herd level in order to predict productivity and methane and nitrogen emissions in dairy cows.

In order to reflect the national variation in dairy, beef and sheep enterprises, we defined model herd typologies from which we could base our CH_4 mitigation modelling. It is pertinent to introduce the typologies at this stage of the report.

Typologies

Dairy

We defined 3 baseline typical dairy farms (extended grazing, conventional intensive and fully-housed intensive) following information from DEFRA projects IS0101 and NT2509. These typologies differed in management factors such as: (i) average milk yield per cow, (ii) the reliance of meeting nutrient/energy cow requirements by different intensities of grazing and diets (iii) animal numbers and (iv) mineral fertiliser rates for the different forage areas (Table 1).

The timing and percentage of mineral fertiliser applied per month was designed to follow the UK fertiliser recommendations for agricultural crops (RB209) (DEFRA, 2000). The temporal patterns of distribution of the total manure applied followed the timing approach described by Smith *et al.* (2001). Slurry (6 % DM) was broadcast-applied. Total manure produced was calculated as an internal flow by the $SIMS_{DAIRY}$ modelling framework.

Table 1. Definition of variables used for dairy farms baselines (farm level)

	Extended Grazing Grazing – limited Concentrate - low N	**Intensive/graz-house** Equal ratio housing/grazing	**Very intensive/housing** Housing - high concentrate – high N
Milk (litres/cow yr)	5700	7125	8625
Grazing days - cows	290	192	60
maize in diet (kg DM/cow)	0	1800	3000
Concentrates fed (kg DM/cow)	440	1800	3000
Fertiliser			
N to grazed grass (kg N/ha)	284	320	100
N to 1-cut grass (kg N/ha)	314	325	150
N to 2-cut grass (kg N/ha)		313	150
N to 3-cut grass (kg N/ha)		275	150
N to other grass (kg N/ha)		304	
N to maize (kg N/ha)		40	40
P to grazed grass (kg P/ha)	27		
P to 1-cut grass (kg P/ha)	30	30	30
P to 2-cut grass (kg P/ha)		40	40
P to 3-cut grass (kg P/ha)		44	44
P to other grass (kg P/ha)			
P to maize (kg P/ha)			
Cattle numbers			
Number of milking cows	236	121	500
Young stock	62	34	137

Although currently it is becoming increasingly popular to grow a wide variety of forage crops within dairy farms, in order to simplify the system, we used maize as the only forage crop in the farm. The total land area for the different land uses varied over different sites and baselines and resulted from matching predicted animal requirements from each use (e.g. grazing days, silage) with predictions of production per unit of area for each use in different sites and under different fertiliser rates. These calculations were made by the $SIMS_{DAIRY}$ modelling framework (*data not* *shown*). Diet profile was adjusted to the requirements of the herd in terms of energy density, fibre (ADF), starch and fat content.

Specific fertility and culling parameters were used to carry out simulations at the herd/animal level (Table 2).

Table 2. Specific fertility and culling parameters for the baseline farms (herd/animal level)

Fertility Parameters	
Oestrus Cycle Length (days)	21
Gestation Length (days)	282
Maximum service interval (days)	200
Fertility Parameters for Cows and Heifers	
Voluntary Waiting Period (after Calving) Days	50
Submission i.e. Heat Detection Rate (%)	55
Conception Rate to First service (%)	45
Conception Rate to 2nd and Further Services (%)	45
Culling Policy	
Average No of Lactations per Cow at start	3
Maximum No of Lactations Allowed	10
Other (NON -FERTILITY) Culling (% of Cows Calving per Year)	10

Beef

We defined 2 baseline typical beef farming systems (lowland and upland) following information from DEFRA project NT2511. These typologies differed in management factors such as: (i) the reliance of meeting nutrient/energy cow requirements by different intensities of grazing and diets (ii) animal numbers and (iii) mineral fertiliser rates for the different forage areas (Table 3).

The timing and percentage of mineral fertiliser applied per month was designed to follow the UK fertiliser recommendations for agricultural crops (RB209), (DEFRA, 2000). The temporal patterns of distribution of the total manure applied followed the timing approach described by Smith *et al.* (2001).

The total area for the different land uses varied over different sites and baselines and resulted from matching predicted animal requirements from each use (e.g. grazing days, silage) with predictions of production per unit of area for each use in different sites and under different fertiliser rates. These calculations were made by the NGAUGE (Brown *et al.,* 2005) model (*data not shown*). Diet profile was adjusted to the requirements of the herd in terms of energy density, fibre (ADF), starch and fat content.

Table 3. Definition of variables used for beef baselines (farm level)

	Lowland	**Upland**
Grazing days - beef	150	240
Concentrates fed (kg DM/cow)	600	50
% white clover in grasslands	10	25
Fertiliser		
N to grazed grass (kg N/ha)	180	75
N to 1-cut grass (kg N/ha)		75
N to 2-cut grass (kg N/ha)	180	
N to 3-cut grass (kg N/ha)		
Cattle numbers		
Number of beef	250	200

Sheep

We defined 2 baseline typical sheep farming systems in England (lowland and upland) following information from DEFRA project NT2511. These typologies differed in management factors such as: (i) the reliance of meeting nutrient/energy sheep requirements by different intensities of grazing and diets (ii) animal numbers and (iii) mineral fertiliser rates for the different forage areas (Table 4).

Table 4. Definition of variables used for sheep baselines (farm level)

	Lowland	Upland
Grazing days - sheep	300	300
Concentrates fed (kg DM/sheep)	125	100
% white clover in grasslands	30	30
Fertiliser		
N to grazed grass (kg N/ha)	120	56
N to 1-cut grass (kg N/ha)		90
Sheep numbers		
Number of sheep	600	400
Number of lambs	75	70

The timing and percentage of mineral fertiliser applied per month was designed to follow the UK fertiliser recommendations for agricultural crops (RB209), (DEFRA, 2000).

The total area for the different land uses varied over different sites and baselines and resulted from matching predicted animal requirements from each use (e.g. grazing days, silage) with predictions of production per unit of area for each use in different sites and under different fertiliser rates. These calculations were made by the NGAUGE (Brown *et al.,* 2005) model (*data not shown*). Diet profile was adjusted to the requirements of the herd in terms of energy density, fibre (ADF), starch and fat content.

Modelling at the animal and herd level

Using this modelling approach, we were able to predict the effect of various mitigation strategies on CH_4 emissions per breeding animal. The herd level model is based on that described by Mottram and Mills (2003) and it simulates the effect of changing fertility levels and reproductive management on animal numbers (including those of replacements) with estimates of methane and milk production. The model is an iterative model based on assessing probabilities through the time course of the simulation. Animals are assigned initially to a calving group or age group and each group is then subject to the biological and management parameters that define the herd under any given management system.

The combined modelling approach, using animal and herd level models, allowed us to examine the effects of calving interval and lactation length on total herd CH_4 production in one analysis. The animal model accounts for dietary effects of fibre (ADF), starch, and energy density on emissions according to Mills et al. (2003), with modifications to incorporate the effect of supplementary fat in line with the predictions of Mills et al. (2001). Diet composition for each typology was estimated to represent an annual mean for each system, thereby assuming a combination of grazed forage and supplementary feed. The models were developed originally for use with dairy cows. For the purposes of this study, the animal model was applied to estimate beef and sheep emissions by correcting for intake, both in terms of chemical composition and quantity. Therefore, the assumption was that rumen function is similar between species (whilst in practice there may be small inter-species differences in rumen metabolism independent of nutrient intake, it is unlikely to be significant given the broad view and up-scaling required by this study).

