Final Report

Student Project No. 41140078/ 41240004

Title: Evaluating strategies to reduce greenhouse gas emissions from dairy production systems. How can we reduce the carbon footprint of UK dairy farms?

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This is the final report of a PhD project that ran from October 2020 to February 2024. The work was co-funded by AHDB and the Dartington Cattle Breeding Trust, Perry Foundation, Seal-Hayne Educational Trust, and West Country Dairy Awards within the AgriFood Charities Partnership (AFCP).

Contents

1. Industry Summary

It is important that greenhouse gas emissions are limited to reduce sea level rise, extreme weather events such as flooding and protect food security (GOV, 2020). In 2019, agriculture accounted for 10% of UK greenhouse gas emissions, which has led to the National Farmers union target of net zero by 2040 (NFU, 2019). However, blueprints of how dairy farmers are to meet this goal and maintain or improve productivity are lacking.

This project has sought to assimilate existing standards for lifecycle analysis, collation of previously published research for the prediction of methane emissions from dairy cattle, and a novel whole farm simulation model (REMEDY) to investigate the impact of nutritional, herd management, sequestration, and offsetting strategies on the greenhouse gas emissions from a typical UK dairy farm.

The estimation of methane emissions from dairy cows is often based on small trials, utilising a large variety of methods to collect and analyse data. This has resulted in extremely variable predictions of methane emissions and uncertainty surrounding the most influential characteristics of dietary composition. A novel prediction equation for methane emissions from dairy cattle was created by combining outputs from 32 previously published studies using 15 dairy cow diets typically fed in the UK, capable of predicting methane emissions based on energy and fibre concentrations in the diet. This new prediction equation was then incorporated within the REMEDY whole farm simulation model and used throughout this study to predict the influence of diet in reducing greenhouse gas emissions.

To study possible blueprints of future strategies to lower dairy farm greenhouse gas emissions, the REMEDY model was used to simulate the production and reproduction on an example typical semi-seasonal UK dairy farm of 124 hectares, containing 140 dairy cows. The scenarios simulated included: management to vary replacement rates, altering the sources of dietary protein and simulating the extent of adaptations that the farm needed to achieve no net emissions.

Three replacement rates were simulated: 10%, 22% and 40%. Thirteen different sources of protein were evaluated in the model, including: soya bean, rapeseed meal, brewers’ grain, wheat distillers’ grain, two bean diets, red clover, lucerne, lupins, peas, peas with soya hulls, a combination of sources excluding soya, and a mixture of rapeseed and soya. The strategies were investigated to meet the challenge of reach net zero greenhouse gas emissions while still maintaining a high level of milk production. Options considered included increasing carbon sequestration (CS) by converting the production system to a fully housed system and converting available land woodland. Other mitigation options included the use of feed additives to achieve a 30% reduction in enteric methane emissions, replacing slurry storage systems with an anaerobic digester to reduce manure emissions and provide electricity to the farm. Other aspects considered were, altering sources of dietary feeds, reduction or elimination of fertiliser use and the reduction of the milking herd size by 10 or 20%.

The results from this simulation study suggests:

- An optimum replacement rate of 22% to reduce GHG emissions without impacting milk production.
- Peas without soya hulls resulted in the lowest emissions per litre of fat protein corrected milk (FPCM)
- Soya bean resulted in the highest emissions per litre of FPCM.
- Net zero is achievable with extensive afforestation and feed additives.

This project provides new evidence for the blueprints on how UK dairy farming can adapt production systems to reduce greenhouse gas emissions and reach net zero targets. Many of these optimal targets to reduce net emissions were found to be optimal from economic and productivity perspectives. However, these results also starkly showcase the extent of adaptation required to achieving net zero and the length of time need for their benefits to accrue, and the difficulty of achieving net zero dairy production by 2040, even if extensive afforestation was widely adopted.

2. Introduction

Global warming is a massive concern (Mostert *et al.*, 2018), and it is only becoming a more pressing issue, as awareness is raised over the potential threat it poses to the world (Tarighaleslami *et al.*, 2020). Greenhouse gas emissions (GHGe) emitted from human activity (Mostert *et al.*, 2018), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) trap heat in the earth's atmosphere, which has increased global temperatures by over two degrees Fahrenheit since the 1880s (The National Aeronautics and Space Administration, 2021). The increase has melted over 13% of arctic sea ice each decade, as well as ice sheets and glaciers, prompting sea levels to rise by almost seven inches since the 1920s. GHGe also cause air and water pollution, effecting the health of living organisms IPCC, 2007), leading to the growth of public concern and the goal set by the government of the United Kingdom (UK) to become net zero by 2050 (Committee on Climate Change, 2019).

When discussing climate change, the focus tends to be CO_2, as it is the highest it has ever been recorded in the past 650,000 years (The National Aeronautics and Space Administration, 2021). However, when assessing the warming potential of gases, using the global warming potential (GWP) 100, methane has a GWP 25 times higher than CO_2, and N_2O 298 times higher than CO_2, which can be seen in Table 1 (IPCC, 2007; AHDB, 2021a). Methane and nitrous oxide have a greater warming effect, as they absorb a higher amount of solar energy and have a greater contribution to global warming over 100 years than CO_2 (Richardson *et al.*, 2021). The main GHGs produced from agricultural in the UK are methane and nitrous oxide, as highlighted in Figure 1 and the sector is also one of the main contributors to both methane (CH_4) and N_2O emissions in the UK (DEFRA, 2021a). The sector contributes to 40% of UK CH_4 emissions, 58% of N_2O emissions, but only 2% of UK CO_2 emissions. Ruminant mammals are also the overall main cause of CH_4 emissions from human activity (Pinares-Patiño *et al.*, 2016). Ruminants' large contribution has placed the industry under the spotlight (Roque *et al.*, 2019) and led to consumers becoming more interested in the environmental impact of the dairy products they are purchasing (Rotz, Holly, *et al.*, 2020). The UK government has also joined the Global Methane Pledge (Department for Business Energy & Industrial Strategy, 2022) to reduce methane emissions by 30% by 2030 (UNEP, 2021).

Table 1: The global warming potential (GWP) of carbon dioxide, methane, and nitrous oxide over 20 and 100 years, as well as their lifetime in the atmosphere in years (IPCC, 2007; AHDB, 2021a)

Greenhouse gas	**Lifetime (years)**	**GWP 20 years**	**GWP 100 years**
Carbon dioxide	Variable 20-200 (to remove 65-80%) Hundreds of thousands of years to remove completely	1	1
Methane	12	72	25
Nitrous Oxide	114	289	298

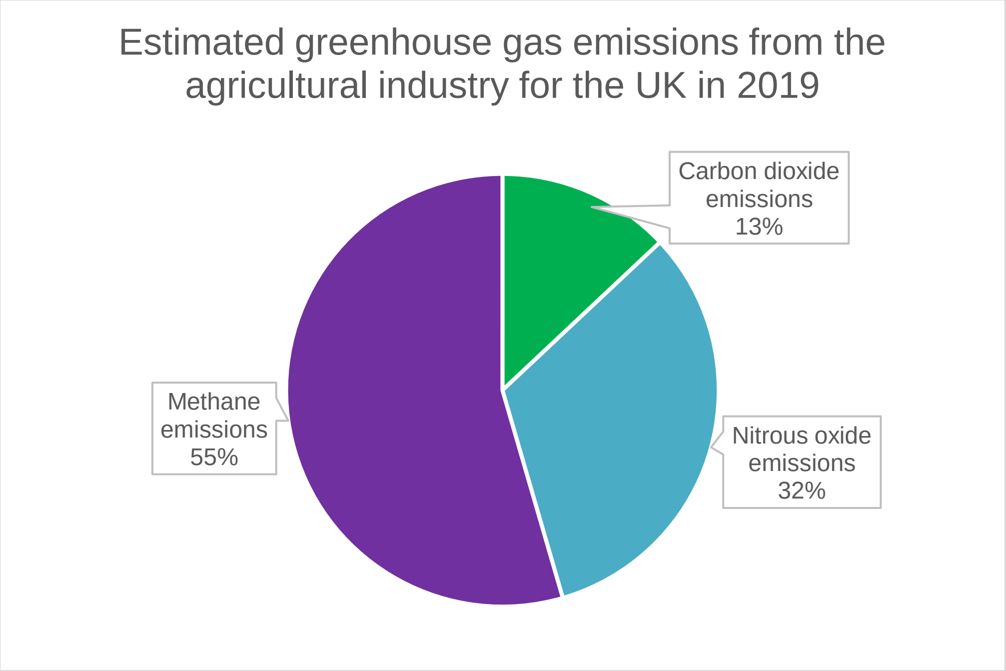

Figure 1: The estimated breakdown percentage of GHG emissions from the agricultural industry in 2019 in the United Kingdom (UK). Figure based on data derived from (DEFRA, 2021a)

The average size of dairy farms in England were 129 hectares in 2019 (DEFRA, 2019), with an average UK dairy herd of 160 in 2021 (AHDB, 2023). In total, the agriculture sector accounts for 14.5% of global emissions (Gerber *et al.*, 2013) and livestock are responsible for most of the sector's emissions. Cattle are a large type of ruminant and are the main cause of global emissions from agriculture, equating to 65% (Dumont, Groot and Tichit, 2018), while the dairy industry is responsible for 30% of that figure (Mostert *et al.*, 2019). Whereas small ruminants account for less than 7% of emissions (Dumont, Groot and Tichit, 2018). The statistics highlight the larger impact cattle have on GHG emissions, which has created a demand for research into the carbon footprint of the dairy industry. On the other hand, in the UK, the agricultural sector contributes to 10% of the country's greenhouse gas (GHG) emissions (NFU, 2019).

2.1. Annual Farm Emissions

Studies vary in their reported annual total farm CO_2e emissions per kg of FPCM. Recent research simulated a dairy farm in Pennsylvania without CS, based on data from the Agricultural Resource Management Survey (Castaño-Sánchez, Karsten and Rotz, 2022). They analysed the farm CO_2e emissions against different cropping and manure management systems. The overall farm CO_2e emissions varied by 1.11 to 1.13 (±0.01) kilogrammes per kilogramme of FPCM. Annual FPCM production was 9,177kg with most of the feed produced on farm. The feed consisted of lucerne, corn silage, grass, and winter rye. The results were similar to average CO_2e emissions for Swedish farms ranging from 0.94 and 1.33 kg CO_2e/kg ECM, with an average value of 1.13 kg CO_2e/kg ECM for Swedish farms without carbon sequestration (CS) (Henriksson *et al.*, 2011). Whereas a study on south African pasture-based system found higher CO_2e emissions from 1.17 to 1.66 kg CO_2e/kg ECM depending on nitrogen use efficiency (Galloway *et al.*, 2018). Another study in Pennsylvania in the USA found a larger range in dairy farms total CO_2e emissions of 1.04 to 1.9 kgCO_2e/FPCM (Rotz, Holly, *et al.*, 2020). The study compared production systems, from all grass (1.46 kgCO_2e/FPCM), grass with grain (1.15 kgCO_2e/FPCM) and housed systems fed TMR (1.28 kgCO_2e/FPCM). The study found a carbon offset capability of 0.6 to 1.3 kg CO_2e/kg FPCM for the all-grass production system farm and 0.4 to 0.8 kg CO_2e/kg FPCM for the grass with grain system, during the transition period of converting cropland to perennial grass, when SOM accumulates, rather than a long-term ability.

The annual emissions tend to vary according to location and production system, as a review using the Integrated Farm System Model compared the average carbon footprint of farms per kg of ECM for different locations and production systems (Rotz, 2018). The model did not include carbon sequestration and found grazing in New Zealand produced an average 1.11 kg of CO_2e/kg of ECM, grazing housed in Ireland 1.21, Freestall housed in Pennsylvania 0.98, free stall with an anaerobic digester in New York 0.75, and Freestall and open lot in Idaho 1.04.

2.2. Summary of knowledge gaps, aims and objectives of the PhD

The project aimed to address the knowledge gaps of a whole farm simulation model for the UK dairy system, to holistically review the effect of various scenarios on carbon dioxide equivalent emissions, and milk production. The project assessed the variation between equation results and their ability to capture the effect of dietary composition factors on GHGe. Previous research has not focussed on or quantified the large variation in enteric methane prediction equations, their prediction results, or their lack of dietary composition detail to compare the emissions of an array of diets. The study also created a combined prediction equation for use as a universal equation, to compare emissions between farms and diets, which includes unexplained variation, such as from measurement method used, cow type and their stage of lactation, which previously published equations have not accounted for.

