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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: AC0209
2. Project title: Ruminant Nutrition Regimes to Reduce Methane & Nitrogen Emmissions
3. Contractor organisation(s):
   Institute of Biological,
   Environmental and Rural Sciences
   Aberystwyth University,
   Llanbadarn Campus,
   Aberystwyth, Ceredigion,
4. Total Defra project costs (agreed fixed price): £ 746495
5. Project: start date 1/04/2007
   end date 30/09/2010

6. It is Defra's intention to publish this form.
   Please confirm your agreement to do so. .... **YES X NO** ☐

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

AC209 was funded with the aim of decreasing methane emissions and nitrogen excretion from ruminant farm livestock in both intensive and extensive systems. The project sought to achieve this through a collaborative programme of interdisciplinary work involving a number of interlinked objectives including:

- Synthesis of existing knowledge of ruminant nutrition and husbandry to identify strategies to decrease methane and nitrogen emissions per animal and per unit output and evaluate the most promising of these within the context of intensive dairy farming.
- Utilize recent advances in grass and legume breeding and evaluate the use of novel pastures to decrease methane and nitrogen emissions per animal and per unit output in extensive farming systems.
- To evaluate the use of novel dietary supplements identified in recent screening programs for the ability to decrease methane emissions and nitrogen excretion per animal and per unit output in both intensive and extensive farming systems.
- To modify and utilize existing farm livestock models and economic benefit and farmer uptake models to expand the interpretation of the data obtained to a whole systems context and to consider wider husbandry, environmental, and economic impacts of the strategies adopted.

To establish an advisory and dissemination committee representing the major stakeholders in both the livestock production and livestock feed supply industries including the major levy boards. This committee will (a) ensure that the project is both informed and driven by the latest industry practice and (b) ensure rapid and effective dissemination and uptake of the results obtained. Representation on the committee will include expertise in the EU regulatory framework with regard to additives and supplements in animal feeds.

In task 1 we concluded that :

- Feeding maize silage based diets reduced the amount of methane produced per kg feed DM consumed compared to feeding a grass silage based ration. These differences may reflect differences in the degradability of the carbohydrate fractions of the forages fed. Cows fed maize silage-based diets had higher dry matter intakes and milk energy yields.
- Milk yield and methane excretion were not affected by dietary protein level, but the incremental response of milk protein yield and feed intake to dietary protein supply differed between the two forage sources.
- The efficiency of dietary nitrogen utilization for milk protein production was higher for grass silage

based rations because feed intake was lower in these short term treatment periods.
- The efficiency of dietary nitrogen utilization for milk protein production was increased by feeding less protein.
- There was a small loss of ammonia N during measurements of nitrogen excretion in urine and faeces

As a result we concluded that feeding more maize silage and less grass silage reduced methane production relative to feed intake and milk yield (a 13 and 6% reduction per unit of dry matter intake and per litre of milk output respectively when shifting from a 75:25 grass silage: maize silage ration to a 25:75 ration). Feeding less protein reduced nitrogen excretion in manure and increased the efficiency of dietary nitrogen utilization.

In task 2 we concluded that:
- The use of high sugar grass varieties reduced methane emissions from sheep by circa 20%.
- Previous studies have shown that high sugar grass varieties stimulate animal productivity and improve the efficiency of dietary nitrogen utilization reducing the excretion of N from the animals
- These reductions seems to result from a stimulation in the efficiency of microbial growth in the rumen leading to an improved capture of N in microbial protein and diverting H away from methane production and into microbial cells.

As a result it appears that high sugar grass has the potential to decrease methane emissions by circa 20% whilst also reducing nitrogen excretion in manure and increasing the efficiency of dietary nitrogen utilization.

In task 3 we concluded that:
- Allicin decreased methane production per unit of live weight gain in sheep by 20%. A subsequent trail investigating the effect of a slightly higher dose rate (60 ml/d of a 50000ppm solution) recorded a 27% ($P<0.05$) decrease in methane emissions in sheep. However in cows whilst allicin tended to increase dry matter intake, but less so in the later periods of the study thus may reflect an effect on silage heating during warmer weather. Allicin had no effect on methane excretion, although methane excreted per kg feed dry matter intake was numerically reduced. Allicin imparted considerable taint to the milk produced. The lack of an effect of allicin on methane production in lactating dairy cows compared to sheep may reflect differences in rumen dynamics and ecology.
- Essential oils decreased methane production per unit of live weight gain in sheep by 10%, however subsequent fermentor trials did not suggest any synergistic effect of allicin and essential oils
- Glycerol had no effects on milk production or methane excretion. Cows tolerated the glycerol in their diets and there were no deleterious effects, apart from an increase in milk urea concentration. This may reflect differences in diet composition and subsequent effects on rumen ammonia absorption.
- In sheep linseed oil and naked oats (Racoon) decreased methane emissions by 22 and 33% respectively. In cattle feeding naked oats reduced methane excretion and the amount of methane produced per unit feed consumed or milk produced (10 and 12 % reductions, respectively). This would be expected based on the fat content of the oats fed and is in line with other studies showing effects of feeding fat on methane production by ruminants.

As a result it appears that allicin reduced methane emissions in sheep by circa 20% in sheep but had no effect in cattle. Naked oats reduced methane emissions in sheep by circa 33% In cattle methane emissions were decreased by 10%. It is not clear if this represents a difference between sheep and cattle as the naked oats used in both trials differed

In task 4 we concluded that:
- At the farm level the dairy farms with more intensive production (higher milk yield per cow) have substantially and significantly lower GHG emissions per litre of milk produced than those with more extensive production.
- On the dairy farms at the farm level high sugar grasses, naked oats and essential oil scenarios have potential to reduce GHG emissions. The reduction in emissions is less than the baseline difference between farm types. At trial results, doses and costs, high sugar grasses have a net economic benefit, naked oats a moderate cost and essential oil an extremely large cost per tonne of carbon dioxide mitigated.
- On the livestock farms high sugar grasses, naked oats, allicin and essential oil scenarios have potential to reduce GHG emissions. At trial results, doses and costs, high sugar grasses have a net economic benefit, naked oats a low cost and essential oil and allicin an extremely large cost

per tonne of carbon dioxide mitigated.

- Adapting dairy cow diet by increasing forage maize content and reducing crude protein has economic and GHG emission benefits. The size of the benefit is dependent on farm geographic location and relative grass and forage maize yield.
- An empirical analysis based on model output demonstrates that even with a market for carbon, uptake of supplements is most likely to be economically driven by increases in productivity rather than decreases in GHG emissions.

As a result it appears that future effort should focus on the differences between maize v grass silage, low v high protein rations and the introduction of high sugar grass and naked oats into ruminant diets

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

AC209 was funded with the aim of decreasing methane emissions and nitrogen excretion from ruminant farm livestock in both intensive and extensive systems. The project sought to achieve this through a collaborative programme of interdisciplinary work involving a number of interlinked objectives including:

1. Synthesis of existing knowledge of ruminant nutrition and husbandry to identify strategies to decrease methane and nitrogen emissions per animal and per unit output and evaluate the most promising of these within the context of intensive dairy farming.
2. Utilize recent advances in grass and legume breeding and evaluate the use of novel pastures to decrease methane and nitrogen emissions per animal and per unit output in extensive farming systems.
3. To evaluate the use of novel dietary supplements identified in recent screening programs for the ability to decrease methane emissions and nitrogen excretion per animal and per unit output in both intensive and extensive farming systems.
4. To modify and utilize existing farm livestock models and economic benefit and farmer uptake models to expand the interpretation of the data obtained to a whole systems context and to consider wider husbandry, environmental, and economic impacts of the strategies adopted.
5. To establish an advisory and dissemination committee representing the major stakeholders in both the livestock production and livestock feed supply industries including the major levy boards. This committee will (a) ensure that the project is both informed and driven by the latest industry practice and (b) ensure rapid and effective dissemination and uptake of the results obtained. Representation on the committee will include expertise in the EU regulatory framework with regard to additives and supplements in animal feeds.

Task 1. Synthesis of existing knowledge of ruminant nutrition and husbandry to identify strategies to decrease methane and nitrogen emissions per animal and per unit output and evaluate the most promising of these within the context of intensive dairy farming.

Measurements of energy and/or nitrogen balance obtained using respiration calorimetry and digestion trials were accumulated into a database for meta-analysis of effects of key parameters on both methane and nitrogen excretion in growing and lactating beef cattle and lactating and non-lactating dairy cows. An existing database of individual measurements of energy and nitrogen balance from The University of Reading, which included measurements of methane and nitrogen excretion, was updated and expanded using more recent data from Reading and existing data from other laboratories as appropriate. Additional data were obtained from research in the USA, Wales, and the Netherlands, giving a total of 1819 individual measurements (1335 records of methane excretion). A multivariate analysis was conducted, with appropriate adjustments for variance associated with location and trial effects, to determine the most important dietary factors that influence methane and nitrogen excretion, based on both linear and nonlinear models. A report of this is included in the appendix.

Currently grass and maize silage represent the majority of the forage fed to intensively managed dairy cows in the UK. In addition, it is common practice to ‘overfeed’ protein to high yielding dairy cows relative to predicted requirements for milk protein yield, particularly in early lactation. However, increasing concerns about excess nitrogen excretion bring pressure on producers to feed protein more restrictively, thereby taking into account the environmental cost. Within the data base established above describing methane and nitrogen excretion in dairy cows, the majority of the diets fed contain dietary protein in excess of predicted requirement. In addition, the importance of diet protein content and type on methane excretion in cows fed maize or grass silage based diets is not certain. Therefore, a foundation trial was conducted to demonstrate the simultaneous response of methane and nitrogen excretion (relative to milk component yield and feed intake) to increments of dietary protein and grass:maize silage.

Six Holstein-Friesian dairy cows in mid-lactation were fed ad libitum total mixed rations consisting of a 50:50 mixture (dry matter [DM] basis) of forage:concentrate, with the forage comprised on a DM basis of either 25:75 or 75:25 grass:maize silage. Concentrates were formulated to provide diet CP levels of approximately 140, 160 and 180 g per kg ration DM, in a 2 x 3 factorial experiment, giving 6 treatments. Diets were formulated to give increments of estimated metabolizable protein (MP) and rumen degradable protein (RDP) relative to predicted requirements using the Feed into Milk (FiM) and NRC rationing systems, in part using rumen-protected soyabean protein. For the 3 increments of dietary protein concentration supply of MP averaged 79, 95, and 109 and 101, 112, and 122% of estimated requirements based on NRC and FiM, respectively. Dietary supply of RDP for the 3 increments of dietary protein averaged 100, 102, and 105 and 88, 97 and 107 % of NRC and FiM estimates, respectively. Cows were randomly assigned to diets in a 6 x 5 incomplete Latin Square design with 4 week periods. Measurements of respiratory exchange and energy and nitrogen digestion, excretion, and balance were obtained in the last week of each period. Measurements of N_2O and NH_3 emissions from respiration chambers were obtained to account for possible losses of N during balance measurements, although urine was acidified to prevent N loss. Data were analyzed statistically using the Mixed procedure of SAS® (SAS Institute Inc.) and a model testing fixed effects of forage source, protein level, and their interaction and random effects of period and cow. The main effect of diet protein level was partitioned into linear and quadratic effects using orthogonal contrasts.

A complete report is included in the appendix however in summary: Feed DMI was increased by feeding the high-maize silage (MS) diets and by increasing dietary protein, but the effect of protein differed with forage type (Table 1). Digestibility of feed DM was increased linearly by increasing dietary protein and was greater for the high-grass silage (GS) diets, thus faecal DM excretion was reduced. In contrast, urine volume was increased linearly by dietary protein and was greater for the GS diets. Milk energy yield was greater for the MS diets. Milk protein yield was increased by feeding the MS diets, whilst milk fat yield increased linearly with increasing dietary protein (data not shown). Dietary protein concentrations were slightly higher than formulations, and there was no effect of dietary protein on milk protein yield, but urine N excretion increased linearly with increasing dietary protein and was greater for the GS diets. Faecal N excretion was increased by dietary protein for MS diets, but not GS diets, perhaps due to differences in total DMI, the ingredients used for diet formulation, and the extent of hindgut fermentation between the 2 forages.

Methane excretion was not affected by diet, but methane excretion per kg DMI and per kg milk yield was greater when the GS diet was fed. There was no emission of N_2O from the chambers, and on average there was a net uptake of 88 mg N_2O N/d from incoming air. Emission of NH_3 in exhaust air increased linearly with increasing dietary protein concentration and NH_3 in air conditioner condensate was greater for GS diets.

Conclusions

1. Feeding maize silage based diets reduced the amount of methane produced per kg feed DM consumed compared to feeding a grass silage based ration. These differences may reflect differences in the degradability of the carbohydrate fractions of the forages fed. Cows fed maize silage-based diets had higher dry matter intakes and milk energy yields.
2. Milk yield and methane excretion were not affected by dietary protein level, but the incremental response of milk protein yield and feed intake to dietary protein supply differed between the two forage sources.
3. The efficiency of dietary nitrogen utilization for milk protein production was higher for grass silage based rations because feed intake was lower in these short term treatment periods.
4. The efficiency of dietary nitrogen utilization for milk protein production was increased by feeding less protein.
5. There was a small loss of ammonia N during measurements of nitrogen excretion in urine and faeces

Key findings: Feeding more maize silage and less grass silage reduced methane production relative to feed intake and milk yield (a 13 and 6% reduction per unit of dry matter intake and per litre of milk output respectively when shifting from a 75:25 grass silage: maize silage ration to a 25:75 ration). Feeding less protein reduced nitrogen excretion in manure and increased the efficiency of dietary nitrogen utilization.

Implications and limitations: The capacity to increase maize v grass silage usage in UK dairying may well be limited by agronomic considerations in terms of which parts of the UK can economically consider maize silage based rations. Feeding less protein would significantly reduce nitric oxide emissions but more studies are required to confirm the minimum amount of dietary N consistent with maintaining yield over a range of diets

Table 1. Components of energy and nitrogen balance in mid-lactation dairy cows fed diets containing two ratios of maize silage:grass silage (MS:GS) and 3 levels of dietary protein.