Representation of herd and flock dynamics for the beef and sheep sectors respectively was provided by calculation of the proportion of time spent in the system by each age group (e.g. heifers <12months etc.). Nutrient intake was assumed to be a mean of requirements across this period. For example, one of the main defining characteristics between upland and lowland beef systems was the time taken to produce an animal ready for slaughter, with upland beef requiring > 4 months more than in the equivalent lowland system. Typical replacement rates (and hence herd turnover) were estimated according to experience of typical practices and the national annual inventory of livestock numbers according to age group.

Model runs at animal and herd level

The models were applied to examine the effects of each typology against the baseline scenario on CH_4 emissions. Each typology was chosen to define the direct effect of the chosen mitigation strategies as defined by nutritional and herd management parameters. Therefore, whilst it could be argued that certain strategies imply indirect effects through associated management factors (e.g. high production being perceived as associated with lower fertility), the effects described by the model in this study take only direct effects into account. This allows the analysis to highlight the root cause of any changes to emissions and to identify the most promising mitigation strategies, without being confounded by indirect and often poorly defined relationships. It would be misleading to assume an additional level of management effects by combining management factors within some typologies, such as linking production and fertility at the expense of other less well described but potentially important relationships, such as production and non-fertility culling. This is especially true where such a relationship as increased production and reduced fertility is not universal with many well managed herds capable of maintaining or even improving fertility against a background of higher milk yields. Therefore, the analysis as delivered in this study allows one to compare magnitude of the potential effects for each mitigation strategy, whilst still being able to provide informed speculation about the ameliorating or exaggerating influences of more loosely characterized associations.

Methane emission factors from the herd model were expressed as kg CH_4 / adult animal + the associated followers.

Objective 3. Whole farm emissions of greenhouse gases-linkage of the Reading and IGER models

Method

The Reading model generated enteric CH_4 emission factors for the dairy, beef and sheep typologies. These model runs only included enteric fermentation as the source of CH_4. The herd typologies, proportions of lactating cattle to followers, feed inputs and methane emissions per herd were used to parameterise the $SIMS_{DAIRY}$ (del Prado *et al.,* 2006, DEFRA project IS0214) and NGAUGE DSS models (Brown et al., 2005). The influences of other on-farm sources of CH_4 were taken into account using the NGAUGE system to generate annual manure production and to partition that manure into the potential sources (within house, storage tank, land spreading). Methane emission factors for each potential source were taken from existing data supplied by IGER (e.g. projects WA0604, NT1836, WA0637, WA0707) and other literature values (e.g. Chadwick et al., 2000). Methane emissions from housed animals and that excreted from the animal while in house were differentiated to avoid double counting from these sources.

Dairy systems

Sustainable and Integrated Management Systems for Dairy Production ($SIMS_{DAIRY}$) is a new modelling framework which integrates existing models for N and P, equations to simulate NH_3 losses from manure application, predict CH_4 losses and cows' nutrient requirements, 'score matrices' for measuring attributes of biodiversity, landscape, product quality, soil quality and animal welfare and an economic model. $SIMS_{DAIRY}$ is capable of simulating farm N flows (and CH_4 outputs) for a given combination of management strategies, soil types and UK agro-climatic areas. $SIMS_{DAIRY}$ simulates flows of dry matter, energy, nitrogen and phosphorus at the animal level through calculations of feed requirements and supply (DM, energy, and N), under different diet profile strategies and for given lactating and young cow types, which represent the whole herd. Calculations are based on the Feed into Milk (FiM) system (Thomas, 2004).

Manure produced during housing and excreta deposited during grazing (N and P) are calculated for each type of cow and subsequently in total (applying number of animals of each type) by subtracting N and P in milk from those ingested by both housing and grazing young and lactating cows. Manure (N and P) produced during housing is simulated to be applied to the different fields on the farm. As mentioned before, forage areas and hence manure rates are subsequently adjusted, once harvest yields per hectare for each type of forage area are calculated and compared with sources of nutrient requirements.

Flows of N and P are simulated within the fields and losses (P, NO_3, N_2O, NO_x, N_2 and NH_3 and CH_4) are calculated. Losses of N and CH_4 from manure management greatly depend on manure system chosen (FYM vs. slurry). Manure N losses are simulated in $SIMS_{DAIRY}$ according to the mass flow approach of Webb and Misselbrook (2004), by which NH_3, N_2O, NO_x and N_2 emissions are calculated from the pool of total ammonium nitrogen (TAN) in manure N according to different emission factors for different manure management stages. Ammonia losses from housing are calculated as a percentage loss from the TAN content of the manure (based on the 2004 inventory of NH_3 emissions from UK agriculture). NH_3, N_2O, NO_x and N_2 losses from storage are predicted as a percentage of the remaining TAN content in the manure. $SIMS_{DAIRY}$ predicts CH_4 losses from manure storage and application according to emission factors for each potential source (e.g. projects WA0604, NT1836, WA0637, WA0707 and other literature values, e.g. Chadwick *et al.,* 2000, Chadwick and Pain, 1997; Yamulki *et al.*, 1999).

Beef and sheep systems

NGAUGE (Brown *et al.,* 2005) is an empirically-based mass-balance model which simulates monthly N flows within and between the main components of grazed or cut grassland systems according to user inputs describing site conditions and farm management characteristics (i.e. monthly fertiliser and manure application).

NGAUGE is an improvement on existing N fertiliser recommendation systems, in that it relates agricultural production to environmental impact and is therefore potentially valuable to policy makers and researchers for identifying pollution mitigation strategies and blueprints for novel, more sustainable systems of livestock production. So far, NGAUGE has been successfully applied in different desk-top studies to assess e.g. the impact of extended grazing on NO_3-leaching losses (Webb *et al.,* 2005), to develop cost-curves for NO_3^- mitigation options (DEFRA project NT2511), and to model N losses at a landscape scale (Theobald *et al.,* 2004).

For the current project we used a modified version of NGAUGE that is capable of simulating white clover-grass swards and is adjusted to beef and sheep animals. Methane losses from manure storage and application were calculated according to emission factors for each potential source based on literature values.

Effects of soil and climate

Although it was assumed that CH_4 emissions would not be affected by soil or climate, we know that these are key controls for emissions of ammonia, nitrous oxide and nitrate leaching. Therefore, it was necessary to generate a single map comprising a simplified overlay of climate (temperature and rainfall) and soil type for England, Wales and Scotland. Without access to (expensive) detailed spatial datasets for this project, this was done by expert judgement, taking into account the major soil types and climate zones. (This part of the study could be improved significantly in the future, if GIS datasets of soil type and climate were acquired for use in further work.). This map can be seen in Figure 1.

Key soil/climate combinations were included in the farm-scale modelling. $\text{SIMS}_{\text{DAIRY}}$ and NGAUGE specifically take into account the effect of climate and soil type on the different N losses.