A knowledge gap is the effect of replacement rates (RR) on UK dairy farm GHGe and milk productivity to find a ‘sweet spot’ for reducing GHGe through RRs, without negatively impacting milk production to ensure feasibility and economic viability. The project addresses this gap in the literature, by comparing a high (40%), medium (22%) and low RR (10%). There is currently limited research on the effect of sources of protein in dairy cattle diets on total emissions from enteric methane and feed production. Research tends to focus on only milk quantity and quality and occasionally enteric methane emissions, not combined with the feed production emissions. The project holistically evaluated the effect of alternative sources of protein to soya on enteric methane emissions and feed production emissions, milk production and economic costs of purchased feeds at the time of the study.
The project also aimed to discover whether net zero is possible for UK dairy farms by the NFU’s 2040 net zero goal. The NFU require a roadmap and information on how to reach their set target, with limited research holistically investigating a combination of strategies and how this goal can be achieved in the UK dairy industry. The study aimed to explore this by combining mitigation strategies to present blueprints for reaching net zero and an indication of the timescale for achieving the goal.

2.2.1. Aims of PhD

The aim of this project was to assess mitigation strategies for reducing the greenhouse gas emissions (GHGe) of dairy cattle, by reviewing previous and current literature on the GHGe of the dairy system, to locate areas in need of research. The project, assisted by the adaptation of the REMEDY whole farm model (WFM), aimed to simulate the various scenarios and calculate the carbon equivalent emissions of a typical dairy production management system in the UK. The model assessed emissions from feed, fertilisers, manure handling, enteric fermentation, poor heath, fertility, fuel, and energy use, whilst evaluating the potential to offset emissions through forestry. Specific aims of the project were to:

Adapt a life cycle assessment (LCA) model of the component of REMEDY with a new enteric methane prediction equation based on the assimilation of the published literature of influential dietary composition variables.

The project also aimed to utilise the REMEDY whole farm simulation model to

1. simulate the effect of replacement rates on the carbon dioxide equivalent emissions of the whole system and total annual milk production.
2. to simulate the effect of different sources of protein in dairy cattle diets on enteric methane, feed production emissions and milk production.
3. to simulate a combination of sequestration and mitigation strategies, to see if net zero is possible in the UK dairy industry using strategies including, converting the production system to a fully housed system and converting the land to woodland to offset greenhouse gas emissions the addition of feed additives.

3. Materials and methods

3.1. Enteric Methane Prediction Equation

A systematic literature review was conducted to collate existing enteric methane prediction equations. 101 equations from 25 articles were collected and coded into R programming language as functions to be tested. 15 diets were formulated with the aid of a dairy nutritionist, representative of different cow stages of production, milk yield, production system types and seasons common in the United Kingdom and Europe, as well as some more extreme variations in dietary compositions. Nutrition values for each dietary component were sourced from the reference feed values, from the feed into milk (FIM) database (Thomas, 2004).

The equations were refined to exclude those that included milk composition factors, livestock other than cattle, such as goats and sheep and simplistic equations, such as dry matter intake (DMI) or gross energy intake (GEI) only. The refinement resulted in a final set of 32 equations from 5 articles, shown in Table 2. The equations were then divided by DMI, to produce methane emissions as grams per kg of DM, to allow comparison between diets with dissimilar DMI.

Table 2: The 32 enteric methane prediction equations used in the model and the authors they were created by. NDF = neutral detergent fibre, MEI = metabolised energy intake, ADF = acid detergent fibre, EE = ether extract, FA = fatty acids

Author	Model	Prediction Equation
Ellis et al. (2007)	4c	CH_4g/day = (4.42 + 1.58 * NDF) / 0.05565
	5c	CH_4g/day = (1.70 + 0.0667 * MEI + 0.0314 * Forage) / 0.05565
	6c	CH_4g/day = (3.44 + 0.502 * DMI + 0.506 * NDF) / 0.05565
	7c	CH_4g/day = (3.63 + 0.0549 * MEI + 0.606 * ADF) / 0.05565
	8c	CH_4g/day = (4.41 + 0.0224 * MEI + 0.980 * NDF) / 0.05565
	10c	CH_4g/day = (3.41 + 0.520 * DMI - 0.996 * ADF + 1.15 * NDF) / 0.05565
	4d	CH_4g/day = (3.14 + 2.11 * NDF) / 0.05565
	5d	CH_4g/day = (5.87 + 2.43 * ADF) / 0.05565
	6d	CH_4g/day = (1.21 + 0.0588 * MEI + 0.0926 * Forage) / 0.05565
	7d	CH_4g/day = 1.64 + 0.396 * MEI + 1.45 * NDF / 0.05565
	8d	CH_4g/day = (2.16 + 0.493 * DMI - 1.36 * ADF + 1.97 * NDF) / 0.05565
Van Lingen et al. (2018)	1	CH_4g/day = -48.5 + 13.9 * DMI + 5.22 * ADF
	3	CH_4g/day = (11.0 + 0.335 * ADF) * DMI
	2	CH_4g/day = [24.51 - 0.788 × EE] × DMI

Author	Model	Prediction Equation
Moate et al. (2011)		
Nielsen et al. (2013)	1	CH_4g/day = (1.36 * DMI - 1.25 * FA - 0.20 * CP + 0.170 * NDF) /0.05565
	2	CH_4g/day = (1.23 * DMI - 1.45 * FA + 0.120 * NDF) /0.05565
	4	CH_4g/day = (1.39 * DMI - 0.91 * FA) /0.05565
Niu et al. (2018)	3	CH_4g/day = 33.2 + 13.6 * DMI + 2.43 * NDF
	4	CH_4g/day = (163 + 13.3 * DMI - 11 * EE)
	5	CH_4g/day = 76 + 13.5 * DMI - 9.55 * EE + 2.24 * NDF
	6	CH_4g/day = 369 - 14.7 * EE + 1.67 * NDF
	16	CH_4g/day = -26 + 15.3 * DMI + 3.42 * NDF
	17	CH_4g/day = 160 + 14.2 * DMI - 13.5 * EE
	18	CH_4g/day = 11.3 + 14.7 * DMI + 2.5 * CP - 10.8 * EE + 3.2 * NDF - 2.87 * ash
	19	CH_4g/day = 435 - 18.7 * EE
	27	CH_4g/day = 49.5 + 12.1 * DMI + 2.57 * NDF
	28	CH_4g/day = 136 + 12.3 * DMI - 2.96 * EE
	29	CH_4g/day = 49.5 + 12.1 * DMI + 2.57 * NDF
	30	CH_4g/day = 279 + 3.53 * NDF
	36	CH_4g/day = (13.8 + 0.185 * NDF) * DMI
	37	CH_4g/day = (21.8 - 0.452 * EE) * DMI
	38	CH_4g/day = (15.4 - 0.354 * EE + 0.173 * NDF) * DMI

The diets were used to analyse the correlations that exist between the various dietary characteristics, so no significant associations between variables would bias the combined equation results. A correlation plot was created in R programming language using the “corrplot” R package, which was also converted to a data frame and table to view the units of each correlation. The combined prediction equation was developed using the 480 EME results from the 32 prediction equations for the fifteen diets and their dietary composition. The range of emissions for each diet can be seen below in Table 3. The dietary composition variables were used in the equations and included: body weight (BW), DM, GE, ME, CP, FA, EE, NDF, and ADF.

Table 3: The range of enteric methane emissions in grams per kilogramme of DM from the minimum to the maximum values for each of the 15 diets. Details on the composition of the diets can be seen in Appendix 1

	Enteric methane emissions	
Diet	Minimum	Maximum
1	15.25	24.4
2	13.15	22.53
3	12.49	22.66
4	16.73	34.27
5	16.03	30.76
6	13.12	23.08
7	13.39	22.68
8	15.08	27.19
9	15.37	28.5
11	15.44	25.92
12	14.48	22.96
13	13.51	21.98
15	14.42	22.85
16	13.45	22.52
18	14.43	22.92

The equation results were plotted into a scatterplot using "ggplot2" to visually evaluate the variation. The variability in emissions between equations was examined using a mixed linear regression model. A total of 480 EME predictions from 32 equations for fifteen diets, including dietary composition were analysed using the "lme4" package and R statistical software (R, 2022). Data were centred, standardised (Thomas, 2004) and included the term 'prediction equation' as a random effect.

Twelve combinations of dietary characteristic variables were selected using the variables: metabolised energy (ME), GE, NDF, EE, CP, and FA. The boxplots, t-values from the fixed effect results, coefficients, residuals of variation, root mean square error and r^2 of each equation were used to aid the decision-making when choosing a dietary characteristic combination for the equation.

3.2. The simulation (REMEDY) model

3.2.1. The REMEDY Model

The Remedy model developed at the University of Nottingham in collaboration with quality milk management services as part of an Innovate UK funded project. Remedy is a whole farm simulation model, developed to use data aggregated from several sources, coupled with machine learning models and lifecycle analysis tools to aid farmers in their decisions across the farm. The model provides a holistic view of the farm by showing the environmental, economic, and technical impacts, by simulating the greenhouse gas emissions created on the farm, impacts on cow performance and milk output by comparing different inputs and herd demographics. During this project simulations we’re based on data from a typical UK dairy farm. The model allows comparison between farms and scenarios within farm based on changes in inputs and management. The effect of these on the farm’s milk outputs, economics and environmental footprint can then be evaluated over a short- or longer-term time horizon.

3.2.2. Model specifications

The model was built using the software Python using the integrated development environment (IDE) PyCharm, which applies objective-oriented programming, where the data is organised into object categories based on their attributes (JetBrains, 2023). Parts of the model function at a Tier 1 level with minimum data requirements, such as purchased feed, fuel, fertilisers, and energy use. However, areas at the Tier 2 level require detail on the complete life cycle of the dairy cow to function including the enteric and manure emissions. A diagram of the model can be seen in Figure 2 below.

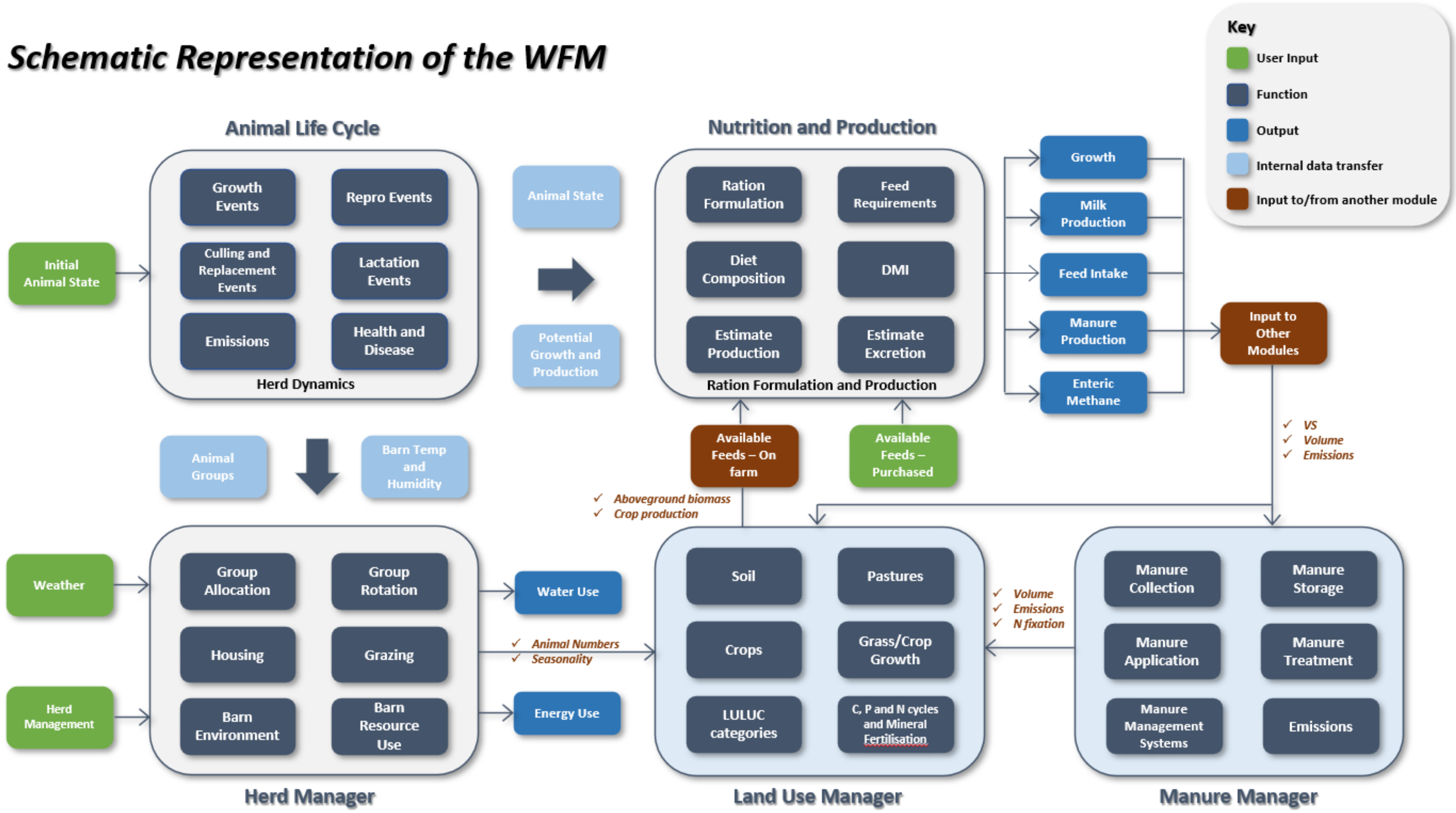

Figure 2: The diagram of the complete Remedy Model.