	75:25 MS:GS			75:25 GS:MS			
Protein, g/kg DM…	140	160	180	140	160	180	SEM
DM Intake, kg/d$^{1, b, ***}$	21.92	22.30	23.10	19.79	21.35	19.76	0.84
DM digested, g/kg$^{2, a}$	0.697	0.713	0.723	0.706	0.729	0.739	0.008
Urine, kg/d$^{1, a}$	18.63	20.17	23.62	22.91	25.68	27.12	1.35
Milk yield, kg/d	32.2	32.8	33.5	30.9	31.3	32.4	2.44
Milk energy, MJ/d^{c}	100.5	101.5	103.0	94.4	95.8	99.8	6.25
CH_4, L/d	636.5	671.0	652.9	643.0	650.5	659.8	37.2
CH_4, L/kg DMI^{1}	28.38	28.94	28.09	32.94	31.78	33.36	1.54
CH_4, L/kg milk^{3}	19.78	19.73	19.94	20.89	22.30	19.89	1.23
N balance, g/d							
Intake$^{1, a, **}$	510	597	689	462	548	588	21.6
Faecal$^{3, **}$	204	232	256	218	215	212	13.9
Urine$^{3, a}$	95	119	160	107	138	165	8.2
Milk$^{1, **}$	168	169	173	160	171	159	8.4
NH_3^{a}	0.81	1.65	2.41	1.32	1.19	1.93	0.26
Condensate NH_3^{1}	1.05	1.14	1.24	1.45	1.35	1.51	0.15
Milk N/Intake N$^{1, a}$	0.327	0.284	0.250	0.344	0.309	0.270	0.094

$^{1, 2, 3}$ Forage effect at $P < 0.01$, 0.05, and 0.10, respectively.

$^{a, b, c}$ Protein effect at $P < 0.01$, 0.05, and 0.10, respectively.

$^{***, **, *}$ Forage by protein interaction at $P < 0.01$, 0.05, and 0.10, respectively.

Task 2 Utilize recent advances in grass and legume breeding and evaluate the use of novel pastures to decrease methane and nitrogen emissions per animal and per unit output in extensive farming systems.

Recently IBERS has developed a range of perennial ryegrass with differing heading dates and very high WSC contents. Feeding such forages significantly increases the capture of N into microbial protein in the rumen (Moorby et al 2006) and as such might be expected to decrease nitric oxide emissions resulting from the animals excreta. There is also evidence that using clovers and grasses with high WSC in animal diets can directly reduce methane emissions (Lovett *et a*l 2006). Within this project we sought to investigate the effect recent IBERS varieties of high sugar grass on methane emissions and N retention in sheep, to investigate 'damping down' and across season variation in WSC content in mixed swards with or without forage legume and to investigate alternative plant-based strategies to improve nitrogen use efficiency in ruminants using red clover.

Ten field plots, replicated ×4, control (cv. Premium), monoculture (cv. AberStar, AberMagic, AberAvon - differing heading dates) and three mixed-culture of high water soluble carbohydrate (WSC) perennial ryegrass varieties with or without white clover, established in August 2007 (a total of 40 plots; 15 m^2 each) were monitored between April and October 2008. Fertiliser, N, P and K (55 kg N/ha, 55 kg P_2O_5/ha and 74 kg K_2O/ha) were added in March 2008 to the grass plots and then only N every 6 weeks. In contrast, the legume swards, received P and K in March only. On average the herbage yield was higher on herbages without white clover compared to those with white clover (8.0 vs. 5.3 tonne/ha). On the grass and white clover swards, the proportion of legume averaged 32% across the season and peaked in July/August. The cultivar, AberMagic, produced the greatest yield during season (9.1 tonne/ha) among all herbages, which is in agreement with previous reports from the plant breeders at IBERS.

In total 360 cut samples were generated, freeze-dried and chemical analyses are reported in full in the appendix 3 but briefly the concentrations of water soluble carbohydrates was higher in the three improved varieties in mono- and mixed-culture were higher than that of Control forage throughout growth period. This was also noted in treatments with white clover. The nitrogen content did not differ between different grass varieties but was consistently higher in pastures with white clover. NDF concentrations tended to be lower in forages collected from plots seeded with white clover particularly in year 2.

Samples collected from the control (cv. Premium) and AberStar, AberMagic, AberAvon monoculture plots were used to investigate methane production in the rumen simulating fermentor Rusitec. As expected WSC content was higher in the test grasses (269, 300, 302, 307 g/kg DM for the control AberStar, AberMagic and AberAvon respectively). However methane production was lower ($P<0.05$) only with the AberAvon (3.65, 3.81, 3.22 and 205 mmol CH_4 per g of dry matter digested).

Evaluation of effects of grass WSC on the utilisation of N and methane production by growing lambs: Four field plots (0.6 ha each), consisting of control (cv. Premium) and tri-mixture (mixture of AberStar, AberMagic, AberAvon) ± white clover were established at Trawsgoed Research Farm in August 2007. These plots were used to examine the effect of WSC content in grass on utilisation of N and methane production by growing lambs. Thirty lambs (initial liveweight ~32 kg) were used in a zero-grazing study between June-August 2008. Six lambs were slaughtered at the beginning for estimate of initial body composition and the remaining lambs were allocated to one of four treatments control ryegrass or tri-mixture ± white clover. Methane production (litre/day) was not different ($P > 0.05$) among herbages (Table 2). However, when expressed per litre/kg liveweight gain, tri-mixture reduced methane production by approximately 25% relative to control), suggesting high WSC forage plays a role in reducing methane emissions. At the end of the experiment, all animals were slaughtered and representative rumen contents were collected for chemical and microbial analysis. Total bacterial number measured by real time PCR were higher in the rumen of the sheep receiving the Tri-mixture suggesting that the decreased methane emission might be due to enhanced capture of metabolic hydrogen into microbial protein thus diverting substrate from the methanogenic archaea. Treatments had no effect on N retention in the sheep.

Table 2. DM intake, live-weight gain (LWTG), methane production, digestibility and N-balance of growing lambs fed high v normal sugar grasses with or without white clover

	Con	Con+WC	Mix	Mix+WC	SED	P
DM intake (kg/d)	1.11	1.01	1.28	1.20	0.066	0.005
LWTG (g/d)	156	92	188	160	23.0	0.004
Methane production						
litre/d	35.7	30.2	34.8	31.7	2.91	NS
litre/kg DM intake	32.7	29.8	27.1	26.1	2.07	0.024
litre/kg LWTG	252	338	188	205	34.5	0.002
Whole tract DM digestibility (g/kg)	823	805	813	822	35.5	NS
N-retention (g/d)	3.2	6.0	5.2	8.4	3.07	NS

Con=control, Con+WC=control with white clover, Mix=mixture of three high WSC cultivars, Mix+WC=mixture of three high WSC cultivars with white clover

Water-soluble carbohydrate rich grasses: impact on lamb productivity and methane production: The impact on production and environment (methane production) of a mixed sward consisting of three perennial ryegrass varieties with different heading dates selected for higher content of high water-soluble carbohydrate (WSC) was assessed relative to a control perennial ryegrass, when offered to growing lambs.

Twenty five lambs (Texel-mule cross) were allocated to each of two ryegrass (*Lolium perenne*) pastures, a control (Con; cv Premium) and a tri-mixture (Trimix) of high WSC varieties with different heading dates (AberStar, AberMAgic and AberAvon). Lambs were grazed continuously through the growing season (April to June 2009) and methane emission measurements made periodically using mobile polytunnels as large dynamic chambers, in-situ on the grazed plots. On each measurement occasion, five lambs were randomly selected from those grazing each plot and were placed inside the polytunnel. Air was drawn through the tunnel at a controlled rate and methane concentrations at the inlet and outlet of each tunnel monitored continuously using a photoacoustic analyser. An equilibrium period of 12 hr was allowed after lambs entered the tunnel, after which emission measurements were made for 24 h. A total of ten paired measurements were made over the grazing season. Ammonia emission was also measured, using acid absorption flasks to measure inlet and outlet concentrations from each tunnel. Measurements were also made of lamb live-weight gain, sward height, estimates of intake (using exclosure cages) and grass composition.

Methane emissions showed a strong diurnal pattern (Figure 1), with peak emissions during the early evening, as typically reported by other authors (e.g. Murray et al., 2001). Over the growing period, mean methane emission rates were c. 20% lower for lambs grazing the Tri-mix sward than for those grazing the control sward (8.0 and 10.5 l/lamb/d, respectively; $P=0.039$). Daily live weight gain was greater for lambs grazing the HWSC than control sward (152 vs 108 g/animal/d; $P<0.01$), therefore methane emission reduction per kg live weight gain was greater than on a per animal basis. There was no significant difference in ammonia emissions from lambs grazing the two swards, with a mean emission rate of 0.51 g NH_3-N/lamb/d.

The live weight gain and methane emission rates were lower than expected, probably because of the poor herbage growing conditions during the spring grazing period. This may have exaggerated the observed differences between treatments. The observed reduction in methane emissions from grazing Tri-mix (high WSC grass) is contrary to a recent modelling study suggesting an expected increase in emissions (Bannink et al., 2010). Further *in situ* measurements of emissions from grazing livestock are required to confirm this finding, to understand the mechanism for emission reduction and to assess impacts over a longer grazing season.

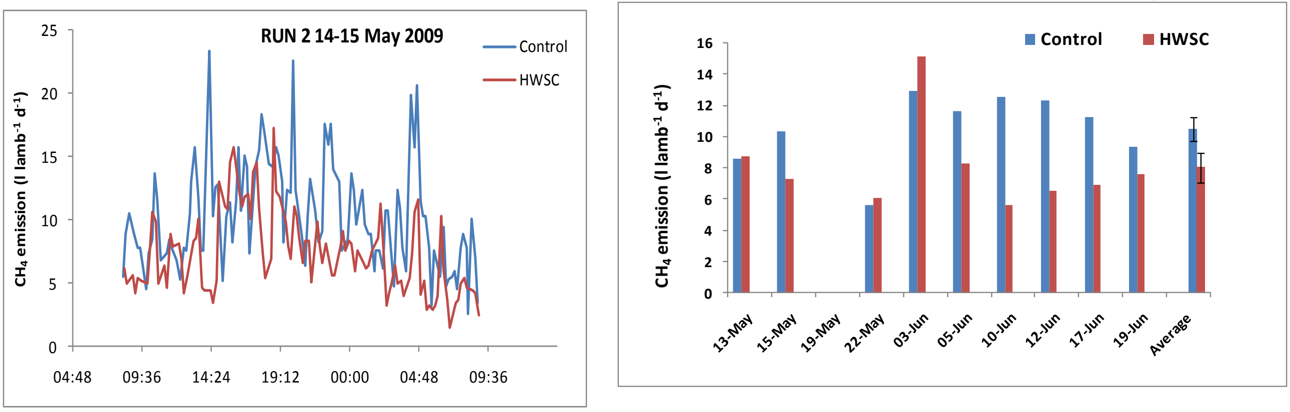
(a) (b)

Figure.1. Diurnal pattern of enteric methane emissions from grazing lambs (a) and methane emissions from lambs over the grazing season (b)

Conclusions

1. The use of high sugar grass varieties reduced methane emissions from sheep by circa 20%.
2. Previous studies have shown that high sugar grass varieties stimulate animal productivity and improve the efficiency of dietary nitrogen utilization reducing the excretion of N from the animals
3. These reductions seems to result from a stimulation in the efficiency of microbial growth in the rumen leading to an improved capture of N in microbial protein and diverting H away from methane production and into microbial cells.

Key findings: High sugar grass has the potential to decrease methane emissions by circa 20% whilst also reducing nitrogen excretion in manure and increasing the efficiency of dietary nitrogen utilization.

Implications and limitations: As the high sugar grass tested here all top the approved lists based on agronomic characteristics there seems to be no reason why the use of high sugar grass should not be promoted for use in ruminant diets. However only a limited amount of UK pasture is reseeded in any year and careful consideration would have to be given before encouraging additional reseeding as soil emissions during reseeding might exceed the subsequent reduction in animal emissions. More work is required to clarify this issue. Care would also be need in terms of pasture shared between ruminant and equine livestock as high sugar grasses would be deleterious to horse health.

Task 3 To evaluate the use of novel dietary supplements identified in recent screening programs for the ability to decrease methane emissions and nitrogen excretion per animal and per unit output in both intensive and extensive farming systems.

Previous work using rumen simulating fermentors has suggested that yeast culture based on *S. cerevisiae* and plant extracts based on garlic and essential oils are likely to have beneficial effects in terms of decreasing N and methane emissions from ruminants. Initially these additives were evaluated in sheep.

Twenty four castrate crossbreed store lambs were allocated into 6 sets based on live weight and one animal from each set randomly allocated to a treatment group (6 sheep per treatment). Sheep were fed 1.2 kg/d (fresh weight) of a dry diet based on chopped hay, barley, soyabean meal, molasses and vitamins mineral mix (50: 30: 10: 9.5: 0.5 on a fresh weight basis) once daily (9 am). Sheep were individual housed bedded on wood shavings and had free access to water. All animals were weighed twice weekly. Treatments yeast (5g/d Biosaff active yeast from Lessafre Feed Additives, France) allicin (40 ml/d of a 5000 ppm solution from Neem Biotech, UK) or essential oil (2 ml/d) or no addition (control) were added to the diet and mixed by hand immediately prior to feeding. Any diet refusals were collected and weighed and feed preparation buckets were marked to ensure that no cross contamination of diets could occur during preparation. Methane measurements were made on 4 sheep at a time (one per treatment group) using methane measurement chambers as described by Yanez et al 2008. Seven days before animals entered the chambers ytterbium was added to the diet daily to diet (200 mg of ytterbium (Yb as YbCl.6H20) per sheep per day). Whilst in chambers samples feed and faeces were collected for digestibility measurements (based on ytterbium). Methane measurements were made for each animal over 3 consecutive days during which time the animals received the diet within the chamber water was freely available within the chamber. A one day change over period between groups of sheep meant that it took 21 days to measure emissions from all 24 sheep (6 measurement periods). Treatments were randomised between chambers to ensure no chamber biases. Following measurement of methane emissions sheep were returned to their original pen and continued to receive the diet and treatment. Following the completion of measurements all sheep were slaughtered. The empty carcasses were retained for whole body N analysis, whole carcass ground and representative sample freeze dried before N analysis. Samples of rumen fluid were collected immediately after death for analysis of fermentation products and microbial numbers.