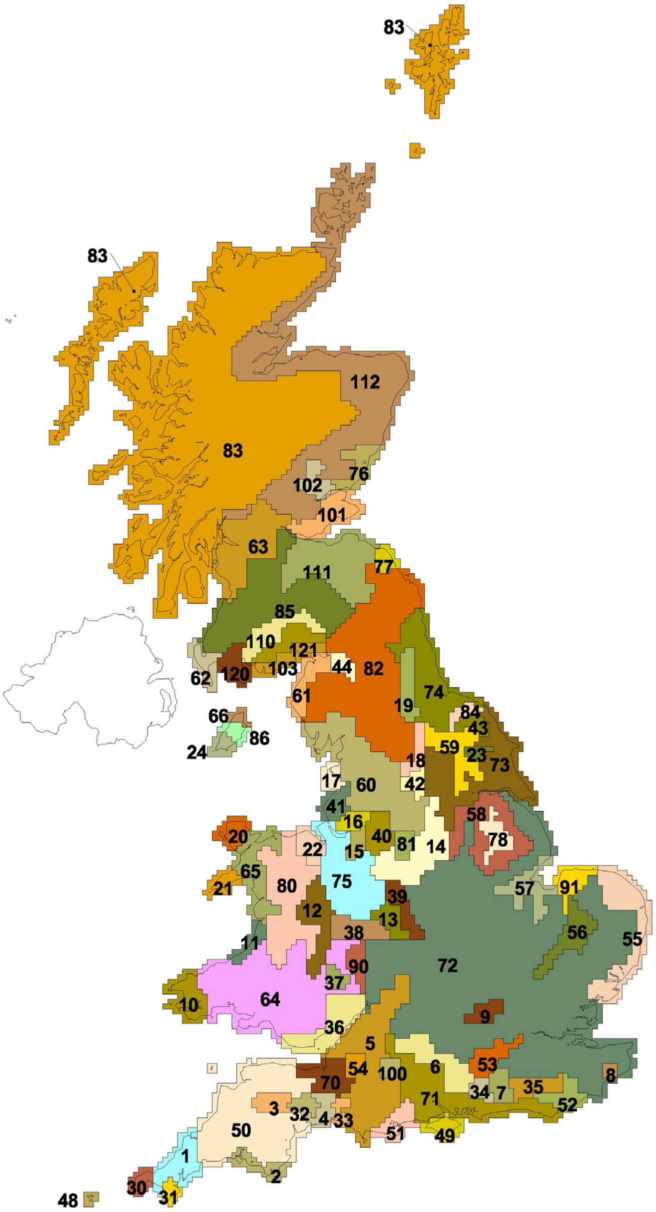

Figure 1. Map of soil / climate zones for NGAUGE and AENEID modelling.

The coupled models took into account enteric sources of CH_4 as well as other CH_4 emission sources at the farm-scale. By simulating typical UK dairy systems, the models linked inputs of N fertiliser, concentrates, feed quality and calving pattern characteristics of the dairy/beef herd with economic outputs (milk) and N losses to the environment. The way that the three models interact in order to scale mitigation measures from animal to herd to national level is shown schematically in Figure 2.

The next step was to determine the farm-scale baseline emissions of CH_4, N_2O, NH_3 emissions and losses of NO_3 for the different typologies using the coupled Reading herd-scale rumen model and the $\text{SIMS}_{\text{DAIRY}}$ and NGAUGE models. The effect of the various mitigation practices was then investigated by modifying the inputs to the Reading herd-scale rumen model, $\text{SIMS}_{\text{DAIRY}}$ and NGAUGE for the range of dairy, beef and sheep typologies. The impacts of the mitigation practices at the farm-scale are summarised in Tables 5 (dairy), 6 (beef) and 7 (sheep).

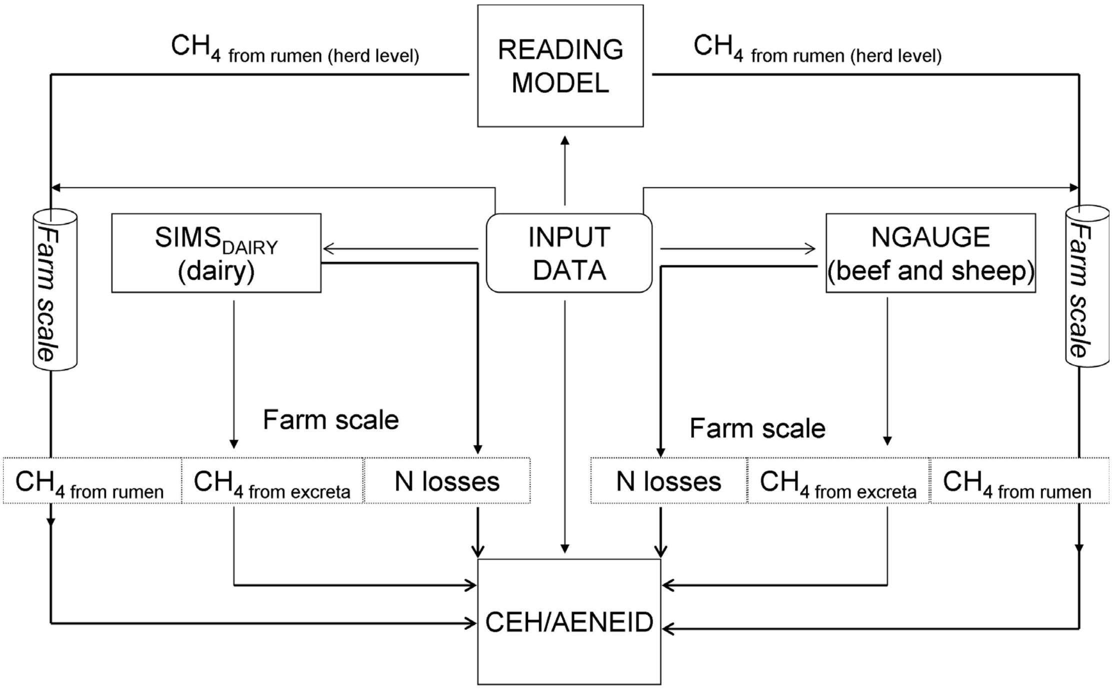

Figure 2. Schematic representation of the modelling system.

Results of the farm level modelling (Reading +IGER models)

The ranges in Table 5, 6 and 7, reflect the effect of the range of soils and climates on emissions. Results show the ranges of losses per animal (including followers) for the soil types and UK agro-climatic areas studied.

Dairy

The fact that the results are expressed as per unit of animal and that the forage area and milk production per dairy cow (including followers) varies between typologies, does not facilitate the assessment of the results per other units of reference (per L of milk or per ha of forage land). In data not shown, for example, losses per L were inversely related to capacity of the cow to produce milk. Differences in CH_4 losses per animal were mostly due to differences in enteric fermentation output as previously shown by the Reading model.

Losses per animal varied between farm typologies, mitigation methods and forms of N lost. Nitrate leaching losses from intensive and very intensive typologies were larger than those from extended grazing systems, being partly related to the amount of concentrates ingested per animal.

Nitrous oxide emissions, though, were largest from the intensive/grazed housing system, suggesting a strong relationship between fertiliser rate and N_2O emissions. Losses of NH_3 from fully housed typology were almost double than those from the other 2 typologies.