Enteric emissions are predicted using the IPCC (2006; 2019) Tier 2 enteric methane prediction equation emission factor for weaned, breeding heifers, and steers. A methane conversion factor (Ym[3]) of 6.3% was used for dairy cows from IPCC (2019b) Table 10.12 for medium producing cattle. The combined equation was used to predict enteric methane for milking and dry cows, based on the dietary variable neutral detergent fibre and metabolised energy. Preweaning calves were assumed to have zero enteric methane emissions, based on the IPCC methodology, as the rumen is inactive at this stage and the calf does not emit significant methane emissions (IPCC, 2019b). The model converts output emissions to their CO_2e based on GWP100.

Dairy farm data was entered into the model at an individual animal level and simulation steps run daily over a ten-year horizon. As the model is stochastic, each ten-year simulation was repeated using 50 times to create reliable means and standard deviations for the evaluation of the model results interval in values. The emissions from feed production were included in the GHGe results for, which were collected from the Agribalyse dataset inventory in OpenLCA, which included emissions from tillage, sowing, mechanical weeding, harvest, swathing, haying, baling and transport to the farm buildings. The feed production emissions were based on those sourced from the UK or the national average, global average or for Europe, if the UK data was unavailable for the feed. The amount of purchased feed was based on the average annual number of milking cows in the herd.

Different aspects of each animal's daily life cycle are simulated, such as reproduction for the oestrus and insemination, pregnancy, calving cycle. The culling and replacement rates were simulated, based on probabilities using typical UK dairy farm parameters, so could be varied per simulation to suit the farm. The body weight (BW) assumptions used were for preweaning and weaned cattle, 400kg for heifers and 600kg for milking cows, dry cows, and bulls. The emissions associated with the production of feed were collected from the INRA feed database per kilogramme of the feed item in the diet and the emissions were calculated per ration. The total average emissions were calculated per animal and multiplied by an average animal number for the average herd feed production emissions. Default factors used in the equation were region specific to the UK or Europe.

DMI was estimated using the IPCC (2019b) Equation 10.18 for growing cattle:

$$DMI = BW^{0.75} * \left[\frac{(0.0582 * NE - 0.00266 * NE^2 - 0.0869)}{0.239 * NE} \right]$$

DMI = dry matter intake (kg/day^{-1}), BW = body weight of the animal (kg), NE = estimated dietary net energy concentration of the diet (MJ kg^{-1} DM^{-1}).

DMI was estimated using the IPCC (2019b) Equation 10.18a for steers and bulls.

$$DMI = 3.83 + 0.0143 * BW * 0.96$$

DMI = dry matter intake (kg/day^{-1}), BW = body weight of the animal (kg).

DMI was estimated using the IPCC (2019) Equation 10.18a for heifers.

$$DMI = 3.184 + 0.01536 * BW * 0.96$$

DMI = dry matter intake (kg/day^{-1}), BW = body weight of the animal (kg).

The Nutritional Model was based on the adapted and improved GrazeIn semi-mechanistic model to estimate grass dry matter intake and milk production of grazing dairy cattle at an individual animal and herd level (O'Neill *et al.*, 2014). The model uses parity, milk quality, age, the BCS of the cow and peak milk yield.

Milk production was estimated from farm data based on the nonlinear MilkBot Lactation Model (Ehrlich, 2011), which previous research has shown to accurately predict milk yield for lactations, ranking higher than other models when analysed against a dataset of six million lactations (Cole, Ehrlich and Null, 2012). The model predicts daily milk production based on a lactation curve and is capable of including the effect of management strategies and health on milk yield.

There were six cow type groups for the herd demographics in the model: preweaning calves, weaned calves, breeding heifers, milking cows, dry cows, and bulls. Static weather was simulated in the model, but the effect of temperature on manure emissions was modelled and the IPCC (2006; 2019) methodology allowed for the modification of climatic zones on carbon sequestration potential for a typical UK climate.

Minor emissions such as from farm machinery, building and livestock medicine were excluded from the model, in line with previous research, as these emissions are not thought to significantly differ between production systems (Foley *et al.*, 2011). Emissions were considered to the farm-gate, a common scope for WFMs (Crosson *et al.*, 2011), thus, emissions after the farm-gate such as transportation and packaging of milk products were not incorporated into the model.

Carbon sequestration of soil was simulated based on the IPCC Tier 1 methodology (IPCC, 2006; 2019). Carbon losses and gains from land use change were simulated based on the IPCC (2006) methodology and updated based on the IPCC (2019) refinements. The methodology presumes no change in dead organic matter for forest land, and zero for non-forest land and no change in mineral soil carbon stocks in forest land.

The hectare proportion of trees and kilometre measurement of hedgerows for the farm data were estimated by the farmer. Hedgerows were over 30 years old, so were presumed to be zero emissions, according to the IPCC (2006; 2019) methodology. The IPCC methodology did not include willow as an option for calculating carbon storage, so birch was used, as an available and suitable substitute.

Manure Management Equations

Manure emissions were simulated based on the IPCC Tier 2 methodology, which calculates the methane and N_2O emissions from manure separately (IPCC, 2006). The equation results were not multiplied by 365, so the results were computed per day, rather than annually and could be multiplied by animal number to calculate annual herd emissions. Firstly, the daily N excretion rate (Nex) was calculated using the updated Equation 10.30 (IPCC, 2019b), shown below. TAM varied per management group: milking, dry and bulls were assumed to be 600kg, and breeding heifers 400kg. The IPCC (IPCC, 2019b) default N excretion rate used for dairy cattle was 0.54 kg N (1000 kg animal mass)$^{-1}$ day^{-1}.

The IPCC (2019) Updated Equation 10.30 was used to calculate the daily N excretion rates.

$$Nex \ = N_{rate(T,P)} * \frac{TAM}{1000}$$

Nex = daily N excretion for dairy cattle (kg N animal/year), N_{rate} = default N excretion rate for dairy cattle (kg N 1000 kg animal mass/day), TAM = typical animal mass for livestock category (kg animal $^{-1}$).

To calculate the methane emissions from manure, the VS excretion rates were calculated using the IPCC (2006) equation 10.24 below, based on feed digestibility, gross energy intake, urinary energy excretion, the ash content of feed and the conversion factor for dietary GE.

$$VS = \left[GEI * \left(1 - \frac{DE}{100}\right) + (UE * GE)\right] * \left[\left(\frac{1 - ASH}{18.45}\right)\right]$$

VS = daily volatiles solid excretion (kg/VS/day^{-1}), GE/GEI = gross energy/gross energy intake (MJ/day^{-1}), DE = percentage digestibility of the feed, UG*GE = urinary energy expressed as fraction of GE, ASH = the fraction of ash content of the dry matter intake, 18.45 = conversion factor for dietary GE per kilogramme of dry matter (MJ kg^{-1}).

The daily CH_4 emission factor for dairy cattle manure was determined using Equation 10.23 (IPCC, 2006). The equation used the VS estimates, based on the animal diet using Equation 10.24 above. The emission factors and methane conversion factors were based on mean annual temperature for the region. The maximum methane producing capacity for manure produced by dairy cattle was 0.24. The MS was equal to one and the MCF was 0.01 for pasture and 0.11 for liquid slurry.

$$EF = \ VS * \left[B_o * 0.67 * \sum \frac{MCF_S}{100} * MS_S\right]$$

EF = daily methane emission factor for dairy cattle (kg/CH_4/cow), VS = daily volatile solid excretion for dairy cattle (kg/dry matter/animal/day), Bo = the maximum methane producing capacity for manure produced by dairy cattle (m^3/CH_4/kg of VS excreted), 0.67 = conversion factor of m^3 CH_4 to kilogrammes CH_4, MCF_S = methane conversion factors for each manure system (S), MS_S = fraction of dairy cattle manure handled using the manure management system (S).

Next, the direct N_2O emissions from livestock manure were calculated using the updated Equation 10.25 (IPCC, 2019b). The AWMS was presumed to be one for the daily emissions, the Nex calculated from Equation 10.30 was used, the emission factor was 0.004 for pasture from Table 11.1, Chapter 11 from the IPCC (IPCC, 2019b) and 0.005 for liquid slurry, from Table 10.21.

$$N_2O_{D(mm)} = \left[\sum\left[\sum\left((N * Nex) * AWMS_{(S)}\right)\right] * EF_{3(S)}\right] * \frac{44}{28}$$

$N_2O_{D(mm)}$ = direct N_2O emissions from manure management (kg/N_2O/year), N = number of cattle, Nex = annual average N excretion per cow (kg/N/year^{-1}), $AWMS_{(S)}$ = fraction of total annual nitrogen excretion for each cow that is managed in the manure management system (S), $EF_{3(S)}$ = emission factor for direct N_2O emissions from manure management system S (kgN_2O-N/kg N), S = manure management system, $\frac{44}{28}$ = conversion of N_2O-$N_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions.

Equation 10.26 was used to calculate the amount of manure nitrogen lost due to volatilisation of NH_3 and NO_x, needed to calculate the indirect N_2O emissions due to volatilisation of N from manure management (IPCC, 2019b). The Nex calculated was used, AWMS equalled one, the amount of nitrogen co-digestates added to biogas plants was not used, as this was not relevant to the represented dairy farm. The fraction of managed manure nitrogen for livestock was 0.11 for pasture and 0.3 for liquid slurry.

$$N_{volatilization-MMS} = \sum_{S}\left[\left((N * Nex) * AWMS_S\right) * Frac_{GasMS(S)}\right]$$

$N_{volatilization-MMS}$ = the amount of manure nitrogen that is lost due to volatilisation of NH_3 and NO_x (kg/N/year^{-1}), N = number of cattle, Nex = annual average N excretion per cow (kg/N/year^{-1}), $AWMS_{(S)}$ = fraction of total annual nitrogen excretion for each cow that is managed in the manure management system (S), $Frac_{GasMS(S)}$ = fraction of managed manure nitrogen for dairy cattle that volatilises as NH_3 and NO_x in the manure management system S.

The N volatilisation calculated in Equation 10.26 above was used to calculate the indirect N_2O emissions in Equation 10.28 below (IPCC, 2019b). The emission factor for N_2O emissions (EF_4) was 0.01 for pasture and slurry.

$$N_2O_{G(mm)} = \left(N_{volatilization-MMS} * EF_4\right) * \frac{44}{28}$$

$N_2O_{G(mm)}$ = indirect N_2O emissions due to volatilization of N from manure management in the country (kg N_2O/year^{-1}), $N_{volatilization-MMS}$ = the amount of manure nitrogen that is lost due to volatilisation of NH_3 and NO_x (kg/N/year^{-1}), EF_4 = emission factor for N_2O emissions from nitrogen on soils and water surfaces (kg N_2O-N (kg NH_3-N + NO_x-N volatilised)$^{-1}$, $\frac{44}{28}$ = conversion of N_2O-$N_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions.

Equation 10.27 was used to calculate the amount of manure nitrogen that is lost due to leaching, as seen below (IPCC, 2019b). Nex calculated using Equation 10.30 was used per management system and AWMS equalled one. The amount of nitrogen co-digestates added to biogas plants was again ignored. The fraction of managed manure nitrogen for dairy cattle that is leached from the manure management system was 0 for slurry, as it is presumed no nitrogen is leached from this manure management system, whereas the value was 0.24 for pasture.

$$N_{leaching-MMS} = \sum_{S}\left[\left(N * Nex * AWMS_{(S)}\right) * \ Frac_{LeachMS(S)}\right]$$

$N_{leaching-MMS}$ = the amount of manure nitrogen that is lost from leaching (kg/N/year), N = number of cattle, Nex = annual average N excretion per cow (kg/N/year^{-1}), AWMS$_{(S)}$ = fraction of total annual nitrogen excretion for each cow that is managed in the manure management system (S), $Frac_{LeachMS(S)}$ = the fraction of managed manure nitrogen for dairy cattle that is leached from the manure management system (S).