Both allicin and the essential oil tended to reduce methane production and boost liveweight gain although these effects were not statistically significant (Table 3). However when methane production was expressed per unit of liveweight gain both allicin and essential oil decreased methane production by between 18 and 20% ($P<0.05$) (Table 3). The decrease in methane production with allicin was associated with a decrease in the relative abundance of methanogenic archaea in the rumen as determined by real time PCR (result not shown). All treatments numerically increased with N retention with some evidence of a trend in the yeast supplemented animals ($P<0.125$).

Table 3 Effect of Allicin (40 ml/d of a 5000 ppm solution) , Essential oil (2ml/d) or yeast (5g/d) on methane production, liveweight gain and nitrogen retention in sheep

	Control	Allicin	EO	Yeast	SED
Methane (l/d)	34.0	28.8	28.6	31.9	2.57
Live weight gain (kg/d)	0. 195	0.203	0.204	0.204	0.222
Methane/ Kg LWG	174	142	140	156	5.9*
N intake (g/d)	23.1	23.1	23.1	23.1	
Faecal N (g/d)	7.23	7.40	6.83	7.28	0.815
Retained N (g/d)	6.42	7.66	7.40	8.66	0.899 (p<0.125)

* Effect significant at $P < 0.05$

A subsequent experiment using the rumen simulation technique Rusitec investigated the possible interaction of allicin and essential oil. Both treatment significant reduced methane emissions (by 35 and 13% respectively for allicin and essential oil) but there was no evidence of a synergistic effect. A further experiment investigated the effect of combining allicin supplementation with either a control grass or the Tri-mixture referred to in Task 2. As previously recorded both allicin and the Tri-mixture resulted in lower methane emissions from the vessels (by 35 and 22% respectively) but again there was no evidence of a synergistic effect.

We have also tried to investigate forage additive interactions in sheep. The impact on production and environment of different forages (grass silage vs. red clover silage) with or without garlic extract was assessed in growing lambs.

Total 32 growing lambs (initial live weight ~32 kg, Cheviot ewes) were selected on the basis of liveweight and condition score, and were allocated to one of four dietary treatments; 1) grass silage (mixture of hybrid ryegrass), 2) grass silage + allicin (40 ml of 5000 ppm liquid / animal), 3) red clover silage and 4) red clover silage + allicin (40 ml of 5000 ppm liquid / animal). Hence 8 lambs per treatment were allocated in a completely randomised block design experiment. Animals (individually penned) were fed on the experimental diets on an *ad libitum* basis, with feed levels designed to ensure a refusal margin of 0.10 to 0.15 each day and the diets were offered at 09:00 once daily. Fresh water and mineral blocks were continually available. Animals were weighed once a week, at the same time during the day. Fresh allicin was supplied by Neem Biotech (UK), stored at 4°C. Following 4 weeks adaptation period to the diets, methane production was measured using methane chambers over a 3-day period. The forage 'as offered' and refusals were recorded accurately, and sub-samples over a week period were be stored at -20°C, freeze-dried and ground prior to chemical analysis. An analysis of variance was conducted with diet as the main factor using GenStat (11th edition) statistical software.

Average daily intake of silage DM over the measurement period was higher (P=0.016) for lambs fed the red clover silage (RCS) versus that for lambs offered grass silage (GS), and allicin (A) did not appear to have any impact on daily intake (Table 4). Overall, daily DM intake was much lower than those fed on fresh forage in the summer which reflected on live-weight gain. Mean growth rate showed also a strong trend (P=0.066) for lambs fed red clover silage than for lambs fed grass silage. Methane production (litre/d) was not different across treatments however, when expressed per kg DM intake, animals fed red clover silage and/or allicin produced less methane compared to those offered grass silage (P=0.099). Due to large variations within and across treatments however, it failed to reach statistical significance at 5% level, especially when the results were expressed per kg of LWTG. It was somewhat surprising that there was little effect of allicin on methane emission as observed from the series of studies within this project however, such large variations in animal performances may have masked true effect of allicin and hence the results are equivocal. Although numerical, large reduction in methane emission in animals offered red clover silage may be attributable to relatively higher content of crude protein in the silage even though crude protein was not a main player for reducing methane emission from the modelling exercise within this project.

Table 4. Animal performance and methane production

	GS	GS+A	RCS	RCS+A	SED	P
DM intake (kg/d)	0.56	0.63	0.80	0.73	0.078	0.016
LWTG (g/d)	47	66	90	100	20.7	0.066
Methane production						
litre/d	22.2	20.0	18.1	20.1	3.04	NS
litre/kg DM intake	37.2	33.6	25.1	29.1	4.96	0.099
litre/kg LWTG	719	528	279	334	197.5	NS

GS=grass silage, GS+A=grass silage with allicin, RCS=red clover silage, RCS+A=red clover silage with allicin. LWGT=live-weight gain.

In addition to plant extracts there is a significant body of evidence to suggest that lipids might reduce methane production in the rumen with Beauchmin et al (2008) suggesting a 5.6% reduction in methane per % of added fat. Based on this a series of short in vitro incubations investigating the effect of high fat products/ by products including distillers waste from biofuel production (encompassing a range of substrates and fermentation plants), full fat soya flakes and a novel naked oat (Racoon) resulting from the IBERS plant breeding program of methane production were carried out.

As the naked oat Racoon gave the most promising results in these trails it was decided to further investigate its use in a sheep trial. Twenty four castrate crossbreed store lambs were allocated into 6 sets based on live weight and one animal from each set randomly allocated to a treatment group (6 sheep per treatment). Sheep were fed 1.2 kg/d (freshweight) of a diet based on chopped hay, barley, soyabean meal, molasses, megalac (a rumen protected fat) and vitamins mineral mix (50: 30: 10: 6: 4:1 on a fresh weight basis) (Control treatment), chopped hay, barley, soyabean meal, molasses, linseed oil and vitamins mineral mix (50: 30: 10: 6: 4:1 on a fresh weight basis) (Linseed treatment), chopped hay, Racoon Oats , soyabean meal, molasses and vitamins mineral mix (50: 40: 5: 5: 1 on a fresh weight basis) (Racoon treatment), chopped hay, control oats, soyabean meal, molasses, megalc and vitamins mineral mix (50: 40: 4: 4:2:1 on a fresh weight basis) (Control oats treatment). All treatments were formulated to be balanced for fat and crude protein. Methane measurements were made on 4 sheep at a time (one per treatment group) using methane measurement chambers as described by Yanez et al 2008. Seven days before animals entered the chambers ytterbium was added to the diet daily to diet (200 mg of ytterbium (Yb as YbCl.6H20) per sheep per day). Whilst in chambers samples feed and faeces were collected for digestibility measurements (based on ytterbium). Methane measurements were made for each animal over 3 consecutive days during which time the animals received the diet within the chamber water was freely available within the chamber. A one day change over period between groups of sheep meant that it took 21 days to measure emissions from all 24 sheep (6 measurement periods). Treatments were randomised between chambers to ensure no chamber biases. Following measurement of methane emissions sheep were returned to their original pen and continued to receive the diet and treatment. Following the completion of measurements all sheep were slaughtered. The empty carcasses were retained for whole body N analysis, whole carcass ground and representative sample freeze dried before N analysis. Samples of rumen fluid were collected immediately after death for analysis of fermentation products and microbial numbers.

Linseed oil decreased methane emissions by 22% whilst the Racoon oats decreased emissions by 33%. As all treatments were balanced for fat this was not an effect of fat concentration, although as the megalac based diets contain as "rumen protected fat" it may have reflected the rumen availability of the lipid. However when the bacterial population in the rumen was investigated by TFLP it was obvious that the bacteria in the rumen of the sheep fed Racoon oats were significantly different from the other three treatments (result not shown) suggesting that the Racoon oats had significantly altered rumen microbial ecology.

Table 5. Methane production and faecal nitrogen excretion in sheep fed diets based on barley plus megalac (control), barley plus linseed oil, Racoon oats or a control oat plus megalac.

	Control	**Linseed**	**Racoon oats**	**Control oats**	**SED**
Methane (l/d)	36	28	24	36	4.7*
Methane (l/ kg dry matter intake)	31	24	21	31	3.4*
Live weight gain (kg/d)	106	105	107	119	19.3
N intake (g/d)	19.2	19.2	19.2	19.2	
Faecal N (g/d)	7.30	6.50	7.05	6.82	0.851
Retained N (g/d)	6.64	6.00	6.66	4.52	0.992

* Effect significant at $P < 0.05$

Based on results obtained oats and allicin were further evaluated in cows based on a literature search glycerol was included as a forth treatment. The effects of allicin on milk flavour were also determined. As sufficient Racoon oats was not available for the trail a commercially available naked oats was used in its place.

Four Holstein-Friesian dairy cows in mid lactation were used. Before the start of the experiment cows were fed a commercial dairy herd diet to meet nutrient requirements after calving and during adaptation to the metabolism facilities and respiration chambers. Cows were fed for ad libitum intakes (10% refusals) for the duration of the trial. For the experiment, 4 diets (a control and 3 treatment diets) were randomly assigned to treatments at approximately 12 weeks postpartum in a 4 x 4 Latin Square design experiment with 5 week periods. The control diet was formulated based on the low protein (140 g/kg DM) high grass silage diet used in the previous experiment for this project. One minor change is that the concentrate mixture included molasses to reduce the dust generated when diets were prepared. The control diet was fed as a TMR consisting of a 50:50 mixture (on a dry matter [DM] basis) of forage:concentrate, whilst the forage consisted of a 75:25 blend (DM basis) of grass:maize silage. Treatment diets were the control diet plus 1 litre (1 kg) per day of an aqueous solution containing 5000 ppm allicin extract from garlic (provided by Neem Biotech Ltd), the control diet plus 10% (wt/wt) food grade glycerol (replacing maize meal), or a diet including 30% naked oats (replacing maize meal, wheat, and wheat feed). Concentrates were formulated to be isonitrogenous and have minimal differences in total starch and sugar, NDF and ADF. Measurement of energy and nitrogen balance were made as described in the previous experiment (Task 1 Foundation Measurement),

Feed DMI was not affected by treatments, but was numerically lowest when naked oats were fed. In spite of the slightly lower DMI for the naked oats diet, oil intake and digestion was increased by over 250 g/d compared to the control diet, and oil digestibility (g/kg consumed) was also higher. Milk yield was increased by 2.7 kg/d when naked oats were fed compared to the control diet and this was accompanied by significant increases in fat corrected milk and milk energy yield, as well as milk casein and lactose yield (Table 6). Milk protein concentration was reduced by feeding naked oats, as often reported when fat is fed. Milk urea concentration was increased when glycerol was fed. This may be due to differences in the concentrates fed and subsequent effects on microbial protein synthesis and ammonia absorption.

Feeding naked oats reduced methane excretion (Table 7) and also the amount of methane excreted per unit feed DMI ($P < 0.06$) and per unit milk yield ($P < 0.01$), fat corrected milk yield ($P < 0.05$) or milk energy ($P < 0.02$). This may be attributable to the fat content of the naked oats, as the reductions in methane production were similar to effects of other fat sources on methane excretion in lactating dairy cows. However, there may be other components of naked oats that contributed to the reductions in methane excretion observed. For example, both NDF and water soluble carbohydrate intakes were reduced when naked oats were fed. Feeding glycerol and allicin had no significant effects on methane excretion, although there was a numerical reduction in methane excretion per kg DMI. Allicin has markedly reduced methane excretion in growing sheep, thus the lack of an effect in lactating dairy cows is surprising. The difference in the response between growing sheep and lactating dairy cattle may be attributable to differences in rumen dynamics and microbiology.

Treatments had little effect on nitrogen excretion and balance in the present study (Table 8). However, because nitrogen intake was lower when naked oats were fed, the efficiency of nitrogen utilization for milk protein production was greater, and the amount of dietary nitrogen excreted in manure was lower.

Table 6. Effects of supplements on milk yield, milk composition, and milk component yield.

	Control	Glycerol	Allicin	Naked Oats	SEM	P <
Milk yield, kg/d	29.7	31.3	30.4	32.6*	2.6	0.239
FCM yield, kg/d	29.6	30.2	29.6	32.1*	2.3	0.234
Milk energy, MJ/d	90.7	93.2	91.2	97.9*	7.1	0.251
Milk composition, g/kg						
Fat	40.5	37.7	38.4	39.4	2.1	0.715
Protein	32.2	31.9	31.8	30.7**	1.4	0.138
Casein	25.3	25.1	25.0	24.3	1.3	0.440
Lactose	46.3	46.7	46.7	46.6	1.3	0.916
Urea	0.179	0.212**	0.189	0.166	0.009	0.028
Milk yield, g/d						
Fat	1185	1180	1164	1275	92	0.426
Protein	937	993	962	990	50	0.398
Casein	733	782	755	785*	34	0.237
Lactose	1388	1465	1423	1527*	155	0.272

[1] During measurements of respiratory exchange (4 d) only.

**Different from control at $P < 0.05$.

Table 7. Effects of supplements on methane production and respiratory exchange of lactating dairy cows.