Soil and climatic conditions affected the ranges for the various losses to different extents. Nitrate, N_2O and NOx losses were quite sensitive to the combination of soil and climatic conditions. In general, heavy soils in very wet areas tended to lose much of their losses via denitrification, a large proportion of which as N_2 losses. For heavy soils and drier areas, a greater proportion of denitrified N was lost as N_2O up to a point where the likelihood of coinciding wet spells and N fertilisation (or excreta deposition) would be small and excess mineral N would accumulate or be lost during the autumn-winter season through NO_3^- leaching. Lighter soils would tend to lose more NO_3^- through leaching than heavy soils and could also emit large amount of N_2O emissions if fertilisation (or excreta deposition) coincided with wet spells.

Ammonia losses per animal, however, tended to be less sensitive to climate and soil type and resulted in narrower ranges than for N_2O and NO_3^- leaching losses. The main differences would actually arise from the indirect effect of the climate and soil type on the protein content of the grass grazed and thereby on the excreta returns. This is actually reflected on the wider ranges of NH_3 losses shown in the 2 typologies with grazing activity.

The CH_4 mitigation measures had similar qualitative effects on N losses across the 3 typologies. Adoption of systems with higher milk yielding cows (+30%) resulted in an increase in CH_4 outputs per cow but a decrease in CH_4 per unit of milk produced (*data not shown*). The same tendency was also found for all the studied N losses. $SIMS_{DAIRY}$ predictions pinpoint the fact that higher yielding cows are more efficient not only in ingesting biomass but also in partitioning that N ingested into milk. Ingestion of diets high in fat resulted in reductions in CH_4 losses both per animal and milk output and losses of N remained similar.

Increasing heat detection rate (fertility parameter) increased fertility and thereby would result in fewer followers needed per dairy cow, resulting in less CH_4 output both per dairy cow (including followers) and per L of milk. The same results were found for the N losses.

Increasing the quality of forage decreased CH_4 output per animal and did not result in significant changes in N losses. Diets with greater starch content resulted in smaller CH_4 outputs and similar N losses. Although $SIMS_{DAIRY}$ predicts a certain shift towards more dung N over urine N in starchy diets (*data not shown*), reductions of N losses as a whole were very small (<2%) and only in NO_3^- and N_2O emissions.

Beef and sheep

The effects on methane emissions per breeding animal for upland versus lowland typologies for beef and sheep species (Tables 6 and 7) appear counter-intuitive, i.e. with upland beef generating more CH_4 than lowland beef, and upland sheep generating less CH_4 than lowland sheep. The reason lies in the fact that beef systems have an inherently longer reproductive cycle, i.e. the time taken to yield a replacement breeding animal or animal for slaughter. The interaction of breed and time to slaughter is greater for sheep than for beef systems, with the breed differences tending to compensate for the chosen management system. Therefore, with upland sheep the time to slaughter is only marginally longer than for lowland systems, albeit with a smaller carcass. With beef animals the carcass may also be smaller in upland systems, but the time to slaughter also tends to be significantly longer as a function of the management system.

Methane mitigations had little effect on N losses per animal.

Table 5. Results at farm level for dairy

Typology	mitigation	NO_3	CH_4	N_2O	NH_3	NO_x
		kg/dairy cow+followers/ yr*				
Extended Grazing						
Extended Grazing	Baseline	12-36	103.9-104.6	0.2-5	31-35	0.0017-0.0028
Extended Grazing	Milk/cow (-30 %)	11-34	84.3-84.8	0.2-4.6	33-33	0.0022-0.0026
Extended Grazing	Milk/cow (+30 %)	13-44	118.2-118.6	0.3-7	31-32	0.0017-0.0022
Extended Grazing	High Fat	12-36	89.3-90	0.2-5	34-36	0.0023-0.0028
Extended Grazing	decrease 30% HDR	13-38	112.8-113.5	0.2-5.2	33-37	0.0019-0.0032
Extended Grazing	Increase 30% HDR	11-33	96.7-97.3	0.2-4.6	28-31	0.0013-0.0021
Extended Grazing	High quality forage	12-36	100.4-101	0.2-5	31-35	0.0017-0.0028
Extended Grazing	Low quality forage	12-36	105-105.6	0.2-5	31-35	0.0017-0.0028
Extended Grazing	High starch concentrate	12-36	99.8-100.4	0.2-5	31-35	0.0017-0.0028
Intensive/graz-house						
Intensive/graz-house	Baseline	16-70	113.9-115.2	0.4-12.2	31-35	0.0008-0.0014
Intensive/graz-house	Milk/cow (-30 %)	15-62	101.5-102.8	0.4-10.8	28-32	0.0009-0.0013
Intensive/graz-house	Milk/cow (+30 %)	18-75	123-124.1	0.5-13.7	33-38	0.0008-0.0015
Intensive/graz-house	High Fat	16-72	98-99.1	0.4-12.5	31-35	0.0008-0.0018
Intensive/graz-house	decrease 30% HDR	17-73	122.7-124.1	0.4-12.6	33-37	0.0009-0.0016
Intensive/graz-house	Increase 30% HDR	15-63	105.5-106.7	0.4-11.3	28-31	0.0006-0.0011
Intensive/graz-house	High quality forage	16-69	110.8-112	0.4-12.1	31-35	0.0008-0.0014
Intensive/graz-house	Low quality forage	16-69	115.9-117.2	0.4-12.1	31-35	0.0008-0.0014
Intensive/graz-house	High starch concentrate	16-69	108.4-109.6	0.4-12.1	31-35	0.0008-0.0014
Very intensive/housing						
Very intensive/housing	Baseline	23-67	107.3-107.4	0.2-6.4	68-68	0.0011-0.0016
Very intensive/housing	Milk/cow (-30 %)	21-62	91.5-91.9	0.2-5.9	62-62	0.0011-0.0015
Very intensive/housing	Milk/cow (+30 %)	25-73	127.1-127.4	0.2-7	74-75	0.0012-0.0017
Very intensive/housing	High Fat	23-68	92.2-92.2	0.2-6.4	68-68	0.0011-0.0016
Very intensive/housing	decrease 30% HDR	24-70	113.4-113.5	0.2-6.6	72-72	0.0013-0.0018
Very intensive/housing	Increase 30% HDR	21-61	100.3-100.3	0.2-5.9	61-61	0.0008-0.0012
Very intensive/housing	High quality forage	23-66	106.5-106.6	0.2-6.3	68-68	0.0011-0.0016
Very intensive/housing	Low quality forage	23-67	111.8-111.9	0.2-6.4	68-68	0.0011-0.0016
Very intensive/housing	High starch concentrate	23-66	100.4-100.4	0.2-6.4	67-68	0.0011-0.0016

* emissions relate to one adult dairy cow + the fraction of followers associated with it. Ranges reflect different soil-climatic zones.

Table 6. Results at farm level for beef

Typology	Measure	NO_3	CH_4	N_2O	NH_3	NO_x
				kg/beef cow + followers/ yr		
Lowland	Baseline	6-35	169.9-171.2	0.2-12	21-37	0.022-0.356
Upland	Baseline	1-14	214-214.4	0.1-6	8-16	0.012-0.237
Lowland	High Starch	6-35	149.4-150.7	0.2-12	21-37	0.022-0.356
Lowland	High WSC	6-35	180.2-181.5	0.2-12	21-37	0.022-0.356
Lowland	High fat	6-35	169.9-171.2	0.2-12	21-37	0.022-0.356
Lowland	Vaccine	6-35	153.1-154.4	0.2-12	21-37	0.022-0.356
Upland	Vaccine	1-14	192.6-193	0.1-6	8-16	0.012-0.237

* emissions relate to one adult beef cow + the fraction of followers associated with it. Ranges reflect different soil-climatic zones.