The indirect N_2O emissions from leaching of manure were predicted by Equation 10.29 below (IPCC, 2019b). The result from Equation 10.27 was used, in addition to the emission factor for N_2O emissions from nitrogen leaching and runoff (EF_5), which was 0.011 for pasture and leaching was zero for slurry.

$$N_2O_{L(mm)} = \left(N_{leaching-MMS} * \ EF_5\right) * \frac{44}{28}$$

$N_2O_{L(mm)}$ = indirect N_2O emissions from leaching and runoff from the manure system (kgN_2O/year)$^{-1}$, N$_{\text{leaching-MMS}}$ = the amount of manure nitrogen that is lost from leaching (kg N/year^{-1}), EF_5 = the emission factor for N_2O emissions from nitrogen leaching and runoff (kg N_2O-N/kg N leached and runoff), $\frac{44}{28}$ = conversion of N_2O-N$_{(mm)}$ emissions to $N_2O_{(mm)}$ emissions.

3.3. Replacement rates

The model simulated three replacement rate scenarios: a low replacement rate of 10%, a medium replacement rate of 22% and a high replacement rate of 40%. A typical UK dairy diet of grazing, dairy cake (Diet 2 in Appendix 1) was used in the model for the replacement rate scenarios. The DMI was maintained in the scenario, as 24.4kg/day for milking cows, 9.08kg/day for heifers, 6.59kg/day for weaned cattle, 10.55kg/day for dry cattle and 13.48kg/day for bulls, based on the presumed body weight of 600kg for milking cattle, dry cattle, and bulls, and 400kg for heifers. It was assumed that heifers were reared on farm from birth, as the baseline farm.

3.4. Protein alternatives to soya bean meal

Thirteen diets using different proportions and mixtures of the protein alternatives: rapeseed meal, brewers' grain, distillers' grain, beans, red clover, lucerne, lupins and peas to soya bean meal (SBM), without impacting the milk quantity or quality, the palatability of the feed or the health of the cow. The diet composition can be seen in Appendix 2. Milk production (35 litres/day) was kept constant in the simulation to avoid being influenced by the change in diet, as well as the milk fat (4%) and protein content (3.3%), body weight per cow type, body condition score (2.75), and average daily gain (0.164 kg/day). DMI, metabolised energy, forage proportion and the dietary composition of the diets varied slightly to support the milk output for the various feeds and the maintenance of the animal. The diets were typical total mixed rations (TMR) of grass silage, maize silage, dairy minerals, sugar beet unmolassed with the protein and some diets rolled barley and wheat.

The scenario investigated the environmental impact of the milking cattle management group only. The diet, milk production, enteric methane, and manure emissions for SBM were the same whether linked to deforestation or not. They only differed by the emissions linked to feed production. The amount of purchased feed was based on the average annual number of milking cows in the herd. The costs of feeds were estimated by the dairy nutritionist using previous costings, based on assumptions at the time. These costs fluctuate and are likely to change over time. The costs were based on purchased feeds in the UK, rather than growing on-farm.

3.5. Net zero scenario

An unconstrained list of scenario parameters was considered to examine whether a typical UK dairy farm can reach net zero. The farm was based on the example UK dairy farm described prior, with a 22% replacement rate, but adapted to minimise greenhouse gas emissions. Multiple mitigation measures were simulated on the farm: afforestation to offset emissions, feed additives to reduce enteric methane, an anaerobic digester to provide renewable energy and dispose of the manure, fertiliser free, high producing efficient milking cows, and the option of reducing the milking herd size.

The scenario consisted of converting the 124 hectares of the farm to woodland of either birch broadleaves, beech, oak, or an even split mixture of the three species. The farm was altered to a fully housed management system with an anaerobic digester on site for manure management providing 100% renewable energy to the farm. The manure methods described above were used, with the methane emission factor of 3.2g CH_4kgVS^{-1}, methane conversion factor (MCF) of 3.55% to represent a high-quality AD management system, with minimal leakage, and open storage. The farm did not produce crops, so there was zero fertiliser usage and electricity were renewably sourced, resulting in zero CO_2e emissions from electricity and fertiliser. The dairy diets were supplemented with 3NOP and an enteric methane reduction of approximately 30% was presumed based on the literature (van Gastelen, Dijkstra and Bannink, 2019; Arndt *et al.*, 2021), to avoid overestimating the additives potential and be representable of alternative additives, such as seaweed (Roque *et al.*, 2019).

The mitigation strategies were also simulated with the option of one removed, such as the 30% 3NOP reduction, anaerobic digester replaced with a slurry tank and the scenarios without CS for comparison. There is limited data available on the carbon sequestration of trees during the early growth stage, so it was assumed the trees in the model had reached 20 years maturity where carbon accumulates (The Forestry Commission, 2012). The carbon sequestration ability of woodlands was based on the IPCC (2006) methodology, in which the trees were under their Latin names. The potential of birch (*Betula*) was -4,040.32kgCO_2e/ha, beech (*Fagus*) -6,185.92kgCO_2e/ha, and oak (*Quercus*) -9,688 kgCO_2e/ha. The potential was then multiplied by the hectares of land for the total carbon sequestration ability of each woodland scenario.
A high production diet (diet 6 in Appendix 1) of 25kg/day was used to meet the demands of a daily 35-litre high milk producing cow, consisting of mainly rapeseed meal and dairy cake. Dry cows were fed 13.6 kg of DMI of straw and concentrates (diet composition shown in the Appendix 1 as diet 4). Heifers were fed 9.08kg/day, 6.59kg/day for weaned cattle, 10.55kg/day for dry cattle and 13.48kg/day for bulls, based on the presumed body weight of 600kg for milking cattle, dry cattle, and bulls, and 400kg for heifers. The number of milking cows in the herd were around 100 for the farm and reduced by 10% and 20% to around 90 and 80 to simulate reducing the milking herd size as a mitigation strategy.

Feed production emissions were calculated based on the INRA database results for each of the rations of the diet for milking and dry cows. The emissions for the milking cattle diet were 8.61

kgCO$_2$e/cow/day and 3.01 kgCO$_2$e/cow/day for the dry cattle diet. The emissions were then multiplied by the average animal numbers for each scenario, and the average days in milk, which were 305 days and the average dry period which was 60 days per year.

4. Results

4.1. Enteric Methane Prediction Equations

The variation in emission results between the 32 refined equations can be seen in Figure 3 below. The figure shows the equations were consistent in their ranking of the diets from most to least emitting, reflected the effect of dietary composition on EME. The refined equation results ranged from 12.49 to 34.27g CH4/kg DM.

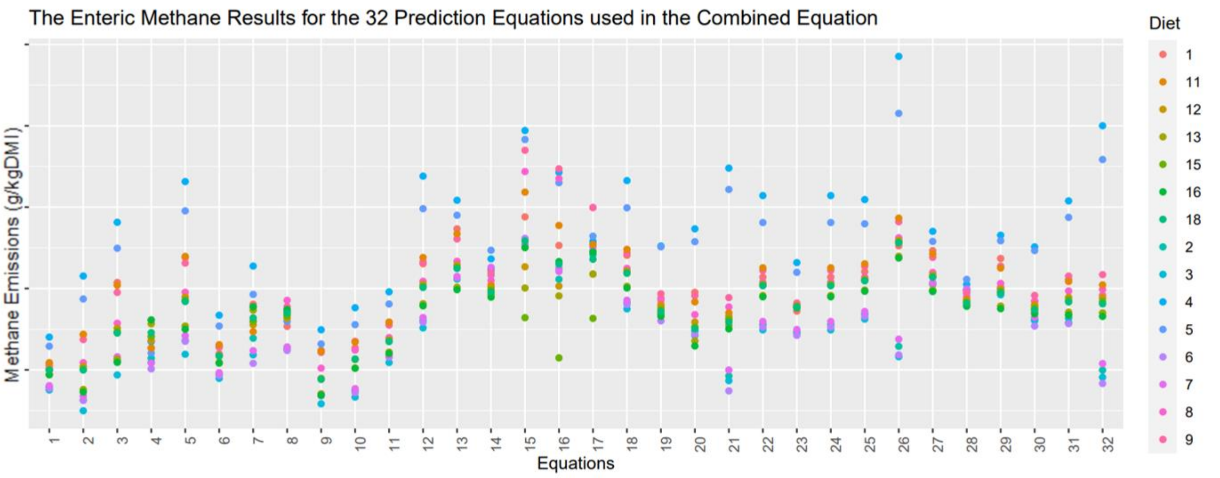

Figure 3: The variation in the results obtained from the 32 prediction equations against 15 dairy diets, as grams of methane per day.

The results were similar between the models, and the fixed effect results are in Table 4 below. Based on the model performance, variation in results, error, and significant t-values, ME and NDF were deemed suitable covariates to represent the combined prediction equation. The performance of model one against each of the 15 diets can also be seen in Figure 4.

Table 4: Presents the performance of the 12 possible character combinations for the combined prediction equations, such as the R^2, root mean square error (RMSE; g CH_4/kg DM), mean absolute error (MAE) and the residuals of variation. ME = metabolized energy, NDF = neutral detergent fibre, GE = gross energy, EE = ether extract, FA = fatty acids, CP = crude protein

			Fixed Effect				Random Error Estimates			Random Effect
Number	Variables		Term	Estimate	Standard Error	t-value	R^2	RMSE	MAE	Residual Variance
1	ME and NDF		Intercept	19.23	0.42	46.06	0.79	1.47	0.97	2.32
		1	NDF	1.88	0.10	19.75*				
		2	ME	0.31	0.10	3.22*				
2	GE and NDF		Intercept	19.23	0.42	46.07	0.79	1.47	0.97	2.31
		1	NDF	1.88	0.10	19.71*				
		2	GE	0.31	0.10	3.21*				
3	NDF and EE		Intercept	19.23	0.42	46.06	0.79	1.48	0.97	2.35
		1	NDF	1.76	0.09	20.63*				
		2	EE	0.16	0.09	1.84				
4	ME, NDF and FA		Intercept	19.23	0.42	46.06	0.79	1.46	1.00	2.30
		1	NDF	1.74	0.11	15.18*				
		2	ME	0.23	0.10	2.27*				
		3	FA	-0.18	0.08	-2.17*				
5	ME, NDF and EE		Intercept	19.23	0.418	46.06	0.79	1.47	0.98	2.31
		1	NDF	1.88	0.10	19.78*				
		2	ME	0.44	0.15	2.85*				
		3	EE	-0.15	0.14	-1.10				
6	ME, CP and NDF		Intercept	19.23	0.42	46.06	0.79	1.47	0.97	2.32

			Fixed Effect				Random Error Estimates			Random Effect
Number	Variables		Term	Estimate	Standard Error	t-value	R^2	RMSE	MAE	Residual Variance
		1	NDF	1.87	0.10	19.21*				
		2	ME	0.32	0.12	2.72*				
		3	CP	-0.03	0.11	-0.26				
7	GE, CP and NDF		Intercept	19.23	0.42	46.06	0.79	1.47	0.97	2.32
		1	NDF	1.87	0.10	19.19*				
		2	GE	0.32	0.12	2.72*				
		3	CP	-0.03	0.11	-0.26				
8	GE, NDF and FA		Intercept	19.23	0.42	46.06	0.80	1.46	1.00	2.30
		1	NDF	1.74	0.12	15.14*				
		2	GE	0.23	0.10	2.26*				
		3	FA	-0.18	0.08	-2.17*				
9	GE, NDF and EE		Intercept	19.23	0.42	46.06	0.79	1.47	0.98	2.31
		1	NDF	1.88	0.10	19.75*				
		2	GE	0.44	0.15	2.84*				
		3	EE	-0.15	0.14	-1.09				
10	CP, NDF, FA and EE		Intercept	19.23	0.42	46.06	0.80	1.46	1.00	2.30
		1	NDF	1.65	0.10	16.19*				
		2	FA	-0.28	0.08	-3.32*				
		3	EE	0.20	0.10	1.99				
		4	CP	-0.00	0.11	-0.02				
11			Intercept	19.23	0.42	46.06	0.80	1.46	1.00	2.30

			Fixed Effect				Random Error Estimates			Random Effect
Number	Variables		Term	Estimate	Standard Error	t-value	R^2	RMSE	MAE	Residual Variance
	GE, CP, NDF, FA and EE	1	NDF	1.68	0.14	12.24*				
		2	FA	-0.24	0.12	-1.98				
		3	GE	0.10	0.25	0.40				
		4	EE	0.13	0.20	0.67				
		5	CP	-0.02	0.11	-0.15				
12	ME, CP, NDF, FA and EE		Intercept	19.23	0.42	46.06	0.80	1.46	1.00	2.30
		1	NDF	1.69	0.14	12.31*				
		2	FA	-0.24	0.12	-1.97				
		3	EE	0.13	0.20	0.65				
		4	ME	0.10	0.25	0.42				
		5	CP	-0.02	0.11	-0.15				

*Asterix shows the t-value is significant for the dietary variable in predicting the EME in the prediction equation. A t-value above two or below minus two is significant.

