

Evaluating strategies to reduce greenhouse gas emissions from dairy production systems

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Abstract

It is important that greenhouse gas emissions (GHGe) are limited to reduce sea level rise, extreme weather events such as flooding and protect food security (GOV, 2020). The United Kingdom (UK) government have set a goal of becoming Net Zero by 2050 to limit the country's impact on climate change (Committee on Climate Change, 2019). In 2019, agriculture accounted for 10% of UK greenhouse gas emissions, which has led to the National Farmers union (NFU) 2040 Net Zero target (NFU, 2019), who require blueprints on how to meet their set goal.

Enteric fermentation makes up most of dairy cattle GHGe, equating to up to 71% (Gilardino *et al.*, 2020). Published prediction equations were collated from the literature and Chapter 3 highlights the large variation in the published enteric methane prediction equations that account for dietary composition. An equation was developed based on the predictions of 32 previously published enteric equations, utilising dietary composition values from a range of diets as inputs. An equation with the dietary composition variables metabolised energy (ME) and neutral detergent fibre (NDF) was found to be the most accurate in estimating the predicted enteric methane emissions (EME) across all published equations. The devised equation resulting from Chapter 3 was used within the farm simulation modelling in the subsequent chapters.

Utilising the adapted farm simulation model, several aspects of strategies were investigated to reduce the GHGe from dairy production systems in the UK. The GHGe considered were from enteric fermentation, manure management, feed production, and maintenance of the farm, such as electricity and fuel. The total emissions were included with and without the carbon offsetting and sequestration potential of land, woodland, and hedgerows. Milk production impacts were estimated to examine the effect of actions taken to reduce GHGe on

productivity and profitability, thus allowing the evaluation of the economic feasibility of the approaches. The strategies analysed included reducing replacement rates, using alternative protein diets to soyabean meal (SBM), and combining multiple management, mitigation, and sequestration strategies to assess whether a UK dairy farm could reach Net Zero by 2040.

Three replacement rates (RRs) were simulated into the model to compare their effect on total farm GHGe and milk production in Chapter 4. The lower the RR the lower the total emissions. However, milk production declined in the low RR scenario and thus, the medium RR was deemed the optimum scenario to avoid compromising productivity and profitability.

In Chapter 5, 13 diets containing different sources of dietary protein were utilised in the model to compare the effect of the alternative sources of protein to SBM on the carbon footprint of the milking herd. The carbon footprint of SBM with and without links to deforestation was compared, which highlighted a potential 7% reduction by using a SBM not associated with deforestation. The alternative proteins showed a potential 28% reduction in total GHGe for the milking herd by converting from SBM completely.

The ability for a UK dairy farm to meet the NFU 2040 Net Zero goal was examined in Chapter 6. A combination of mitigation strategies was analysed such as a medium RR highlighted in Chapter 4, feed additives to reduce EME, anaerobic digestion (AD) of manure to provide renewable energy, reducing the milking herd size, afforestation, increasing efficiency, and removing fertiliser usage. The scenario showed Net Zero is possible, but not without afforestation and carbon offsetting. The modelling showed that, although possible, given the dramatic changes required, it is unlikely that dairy farms will reach Net Zero by 2040, but 2050 is possible, if strategies are implemented in the next six years. The findings from the study provide blueprints on how the UK dairy industry can reach Net Zero and educate farmers on the potential mitigation measures available.

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Abbreviations

3-NOP	3-Nitrooxypropanol
AD	Anaerobic Digestion
ADF	Acid detergent fibre
AHDB	Agriculture and Horticulture Development Board
AIC	Agricultural Industries Confederation
AP	Acidification potential
AW	Animal welfare
BW	Body weight
CF	Carbon footprint
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CP	Crude protein
CS	Carbon sequestration
CSPO	Certified sustainable palm oil
DEFRA	Department for Environment, Food & Rural Affairs
DDGS	Dried distillers' grains
DIM	Days in milk
DM/DMI	Dry matter/dry matter intake
ECM	Energy corrected milk
EE	Ether extract
EF	Enteric fermentation