Table 7. Results at farm level for sheep

Typology	Measure	NO_3	CH_4	N_2O	NH_3	NO_x
				kg/sheep + lambs/ yr		
Baseline	Lowland	0.2-2.1	25.1-25.1	0.02-0.7	0.8-1.4	0.001-0.028
Baseline	Upland	0.2-1.9	20.2-20.2	0.02-0.4	0.7-0.9	0.001-0.028
High Starch	Lowland	0.2-2.1	24.4-24.4	0.02-0.7	0.8-1.4	0.001-0.028
High WSC	Lowland	0.2-2.1	25.3-25.3	0.02-0.7	0.8-1.4	0.001-0.028
Vaccine	Lowland	0.2-2.1	22.6-22.6	0.02-0.7	0.8-1.4	0.001-0.028
Vaccine	Upland	0.2-1.9	18.1-18.1	0.02-0.4	0.7-0.9	0.001-0.028

* emissions relate to one adult sheep + the fraction of lambs/followers associated with it. Ranges reflect different soil-climatic zones.

Objective 4. Modelling of mitigation strategies at the national scale for Great Britain

For each of the soil-climate zones in Figure 1, it was necessary to estimate the proportion of dairy cows present in the area that were in each of the typologies (very intensive/housed, intensive/grazed, extended grazing). For beef and sheep, each area was also allocated a proportion of 'upland' and 'lowland' typologies. The $SIMS_{DAIRY}$ and NGAUGE runs for all combinations of the soil / climate combinations for each of the dairy, beef and sheep typologies (as well as mitigation options) was then allocated a set of $SIMS_{DAIRY}$ and NGAUGE emission factors (Tables 5, 6 and 7). It was this information that was passed to the CEH AENEID model for the upscaling of CH_4, N_2O, NH_3 and NO_3 losses to the national level.

It is important to note that the method used for scaling the impact of the CH_4 mitigation practices to the national emissions was to determine the percentage change from the baseline, as estimated by the $SIMS_{DAIRY}$ and NGAUGE methodology, and to modify the IPCC baseline for each livestock group with the percentage difference. The same rationale was used for scaling the effects of CH_4 mitigation on N_2O emissions. For NH_3 emissions, the UKAEI national totals were modified according to the percentage difference from the baseline estimated using NGAUGE. For NO_3 leaching, the baseline was taken from project ES0203 and modified according to the percentage difference as estimated by NGAUGE.

Based on the findings of the review and farm scale modelling of selected CH_4 mitigation options, CEH incorporated the $SIMS_{DAIRY}$ and NGAUGE modelling results to scale up to the national estimates required under UK obligations to international conventions (UNFCCC, UNECE-CLRTAP). The AENEID (Atmospheric Emissions for National Environmental Impacts

Determination) model was originally developed for the spatial distribution of NH_3 for the UK (Dragosits et al., 1998) and is currently used for annual modelling and mapping of the spatial distribution of both agricultural and a range of non-agricultural emissions of NH_3 for the National Atmospheric Emissions Inventory (NAEI, www.naei.org.uk), and also for CH_4 and N_2O for the UK Greenhouse Gas Inventories. It has also been applied in several other Defra projects (e.g. AM0101-NARSES, AM0118-FMD trace gases) (Sutton et al., 2004, 2006).

Key input data for the AENEID model are detailed agricultural census statistics, emission source strength estimates per animal or hectare of crop/managed grassland, and a fine-scale satellite-based landcover map. The model spatially distributes livestock and crop statistics as emission sources onto suitable landcover types based on a weighted approach, at a 1 km grid resolution. To ensure non-disclosivity of the input census statistics, as well as to reduce uncertainty in the spatial location of some of the less land-based emission sources (e.g. intensive poultry or pig farming), the model results are subsequently aggregated to a 5 km resolution for mapping as a standard procedure. Although the AENEID model normally operates for the UK, the mitigation scenarios in this project were run for Great Britain only, as, unfortunately, soil data for Northern Ireland were not readily available at the time for inclusion in the project. The most recent year where data were available to be modelled at the national scale was 2003.

The output from the coupled Reading – IGER models (CH_4, N_2O, NH_3, NO_3^-) was expressed on a per adult animal basis for each of the typical mitigation scenarios and each farm typology simulated, and converted into spatially variable emission source strength maps for up-scaling to the national scale for each of the typical (spatially distributed) management systems.

Results of national scale modelling

The main results from the national upscaling of the relative impacts of mitigation methods on CH_4, N_2O and NH_3 emissions as well as for NO_3^- leaching are summarized in Table 8. These results were used to adjust the national emissions of methane as calculated by the IPCC methodology, and are shown in Table 9.

From the results of Tables 8 and 9, it appears that the most effective CH_4 mitigation measure for beef cattle and sheep is vaccination (-10%), while a diet high in starch also appears effective at reducing emissions from beef cattle at the national level (-5%). Diets high in WSC appear to be counter-productive and actually increased modelled national CH_4 emission estimates slightly.

For dairy cattle, an increase in milk yield per cow (30% in the modelled scenario), coupled with a reduction in dairy cow numbers to maintain the national milk production level, appears to result in the largest reduction in CH_4 emissions at the national level (-24%). The next most effective mitigation strategy is a high fat diet, which provides a 14% saving in CH_4 emissions, followed by increased heat detection rate (HDR) at 7% and a high starch diet at 5%. Garnsworthy (2004) estimated that by restoring fertility to 1995 levels, CH_4 emission could be reduced by 10-11%, but that further improvements in fertility could reduce CH_4 emissions by up to 24%.

Changes in diet to high quality forage do not appear to result in large differences in the national emission of CH_4 (-3%), whereas scenarios modelling an increase in low quality forage or decreased HDR result in marginal increases in CH_4 emissions. A reduction in the milk yield per dairy cow by 30%, coupled with an increase in the number of dairy cows to maintain national milk production, results in an increase in CH_4 emissions by almost 15%.

The effects of CH_4 mitigation measures on emissions of NH_3, N_2O and NO_3^- leaching were also scaled up to the national level for dairy cattle. (For beef and sheep, the farm/herd model was not sufficiently sensitive to produce differences in emission factors for the N compounds.) This allows the assessment of potential "pollution swapping" issues, i.e. in this case the increase in emissions of N compounds or NO_3^- leaching while attempting to reduce CH_4 emissions.

The effectiveness of increasing milk yield per cow as a measure to decrease CH_4 emissions is matched by similar decreases in emissions of NH_3, N_2O and NO_3^- leaching (see Table 8). Increasing HDR resulted in a ca 10% reduction in NH_3 emissions. Garnsworthy (2004) predicted that restoring fertility to 1995 levels would reduce CH_4 emissions but also reduce NH_3 emissions by about 9%. Further improvements in fertility could reduce ammonia emissions by about 17%.While high fat diets for dairy cows appear to decrease CH_4 emissions by 14%, emissions of NH_3 and NO are only slightly decreased by applying this mitigation measure, but N_2O emissions and NO_3^- leaching show a slight increase compared with the base scenario. Small decreases in CH_4 emissions through the introduction of high starch diets or high quality forage are not matched by similar decreases for the N compounds under investigation, which show very marginal decreases following the implementation of these measures.