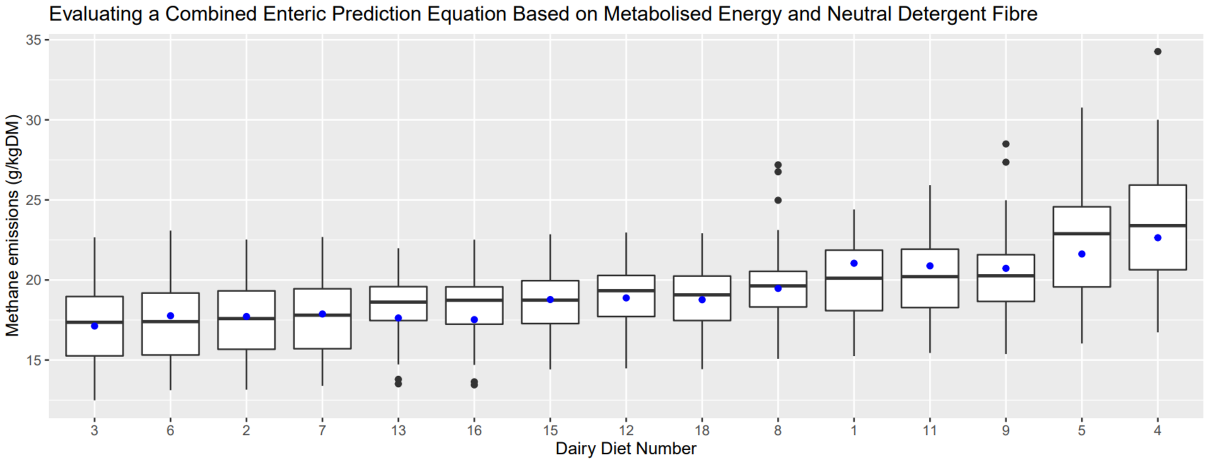

Figure 4: The performance of the combined prediction equation based on metabolised energy (ME) and neutral detergent fibre (NDF) including the random effect, against the variation in results between equations represented by the boxplots and the median of the equations, signified by the line extending through the middle of each boxplot. Methane emissions as grams per kilogramme of dry matter

The distribution of random effects for the 32 chosen equations are shown below in Figure 5. The figure highlights the variation between the published equations included in the combined prediction equation. The equations were from five papers and show large variation even when created by the same author.

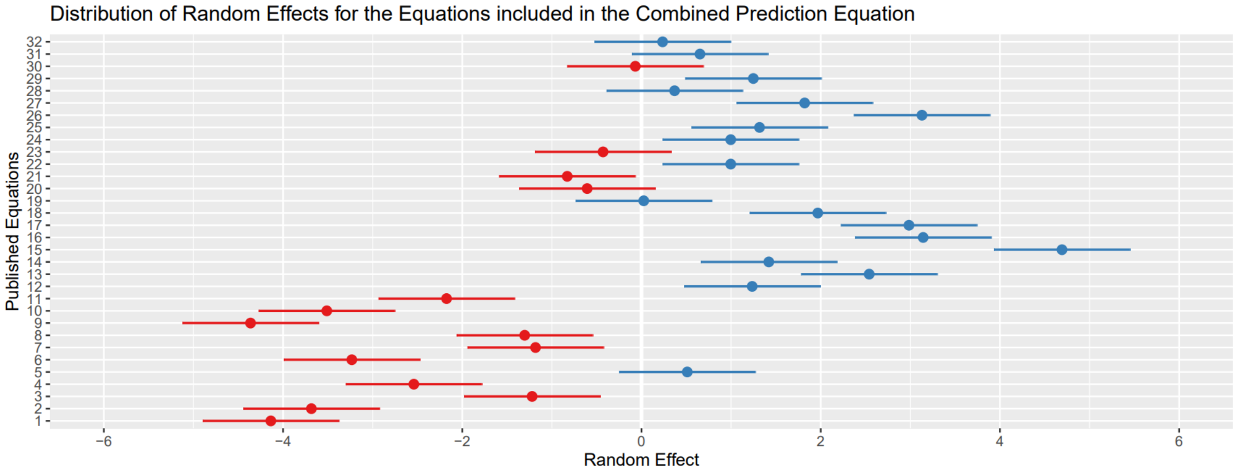

Figure 5: The distribution of random effects for the 32 refined equations used in the combined prediction equation

4.2. Replacement rates

Table 5 shows the annual total of the overall number of livestock on farm per management group, which shows the higher replacement rate also had a larger annual average of animal numbers on the farm.

Table 5: The total annual average number of livestock animals per management group for the dairy farm, calculated from the last 3 simulation years (01 November 2028 – 31 October 2031)

Replacement rate	Management group	Mean annual animal number	Standard deviation
Low	Preweaning calf	10	±3
	Weaned calf	53	±6
	Breeding heifer	26	±5
	Milking cow	127	±5
	Dry cow	22	±5
	Bull	2	±1
Medium	Preweaning calf	12	±4
	Weaned calf	57	±6
	Breeding heifer	39	±6
	Milking cow	130	±4
	Dry cow	22	±4
	Bull	2	±2
High	Preweaning calf	13	±3
	Weaned calf	66	±7
	Breeding heifer	60	±8
	Milking cow	132	±3
	Dry cow	21	±4
	Bull	3	±2

The average milk production was highest for the medium RR, followed by the high RR and lastly the low RR. The average milk productivity decreased by 2.04% from the medium replacement rate to the high RR and 3.83% from the medium to the low RR. While reducing the RR from the high to the low scenario reduced milk production by 1.82%.

Table 6: The annual average total annual milk production as litre of fat-protein corrected milk (FPCM) of all parity dairy cows on farm, creating a mean using the last 3 years (01 November 2030 – 31 October 2031) per replacement rate management system

Replacement rate	Mean annual average total annual milk production (litre/FPCM)	Standard deviation
Low	1,178,766	±32,478.77
Medium	1,225,702	±22,326.90
High	1,200,650	±16,972.79

Table 7: The total annual average enteric methane emissions (kg) for milking and dry cows at the herd level, comparing predictions using the combined equation and the IPCC (2006) equation

Equation	Replacement rate	Dry cattle	Milking cattle
Combined	Low	1,424.26 (±55.74)	20,029.93 (±323.56)
	Medium	1,487.96 (±49.20)	20,474.79 (±290.76)
	High	1,513.45 (±45.38)	20,959.73 (±153.44)
IPCC[1]	Low	1,241.37 (±43.84)	17,198.60 (±205.26)
	Medium	1,284.31 (±30.99)	17,704.55 (±150.48)
	High	1,301.50 (±33.19)	18,107.28 (±117.14)

The average total annual methane and N_2O emissions from livestock manure were calculated and converted to CO_2e emissions. The CO_2e emissions from feed production were calculated based on the typical UK dairy diet if the diet was purchased externally. The annual CO_2e emissions for the farm and various sources can be seen below in Table 8. The total annual CO_2e emissions for the farm were highest for the high RR, followed by the medium RR and low RR.

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[1] Intergovernmental panel on climate change (IPCC)

Table 8: The total carbon dioxide equivalent (kg CO_2e) emissions of each source on farm with and without carbon sequestration (CS) for the three replacement rate scenarios

Replacement rate	Enteric	Manure	Feed Production	Fertiliser	Fuel	Electricity	Land	Total	Total with CS	Total standard deviation
Low	689,924.76 (±16348.1)	201,156.10 (±5,613.46)	578,239.62 (±13,175.93)	17557.62	18225.07	13410	-243,464.4	1,518,511.13	1,275,046.72	±21,771.44
Medium	732,879.28 (±12177.5)	217,708.40 (±5,179.66)	597,184.04 (±7,065.52)	17557.62	18225.07	13410	-243,464.4	1,596,962.49	1,353,498.08	±17,163.05
High	782,752.32(±12809.2)	238,709.90 (±5,665.68)	609,453.90 (±5,303.78)	17557.62	18225.07	13410	-243,464.4	1,680,106.68	1,436,642.28	±18,319.49

Table 9: The mean carbon dioxide equivalent (kg CO_2e) emissions from the farm per litre of fat-protein corrected milk (FPCM), including feed production emissions for each replacement rate and the standard deviation from the mean for the 50 repetition results. The results are presented with and without carbon sequestration (CS) subtracted from the total CO_2e emissions

Replacement rate	Mean annual farm CO_2e emissions per litre of FPCM	Mean annual farm CO_2e emissions with CS per litre of FPCM	Standard deviation
Low	1.27	1.07	±0.01
Medium	1.29	1.09	±0.02
High	1.41	1.20	±0.01

4.3. Protein alternative diets to soya bean meal scenario

The scenario comparing total CO_2e emissions for the milking herd for protein alternative diets to soya bean meal are shown below without carbon sequestration (CS) in Figure 6 and with CS in Figure 7.

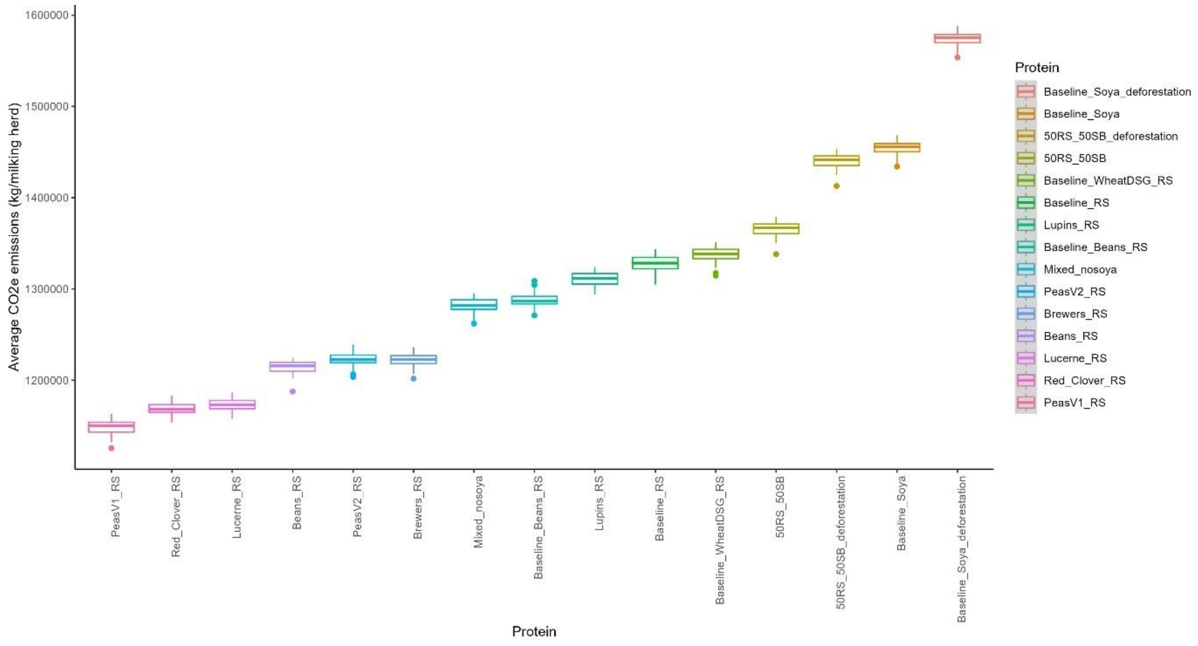

Figure 6: The annual average total farm CO_2e emissions and standard deviation for the 15 protein alternative diets in kilogrammes per the milking herd