	Control	Glycerol	Allicin	Naked Oats	SEM	P <
CH_4, L/d	566	612	573	494*	34.6	0.083
CO_2, L/d	7069	7130	7260	6944	431	0.794
O_2, L/d	7070	7304	7327	6905	464	0.396
RQ	1.00	0.99	1.00	1.01	0.02	0.701
CH_4, MJ/d	22.4	24.2	22.7	19.6*	1.4	0.083
CH_4, MJ/MJ milk	0.255	0.261	0.249	0.201***	0.019	0.019
Heat, MJ/d	148.7	152.7	153.8	145.5	9.5	0.495
CH_4, L/kg DMI	30.74	31.30	28.51	27.50*	1.51	0.157
CH_4, L/kg milk	20.1	19.7	19.1	15.3***	1.9	0.029
CO_2 Equivalents						
CH_4, g/d	8518	9203	8622	7436*	521	0.083
CH_4, g/kg milk	302	296	287	230***	29	0.029
CH_4, g/kg FCM	297	307	292	233***	23	0.016
CO_2, g/d	13888	14009	14263	13643	848	0.794
CO_2, g/kg milk	492	451	471	419	38	0.45
CO_2, g/kg FCM	485	467	483	423	31	0.413

***Different from control at $P < 0.01$. **Different from control at $P < 0.05$.
*Different from control at $P < 0.10$.

Table 8. Effects of supplements on nitrogen balance (g/d) of lactating dairy cows.

	Control	Glycerol	Allicin	Naked Oats	SEM	P <
Intake	426	444	449	404	17.1	0.139
Faecal	161	163	160	151	7.9	0.718
Digested	265	281	289*	252	12.8	0.084
g/g	0.624	0.632	0.644	0.624	0.013	0.500
Urine	87	97	83	73	8.7	0.189
Milk	150	159	154	158	8.0	0.398
Ammonia loss, g N/d						
Exhaust NH_3	1.45	1.71	1.50	1.91	0.58	0.873
AC water NH_3	0.78	0.82	0.65	0.67	0.14	0.709
Tissue	26.5	22.1	48.5	18.7	12.1	0.312
Ratios						
Milk N/Intake N	0.351	0.359	0.345	0.393**	0.013	0.084
Manure N/Intake N	0.578	0.585	0.543	0.557	0.020	0.478
Manure N/Milk N	1.66	1.63	1.58	1.42**	0.062	0.100
Manure N/kg Milk	8.61	8.35	8.03	6.97**	0.561	0.085
Urine N/Manure N	0.350	0.368	0.341	0.325	0.020	0.220

**Different from control at $P < 0.05$. *Different from control at $P < 0.10$.

Control Milk (CC), allicin Control (milk from cows fed allicin) (AC), Control Spun (control milk processed through spinning cone) (CS) and allicin Spun (milk from cows fed allicin, processed through spinning cone) (AS) were stored at 4°C for 4 days post processing and served at 15 to 17 °C (room temperature 23°C) to 40 untrained assessors in balanced order. Assessors tasted samples once, with no retasting , on one day. Assessors allowed to rinse their mouth with water between samples. Tasting was carried out in isolated tasting booths under artificial daylight. Friedmans test found a significant difference between samples ($p < 0.0001$). The allicin sample (AC) was significantly higher in garlic than the other samples. The allicin spun (AS) sample was not found be significantly different from the control spun sample.

Conclusions:

1. Allicin decreased methane production per unit of live weight gain in sheep by 20%. A subsequent trail investigating the effect of a slightly higher dose rate (60 ml/d of a 50000ppm solution) recorded a 27% ($P<0.05$) decrease in methane emissions in sheep. However in cows whilst allicin tended to increase dry matter intake, but less so in the later periods of the study thus may reflect an effect on silage heating during warmer weather. Allicin had no effect on methane excretion, although methane excreted per kg feed dry matter intake was numerically reduced. Allicin imparted considerable taint to

the milk produced. The lack of an effect of allicin on methane production in lactating dairy cows compared to sheep may reflect differences in rumen dynamics and ecology.
2. Essential oils decreased methane production per unit of live weight gain in sheep by 10%, however subsequent fermentor trials did not suggest any synergistic effect of allicin and essential oils
3. Glycerol had no effects on milk production or methane excretion. Cows tolerated the glycerol in their diets and there were no deleterious effects, apart from an increase in milk urea concentration. This may reflect differences in diet composition and subsequent effects on rumen ammonia absorption.
4. In sheep linseed oil and naked oats (Racoon) decreased methane emissions by 22 and 33% respectively. In cattle feeding naked oats reduced methane excretion and the amount of methane produced per unit feed consumed or milk produced (10 and 12 % reductions, respectively). This would be expected based on the fat content of the oats fed and is in line with other studies showing effects of feeding fat on methane production by ruminants.

Key findings: Allicin reduced methane emissions in sheep by circa 20% in sheep but had no effect in cattle.Naked oats reduced methane emissions in sheep by circa 33% In cattle methane emissions were decreased by 10%. It is not clear if this represents a difference between sheep and cattle as the naked oats used in both trials differed

Implications and limitations: Allicin or other garlic derived products may turn out to useful additives in some situations. However there is a need for a complete life cycle analysis on the use of allicin to look at the possible carbon cost of production etc, similarly longer term trials are need to investigate effectiveness of different formulations under different dietary situations, particularly if consideration is to be given to preparing a feed additives dossier for submission to the relevant EU authorities. Neem Biotech together with other industrial and academic partners including Aberystwyth University have been invited to negotiate a contract with the EU for a research contract under the EU support for SME scheme which will allow much of this data to be collected .Naked oats in general and Racoon oats in particular seem to have potential to decrease methane emissions. More work is required to explore this over a variety of basal diets and inclusion rates. This should be integrated with the ongoing oatlink project.

Task 4 .To modify and utilize existing farm livestock models and economic benefit and farmer uptake models to expand the interpretation of the data obtained to a whole systems context and to consider wider husbandry, environmental, and economic impacts of the strategies adopted.

The aim of this task was to assess the impacts of the dietary changes being evaluated in earlier tasks of the project at the whole-farm system level and at a national scale for a number of defined scenarios. The farm-systems scale modelling included interactions between pollutant (and production) pathways and explored the possibilities of pollution swapping or win-win scenarios. For the national scale modelling, the simple reduction efficiencies associated with particular dietary changes were combined with estimates of applicability within the sector to assess the potential impacts on the national inventory total for the relevant ruminant sector and for agriculture as a whole.

Based on the outcomes of the experimental part of the project, 5 dietary change scenarios were selected for modelling at the farm- and national-scales: dietary supplementation with allicin; dietary supplementation with an essential oil; replacement of improved grazing with high sugar grass varieties; incorporation of naked oats; replacement of grass silage with maize silage. Broadly the scenarios can be grouped as novel supplements (allicin and essential oil), replacement of existing feed (naked oats and high sugar grasses) and adapting diets (changing forage maize and crude protein contents). Scenarios were assessed for the major UK ruminant sectors: dairy, beef and sheep. Details of the assumptions relating to the individual scenarios for model parameterisation are given in Table 9. In the experimental trials conducted as part of this project, allicin had no effect on CH_4 emission from dairy cattle. There was also a known issue with milk taint, so the allicin scenario was not applied to the dairy sector. By analogy, allicin was presumed not to be effective at reducing CH_4 emission in beef cattle, so the scenario was only applied to the sheep sector (where it was assumed to be made available through licks), where trials in this project had shown a significant reduction in CH_4 emission. Essential oil supplementation was applicable to all sectors, although to a lower proportion of the beef and sheep sectors as they are predominantly grazing management systems. High sugar grasses were assumed to be as a replacement for short-term leys and therefore applicable to only a proportion of each ruminant sector (reflecting the estimated proportion of short-term ley) and only for the proportion of the year when grazing is practised. Nitrogen excretion effects were estimated from previous trial work involving the grazing of high sugar grasses. While naked oats were shown to have an effect on CH_4 emissions from sheep, they were not deemed to be a realistic dietary scenario for sheep, so were applied only to the dairy and beef sectors, where they were included in the diet at 30%. The forage maize/reduced CP scenario assumed a switch from a predominantly grass silage forage component of the diet to 75% maize silage 25% grass silage, and a reduction in dietary CP from 18% to 14%. The higher sugar grass and the forage maize/low crude protein dietary scenarios were the only ones for which a reduction in nitrogen excretion was assumed.

Farm-system scale modelling : Herd typologies based on DEFRA project CC0333 (2001) were used to carry out farm system scale modelling using both the $SIMS_{DAIRY}$ (del Prado et al., 2009; del Prado et al., 2010) and NGAUGE DSS model (Brown et al., 2005) for dairy and beef/sheep systems, respectively.

For each type of farm system we defined the set of farm input variables to be used by the models. We defined 3 baseline typical farming systems for dairy systems: extended grazing, medium and high intensity. We defined 2 baseline typical farming systems (lowland and upland) for each other livestock type (i.e. beef and sheep). 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 types (iii) mineral fertiliser rates for the different forage areas, (iv) % clover content of the sward and (v) manure management (see appendix). The timing and percentage of mineral fertiliser applied per month was designed to follow the UK fertiliser recommendations for agricultural crops (RB209), (DEFRA, 2000). Detailed description of the models used and the assumption used are described in the appendix.

Results both per L of milk and per hectare of pollutant losses are shown at the farm level for the baseline and mitigation scenarios (extended: Table 10, medium: Table 11 and intensive-fully housed: Table 12). Predicted % changes in GHG, soil C storage, NH_3, NO_x emissions, and leaching of NO_3^- and P after the implementation of mitigation measures are also shown in Tables 10-12. Baseline scenarios resulted in different pollution losses. Total GHG per L of milk varied between 1599 (extended) and 817 (medium) g CO_2 eq GWP. Main differences for N_2O were caused by the different soil and climatic conditions (e.g. the typology on clay loam heavy soil showed much greater N_2O emissions than the lighter soil types from the other typologies). Main differences for CH_4 output among typologies were very much determined by differences in milk yield genetic merit of the dairy animals. Higher yielding cows resulted in lower CH_4 emissions per L of milk produced. This effect was not linear, particularly when taking into account that we included the greater numbers of followers required for more productive cows. $SIMS_{DAIRY}$ includes a positive relationship between milk yield production per cow and (via longevity and replacement rate) the need for followers (e.g. 2% more followers for an increase of 1L of milk per day and per dairy cow) (del Prado et al., *submitted*).

The extended typology, which had the less productive cows, resulted in greatest CH_4 output per L of milk. Differences in pre farm-gate CO_2 emissions and potential C soil storage was determined by the concentrates and inorganic fertilizer purchased (CO_2) and by the proportion of arable land (as maize) on the farm (for C soil storage). The extended grazing scenario, for example, resulted in greater pre farm-gate CO_2 emissions because of greater total mineral fertilizer required from grass (as opposed to medium scenario which has some maize requiring less mineral fertilizer N per hectare). Potential C soil storage was greater in the scenarios with less maize (extended>medium>intensive-fully housed).

Ammonia losses per L of milk ranged from 5.1 to 4.4 g NH_3-N/L of milk (medium> intensive-fully housed>extensive). Nitric oxide emissions per L of milk ranged from 0.04 to 0.28 g NO_x-N/L of milk (intensive-fully housed>extended>medium). Main differences were caused by differences in the interaction between soil and climatic characteristics. Nitrate and P losses to waters were very strongly affected by soil and climatic conditions. Heavier soils such as clay loam (extended) resulted in lower NO_3 leaching losses (19 kg NO_3-N/ha yr) and greater concentrations of P in the leachate (0.009 mg P/L) than the other soil textures.

As expected, most of the methods acting singly decreased overall GHG emissions at the farm level. However, the efficiency of these measures to reduce such emissions was substantially different in some cases depending on: (i) site conditions, (ii) the functional unit used to evaluate such emissions, (iii) the specific GHG, and (iv) the specific typology system studied. Knock-on effects on other forms of N (pollutants) were also found for some of the mitigation measures.

Differences between output values per L of milk and those per ha will be reflected by differences in forage farm area required. Differences in forage farm area required were in fact only found for the HSG scenarios, which were mainly driven by the more productive grasses with high sugar content and thereby, a lower requirement of surface.

Table 9. Details of dietary change scenarios used in the farm- and national-scale modelling

	Dairy	**Beef**	**Sheep**
1. Allicin supplementation			
Rate of addition (l/d)	1	0.5	0.040
Cost (£/l)	5	5	5
Production effect (%)	0	0	0
Enteric CH_4 effect (%)	0	0	-20
N excretion effect (%)	0	0	0
Fraction of year applicable (%)	100	100	100
Fraction of sector applicable (%)	0	0	25
2. Essential oil supplementation			
Rate of addition (l/d)	0.02	0.01	0.002
Cost (£/l)	350	350	350
Production effect (%)	0	0	0
Enteric CH_4 effect (%)	-10	-10	-10
N excretion effect (%)	0	0	0
Fraction of year applicable (%)	100	100	100
Fraction of sector applicable (%)	100	50	25
3. High sugar grasses			
Cost (%)	0	0	0
Production effect (%)	+20	+25	+25
Enteric CH_4 effect (%)	-10	-20	-20
N excretion effect (%)	-15	-15	-15
Fraction of year applicable (%)	50	75	90
Fraction of sector applicable (%)	60	25	25
4. Naked oats			
Production effect (%)	0	0	N/A
Enteric CH_4 effect (%)	-10	-10	N/A
N excretion effect (%)	0	0	N/A
Fraction of year applicable (%)	100	100	N/A
Fraction of sector applicable (%)	100	50	N/A
5. Forage maize and lower CP			
Production effect (%)	0	N/A	N/A
Enteric CH_4 effect (%)	-5	N/A	N/A
N excretion effect (%)	-20	N/A	N/A
Fraction of year applicable (%)	100	N/A	N/A
Fraction of sector applicable (%)	50	N/A	N/A

Overall GHG emissions were reduced up to 19% (using HSG in extended systems) and 11% (using –CP/+maize in medium systems) per L of milk and hectare, respectively. Methane reduction per L of milk ranged from 23% (for HSG in extended systems) to 5% (for HSG in intensive-fully housed systems). It must be noted that as mentioned in previous sections the -CP/+maize measure was not efficient to reduce any CH_4 in intensive-fully housed systems as no increase in maize in the diet was simulated. The inclusion of essential oil and naked oats in the diet reduced CH_4 emissions by about 10%. It must be noted that $SIMS_{DAIRY}$ does not predict any of the possible, but still speculative, consequences of elevated levels of unsaturated fat supplementation on the rumen function and DM intake (del Prado *et al.,* 2010). The effect of using HSG on the reduction of farm CH_4 depended entirely on the grazing period spent by cows (extensive >medium> intensive-fully housed).