Table 8. Relative impact of methane mitigation methods at the national scale on methane, ammonia, nitrous oxide, nitric oxide and nitrate leaching (for year 2003)

	scenario	**comparison with base scenario emissions**				
		CH_4	**NH_3**	**N_2O**	**NO**	**NO_3^-**
Dairy Herd						
	base	100.0%	100.0%	100.0%	100.0%	100.0%
	milk yield decreased by 30%*	114.9%	118.1%	113.4%	121.5%	121.1%
	milk yield increased by 30%*	76.1%	72.6%	79.1%	63.0%	78.4%
	high fat	86.0%	98.5%	100.4%	95.6%	103.8%
	HDR decreased	107.8%	105.8%	103.5%	114.8%	105.0%
	HDR increased	92.7%	89.3%	93.1%	74.3%	91.2%
	high quality forage	97.2%	99.7%	99.4%	99.7%	99.4%
	low quality forage	101.7%	99.7%	99.7%	99.9%	99.7%
	high starch	95.2%	99.1%	99.6%	99.7%	99.5%
Beef herd						
	base	100.0%	-	-	-	-
	high starch	95.2%	-	-	-	-
	high WSC	102.4%	-	-	-	-
	high fat	100.0%	-	-	-	-
	vaccine	90.1%	-	-	-	-
Sheep flock						
	base	100.0%	-	-	-	-
	high starch	98.7%	-	-	-	-
	high WSC	100.3%	-	-	-	-
	vaccine	89.8%	-	-	-	-

* numbers of dairy cows increased/reduced at the same time to keep the national milk yield constant

Table 9. Quantitative effect of methane mitigation methods on the 2003 national emission

	Scenario	**CH_4** kt
Dairy Herd		
	Base#	277.3
	milk yield decreased by 30%*	318.6
	milk yield increased by 30%*	211.0
	high fat	238.5
	HDR decreased	298.9
	HDR increased	257.1
	high quality forage	269.5
	low quality forage	282.0
	high starch	264.0
Beef herd		
	Base#	391.6
	high starch	372.8
	high WSC	401.0
	high fat	391.6
	vaccine	352.8
Sheep flock		
	Base#	176.3
	high starch	174.0
	high WSC	176.8
	vaccine	158.3

* numbers of dairy cows increased/reduced at the same time to keep the national milk yield constant

\# Baseline data from the UK N_2O and CH_4 inventories.

Objective 5. Extrapolation of model outputs over a 10 year time framework

Method

For the most effective CH_4 mitigation measures calculated at the farm scale, projections into the future from the 2003 reference year were explored taking account of the projected forecasts in ruminant numbers over the next 10-12 years.

The "Business as usual" (BAU, 2006) scenario was based on the *Business As Usual – BAU Phase 2* report by Edinburgh University / SAC, which estimates that the national dairy cattle population will be reduced by 30% in Less Favoured Areas (LFAs) and by 25% in lowland areas by 2015. For beef, the herd is estimated to have declined by 20% in LFAs and by 15% elsewhere by 2013. The sheep flock is estimated to decline by 6% in LFAs and by 2% elsewhere over the same period.

For this study, it was assumed that the majority of dairy cattle would be based outwith LFAs, therefore a scaling factor of -25% was applied to the dairy population for applying BAU assumptions to the different CH_4 mitigation scenarios. The only exception is the scenario where milk production per dairy cow is increased by 30%, and the 30% reduction in the dairy population associated with this scenario (see previous section) was retained to keep the national milk production stable.

For the national beef herd and sheep flock, the upland and lowland typologies applied in this study are not the same as the LFA/non-LFA areas applied in the BAU report. However, for the purposes of the study the population reduction estimates were interpreted to apply to our upland/lowland typologies in the absence of better data. According to the beef cattle typologies applied in this study, 54.5% of the cattle are located in areas classified as "upland" and 45.5% in areas classified as "lowland". For sheep, the proportions are 62% in the uplands and 38% in the lowlands, according to the typology derived for this study. Another independent estimate for upland and lowland sheep populations is used in the annual UK Ammonia Emission Inventory of Misselbrook et al. (e.g. 2006), which has been derived from expert knowledge (51.5% upland sheep, 48.5% lowland sheep). While the two estimates differ, they both estimate a higher proportion of the UK sheep flock to be present in upland areas, and the former was applied here.

The reduction in the population of beef cattle and sheep according to the BAU estimates was applied in the AENEID model to the upland and lowland areas, and a 100% adoption of each CH_4 mitigation measure was assumed for each scenario in turn, to show maximum achievable savings in emissions.

The results of applying BAU assumptions for ruminant populations to estimate effects on baseline CH_4, NH_3 and N_2O emissions are shown in Table 10. Emissions of CH_4 from beef cattle are modelled to decline by approx. 18% compared with the current estimate for the (2003) beef cattle population. These reductions are estimated to result in decreases in emissions of N compounds and NO_3 leaching of approx. 16%. For sheep, reductions in the national flock are estimated to result in reductions in CH_4 emissions of approx. 4%, compared with current (2003) sheep populations, and similar reductions in N pollutants. Emissions from the national dairy herd are estimated to decrease by 25% due to reductions in animal numbers according to BAU predictions.

Table 10. Estimated change in emissions of methane, ammonia and nitrous oxide under BAU predictions of ruminant populations.

	scenario	**(kt) / year** **CH_4**	 **NH_3**	 **N_2O***
Dairy Herd				
	2003 base	277.3	71.5	6.3
	2015 base	208.0	53.6	4.8
Beef herd				
	2003 base	391.6	62.3	9.8
	2015 base	321.1	52.0	8.3
Sheep flock				
	2003 base	176.3	14.8	6.2
	2015 base	168.4	14.2	6.0

Methane and nitrous oxide baseline data from the UK inventories for 2003.
Ammonia baseline data from the UK Ammonia Emissions Inventory 2003 (excluding hardstandings)
* direct N_2O emissions only

The additional effects of CH_4 mitigation measures on the 2015 baseline are summarised in Table 11.

Table 11. Estimated change in emissions of methane, under BAU predictions of ruminant populations for 2015 for methane mitigation scenarios, assuming full implementation of mitigation measures.

	scenario	CH_4 (kt / year)	% change from 2003 estimation (Table 9)
Dairy Herd			
	2015 base	208.0	-25.0
	2015 milk decreased by 30%	239.0	-25.0
	2015 milk increased by 30%	211.0	0.0
	2015 high fat	178.9	-25.0
	2015 HDR decreased	224.2	-25.0
	2015 HDR increased	192.8	-25.0
	2015 high quality forage	202.1	-25.0
	2015 low quality forage	211.5	-25.0
	2015 high starch	198.0	-25.0
Beef herd			
	2015 base	321.1	-18.0
	2015 high starch	305.0	-18.2
	2015 high WSC	329.2	-17.9
	2105 high fat	321.1	-18.0
	2105 vaccine	289.3	-18.0
Sheep flock			
	2015 base	168.4	-4.5
	2015 high starch	166.5	-4.3
	2105 high WSC	169.2	-4.3
	2105 vaccine	151.5	-4.3

Conclusions

- Linking the outputs of the Reading University rumen and herd models with the IGER farm-scale models (NGAUGE and SIMS$_{DAIRY}$) and linking the output from them to the CEH national scale model (AENEID) provided a successful framework from which to upscale the impacts of methane mitigation from individual/groups of animal to the national scale and estimate the impacts on other environmental losses.