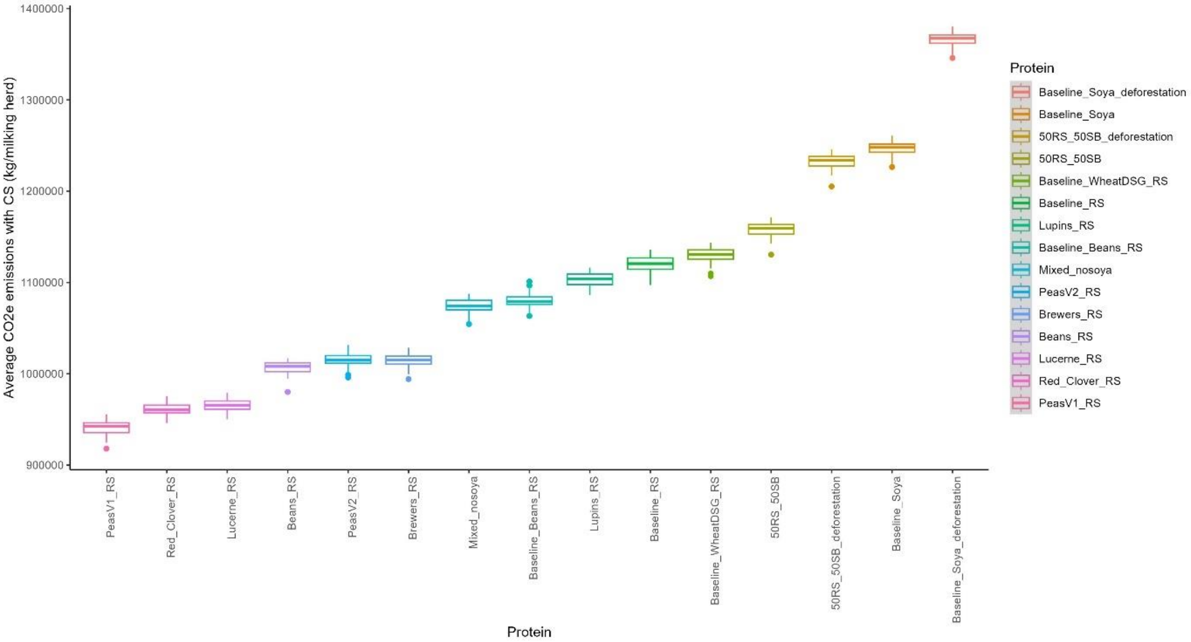

Figure 7: The annual average total farm CO_2e emissions for the milking herd and standard deviation with carbon sequestration (CS) for the 15 protein alternative diets in kilogrammes (kg)

The annual CO_2e emissions from the various sources of emissions are shown in Table 10 below.

Table 10: The carbon dioxide equivalent (kg CO_2e) emissions from the various sources from the farm

Protein	Enteric	Manure	Feed Production	Fertiliser	Fuel	Electricity	Land	Total	Total with CS
Red_Clover_RS	674441.4	126,100.1	267,787.39	17,557.62	18,225.07	13,410	-243,464.4	1,104,125	896,456.7
Brewers_RS	687849.2	125,687.6	306,550.78	17,557.62	18,225.07	13,410	-243,464.4	1,155,884	948,215.3
Baseline_Beans_RS	689070.9	125,476.7	372,260.16	17,557.62	18,225.07	13,410	-243,464.4	1,222,604	1,014,935
Mixed_nosoya	684663.3	124,721.2	371,025.34	17,557.62	18,225.07	13,410	-243,464.4	1,216,206	1,008,538
Baseline_RS	684619.9	124,601.6	418,131.10	17,557.62	18,225.07	13,410	-243,464.4	1,263,149	1,055,480
PeasV2_RS	676535.9	124,590.8	320,487.87	17,557.62	18,225.07	13,410	-243,464.4	1,157,411	949,742.4
PeasV1_RS	672940.4	124,488.2	248,794.14	17,557.62	18,225.07	13,410	-243,464.4	1,082,019	874,350.5
Lucerne_RS	670083.1	124,434.7	277,020.38	17,557.62	18,225.07	13,410	-243,464.4	1,107,334	899,666
Lupins_RS	685544.6	123,704.8	399,848.26	17,557.62	18,225.07	13,410	-243,464.4	1,244,894	1,037,225
50RS_50SB	683219.1	123,688.3	458,509.07	17,557.62	18,225.07	13,410	-243,464.4	1,301,213	1,093,544
Baseline_WheatDSG_RS	684277.1	123,630.8	428,174.89	17,557.62	18,225.07	13,410	-243,464.4	1,271,879	1,064,211
Beans_RS	677563.1	123,537.8	312,346.17	17,557.62	18,225.07	13,410	-243,464.4	1,149,243	941,574.8
Baseline_Soya	686761.4	123,498.3	543,069.99	17,557.62	18,225.07	13,410	-243,464.4	1,389,126	1,181,457
Baseline_Soya_deforestation	686761.4	123,498.3	662,510.90	17,557.62	18,225.07	13,410	-243,464.4	1,508,567	1,300,898
50RS_50SB_deforestation	683219.1	123,688.3	533,159.64	17,557.62	18,225.07	13,410	-243,464.4	1,375,863	1,168,195

Milk production was maintained between the protein alternatives, only slightly differing between the protein scenarios. The mean total annual FPCM for the milking herd with standard deviation for the protein scenarios can be seen in Table 11 below. Lupins with rapeseed had the largest mean total fat-protein corrected milk (FPCM) and peas version 2 (with soya hulls) and rapeseed the lowest production.

Table 11: The average total annual milk production as fat-protein corrected milk (FPCM) for the milking herd with standard deviation

Protein	Mean total milk production (litres/herd)	Standard deviation
PeasV2_RS	1,224,478	±21,700.60
Mixed_nosoya	1,224,546	±21,300.06
Baseline_Beans_RS	1,225,874	±22,020.38
PeasV1_RS	1,226,062	±19,592.56
Red_Clover_RS	1,227,358	±18,277.89
Beans_RS	1,227,664	±21,519.27
Baseline_Soya	1,228,267	±21,801.09
Baseline_RS	1,228,649	±19,960.89
50RS_50SB	1,229,125	±20,014.63
Brewers_RS	1,229,300	±18,396.00
Lucerne_RS	1,229,459	±20,027.52
Baseline_WheatDSG_RS	1,229,921	±23,321.66
Lupins_RS	1,230,129	±21,590.30

4.3.1. Total farm CO_2e emissions and milk production

The total average annual CO_2e emissions (kg) per litre of FPCM for the farm, were assessed for each of the 15 protein alternative scenarios, as shown in Figure 8 and Figure 9 with CS below. The ranking of the diets from least to most CO_2e emitting per litre of FPCM, were peas without soya hulls (version one), red clover and rapeseed (RS), lucerne and RS, brewers and RS, beans and RS, peas with soya hulls (version 2), mixed protein without soya, baseline beans with RS, lupins and rapeseed (RS), baseline RS, wheat distillers' grains with RS, 50-50 RS and SBM, 50-50 RS and SBM related to deforestation, baseline SBM, baseline SBM linked to deforestation.

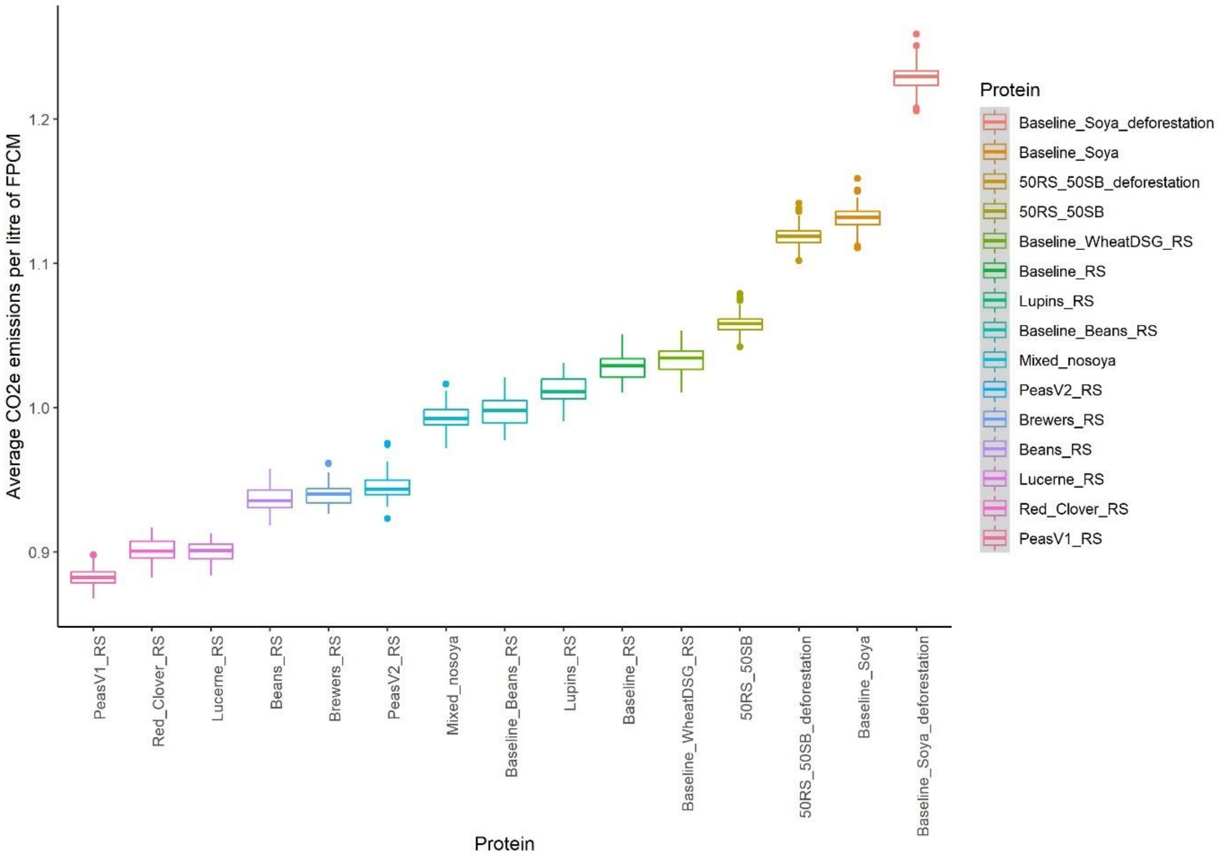

Figure 8: The average total annual farm carbon dioxide equivalent (CO_2e) emissions as kilogrammes (kg) for the milking herd per litre of fat-protein corrected milk (FPCM) for each of the five simulation runs and 15 protein alternative diets

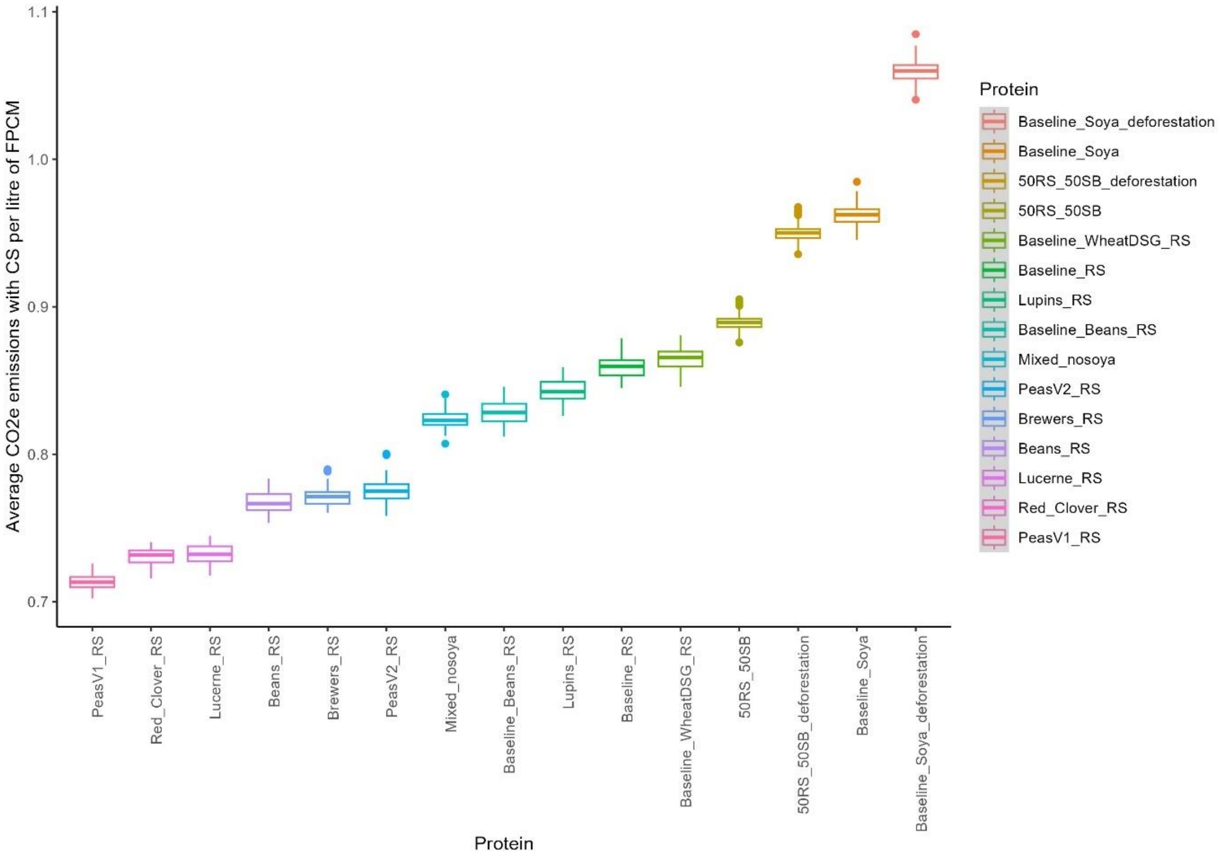

Figure 9: The average total annual farm carbon dioxide equivalent (CO_2e) emissions (kg) for the milking herd with carbon sequestration (CS) included, per litre of as fat-protein corrected milk (FPCM) for each of the five simulation runs and 15 protein alternative diets

The economic costings for the diets were estimated at the time of the study, by the dairy nutritionist, shown in Figure 10. Diet costings fluctuate and cannot be used as a definite cost. The most expensive diet at the time of the study, was lucerne and RS and the least was the brewer’s diet with RS. The diets varied by 22%, between the most and least expensive.