Mitigation measures affected N_2O emissions only for the HSG and –CP/+maize scenarios. Whereas for HSG scenarios N_2O emissions per L of milk were reduced up to 18% due to greater N use efficiency in the farm system with increasing HSG, for the –CP/+maize scenarios there was an increase in N_2O emissions of up to 53% (extended scenario). The main reason for this increase was the replacement of grassland with maize land and the changes in manure application timing and rates per hectare. Differences in pre-farm gate CO_2 and potential C soil storage were only found for the HSG and -CP/+maize measures. For the pre-farm gate CO_2 emissions per L of milk, the HSG measures showed a reduction of up to 15% closely related to the amount of hectares required (i.e.

total farm mineral N fertilizer required), whereas -CP/+maize measures gave a reduction of up to 21% (extended) closely related to the proportion of hectares of maize required (i.e. area to which a lower rate of inorganic N fertilizer is applied). The same factors influenced the amount of potential C stored in the soil, but with an opposite effect. In fact, most scenarios which decreased pre-farm gate CO_2 emissions per L of milk increased the amount of potential C soil loss. Soil C per unit of L of milk in HSG scenarios was increasingly stored with decreasing requirements of hectares to produce the same amount of milk. For the -CP/+maize measures, the proportion of land use change from grassland to arable (maize) determined the extent of this potential C storage in the soil. A decrease in potential C storage of up to 41% was found for the -CP/+maize measure applied to the medium scenario. A decrease of up to 15% in potential soil C storage was found for the HSG scenario in the extended system.

Changes of NH_3 and NO_x emissions with respect to the baseline scenarios were only found for HSG and –CP/+maize scenarios. Ammonia emissions per L of milk were reduced by up to 22% for the HSG measures (extensive >medium> intensive-fully housed), mainly due to the combination of less hectares required to produce 1 L of milk and also due to reductions in excreted N (particularly urine N) in the grazed HSG. For the –CP/+maize scenarios, a reduction of 6% and an increase in 19% was found for medium and extended scenarios, respectively. For the medium scenario, the main factor affecting differences in NH_3 emissions was the fact that N excretion was lower (particularly urine N) due to a decrease in CP content in the diet, whereas for the extended scenario, the land use change after replacing grass with maize led to a change in timing of manure application towards the drier season, resulting in greater NH_3 losses. Nitric oxide emissions per L of milk were significantly reduced for both HSG and –CP/maize scenarios in the extended and medium scenario. These reductions were mainly caused by the decreases in N in the urine and total N excretion, thereby reducing the pool of inorganic N subject to nitrification.

Changes in NO_3 losses were only large for –CP/+maize scenarios (extended and medium). For both scenarios an increase in NO_3 leaching losses was found despite the reduced farm pool of inorganic N. The main factor affecting this increase was the larger proportion of forage area sown as arable (maize) and the seasonal changes in manure application.

Results beef/sheep: Pollutant losses at the farm level for the baseline and mitigation scenarios, per adult animal and per adult animal corrected with live-weight gain (meat production) are presnted in the Appendix Predicted % changes in GHG, soil C storage, NH_3, NO_x emissions, and leaching of NO_3^- after the implementation of mitigation measures are shown in Tables 13 (lowland beef), 14 (lowland sheep), 15 (upland beef) and 16 (upland sheep).

As expected, most of the measures acting singly decreased overall GHG emissions at the farm level compared to the GHG results from the baseline scenarios. In beef systems, CH_4 reduction per animal was around 10-11% and ranged from 27-28% (in HSG) to 10% as CH_4 reduction per animal corrected with meat. In sheep systems, CH_4 reduction per animal ranged between 10% (essential oil) to 20% (allicin) and CH_4 reduction per animal corrected with meat ranged from 10% (essential oil) to 33% (HSG). Differences in CH_4 emissions between upland and lowland in each animal system were negligible. Liveweight gain (expressed as meat production) was greater in HSG scenarios, as an increase in plant and animal productivity was simulated when HSG were used. Therefore, for HSG scenarios, losses per unit of meat were always smaller than losses per animal.

Table 10. Pollutant losses from the extended dairy (Leicestershire) baseline and mitigation scenarios

	Baseline		Allicin	essential oil		HSG		Naked oats		-CP/+maize	
Warming potential (GHG)											
	g/Lmilk	kg/ha		g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha
CO_2-eq GWP	1599	14584	NE*	1549 (-3%)	14129	1297 (-19%)	13872 (-5%)	1549 (-3%)	14129	1429 (-11%)	13051
N_2O-N	1.5	13	NE*	1.5 (0%)	13	1.2 (-18%)	13 (-3%)	1.5 (0%)	13	2.2 (53%)	20
CH_4	24	218	NE*	21 (-10%)	196	18 (-23%)	195 (-10%)	21 (-10%)	196	20 (-14%)	188
CO_2	410	3789	NE*	410 (0%)	3789	350 (-15%)	3743 (-1%)	410 (0%)	3789	322 (-21%)	2975
C soil storage	25	231	NE*	25 (0%)	231	22 (-15%)	232 (0%)	25 (0%)	231	20 (-20%)	184
Acidifying Gases											
	g/Lmilk	kg/ha		g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha
NH_3-N	4.4	40	NE*	4.4 (0%)	40	3.5 (-22%)	37 (-8%)	4.4 (0%)	40	5.3 (19%)	48
NO_x-N	0.26	2.4	NE*	0.26 (0%)	2.4	0.2 (-25%)	2.1 (-12%)	0.26 (0%)	2.4	0.23 (-12%)	2.1
Losses to Waters											
	mg/L	kg/ha		mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
NO_3-N	13	19	NE*	13 (0%)	19	13 (-1%)	18 (-1%)	13 (0%)	19	34 (156%)	48
P	0.009		NE*	0.009 (0%)		0.009 (12%)		0.009 (0%)		0.011 (35%)	

**NE: no effect*

Table 11. Pollutant losses from the medium dairy (Lancashire) baseline and mitigation scenarios

	Baseline		**Allicin**	**essential oil**		**HSG**		**Naked oats**		**-CP/+maize**	
Warming potential (GHG)											
	g/Lmilk	kg/ha		g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha
CO_2-eq GWP	817	8682	NE*	777 (-5%)	8263	734 (-10%)	8949 (3%)	777 (-5%)	8263	729 (-11%)	7600
N_2O-N	0.3	3	NE*	0.3 (0%)	3	0.2 (-15%)	3 (-2%)	0.3 (0%)	3	0.3 (9%)	3
CH_4	19	201	NE*	17 (-10%)	182	18 (-7%)	215 (7%)	17 (-10%)	182	18 (-6%)	186
CO_2	298	3179	NE*	298 (0%)	3179	262 (-12%)	3200 (1%)	298 (0%)	3179	270 (-9%)	2821
C soil storage	11	117	NE*	11 (0%)	117	10 (-15%)	116 (-1%)	11 (0%)	117	7 (-41%)	67
Acidifying Gases											
	g/Lmilk	kg/ha		g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha
NH_3-N	5.1	54	NE*	5.1 (0%)	54	4.2 (-17%)	51 (-5%)	5.1 (0%)	54	4.8 (-6%)	50
NO_x-N	0.28	3.0	NE*	0.28 (0%)	3	0.22 (-23%)	2.7 (-11%)	0.28 (0%)	3	0.21 (-25%)	2
Losses to Waters											
	mg/L	kg/ha		mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
NO_3-N	24	113	NE*	24 (0%)	113	24 (1%)	115 (1%)	24 (0%)	113	30 (27%)	144
P	0.0003		NE*	0.0003 (0%)		0.0004 (8%)		0.0003 (0%)		0.0003 (4%)	

**NE: no effect*

Table 12. Pollutant losses from the intensive dairy (Wiltshire) baseline and mitigation scenarios

	Baseline		**Allicin**	**essential oil**		**HSG**		**Naked oats**		**-CP/+maize**	
Warming potential (GHG)											
	g/Lmilk	kg/ha		g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha
CO_2-eq GWP	829	9596	NE*	791 (-5%)	9161	795 (-4%)	9503 (-1%)	791 (-5%)	9161	828 (0%)	9559
N_2O-N	0.1	1	NE*	0.1 (0%)	1	0.1 (-4%)	1 (0%)	0.1 (0%)	1	0.1 (0%)	1
CH_4	18	207	NE*	16 (-10%)	186	17 (-5%)	203 (-2%)	16 (-10%)	186	18 (0%)	206
CO_2	420	4864	NE*	420 (0%)	4864	406 (-3%)	4854 (0%)	420 (0%)	4864	420 (0%)	4850
C soil storage	4	46	NE*	4 (0%)	46	4 (-9%)	44 (-3%)	4 (0%)	46	4 (0%)	46
Acidifying Gases											
	g/Lmilk	kg/ha		g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha	g/Lmilk	kg/ha
NH_3-N	4.9	57	NE*	4.9 (0%)	57	4.6 (-8%)	54 (-5%)	4.9 (0%)	57	4.5 (-8%)	52
NO_x-N	0.04	0.4	NE*	0.04 (0%)	0	0.04 (-4%)	0.4 (0%)	0.04 (0%)	0	0.04 (0%)	0
Losses to Waters											
	mg/L	kg/ha		mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha	mg/L	kg/ha
NO_3-N	40	153	NE*	40 (0%)	153	39 (-1%)	152 (-1%)	40 (0%)	153	39 (-2%)	150
P	0.0003		NE*	0.0003 (0%)		0.0003 (2%)		0.0003 (0%)		0.0003 (0%)	

**NE: no effect*

Experiments carried out within this project indicated that the effect of most measures on other N losses was negligible. The use of HSG, however, implied changes in the N cycle. In terms of N_2O emissions (GHG) and potential soil C storage, for example, each HSG mitigation scenario, combination of grass/clover content and frequency of reseeding, led to different losses results: For lowland scenarios, when frequency of reseeding and the % clover content is not altered (e.g. HSG3 and HSG4 mitigation scenarios), N_2O emissions were reduced in both per animal (around 4 %) and per animal corrected with meat (21%) with no change in potential C soil storage. If clover is replaced 100% by HSG (HSG4), a reduction and a slight increase in N_2O emissions per animal were found for beef and sheep, respectively (with no change in potential C soil storage). A decrease of over 15% was found if expressed per animal corrected with meat. Overall GHG emissions were reduced by 8% (beef), 12% (sheep) per animal and 25% (beef), 28% (sheep) per animal corrected with meat. **It must be noted that soil C storage changes are not factored into the value of overall GHG emissions.** Despite the potential beneficial effect of HSG on GHG emissions, if reseeding management had to be changed, the CH_4 mitigation effect could be counteracted by an increase in N_2O emissions and a decrease in potential soil C storage. For example, changes to a more frequent reseeding (HSG1, HSG2) increased N_2O emissions up to 12% and 21% for lowland beef and sheep, respectively. These results, if expressed per unit of animal corrected with meat production will be improved, with reductions in N_2O emissions of 8 and 10 % for lowland beef and sheep, respectively. However, soil C storage would decrease significantly due to frequent aeration of the soil. For upland scenarios, the change from long term grasslands to a more frequent reseeding led to increasing N_2O emissions and decreased soil C storage. It must be remembered from previous sections that for upland scenarios rough grazing areas remain as long-term grassland in all cases. Reseeding more frequently (HSG1 and HSG4: 1-2 years) generally in larger N_2O emissions (up to 10 and 22% for beef and sheep respectively in HSG1 scenario) and smaller potential C stored in the soil than those scenarios with more infrequent reseeding (HSG2 and HSG3: 4-6 years). The only HSG scenario for upland systems with no significant changes in N_2O emissions was HSG2, where 100% grass replaced a 25% clover sward. These N_2O results, if expressed per unit of animal corrected with meat production would result in reduction in all HSG scenarios from a range of 1% (sheep HSG1) to 20% (beef HSG2). Even accounting for changes in frequency reseeding, overall GHG emissions for upland scenarios were reduced from 6 to 8 % (beef), 10 to 14% (sheep) per animal and 25 to 27 % (beef) and 27 to 30% (sheep) per animal corrected with meat.

Ammonia losses were reduced in all cases for upland systems (up to 2%). For lowland systems, they were only reduced where no changes in frequency of reseeding took place; for HSG3 (with no change in clover content) in both beef and sheep and HSG4 in beef systems (up to 9%). Feeding animals with HSG resulted in a decrease in total N excreted and lower urine:dung N ratio, thereby less NH_4 was predicted to be hydrolysed and volatilized to the air. Changing from a mixed grass/clover sward to a 100% grass sward resulted in changes in the CP content of the grazed sward and thereby, changing the composition of the N excreted. The effect remains unclear however, as for lowland sheep this seemed to reduce excreted N and urine N:dung N ratio, but the opposite was found for lowland beef systems. If NH_3 results are expressed per animal corrected with meat there was a reduction in all cases.

Nitric oxide losses per animal were only affected in upland systems: small changes were found for grasslands with more frequent reseeding (HSG1 and HSG2) and reductions of around 8-9% in less frequent reseeding scenarios (HSG3 and HSG4). If NO_x results are expressed per animal corrected with meat there was a reduction in all cases.