Dairy cattle

- An increase in milk yield per cow (30% in the modelled scenario), coupled with a reduction in dairy cow numbers to maintain the national milk production level, appears to result in the largest reduction in CH_4 emissions at the national level (-24%).

- A reduction in the milk yield per dairy cow by 30%, coupled with an increase in the number of dairy cows to maintain national milk production, results in an increase in methane emissions by almost 15%.

- A high fat diet or a high starch diet reduced methane emissions by 14% or 5%, respectively.

- Increased heat detection rate reduced methane emissions by 7% .

Beef and Sheep

- The most effective methane mitigation measure for beef cattle and sheep is vaccination (-10%), while a diet high in starch also appears effective at reducing emissions from beef cattle at the national level (-5%).

Impacts on other emissions

- The effectiveness of increasing milk yield per cow as a measure to decrease methane emissions is matched by similar decreases in emissions of ammonia, nitrous oxide and nitrate leaching.

- Increasing heat detection rate resulted in a *ca* 10% reduction in ammonia emissions.

- High fat diets for dairy cows (decreased methane emissions by 14%) had little effect on emissions of ammonia and nitric oxide, but nitrous oxide and nitrate leaching losses were slightly increased compared with the base scenario.

- Small decreases in methane emissions through the introduction of high starch diets or high quality forage are not matched by similar decreases for the N compounds under investigation

Impacts of projected changes in livestock numbers

The results of applying 'business as usual' assumptions for projections in ruminant populations on methane emissions are:

- Emissions from the national dairy herd are estimated to decrease by 25%, emissions of methane from the national beef herd are modelled to decline by approx. 18%, and emission from the national sheep flock are estimated to reduce by approx. 4%, compared with the current estimate for the (2003) populations.

Recommendations for further research

- Due to resource constraints, we were not able to purchase and hence make use of spatial soil and climate maps of the UK, thus relying on simplified overlaying of maps. The use of spatial soil and climate maps of the UK would increase accuracy of the spatial scaling.

- A full cost-effectiveness, cost-benefit analysis of the effects of the mitigation methods needs to be undertaken, taking into account the likely degree of uptake and efficacy of methods across the different ruminant sectors. This cost-benefit analysis should encompass the primary impacts (i.e. on changes in methane emissions) but also any significant secondary impacts on other pollutants such as ammonia and nitrous oxide emissions and nitrate leaching.

- Methane generation by livestock impact on climate change. However, climate change may also impact on livestock farming, e.g. through changed cropping in response to climate change and changed calving patterns in response to forage availability. The return effect on environmental emissions needs to be estimated.

- The rumen model predicts nitrogen excretion and methane emissions from dietary intake. It is important to understand the implications of modifying diets to control methane not only on N excretion but to follow the impacts through to understanding the effects on ammonia and nitrous oxide emissions. These effects have been modelled. However, validation of the different feeding strategies on methane, ammonia and nitrous oxide emissions is required to understand which feeding strategies are win-win, and which, if any, result in trade-offs.

References

Asanuma N., Iwamoto M. and Hino T. (1999). Effect of the addition of fumarate on methane production by ruminal microorganisms in vitro. *Journal of Dairy Science* 82: 780-787.

Baker S.K. (1995). *Method for improving utilization of nutrients by ruminant or ruminant like animals*. International Patent No WO9511041.

Bayaru E., Kanda S., Kamada T., Itabashi H., Andoh S., Nishida T., Ishida M., Itoh T., Nagata K. and Isobe Y. (2001). Effect of fumaric acid on methane production, rumen fermentation and digestibility of cattle fed roughage alone. *Animal Science Journal* 72: 139−146.

BAU (2006). Business as Usual Projections of Agricultural Activities for the Water Framework Directive: Phase 2. Final Report to Defra. 129 pp.

Brown L., Scholefield D., Jewkes E.C., Lockyer D.R. and del Prado A. (2005). NGAUGE: a decision support system to optimise N fertilisation of British grassland for economic and/or environmental goals. *Agriculture, Ecosystems and Environment* 109: 20-39.

Broudiscou L., van Nevel C.J. and Demeyer D.I. (1990). Incorporation of soya oil hydrolysate in the diet of defaunated or refaunated sheep: effect on rumen fermentation in vitro. *Archives Tierernahr* 40: 329-337.

Chadwick D.R., Pain B.F. and Brookman S.K.E. (2000). Nitrous oxide and methane emissions following application of animal manures to grassland. *Journal of Environmental Quality* 29: 277-287.

Chadwick D.R. and Pain B.F. (1997). Methane fluxes following slurry applications to grassland soils: laboratory experiments. *Agriculture, Ecosystems and Environment* 63: 51-60.

DEFRA. (2000). Fertiliser recommendations for agricultural and horticultural crops (RB209). The Stationary Office, UK.

Del Prado A, Scholefield D, Chadwick D, Misselbrook T, Haygarth P, Hopkins A, Dewhurst R, Davison P, Lord E, Turner M, Aikman P and Schröder J. (2006). EGF: 21st General Meeting on 'Sustainable grassland productivity", Badajoz, Spain, 3-6 April 2006.

Dohme F., Machmüller A., Estermann B.L., Pfister P., Wasserfallen A. and Kreuzer M. (1999). The role of the rumen ciliate protozoa for methane suppression caused by coconut oil. *Lett. Appl. Microbiol.* 29: 187- 192.

Dong Y., Bae H.D., McAllister T.A., Mathison G.W. and Cheng K.J. (1997). Lipid-induced depression of methane production & digestibility in the artificial rumen system (RUSITEC). *Canadian Journal of Animal Science* 77: 269-278.

Dragosits U., Sutton M.A., Place C.J. and Bayley A.A. (1998). Modelling the Spatial Distribution of Agricultural Ammonia Emissions in the UK. *Environmental Pollution* 102, 195-203.

Garnsworthy P.C. (2004) The environmental impact of fertility in dairy cows: a modelling approach to predict methane and ammonia emissions. *Animal Feed Science and Technology* 112: 211-223.

Henderson C. (1973). The effects of fatty acids on pure cultures of rumen bacteria. *Journal of Agricultural Science, Cambridge* 81: 107-112.

Johnson K.A. and Johnson D.E. (1995). Methane emissions from cattle. *Journal of Animal Science* 73: 2483-2492.

Kowalcyk J., Ørskov E.R., Robinson J.J. and Stewart C.S. (1977). Effect of fat supplementation on voluntary food intake and rumen metabolism in sheep. *British Journal of Nutrition* 37: 251-257.

Lana R.P., Russell J.B. and Van Amburgh M.E. (1998). The role of pH in regulating methane and ammonia production. *Journal of Animal Science* 76: 2190-2196.

López S., Valdes C., Newbold C. J. and Wallace R. J. (1999). Influence of sodium fumarate addition on rumen fermentation in vitro. *British Journal of Nutrition* 81: 59-64.