EP	Eutrophication potential
FA	Fatty acids
FAO	Food and Agriculture Organization of the United Nations
FB	Faba beans
FPCM	fat-and-protein-corrected milk
FPS	Farm Practices Survey
GE/GEI	Gross energy/Gross energy intake
GHGe	Greenhouse gas emissions
GLEAM	Global Livestock Environmental Assessment Model
GS	Grass silage
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment/analysis model
LPL	Length of production lifespan
ME/MEI	Metabolised energy/Metabolised energy intake
MS	Maize silage
MY	Milk yield
N	Nitrogen
N_2O	Nitrous oxide
NDF	Neutral detergent fibre
NFU	National Farmers Union
NH_3	Ammonia
RR	Replacement Rate
RS/RSM	Rapeseed/rapeseed meal
RSPO	Roundtable on Sustainable Palm Oil
SB/SBM	Soya bean/soya bean meal

SD	Standard deviation
SF_6	Sulphur hexafluoride
SFI	Sustainable Farming Incentive
SLS	Solid Liquid Separation
SOC	Soil organic carbon
SOM	Soil organic matter
UK	United Kingdom
VFA	Volatile fatty acids
VS	Volatile solids
WCC	Woodland Carbon Code
WFM	Whole farm model

Ethical Approval

Ethical approval was accepted by the University of Nottingham School of Veterinary Medicine and Science Research Ethics Committee (CARE). Ethics number: 2820 190926.

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1 Introduction

1.1 Background to the topic

1.1.1 General Introduction to Climate Change

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 rouhgly one degrees celsius 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 18 centimetres since the 1920s. GHGe also cause air and water pollution, affecting 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). Carbon neutral meaning an 80-95% reduction in GHGe from those reported in 1990 (ibid). Net zero defined as removing and offsetting GHGe so that zero emissions are left in the environment (United Nation, 2024).

1.1.1.1 The Risk of Flooding

The increase in temperature and sea level rise is also predicted to amplify evaporation and the formation of clouds across the globe, which will in turn intensify the occurrence and strength of rainfall (UNEP, 2020; Met Office, 2023). The Met Office estimate that for every one-degree Celsius (ºC) increase in temperature, the air can hold 7% more water, leading to the increase in rainfall, which also increases the risk of flooding events (Met Office, 2023). Extreme weather events such as increased flooding frequency endangers livestock and

humanity's food security, as well as leading to economic costs. For example, the summer floods caused huge damage across England in 2007, leading to vast financial costs including more than 40,000 hectares of flooded agricultural land, costing £50 million due to infrastructure damage and production losses (ibid). In 2020, modelled estimated annual damage for the UK from flooding was estimated as £730 million, showing an increase in damage from flooding (Bates *et al.* (2023).

The risk to food security includes the importation and exportation of food, which the UK greatly relies on, as in 2020, 46% of vegetables and 83.6% of fruit in the UK were imported from abroad (DEFRA, 2021c). If emissions are not controlled, access to these items could become limited, which would reduce required nutrients and vitamins to the population, impacting the health of residents. Additionally, the global population is predicted to increase to nine billion by 2050 (FAO, 2015), which will increase demand and emissions further (Richardson *et al.*, 2021), when current pressure is already a strain on the environment (Ruviaro *et al.*, 2020).

1.1.2 The Benefits of the Dairy Industry

Cattle have the valuable ability to live on land unsuitable for crop growth and convert it to food of nutritional value (Herremans *et al.*, 2020). There are different animal sources of milk, and a life cycle assessment (LCA) study investigated the carbon emissions of cow, sheep, goat, and buffalo milk, per gram of protein (Gaillac and Marbach, 2021). The results found cow's milk was the least carbon intensive. The dairy products cattle produce, provide humanity with essential nutrients, from protein to calcium (Üçtuğ, 2019; Gilardino *et al.*, 2020; Rotz, Holly, *et al.*, 2020; Segerkvist *et al.*, 2020), for example, Table 1 below shows the nutrients a 200-millilitre glass of whole milk provides. These components together ensure the body functions healthily, such as maintaining a beneficial metabolic rate, by aiding the thyroid hormone process and regulating an individual's heartbeat (NHS, 2020). A small

meta-analysis of eight papers also highlighted that cow's milk during pregnancy, can have a positive effect on birthweight, length, and foetus femur length (Brantsæter *et al.*, 2012). Plus, the nutrients and vitamins milk supplies are a vital component of a child's diet, being a suitable source of a proportion of their required daily calories (NHS, 2021), whereas alternatives may not offer the same level of nourishment (Verduci *et al.*, 2019).