Nitrate leaching losses were very much affected by the changes in reseeding frequency and clover content in the sward. For lowland scenarios, NO_3 leaching losses were very much reduced if the area was converted to 100% grass sward and no changes made to the frequency of reseeding (39 and 31% reduction in beef and sheep systems). Losses remained similar in grass clover swards with no changes to the reseeding frequency. For scenarios with frequent reseeding, NO_3 leaching losses were much greater than in the baseline scenarios, with increases of up to 35 and 26% (HSG2: reseeding frequency: 1-2 years with no changes in % clover in the sward). If NO_3 leaching results are expressed per animal corrected with meat there was a reduction in all cases except for HSG2. For upland scenarios, NO_3 leaching losses were only reduced in HSG3 scenario at 29 and 24% for upland beef and sheep, respectively. For the rest of the HSG scenarios there was a large increase in NO_3 leaching losses of up to 92 and 77% for beef and sheep, respectively. A greater frequency of reseeding led to larger NO_3 leaching losses. Even if NO_3 leaching results are expressed per animal corrected with meat there was only a significant reduction for HSG3 scenario. There were no changes in NO_3 leaching expressed per animal corrected with meat for the scenario where grass/clover sward is converted into grass only (HSG4).

Table 13. Change (%) in pollutant losses from Lowland beef mitigation scenarios

		Allicin	essential oil	HSG1	HSG2	HSG3	HSG4	Naked oats
		TOTALS/per adult animal						
N_2O	kg N	0%	0%	12%	12%	-4%	-6%	0%
NO	kg N	0%	0%	0%	0%	0%	0%	0%
NH_3	kg N	0%	0%	1%	3%	-6%	-9%	0%
NO_3 leaching	kg N	0%	0%	11%	35%	-1%	-39%	0%
CH_4	kg CH4	0%	-10%	-11%	-11%	-11%	-11%	-10%
C storage	kg C	0%	0%	-100%	-100%	0%	0%	0%
GHG	kg CO2 eq.	0%	-7%	-3%	-3%	-8%	-9%	-7%
	per adult animal*corrected with meat production							
N_2O	kg N	0%	0%	-8%	-8%	-21%	-23%	0%
NO	kg N	0%	0%	-18%	-18%	-18%	-18%	0%
NH_3	kg N	0%	0%	-17%	-15%	-23%	-25%	0%
NO3 leaching	kg N	0%	0%	-9%	11%	-18%	-50%	0%
CH_4	kg CH4	0%	-10%	-27%	-27%	-27%	-27%	-10%
C storage	kg C	0%	0%	-100%	-100%	22%	22%	0%
GHG	kg CO2 eq.	0%	-7%	-20%	-20%	-25%	-25%	-7%

HSG1= replace grass clover sward with grass only and changes the frequency of reseeding (<2 years).
HSG2= changes the frequency of reseeding (<2 years).
HSG3= same scenario.
HSG4= replace grass clover sward with grass only.

Table 14. Change (%) in pollutant losses from Lowland sheep mitigation scenarios

		Allicin	essential oil	HSG1	HSG2	HSG3	HSG4
		TOTALS/per adult animal					
N_2O	kg N	0%	0%	21%	9%	-4%	3%
NO	kg N	0%	0%	0%	0%	0%	0%
NH_3	kg N	0%	0%	12%	2%	-7%	2%
NO_3 leaching	kg N	0%	0%	7%	26%	-1%	-31%
CH_4	kg CH_4	-20%	-10%	-18%	-18%	-18%	-18%
C storage	kg C	0%	0%	-100%	-100%	0%	0%
GHG	kg CO_2 eq.	-11%	-6%	-1%	-6%	-12%	-9%
		per adult animal*corrected with meat production					
N_2O	kg N	0%	0%	0%	-10%	-21%	-15%
NO	kg N	0%	0%	-18%	-18%	-18%	-18%
NH_3	kg N	0%	0%	-8%	-16%	-24%	-17%
NO_3 leaching	kg N	0%	0%	-12%	4%	-19%	-43%
CH_4	kg CH_4	-20%	-10%	-32%	-32%	-32%	-32%
C storage	kg C	0%	0%	-100%	-100%	22%	22%
GHG	kg CO_2 eq.	-11%	-6%	-19%	-23%	-28%	-25%

HSG1= replace grass clover sward with grass only and changes the frequency of reseeding (<2 years).
HSG2= changes the frequency of reseeding (<2 years).
HSG3= same scenario.
HSG4= replace grass clover sward with grass only.

Table 15. Change (%) in pollutant losses from upland beef mitigation scenarios

		Allicin	essential oil	HSG1	HSG2	HSG3	HSG4	Naked oats
		TOTALS/per adult animal						
N_2O	kg N	0%	0%	10%	0%	7%	9%	0%
NO	kg N	0%	0%	-1%	1%	-8%	-9%	0%
NH_3	kg N	0%	0%	-2%	-1%	-1%	-2%	0%
NO_3 leaching	kg N	0%	0%	92%	32%	-29%	25%	0%
CH_4	kg CH4	0%	-10%	-11%	-11%	-11%	-11%	-10%
C storage	kg C	0%	0%	-45%	-45%	-24%	-24%	0%
GHG	kg CO2 eq.	0%	-8%	-6%	-8%	-7%	-6%	-8%
	per adult	**animal*corrected with meat production**						
N_2O	kg N	0%	0%	-12%	-20%	-14%	-12%	0%
NO	kg N	0%	0%	-21%	-19%	-26%	-27%	0%
NH_3	kg N	0%	0%	-21%	-20%	-20%	-22%	0%
NO3 leaching	kg N	0%	0%	54%	6%	-43%	0%	0%
CH_4	kg CH4	0%	-10%	-28%	-28%	-28%	11%	-10%
C storage	kg C	0%	0%	-31%	-31%	-6%	-6%	0%
GHG	kg CO2 eq.	0%	-8%	-25%	-27%	-25%	-25%	-8%

HSG1= replace grass clover sward with grass only and changes the frequency of reseeding (<2 years).
HSG2= changes the frequency of reseeding (<2 years).
HSG3= changes from long-term grassland to 4-6 years old swards (for cut&grazed area, this doesn’t include rough grazing area).
HSG4= replace grass clover sward with grass only.
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Table 16. Change (%) in pollutant losses from Upland sheep mitigation scenarios

		Allicin	essential oil	HSG1	HSG2	HSG3	HSG4
		TOTALS/per adult animal					
N_2O	kg N	0%	0%	22%	0%	8%	10%
NO	kg N	0%	0%	-1%	1%	-8%	-9%
NH_3	kg N	0%	0%	-1%	-1%	-1%	-2%
NO_3 leaching	kg N	0%	0%	77%	28%	-24%	22%
CH_4	kg CH4	-20%	-10%	-18%	-18%	-18%	-18%
C storage	kg C	0%	0%	-45%	-45%	-24%	-24%
GHG	kg CO2 eq.	-16%	-8%	-10%	-14%	-13%	-12%
		per adult animal*corrected with meat production					
N_2O	kg N	0%	0%	-1%	-19%	-13%	-11%
NO	kg N	0%	0%	-20%	-18%	-25%	-26%
NH_3	kg N	0%	0%	-20%	-19%	-19%	-20%
NO3 leaching	kg N	0%	0%	43%	4%	-38%	-1%
CH_4	kg CH4	-20%	-10%	-33%	-33%	-33%	-33%
C storage	kg C	0%	0%	-32%	-32%	-7%	-7%
GHG	kg CO2 eq.	-16%	-8%	-27%	-30%	-29%	-29%

HSG1= replace grass clover sward with grass only and changes the frequency of reseeding (<2 years).
HSG2= changes the frequency of reseeding (<2 years).
HSG3= changes from long-term grassland to 4-6 years old swards (for cut&grazed area, this doesn't include rough grazing area).
HSG4= replace grass clover sward with grass only.

National scale modelling

The models developed and used by North Wyke for compiling the national inventories for 2007 were used for the national scale impact modelling. For the CH_4 and N_2O modelling, the spreadsheet-based GHG inventory model (as described in MacCarthy et al., 2010) was used. Inventory model emission factors for enteric CH_4 fermentation were modified according to the scenarios, including a weighting factor to account for year and sector applicability. Any production effect was included by reducing livestock numbers proportionately, so that the model reflected a fixed production level. Model parameters for nitrogen excretion were amended according to the scenario, again including weighting factors to account for year and sector applicability. For NH_3, the spreadsheet-based NH_3 inventory model (Webb and Misselbrook, 2004; Misselbrook et al., 2004) was used.

The impacts of the various dietary scenarios on the N_2O and CH_4 emissions from the different ruminant sectors and from UK agriculture as a whole are given in Table 17 – 20. These are presented as percentage reductions against the 2007 GHG CO_2eq baseline in Fig. 2. The use of high sugar grasses showed the greatest potential reductions in GHG emissions for each of the ruminant sectors, largely because of the reductions in both CH_4 and N_2O as well as increasing productivity (a 'win-win-win' scenario). Emission reduction potential tended to be greatest in the dairy sector, where the scope for implementation is greatest, and least in the sheep sector (with the exception of high sugar grasses). The dietary change scenarios explored in this project have the potential to deliver emission reductions from UK agriculture in the order of 0.5 – 5.0%. Greater emission reductions would require dietary changes which give greater CH_4 emission and/or nitrogen excretion reductions at the animal level (productivity increases give added benefit) combined with a greater potential applicability within the ruminant sectors.

Table 17. Impact of dietary change scenarios on GHG emissions from the UK Dairy sector (2007)

	Baseline	Essential oil	High sugar grass	Naked oats	Forage maize and low CP
Methane (Kt)					
Enteric fermentation	262.0	235.8	238.9	235.8	255.5
Manure management	57.0	57.0	57.0	57.0	57.0

Total CH_4	319.0	292.8	295.9	292.8	312.4
Nitrous oxide (Kt)					
Manure management	1.0	1.0	0.9	1.0	0.9
Soils – direct	9.1	9.1	8.5	9.1	8.4
Soils -indirect	5.7	5.7	5.4	5.7	5.3
Total N_2O	15.8	15.8	14.7	15.8	14.6
Total GHG (CO_2eq)	11.6	11.0	10.8	11.0	11.1

Table 18. Impact of dietary change scenarios on GHG emissions from the UK Beef sector (2007)

	Baseline	Essential oil	High sugar grass	Naked oats
Methane (Kt)				
Enteric fermentation	297.7	282.8	273.1	282.8
Manure management	27.9	27.9	27.9	27.9
Total CH_4	325.6	310.8	301.0	310.8
Nitrous oxide (Kt)				
Manure management	2.1	2.1	1.9	2.1
Soils – direct	11.4	11.4	10.9	11.4
Soils -indirect	7.0	7.0	6.6	7.0
Total N_2O	20.5	20.5	19.4	20.5
Total GHG (CO_2eq)	13.2	12.9	12.3	12.9

Table 19. Impact of dietary change scenarios on GHG emissions from the UK Sheep sector (2007)

	Baseline	Allicin	Essential oil	High sugar grass
Methane (Kt)				
Enteric fermentation	158.8	150.9	154.8	143.1
Manure management	3.8	3.8	3.8	3.8
Total CH_4	162.6	154.6	158.6	146.9
Nitrous oxide (Kt)				
Manure management	0.1	0.1	0.1	0.1
Soils – direct	7.0	7.0	7.0	6.6
Soils -indirect	3.8	3.8	3.8	3.6
Total N_2O	11.0	11.0	11.0	10.4
Total GHG (CO_2eq)	6.8	6.6	6.7	6.3

Table 20. Impact of dietary change scenarios on GHG emissions from UK agriculture (2007)

	Baseline	Allicin	Essential oil	High sugar grass	Naked oats	Forage maize and low CP
Methane (Kt)						
Enteric fermentation	733.1	725.1	688.0	669.7	692.0	726.5
Manure management	136.0	136.0	136.0	136.0	136.0	136.0
Total CH_4	869.1	861.2	824.1	805.7	828.0	862.6
Nitrous oxide (Kt)						
Manure management	5.4	5.4	5.4	5.2	5.4	5.3
Soils – direct	49.4	49.4	49.4	47.8	49.4	48.7
Soils -indirect	25.7	25.7	25.7	24.8	25.7	25.3
Total N_2O	80.5	80.5	80.5	77.8	80.5	79.3
Total GHG (CO_2eq)	43.2	43.1	42.3	41.0	42.4	42.7

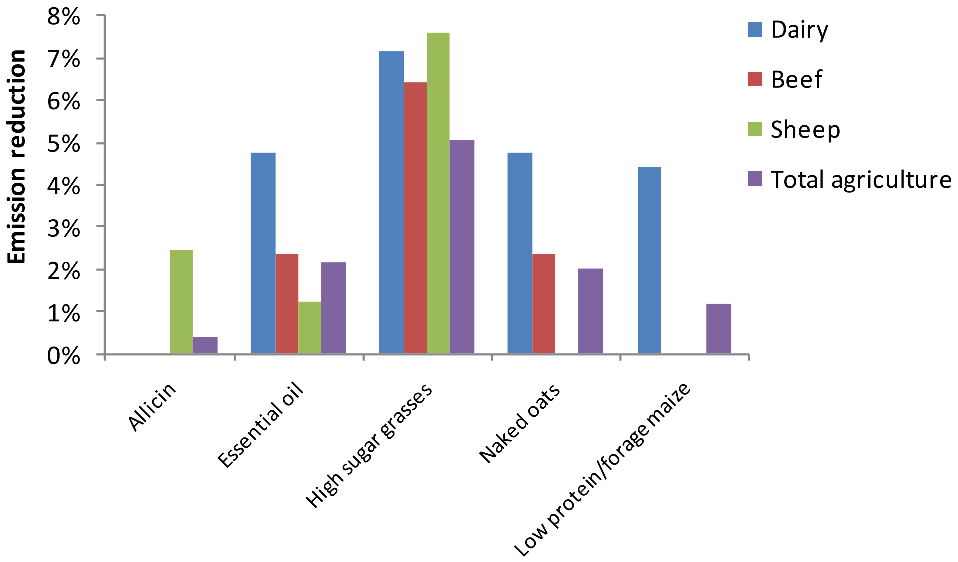

Figure 2. Proportional impact of dietary change scenarios on GHG emissions (as CO_2eq) from UK agriculture (2007)