Machmuller A., Ossowski D.A., Wanner M. and Kreuzer M. (1998). Potential of various fatty feeds to reduce methane release from rumen fermentation in vitro (Rusitec). *Animal Feed Science & Technology* 77: 117-130.

Machmüller A., Soliva C.R. and Kreuzer M. (2003). Effect of coconut oil and defaunation treatment on methanogenesis in sheep. *Reprod. Nutr. Dev.* 43: 41-55.

Machmüller A., Dohme F., Soliva C.R., Wanner M. and Kreuzer M. (2001). Diet composition affects the level of ruminal methane suppression by medium-chain fatty acids. *Australian Journal of Agricultural Research* 52:713-722.

Martin S.A. (1998). Manipulation of ruminal fermentation with organic acids: a review. *Journal of Animal Science* 76: 3123-32.

Mills J.A.N., Kebreab E, Yates C.M., Crompton L.A., Cammell S.B., Dhanoa M.S., Agnew R.E. and France J. (2003). Alternative approaches to predicting methane emissions from dairy cows. *Journal of Animal Science* 81 (12): 3141-3150

Mills J.A.N., Dijkstra J., Bannink A., Cammell S.B., Kebreab E. and France J. (2001). A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation, and application. *Journal of Animal Science* 79 (6): 1584-1597.

Machmuller A. and Kreuzer M. (1997). Methane suppression by coconut oil & associated effects on nutrient & energy balance in sheep, *Proceedings of the Society of Nutrition and Physiology* 6: 65-72.

Moss A.R., Jouany J. and Newbold C.J. (2001). Methane production by ruminants: its contribution to global warming. *Annales de Zootechnie* 49: 231-253.

Moss A.R. (1993). Methane-*Global Warming and Production by Animals*. Canterbury, UK. Chalcombe Publications.

Mottram T. and Mills J.A.N. (2003). Defra project IS0102 final report. Environmental and Welfare Benefits of IMS for Dairy Cows.

Newbold C.J., Lassalas B. and Jouany J.P. (1995). The importance of methanogenesis associated with ciliate protozoa in ruminal methane production *in vitro*. *Letters of Applied Microbiology* 21: 230-234.

Newbold C.J. and Chamberlain D.G. (1988). Lipids as rumen defaunating agents. *Proceedings of the Nutrition Society* 47: 154A.

Newbold C. J., Lopez S., Nelson N., Ouda J. O., Wallace R. J. and Moss A. R. (2005). Proprionate precursors and other metabolic intermediates as possible alternative electron acceptors to methanogenesis in ruminal fermentation in vitro. *British Journal of Nutrition* 94(1):27-35.

Prins R.A., Van Nevel C.J. and Demeyer D.I. (1972). Pure culture studies of inhibitors for methanogenic bacteria. *Ant Van Leeuwen* 38: 281-287.

Shu Q., Gill H.S., Hennessy D.W., Leng R.A., Bird S.H. and Rowe J.B. (1999). Immunisation against lactic acidosis in cattle. *Research into Veterinary Science* 67: 65-71.

Smith K.A., Brewer A.J., Crabb J. and Dauven A. (2001). A survey of the production and use of animal manures in England and Wales. III. Cattle manures. *Soil Use and Management*. 17(2): 77-87.

Smith K.A., Brewer A.J., Crabb J. and Dauven A. (2001). A survey of the production and use of animal manures in England and Wales. III. Cattle manures. *Soil Use and Management* 17(2): 77-87.

Sutton M.A., Dragosits U., Dore A.J., McDonald A.G., Tang Y.S., van Dijk N., Bantock T., Hargreaves K.J., Skiba U., Fowler D., Misselbrook T., Brown L. and Hobbs P. (2004). The potential to use trace-gas changes following the 2001 outbreak of Foot and Mouth Disease in Great Britain to reduce the uncertainties in agricultural emissions abatement. *Journal of Environmental Science and Policy* 7: 177-194.

Sutton M.A., Dragosits U., Simmons I., Tang Y.S., Hellsten S., Love L., Vieno M., Skiba U., di Marco C., Storeton-West R.L., Fowler D., Williams J., North P., Hobbs P. and Misselbrook T. (2006). Monitoring & modelling trace-gas changes following the 2001 outbreak of Foot & Mouth Disease to reduce the uncertainties in agricultural emissions abatement. *Journal of Environmental Science & Policy* 9: 407-422.

Theobald M.R., Dragosits U., Place C.J., Smith J.U., Brown L., Scholefield D., del Prado A., Webb J., Whitehead P.G., Angus A., Hodge I.D., Fowler D. and Sutton M.A. (2004). Modelling nitrogen fluxes at the landscape scale. *Water, Air and Soil Pollution* 4: 135-142.

Thomas C. (2004). Feed into milk: A new applied feeding system for dairy cows. Nottingham University Press, UK.

Van Soest P.J. (1982). *Nutritional Ecology of the Ruminant*, pp. 40-41. Oregon: O & B Books.

Wallace R.J. (2004). Antimicrobial properties of plant secondary metabolites. Proc Nutr Soc. 63:621-629.

Wallace R.J., Wood T.A.,. Rowe A, Price J., Yanez D.R., Williams S.P. and Newbold C.J. (2006). Encapsulated fumaric acid as a means of decreasing ruminal methane emissions. *International Congress Series* 1293: 148-151.

Webb J. and Misselbrook T.H. (2004). A mass-flow model of ammonia emissions from UK livestock production. *Atmospheric Environment* 38: 2163-2176.

Webb J., Anthony S.G., Brown L., Lyons-Visser H., Ross C., Cottrill B., Johnson P. and Scholefield D. (2005). The impact of increasing the length of the cattle grazing season on emissions of ammonia and nitrous oxide and on nitrate leaching in England and Wales. *Agriculture, Ecosystems and Environment* 105: 307-321.

Wright A.D., Kennedy P., O'Neill C.J., Toovey A.F., Popovski S., Rea S.M., Pimm C.L. and Klein L. (2004). Reducing methane emissions in sheep by immunization against rumen methanogens. *Vaccine*. 22: 3976-85.

Yamulki S., Jarvis S.C. and Owen P.M. (1999). Methane emission and uptake from soils as influenced by excreta deposition from grazing animals *Journal of Environmental Quality* 28 (2): 676-682.

DEFRA PROJECT LIST

AM0101. National ammonia reduction strategy evaluation system (NARSES). Final Report to Defra.

AM0118. Monitoring and modelling trace-gas changes following FMD to reduce the uncertainties in agricultural emissions abatement. Final Report to Defra.

CC0233. Nitrous oxide emissions from agricultural soils, and the potential for their reduction. Final Report to Defra.

ES0203. The cost-effectiveness of integrated diffuse pollution mitigation measures. Final Report to Defra.

IS0214. New Integrated dairy production systems: specification, practical feasibility and ways of implementation.

NT1836. Nitrous oxide emissions from housing, storage and landspreading in straw and slurry cattle systems in relation to ammonia losses. Final Report to Defra.

NT2511. Cost curve of nitrate mitigation options.

WA0604. Measurements of nitrous oxide and methane following manure applications to land. Final Report to Defra.

WA0637. Denitrification and nitrous oxide emissions following new slurry application techniques for reducing ammonia losses. Final Report to Defra.

WA0707. Will storing FYM in compact anaerobic heaps reduce emissions of ammonia and nitrous oxide during storage and spreading? Final Report to Defra.