Table 1: The average recommended daily intake of various minerals/nutrients for adults (NHS, 2020, 2021) and the amount obtained from one 200ml glass of whole milk, as well as the percentage of the daily requirements one glass of milk provides (NHS, 2019). Including the health benefits of the nutrients. Units used are: µg = micrograms, mg=milligrams, g = grams.

Mineral/ Nutrient	Average recommended daily intake for adults	Amount obtained from one glass of whole milk (200ml)	Percentage (%) of daily requirement obtained from one glass of whole milk (200ml)	Helps maintain a healthy:
Iodine	140 µg	64 µg	46	Metabolic rate
Calcium	700mg	247mg	35	Bones, teeth, blood clotting, heartbeat
Vitamin C	40mg	4mg	10	Skin, bones, cartilage, blood vessels, skin regeneration and prevent scurvy
Riboflavin (vitamin B2)	1.2mg	0.47mg	39	Eyes, skin, sensory system
Protein	50g	7	14	Body growth and repair
Phosphorus	550mg	198	36	Bones and teeth

The dairy industry is a huge source of employment, providing an income to an estimated 240 million individuals worldwide, that work in an area related to the dairy sector (Üçtuğ, 2019). Milk is also one of the most valuable products in the industry (Soteriades *et al.*, 2020) and in 2021, the UK was the 13th biggest dairy producer globally (The House of Commons Library, 2021). In 2020, in the UK, milk contributed to 16.4% of the overall agricultural output, totalling £4.4billion in the market (The House of Commons Library, 2021). The industry also has a huge contribution to the global economy, helping to combat poverty (FAO, 2015), by

significantly increasing income to rural areas, where poverty is threefold more than urban (The United Nations, 2019). The additional income supports the United Nations first Sustainable Development Goal (SDG) to reduce poverty (The United Nations, 2019) by aiding this process (Dumont, Groot and Tichit, 2018; Gilardino *et al.*, 2020; Segerkvist *et al.*, 2020). It is therefore vital the industry reduces emissions, without compromising the economic value of the product or reducing milk output (Richardson *et al.*, 2021).

1.1.3 The Threat of Climate Change to the Agriculture Sector

In 2021, the Farm Practices Survey (FPS) highlighted that around 44% of farmers were not implementing methods to limit their farm's GHGe and 35% of farmers stated their farm did not contribute to a high enough proportion of emissions (DEFRA, 2021b). However, as temperatures increase, instances of poor health in cattle are also likely to increase, which will decrease milk production and therefore the economic output of livestock (Dunn *et al.*, 2014; Tao *et al.*, 2020). For example, the higher temperatures are suitable for insects from other climates, which could migrate to the UK and spread disease, as well as increase those already in the UK, such as ticks carrying Lyme disease (Baylis, 2017). Insects carrying bluetongue disease have already spread across Europe due to climate change, increasing the risk to ruminants, such as sheep and cattle (GOV, 2019). Research suggests the virus is likely to become more common in the UK (Hendrickx, 2009), but fortunately, two strains of the bluetongue virus are preventable through a vaccine, which may mean vaccinations will need to be increased.

However, it is not only disease that threatens the health of cattle, but the increased risk of heat stress (Dunn *et al.*, 2014; Britt *et al.*, 2021). Currently, the severity and number of reports of heat stress vary by region of the UK, but the rise in temperatures from global warming, predicts an increase (Dunn *et al.*, 2014; Britt *et al.*, 2021). The temperature

humidity index (THI) accounts for temperature and humidity to predict the level of potential heat stress. Heat stress usually occurs when temperatures increase above 70, on the THI and the predictions suggest an increase of cases by on average 20 times higher, by 2100. Areas such as the Southeast, the Midlands, and East Anglia are predicted to be more at risk and affected than northern England and Scotland. However, any increase in heat stress is a concern, as heat and humidity increase incidences of mastitis (Tao *et al.*, 2020), which particularly negatively impacts milk production (Dunn *et al.*, 2014; Tao *et al.*, 2020). Thus, highlighting the negative cycle emissions create (Tao *et al.*, 2020), as the health problems caused by global warming reduce milk production and efficiency, increasing GHGe per unit of milk produced (Dunn *et al.*, 2014; Tao *et al.*, 2020). It is therefore vital that emissions are reduced sooner rather than later, to limit the effect of this negative cycle. However, it is not only dairy cows affected by heat stress and increases in temperature (Dunn *et al.*, 2014), as it impacts the whole ecosystem, which could be devastating for wildlife and biodiversity.