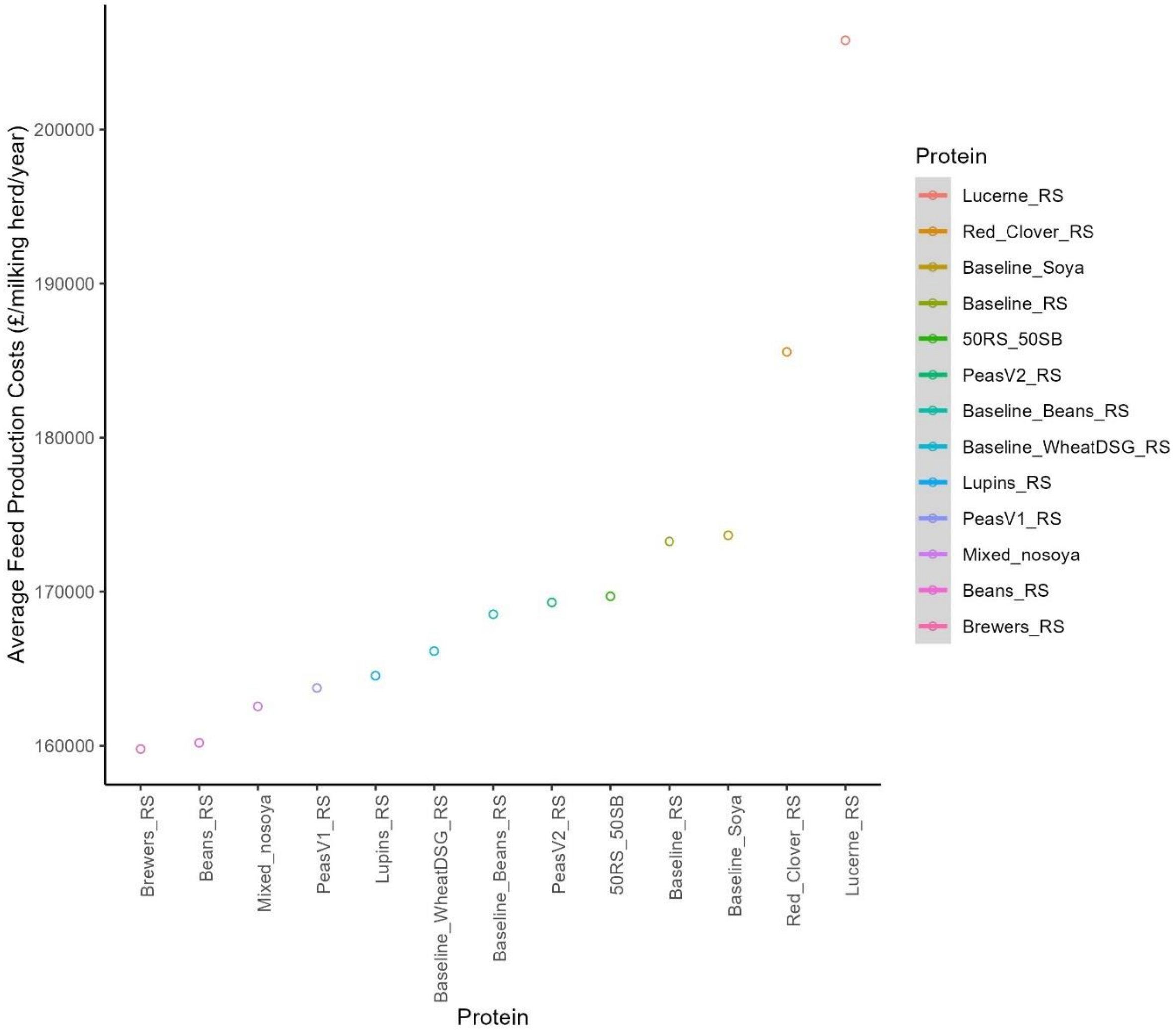

Figure 10: The estimated annual cost of the protein alternative diets in British sterling pounds (£/milking herd/year)

4.4. Net zero scenarios

The results show that with the mitigation systems in place, the farm had low CO_2e emissions of 0.75kg CO_2e/kg FPCM. The inclusion of carbon sequestration allowed the farm to reach net zero, reducing total emissions by between 62% and 185%. The results for whether the scenarios reached net zero, can be seen below in Figure 11. The reduction in milking cattle herd size only reduced CO_2e emissions per litre of FPCM, when carbon sequestration was subtracted from the total. The feed additives removed, or anaerobic digestion replaced by a slurry tank for manure storage, reached net zero only when oak trees were planted.

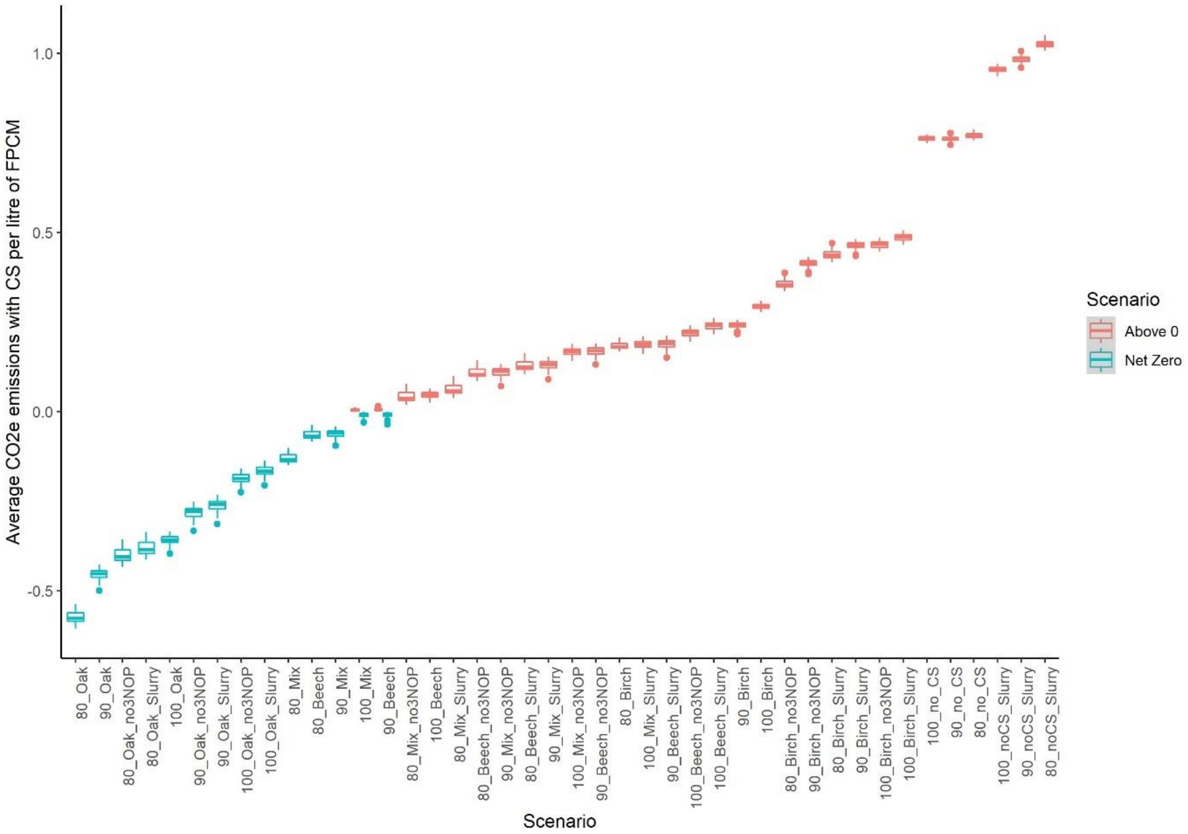

Figure 11: A boxplot of the scenarios with the various mitigation strategies that reached net zero or minus emissions per litre of FPCM.

The scenarios that reached net zero are shown in blue, while those that were not net zero are presented in red. 100, 90 and 80 refer to the milking cow herd size numbers, “no3NOP” mean the scenarios where the 30% reduction in enteric methane were from the feed additive were removed and “no_CS” refers to the scenarios without carbon sequestration for comparison. The “Slurry” scenarios refer to those that use a slurry tank on farm, rather than an anaerobic digester. “Mix” refers to the even mix of tree species beech, birch, and oak on the farm. The scenarios “100 mix” and “90 beech” means were net zero, however, with standard deviation, part of their results was above 0, so the scenarios were mixed in whether they reached net zero using the model.

4.4.1. Tree Species

The tree species influenced the carbon sequestration ability; oak had the largest, followed by the mixture of tree species, beech and lastly, birch. The CS potential can be seen below in Table 12. The farmland was converted to 124 hectares of woodland and reached net zero for the mixture and oak tree scenarios. The numbers in the milking herd were also reduced by both 10% and 20% to assess whether the birch and beech woodlands reached net zero. The farm did not reach net zero when the woodlands consisted of birch trees, even when the herd was reduced by 20%. The farm did, however, reach net zero when the herd was reduced by both 10% and 20% in the beech woodlands scenario, as highlighted in Table 12. The table also shows the total average CO_2e emissions for the farm, with and without CS and with a 10% or 20% reduction.

Table 12: The carbon sequestration potential from the various tree species proportions and their annual offsetting potential from carbon sequestration (CS) from the total farm carbon dioxide equivalent (kg CO_2e) emissions

Tree Species	Milking herd size scenario	Land CS	Total CO_2e	Total CO_2e with CS	Total CO_2e standard deviation
Birch	100	-501,274.20	807,745.70	306,471.50	±4,237.64
	90	-501,274.20	740,428.60	239,154.40	±11,289.78
	80	-501,274.20	647,839.70	146,565.50	±5,320.84
Beech	100	-767,054.08	807,745.70	41,912.12	±4,237.64
	90	-767,054.08	740,428.60	-26,544.58	±11,289.78
	80	-767,054.08	647,839.70	-117,962.88	±5,320.84
Oak	100	-1,201,312.00	807,745.70	-392,345.80	±4,237.64
	90	-1,201,312.00	740,428.60	-460,802.50	±11,289.78
	80	-1,201,312.00	647,839.70	-552,220.80	±5,320.84
Mixture (1/3 each)	100	-823,121.50	807,745.70	-14,155.30	±4,237.64
	90	-823,121.50	740,428.60	-82,612.00	±11,289.78
	80	-823,121.50	647,839.70	-174,030.30	±5,320.84

Milking herd size was reduced by 10 and 20% as a reduction strategy and the animal numbers for each management group can be seen in Table 13 below. The total annual milk production for the farm varied according to the number of cattle on-farm, decreasing with the reduction in milking herd size, as shown in Table 14. The total annual farm greenhouse gas emissions were converted to CO_2e emissions per kilogramme of FPCM, as shown in Table 15. Enteric methane contributed to the majority of CO_2e emissions, followed by feed production, manure management and lastly, fuel from on-farm vehicles. CO_2e emissions from electricity and fertiliser were zero for the scenario.