Economic Modelling: Estimates of the economic impact of the mitigation scenarios by scaling up the experimental results to the farm level were made. The same farm typologies and mitigation scenarios as above are used. A farm level farm management model was used to estimate changes in farm net-margin and greenhouse gas emissions and the robustness of the results to price scenarios for 2008-2019. The Farm-adapt farm management model was used to estimate the economic impact and changes to farm plans resulting from the adaptation of the AC209 mitigation scenarios. Farm-adapt is a mixed integer programming model that maximises annual farm net-margin by selecting the optimal labour, animal, crop, machinery and building mix. Net margin does not include the Single Farm Payment or many fixed costs so is proportional to but different from profit or net income. Greenhouse gas emissions are estimated based on IPCC methodology, improved using additional information available within the model (e.g. dry matter intake) and some estimates of indirect emissions (fertilizer and feed). For a more detailed description of Farm-adapt in a similar contest to this project see Gibbons et al. (2006). Prices and costs were taken from Nix (2009). The same farms were modelled as used above. As these typologies represent an average farm in each sector at historic prices it is likely that, in terms of net margin, they are not the optimal farm plan at 2010 prices. Therefore, for each farm Farm-adapt was run i) constraining the forage area and stock numbers to the typologies (Fixed runs) and ii) allowing forage areas and stock to vary (Variable runs). For both sets of runs labour allocation and machinery were optimised by Farm-adapt. Each farm type was allocated sufficient existing animal housing and storage for the typology animal numbers and forage production. Net margin from the variable runs will always be greater or equal than the fixed runs and any difference in net margin between the quantifies the lack of optimality of the typologies. The runs for the dairy farms with specific adapted diets (Forage maize and crude protein) were run only as variable runs as the forage areas required varied with diet. The summary marginal cost of mitigation figures presented later include only the results from the variable runs.

The same mitigation scenarios were run for the same farms as above. Broadly the scenarios can be grouped as novel supplements (allicin and essential oil), replacement of existing feed (naked oats and high sugar grasses) and adapting diets (changing forage maize and crude protein contents). The *supplement* and *replacement* scenarios require no change in farm plan while changes are required for the *adaptation* scenarios (forage mix etc.). Hence, the economic and GHG effects of the supplement and mitigation scenarios were estimated from Farm-adapt baseline output with no extra model runs while the adaptation scenarios required additional model runs to determine the optimal farm plan.The robustness of the estimation of the economic impact of the mitigation scenarios was tested using price scenarios developed from FAPRI (2010-2019) and OECD-FAO (2009-2018) agricultural outlook reports. The FAPRI and OECD-FAO predictions are made using scenarios of population growth and world trade aggregated at the regional level (e.g. the EU-27 countries) and assume no extreme climatic years or other shocks to supply, demand or trade. Therefore it is likely that the future price variation experienced at the individual farm level is substantially underestimated. To account for this underestimation price scenarios were generated by taking the combined distribution of FAPRI and OECD-FAO prices for the EU-27 countries relative to the 2010 price and smoothed using kernel density analysis with five times Silverman's "rule of thumb" bandwidth (Silverman, 1986). Using this method, relative milk, sheep and beef prices were based on the OECD-FAO/FAPRI prices while feed prices were estimated using the annual mean of wheat, coarse grain and oilseed prices. Long term predictions of nitrogen price are unavailable, so a triangular distribution between 0.5 and 1.5 times the 2010 price was modelled.

The effect of price changes on a fully constrained farm plan can be estimated by simple calculation. However, when not fully constrained the optimal farm plan is sensitive to input and output prices as it is possible to mitigate the impact of low output prices (and high input prices) and take advantage of high output prices (and low input prices). Therefore, to estimate the impact of the price scenarios required Farm-adapt runs for the modelled price range. For computation efficiency each price scenario was then divided into 100 discrete intervals with an associated weight and Farm-adapt was run for each farm type for each of the price scenarios for each commodity and input. The results for each scenario were then estimated by taking a weighted combination of the 100 runs, either as a weighted distribution or summarised as a weighted mean. An advantage of this procedure is that alternative price scenarios can be directly estimated from model output by changing the weights so extra runs are not required. The results presented are sensitive to assumptions about price variability, the farm typologies, the experimental results and the modelled estimation of GHG emissions. No direct testing was carried out in beef cattle so estimates for the beef sector are based on sheep results. The essential oil treatment was not directly tested in dairy cows. The estimated change in emissions does not account for the emissions associated with the production of the supplements or any additional reseeding for the high sugar grasses. We emphasise that the only measure of uncertainty in the results is from the price scenarios so total uncertainty is underestimated. Price data for the mitigation scenarios is based on trial data and doses. It is possible that economies of scale could reduce the cost of the supplements and that future work may identify smaller effective doses. The results are best interpreted as a guide to the relative ranking of the economic impact of the mitigation scenarios both at the farm level and in terms of carbon mitigation cost.

In terms of GHG emissions, estimated emissions are lower and less variable for the intensive and extensive dairy farm fixed at the typologies compared to the variable runs. Using an empirical quantile based significance test the difference in emissions from the dairy farm types are significant at $p=0.05$ for both the fixed and variable runs. Estimated emissions for the livestock runs are higher for the fixed runs compared to the typologies. It is notable that emissions per unit of production are lower for the intensive dairy farm compared to the medium and extensive farm. This result is largely accounted for by milk yield per cow, at higher yields there are proportionally less emissions from maintaining basal metabolism.

Emissions from diets with increased forage maize content (75%) and reduced crude protein (14%) were compared to a baseline diet of 25% forage maize and 18% crude protein (Figure 3). On the intensive and extensive dairy farm moving from a 25% to 75% forage maize diet substantially reduced GHG emissions. The effect was smaller on the medium dairy farm. The result for the medium dairy farm is largely climate driven, it is the most northerly farm modelled and forage maize yields are relatively low. The effect of moving from 18% to 14% crude protein had a small effect on emissions on all three dairy farm types.

Figures 4-6 summarize the cost of mitigation and the mitigation potential for the modelled farm types and scenarios. Scenarios are ranked from those of the least mitigation cost at the left hand side to those with the greatest cost at the right hand side. Mitigation potential (on the horizontal axis) is presented as kg CO_2-equivalent per unit of output (milk or meat) this allows straightforward scaling of the results beyond the single modelled farms. For example, for the high sugar grasses scenario on the intensive dairy farm there is a maximum mean mitigation potential of 0.009 kg CO_2-equivalent l^{-1} milk so if this scenario was fully applied to farms producing a total of 10,000,000 litres of milk, then 10,000,000*0.009/1,000 = 90 tonnes of CO_2-equivalent emissions would be mitigated. The vertical bar then indicates the mean cost per tonne of CO_2-equivalent mitigated. If this figure is negative then there is an economic benefit to farmers. To continue the previous example on an intensive dairy there is a net benefit to farmers of £597 tonne of CO_2-equivalent when growing high sugar grasses so the estimated increase in income would be 90*597 = £53,730.

There was a similar pattern of marginal abatement costs for all the dairy farms (Figure 4) with conversion of grassland to high sugar grasses resulted in an economic benefit to farmers even when limited grazing occurred on the farm (intensive dairy). Naked oats resulted in an estimated net cost but the order of this cost (£117-360 t^{-1} CO_2-equivalent) suggest that a modest reduction in the price from that paid for the trials could make this scenario viable especially if there was a carbon market. The marginal abatement cost of the essential oil treatment was extremely high suggesting that at current dosages and production costs the scenario is not economically viable. Note that, while the mitigation potential for the extensive dairy farm is higher than for the intensive dairy farm, the potential is not sufficient to make production as GHG efficient as on the medium or intensive farms.

The pattern in abatement cost for the livestock farms (Figure 5) was similar to that of the dairy farms. Again high sugar grasses resulted in a direct economic benefit, naked oats were near viable (£35-92 t^{-1} CO_2-equivalent) and essential oil costly. The allicin treatment while less costly and with more potential for reducing emissions than essential oil was still not viable at current dosages and production costs.

For all the dairy farm types changing diets away from 25% forage maize and 18% crude potential has potential for economic gains and emission reduction (Figure 6). The largest GHG mitigation potential is from moving from 25% to 75% forage maize and the reductions achieved are greater than for the substitution or supplement scenarios (Figure 4). The economic effect on farm net-margin is largely driven by the relative forage maize and grass yields which is a geographic rather than farm system effect. The intensive dairy farm located in relatively warm and dry Wiltshire has relatively high forage maize yields and relatively low grass yields so strongly favours a forage maize based diet. The medium dairy farm is located in relatively cold and wet Lancashire and consequently has relatively low forage maize yields and high grass yields favouring a grass diet. Therefore the GHG mitigation potential of adapting dairy diets is very dependent on the forage maize yields achievable on farms not already growing maize.

Uptake of novel practices and adaptation by farmers is clearly driven by factors in addition to economics. Other factors such as skill, knowledge, familiarity, and labour requirements should be taken into account when considering likely uptake. In a farm modelling context a simple summary measure of these other factors is the size of the difference between the baseline farm plan and the farm plan with the adaptation. It is unlikely that even a knowledgeable and skilled farmer would make large changes to existing practice for a small economic return. In this framework, for a given economic return, supplement scenarios are most likely to be adopted, replacement strategies less likely and adaptation strategies least likely. For the specific scenarios considered in this project, assuming widespread availability, the non-economic barriers to adoption of high sugar grasses, naked oats, allicin and essential oil are low. The supplements can be added to existing rations, while the substitutions require no technological change. Adapting dairy diets requires diet reformulation, change in forage areas and possibly growing a crop not already grown on the farm (forage maize). However, the competitive nature of the dairy sector means that these barriers are likely to be overcome in the case of forage maize which is already in widespread use. There is likely to be more resistance to a move to 14% crude protein without evidence from more long-term trials and across a range of dairy systems.

Conclusions

- At the farm level the dairy farms with more intensive production (higher milk yield per cow) have substantially and significantly lower GHG emissions per litre of milk produced than those with more extensive production.
- On the dairy farms at the farm level high sugar grasses, naked oats and essential oil scenarios have potential to reduce GHG emissions. The reduction in emissions is less than the baseline difference between farm types. At trial results, doses and costs, high sugar grasses have a net economic benefit, naked oats a moderate cost and essential oil an extremely large cost per tonne of carbon dioxide mitigated.
- On the livestock farms high sugar grasses, naked oats, allicin and essential oil scenarios have potential to reduce GHG emissions. At trial results, doses and costs, high sugar grasses have a net economic benefit, naked oats a low cost and essential oil and allicin an extremely large cost per tonne of carbon dioxide mitigated.
- Adapting dairy cow diet by increasing forage maize content and reducing crude protein has economic and GHG emission benefits. The size of the benefit is dependent on farm geographic location and relative grass and forage maize yield.
- An empirical analysis based on model output demonstrates that even with a market for carbon, uptake of supplements is most likely to be economically driven by increases in productivity rather than decreases in GHG emissions.

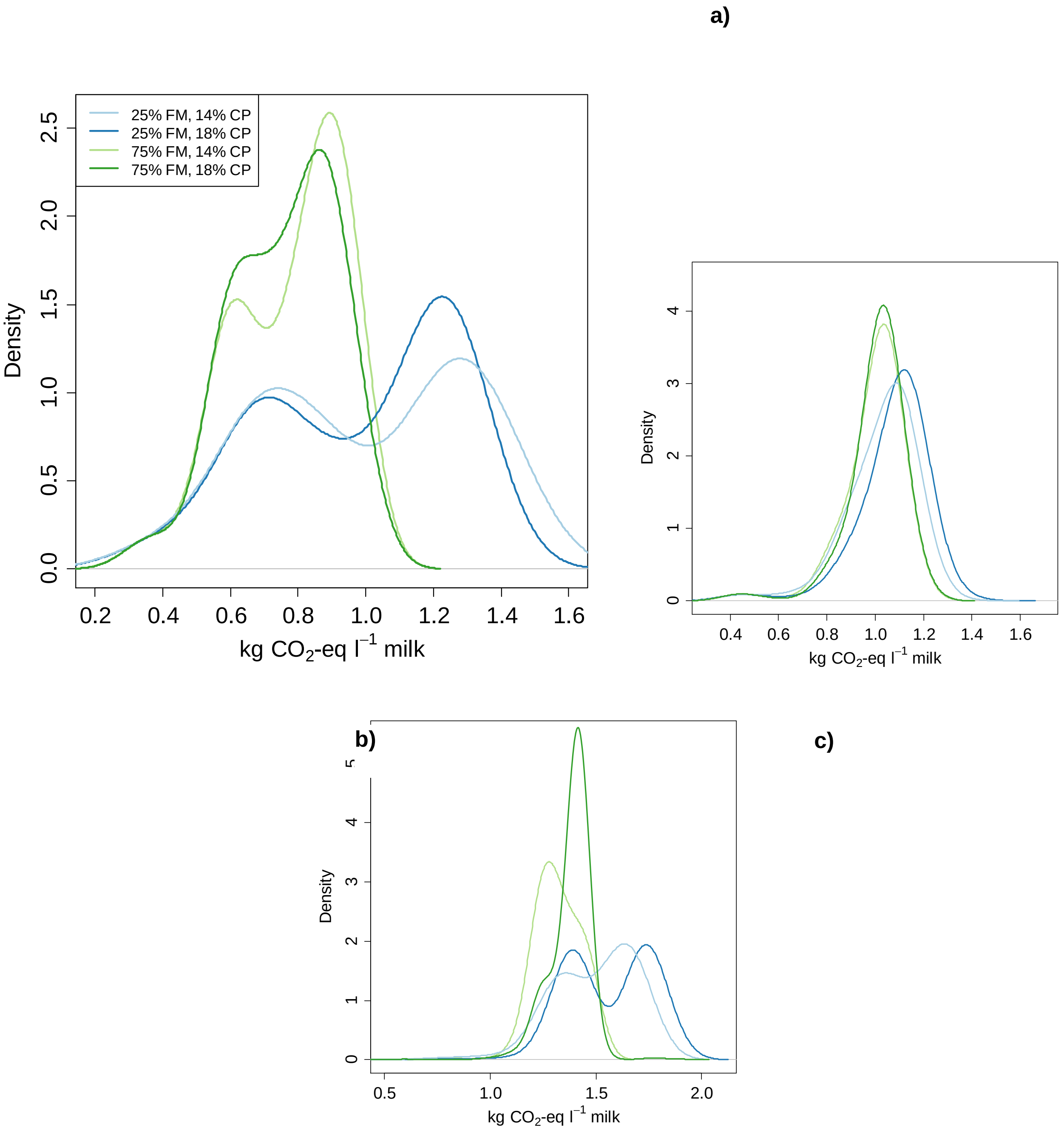

Figure 3. Comparison of distribution of emissions by dairy diet with varying forage maize (FM) and crude protein (CP) content. a) Intensive dairy farm, b) medium dairy farm, c) extensive dairy farm. Not different x-axis scale between farms.