1.1.4 Agriculture's Contribution to Climate Change

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 GHGe, which has created a demand for research into the carbon footprint (CF) of the dairy industry. On the other hand, in the UK, the agricultural sector contributes to 10% of the country's GHGe (NFU, 2019), which can be seen in Figure 1 (BEIS, 2019). However, the industry accounts for most of the UK's ammonia (NH_3) emissions, equating to 88% (GOV, 2018), of which the dairy industry was responsible for 23% in 2017 (DEFRA, 2017). NH_3 is

of particular concern, as it combines with other gases in the atmosphere to form secondary particulate matter (Air Quality Expert Group, 2018; Britt *et al.*, 2021), which can cause serious health problems (GOV, 2018).

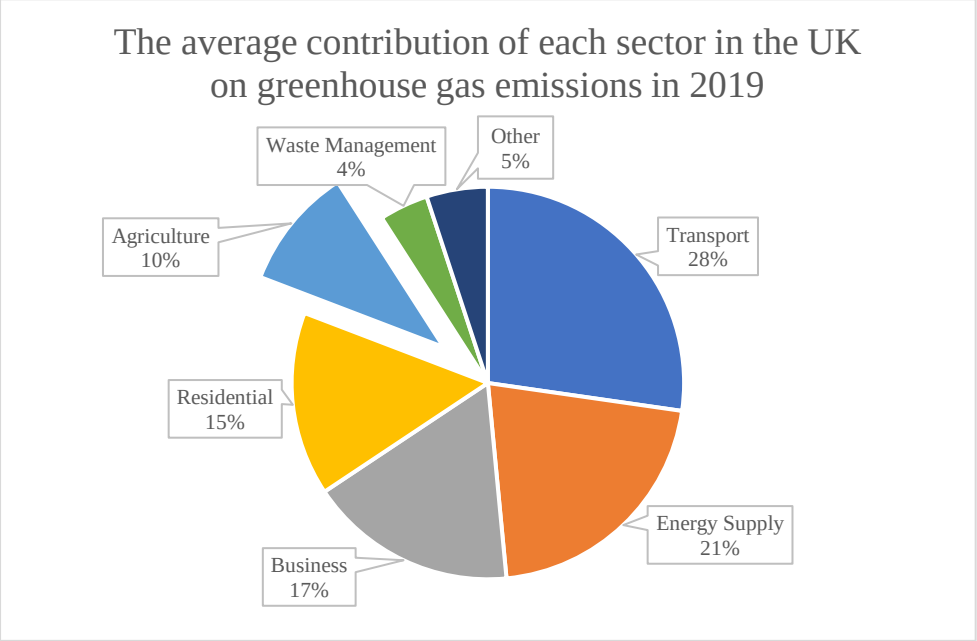

Figure 1: The average contribution of sectors in the United Kingdom (UK) to greenhouse gas emissions in 2019. It is important to note that the amount might not equal 100% as the numbers have been rounded to whole numbers. Data was taken from the Department for Business, Energy and Industrial Strategy (2019) to create the figure (BEIS, 2019).

1.1.5 Global Warming Potential

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). GHGe are often assessed based on global warming potential (GWP) to allow easy comparison between gases and their warming potential in comparison to CO_2. GWP 100 is the most used metric by the United Nations and IPCC, which converts the warming potential of the gas relative to one ton of CO_2 over 100 years (IPCC, 2007; EPA, 2024). CH_4 has a GWP 28 times higher than CO_2, and N_2O 265 times higher than CO_2, using GWP100, which can be seen in Table 2 (IPCC, 2007; AHDB, 2021a). CH_4 and N_2O 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). However, CH_4 is also a short-lived gas with a lifetime of 12 years in the atmosphere, significantly less than CO_2 (20-200 years) and N_2O (114 years). The difference in lifetime has led to te development of GWP* metric, which treats CH_4 as a short-lived gas and includes the removal of the gas from the atmosphere after 12 years (Lynch *et al.*, 2020). The application of GWP* however, is controversial, as it could underestimate GHGe (Cusworth *et al.*, 2022; Agrecalc, 2024b). The main GHGs produced from agriculture in the UK are CH_4 and N_2O, as highlighted in Figure 2 and the sector is also one of the main contributors to both 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 CH_4 emissions by 30% by 2030 (UNEP, 2021).

Table 2: The global warming potential (GWP) of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) over 20 and 100 years, as well as their lifetime in the atmosphere in years (IPCC, 2007; AHDB, 2021a).