Table 13: The mean animal numbers for the different milking herd size scenarios with standard deviation for the six management groups

	Milking herd size scenario mean animal numbers		
Management Group	80	90	100
Preweaning calf	6 (±2)	7 (±3)	8 (±3)
Weaned calf	34 (±5)	37 (±5)	42 (±5)
Breeding heifer	24 (±5)	27 (±5)	30 (±5)
Milking cow	78 (±3)	87 (±3)	98 (±4)
Dry cow	13 (±3)	15 (±3)	17 (±4)
Bull	1 (±1)	2 (±1)	2 (±1)

Table 14: The total mean annual total milk production as fat-protein corrected milk (FPCM) for the three milking herd size scenarios

Milking herd size scenario	Total Milk Yield (kg/FPCM/year)
100	1,071,741.0 (±18,050.54)
90	963,817.2 (±15,896.74)
80	853,895.1 (±15,154.47)

Table 15: The average kilogrammes of carbon dioxide equivalent (CO_2e) emissions per kilogramme of fat-protein corrected milk (FPCM) for the carbon sequestration (CS) scenario

Scenario	Milking herd size	Enteric	Manure	Feed Production	Fertiliser	Fuel	Electricity	Land	Total	Total with CS
Birch	100	0.40	0.08	0.24	0.00	0.03	0.00	-0.47	0.75	0.29
	90	0.40	0.08	0.24	0.00	0.04	0.00	-0.52	0.77	0.25
	80	0.40	0.08	0.24	0.00	0.04	0.00	-0.59	0.76	0.17
Beech	100	0.40	0.08	0.24	0.00	0.03	0.00	-0.72	0.75	0.04
	90	0.40	0.08	0.24	0.00	0.04	0.00	-0.80	0.77	-0.03
	80	0.40	0.08	0.24	0.00	0.04	0.00	-0.90	0.76	-0.14
Oak	100	0.40	0.08	0.24	0.00	0.03	0.00	-1.12	0.75	-0.37
	90	0.40	0.08	0.24	0.00	0.04	0.00	-1.25	0.77	-0.48
	80	0.40	0.08	0.24	0.00	0.04	0.00	-1.41	0.76	-0.65
Mix	100	0.40	0.08	0.24	0.00	0.03	0.00	-0.77	0.75	-0.01
	90	0.40	0.08	0.24	0.00	0.04	0.00	-0.85	0.77	-0.09
	80	0.40	0.08	0.24	0.00	0.04	0.00	-0.96	0.76	-0.20

4.4.2. Feed additives

The average enteric methane emissions as carbon dioxide equivalent (CO_2e) were compared for the herd against an approximate 30% reduction in enteric methane emissions by substituting the diet with feed additives. The emissions are shown in Table 16 below.

Table 16: The annual enteric methane emissions as carbon dioxide equivalent (CO_2e) as kilogrammes per herd with and without feed additives

Milking herd size scenario	Annual mean enteric methane emissions as CO_2e with feed additives	Annual mean enteric methane emissions as CO_2e without feed additives
100	431,747.96 (±348.13)	616,782.8 (±348.13)
90	387,445.80 (±339.51)	553,494.0 (±339.51)
80	344,119.16 (±328.70)	491,598.8 (±328.70)

4.4.3. Manure management

The average manure emissions were compared using anaerobic digestion and a slurry tank. The AD significantly reduced total manure emissions from the farm, by around 70%, which can be seen in Table 17 below.

Table 17: The annual manure carbon dioxide equivalent (kg CO_2e) emissions from anaerobic digestion compared to all year slurry

Milking herd size scenario	Slurry (total kg CO_2e/year)	Anaerobic Digestion (total kg CO_2e/year)
100	293,585.67 (±7,116.50)	87,047.09 (±2,397.11)
90	263,240.27 (±7,038.15)	78,047.20 (±2,347.39)
80	233,975.27 (±6,833.07)	69,376.79 (±2,291.00)

5. Discussion

The current project utilised a whole farm simulation model to analyse how to reduce total CO_2e emissions from UK dairy farms. The results provide options on how UK dairy farmers can adapt farming practices to limit their CO_2e emissions and to provide insights that may support the transition to more sustainable practices. A LCA model was determined based on previous literature for the foundation of the simulation model to cover the various aspects of the dairy farm, such as from feed, manure, enteric methane, health, milk production and reproduction. Literature predicting enteric methane emissions by use of equations was reviewed and collected to create a combined equation to act as a compromise measure, based on current literature. The equation was based on the most influential dietary composition factors, namely: metabolised energy and neutral detergent fibre.

In 2019, agriculture equated to 10% of the UK's total CO_2e emissions (BEIS, 2019) and the NFU have a net zero goal of 2040 (NFU, 2019). However, farmers are unsure how to reduce their carbon footprint and reach net zero without impacting production (DEFRA, 2021b). UK farmers and the government would therefore benefit from research and education on mitigation strategies to aid the industry and country on their net zero journey.

5.1. Replacement rates scenario

A petrol car produces an average of 0.22kg of CO_2 per mile (Department for Transport, 2022), and in 2019 the average car drove 7,400 miles a year (NimbleFins, 2023). The value suggests the average annual emissions from a standard combustion engine car in the UK are 1,628kg of CO_2. Based on the average car emissions, the annual emissions from the high replacement rate were the equivalent of the annual emissions from 1,032 cars. While the medium replacement rate was the equivalent of 981 cars and the low replacement rate 933 cars. The emissions were significantly lower when CS was included in the figures, with the high RR equating to 883 annual cars, the medium RR 831 cars, and the low RR an average of 783 annual cars.

The high replacement rate, therefore, produced the equivalent of almost 100 more cars than the low replacement rate and over 50 more than the baseline. There was a similar difference between the medium and low replacement rate of 48 cars. Emissions could thus, be reduced by changing replacement rates, reducing emissions by the equivalent of removing between 48 and 99 cars a year from the road. The potential car reduction was the same whether CS was included or excluded from the total CO_2e emissions.

The findings suggested that increasing LPL and reducing RRs decreased CO_2e emissions, but that RRs could be reduced further, so that it reduced milk productivity and thus, profitability. The study highlighted a ‘sweet spot’ of a 22% RR as the optimum RR to reduce emissions and maintain milk production. The results can be used to guide farmers on the best management practices without negatively impacting their livelihood.

5.2. Protein Alternatives to SBM scenario

The UK are transitioning away from the use of SBM (DEFRA, 2022a), due to the devastating effects of deforestation linked to the growth and harvesting of SBM (Fraanje and Garnett, 2020). Dairy cattle are a small consumer of SBM in the UK but require alternative options for growing demand (Aquilas *et al.*, 2022), that will maintain milk production and limit enteric methane emissions. Currently, there is limited research on the effect of alternative proteins to SBM on dairy cattle total CO_2e emissions from enteric methane or inclusion of GHGe from feed production. Enteric methane contributes to as much as 71% of GHGe from a dairy cattle farm (Gilardino *et al.*, 2020), which makes it a vital area to limit emissions for the industry.

It is important that as the industry transitions from SBM to an alternative diet, that the alternatives are researched to ensure that they are low emitting diets to help national net zero goals. The chapter highlighted the array of protein alternatives to SBM without impacting milk production. Peas (version one) resulted in the lowest overall CO_2e emissions. However, it would be unwise to conform to one feed type, as this would lower biodiversity and increase risk to food security, from disease, parasites, and climate change if the weather became unsuitable for growing certain plants. The costings were also estimated based on the time of the year, which showed trade-offs between some of the lowest emitting diets and the cost of the diets, such as lucerne being the most expensive diet, as well as one of the lowest carbon footprint diets.

5.2.1. Emissions in relation to combustion vehicle emissions

UK averages estimate farm emissions for SBM as the equivalent of 853 annual car emissions. The lowest emissions from the pea’s version one (no soya hulls) diet on the other hand were 665 cars and the highest SBM alternative of wheat distillers’ grain with RS were 781 annual car emissions. The possible reduction in total annual farm emissions by changing the protein source in dairy cattle diets could therefore reduce annual emissions by the equivalent of removing approximately between 72 and 189 petrol cars from the road each year.

Switching to a protein alternative from SBM linked to deforestation had an even larger reduction in emissions from cars, equivalent to the removal of between 145 and 216 petrol cars from the road each year. SBM linked to deforestation had the largest annual total farm emissions equivalent to 927 petrol vehicles.

The CO_2e emissions produced from the simulation model were comparable to previous research without CS (Henriksson *et al.*, 2011; Galloway *et al.*, 2018; Niu *et al.*, 2018; Rotz, 2018; Rotz, Holly, *et al.*, 2020; Castaño-Sánchez, Karsten and Rotz, 2022), as CS was not included in the existing research. Future research should assess whether changes in forage type and quality impact the CO_2e emissions of the diet and milk productivity. The study highlighted that SBM resulted in the highest carbon footprint of the diets analysed and substituting the protein had a potential to reduce CO_2e emissions from the milking herd by up to 28% in the UK. The optimum diet was peas without soya hulls, and it was considered economically viable.

5.3. Net zero scenario

The overall aim of the thesis was to create blueprints on how the dairy industry can mitigate CO_2e emissions and whether it can reach net zero by 2040. The net zero scenario addressed the question, by combining multiple mitigation measures to see if the net zero goal could be met to provide these vital blueprints. The chapter highlighted the possibility of UK dairy farms reaching net zero, but not without offsetting emissions through woodland. The trees also required 20 years to gain maturity, which meant that unless they were planted prior, that net zero would not be met until 2044 at the earliest. Four years after the NFU 2040 net zero goal, but before the UK governments 2050 net zero goal.

5.3.1. Emissions in relation to combustion vehicles

The overall annual farm CO_2e emissions with the complete herd equated to the annual emissions of 496 petrol combustion vehicles a year, 455 when the milking herd size was reduced by 10% and 398 annual petrol combustion vehicles when milking herd size was reduced by 20%. Carbon sequestration reduced the equating emissions by 308 annual petrol vehicles from birch woodland, 470 from beech woodland, 505 from the mixture woodland and 737 from oak woodland.

Future research should assess the CS potential of silvopasture systems and the possibility of cattle grazing in woodlands. The model showed net zero is possible for UK dairy farms, by using multiple mitigation including vast woodlands to offset GHGe. But net zero would not be reached by 2040 but could be met by 2050.

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7. Appendices

7.1. Appendix 1:

The breakdown of the diet composition of the 15 diets used to evaluate the variability between the published prediction equation results and in the creation of the combined equation.

Diet	MEI	CP (%)	FA (%)	EE (%)	NDF (%)	ADF (%)	Forage (%)
1	202.3	18.08	3.4082	4.32	46.11	37.81	81.89
2	262.6	15.6	4.3289	4.14	34.87	28.593	69.2
3	271.7	17.98	3.5567	4.12	32.78	26.88	53.36
4	125.3	13.97	1.7256	3.41	52.5	43.05	81.44
5	136.5	12.58	1.5837	2.74	49.16	40.311	73.86
6	268.9	16.05	3.7412	4.7	35.15	28.823	50.51
7	255.2	17.43	3.9059	4.07	35.47	29.085	57.69
8	222.3	19.25	0	5.1	38.85	31.857	50
9	207	16.95	0	4.55	43.85	35.957	50
11	196.2	15.2	2.5	5.45	45	36.9	50
12	203.4	19.75	4.5	5.65	38.05	31.201	50
13	218.7	22.05	4.5	6.2	33.05	27.101	50
15	207	16.2	7.5	5.85	37.5	30.75	50
16	222.3	18.5	3	6.4	32.5	26.65	50
18	210.6	17.4	3.5	6	37.25	30.545	50

7.2. Appendix 2:

The diet composition for the 13 diets in the protein alternatives scenario.

Diet	DMI (kg/day)	GE	ME (MJ/kg)	CP	FA	EE	NDF	Forage (%DM)
Baseline - beans rape	22.91	13.45	11.03	15.63	2.95	3.28	33.23	53.42
Beans rape	22.70	13.57	11.13	15.70	2.94	3.28	32.82	57.36
Mixed - no soya	22.85	13.61	11.16	16.07	3.51	3.88	32.94	57.00
Baseline - RS	22.82	13.52	11.09	16.24	3.16	3.90	33.09	52.41
Soya	22.69	13.61	11.16	16.31	3.15	3.28	33.80	57.38
Baseline - 50-50 SB RS	22.71	13.57	11.13	16.44	3.19	3.46	33.40	57.35
Peas v1 and rape	22.84	13.67	11.21	16.54	3.04	3.41	31.73	57.01
Peas v2 and rape	22.84	13.55	11.11	16.69	2.98	3.36	32.28	54.24
Lupins and rape	22.76	13.80	11.32	16.88	3.86	4.35	33.29	57.22
Clover and RS	22.97	13.43	11.01	16.89	3.71	5.15	31.38	52.38
Lucerne and rape	22.78	13.59	11.14	17.04	3.32	5.34	31.56	57.13
Baseline – wheat distillers’ grains RS	22.73	13.61	11.16	17.07	4.33	4.67	33.34	53.83
Baseline - Brewers RS	22.96	13.54	11.10	17.57	4.41	5.18	32.85	52.54