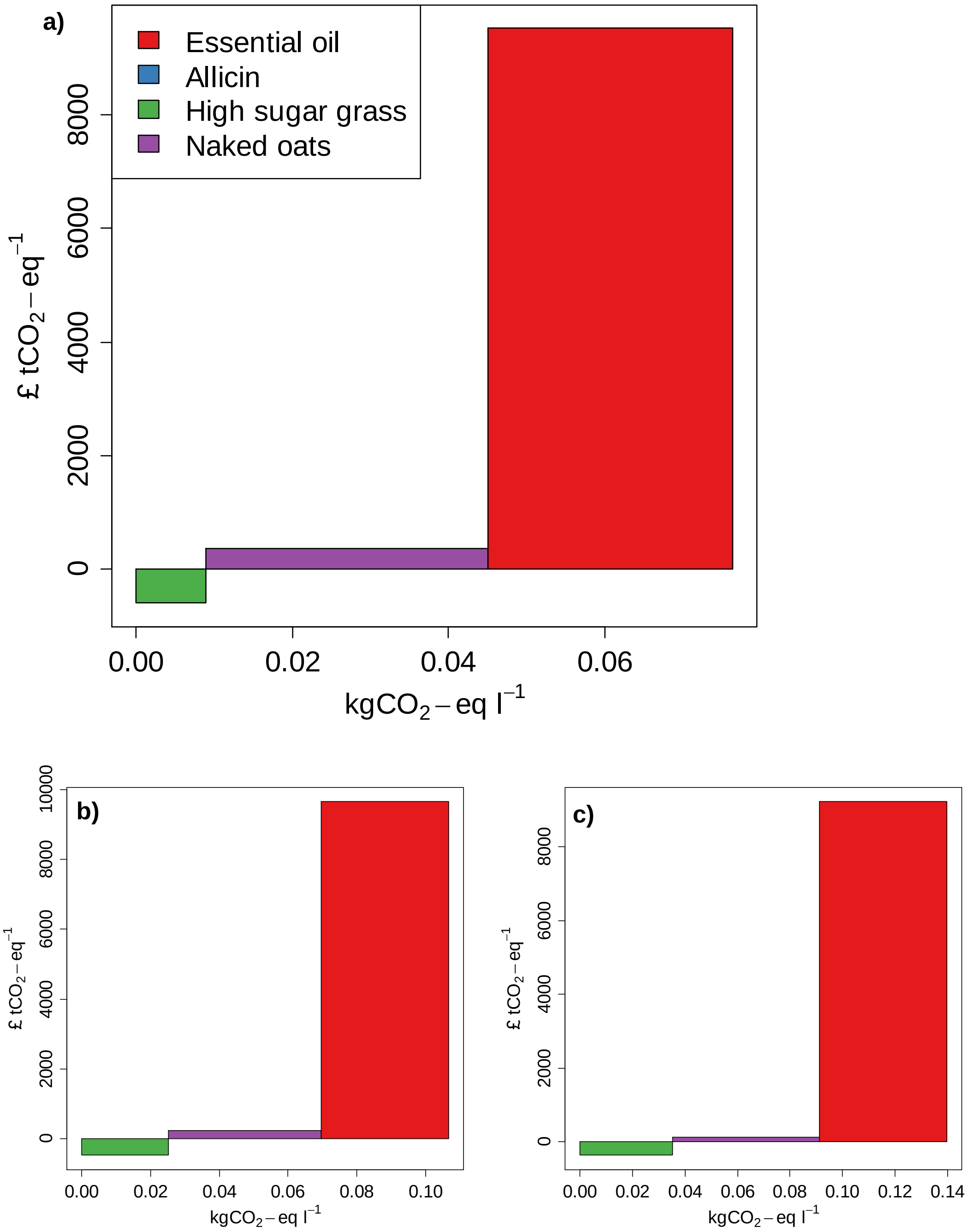

Figure 4. Mean marginal cost curve of carbon abatement for dairy farms for supplement and substitution scenarios. X-axis is greenhouse gas emissions mitigated as CO_2-equivalent per unit of output, y-axis is cost per tonne of CO_2-equivalent mitigated. a) intensive dairy farm, b) medium dairy farm and c) extensive dairy farm. There is no bar for allicin as the experimental results suggest no effect on emissions fro dairy cattle at the doses used. Note different x- and y-axis scales between farms.

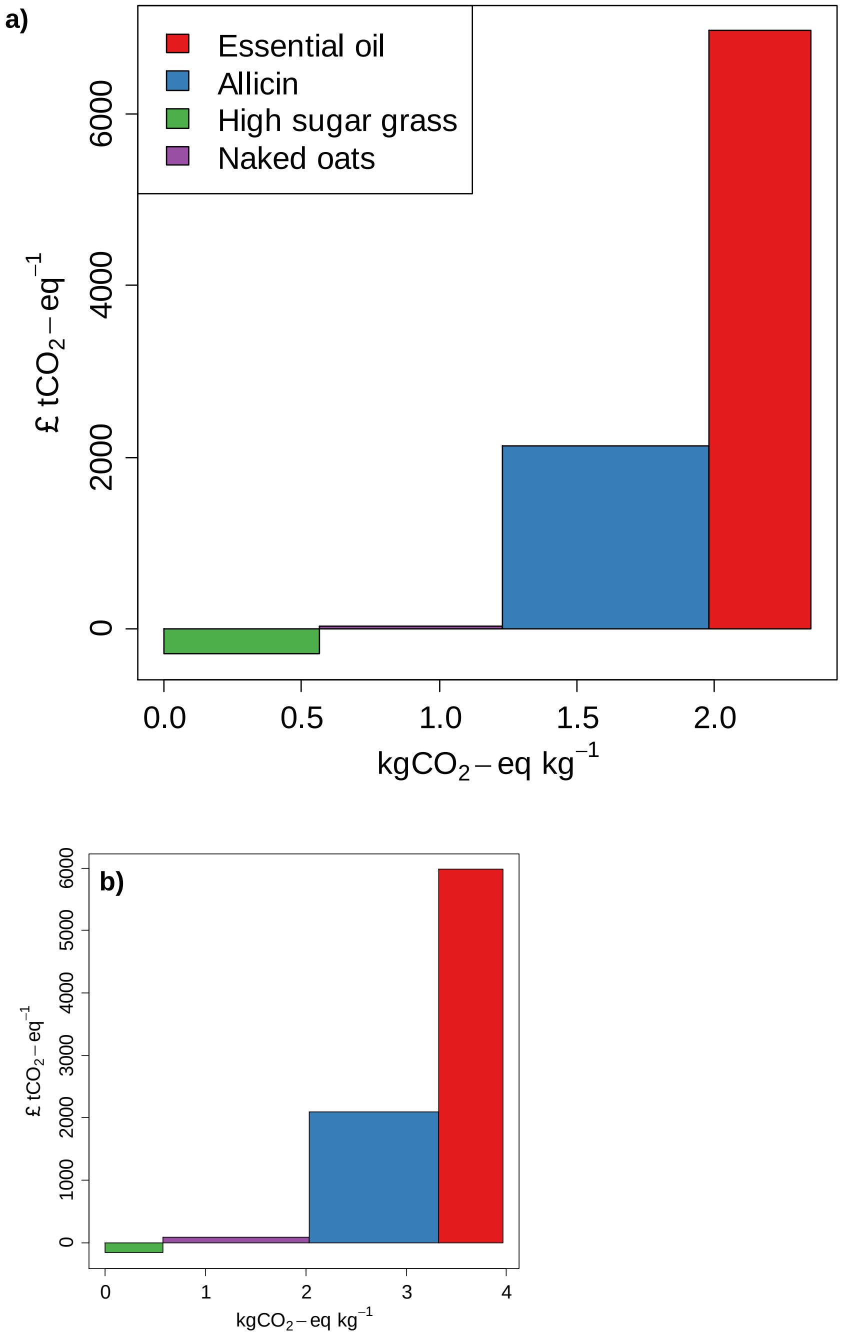

Figure 5. Mean marginal cost curve of carbon abatement for livestock farms for supplement and substitution scenarios. X-axis is greenhouse gas emissions mitigated as CO_2-equivalent per unit of output, y-axis is cost per tonne of CO_2-equivalent mitigated. a) lowland farm, b) upland farm. Note different x- and y-axis scales.

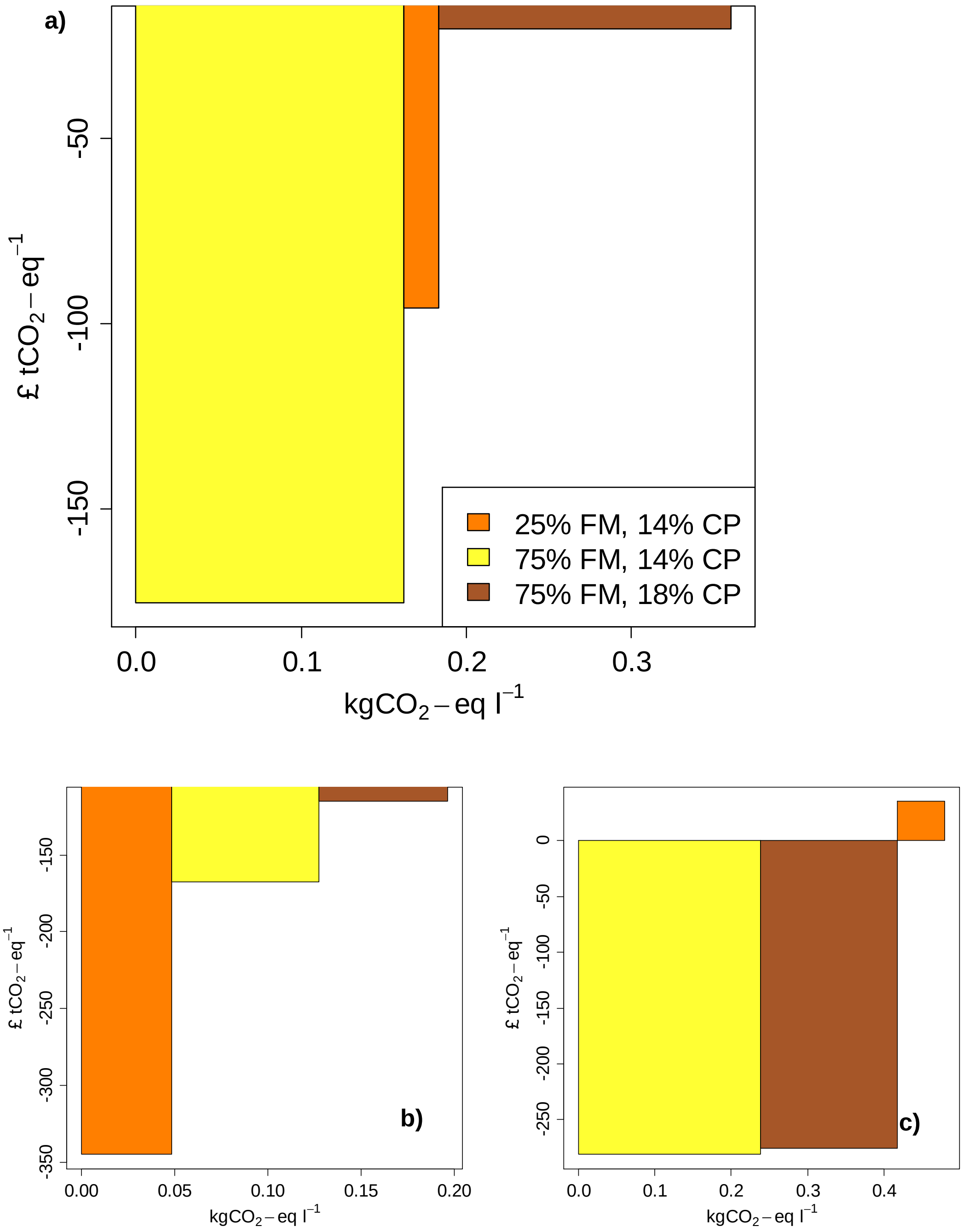

Figure 6. Mean marginal cost curve of carbon abatement for dairy farms for diet adaptation scenarios compared with a baseline diet of 18% crude protein (CP) and 25% forage maize (FM). X-axis is greenhouse gas emissions mitigated as CO_2-equivalent per unit of output, y-axis is cost per tonne of CO_2-equivalent mitigated. a) intensive dairy farm, b) medium dairy farm and c) extensive dairy farm. Note different x- and y-axis scales.

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References to published material

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