Greenhouse gas	**Lifetime (years)**	**GWP 100 years**
CO_2	Variable 20-200 (to remove 65-80%) Hundreds of thousands of years to remove completely	1
CH_4	12	28
N_2O	114	265

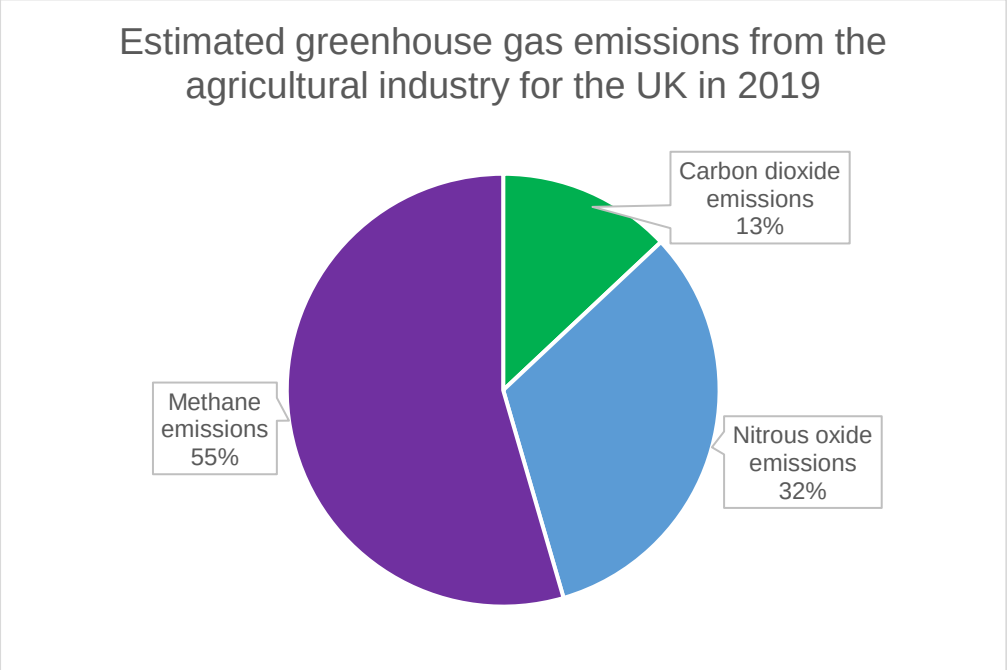

Figure 2: The estimated breakdown percentage of greenhouse gas emissions as CO_2e using GWP100 from the agricultural industry in 2019 in the United Kingdom (UK). Figure based on data derived from (DEFRA, 2021a).

2 Literature Review

2.1 Management of Dairy Production Systems

There are three main management systems in developed countries: pasture-based systems and housed systems, as well as a mixture of the two, known as mixed systems (Lorenz *et al.*, 2019). Pasture-based systems being defined in a meta-analysis, by Lorenz *et al.* (2019) as low input, with a 50% minimum pasture feed and maximum 25% concentrate feed. Compared to a mixed system of a maximum 50% pasture feed and at least 25% concentrate feed, where the cattle are housed in barns, but allowed to graze in the warmer summer months (Rotz, Stout, *et al.*, 2020). In contrast, cattle in housed systems have no access to grazing when the cattle are lactating (Lorenz *et al.*, 2019) and are housed in barns, except heifers that are sometimes pasture-based during maturation (Rotz, Stout, *et al.*, 2020).

2.2 The Average UK Dairy Farm

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, 2023b). The average herd size was largest in Scotland at 208, followed by England at 166, Wales 164 and Northern Ireland 124 cows. Holstein-Friesian breeds of cattle including the British Friesian and Holstein are considered the most common breeds in UK dairy farms, equating to almost 80% in 2019 (AHDB, 2020b). They are highly prevalent breeds due to being the greatest in size and therefore having the highest milk production (McGuffey and Shirley, 2011). However, mix breeds have increased since 2014, due to increased knowledge on the productivity benefits (AHDB, 2020b). The average lactating cow produced around 8,166 litres of milk annually in 2020 (GOV, 2023a) and in 2022-2023 the average UK Farm Business income was £229,200 (DEFRA, 2023b). The average lactation length in the UK was 315 days (AHDB, 2021c) and average calving interval 395 days (AHDB, 2023a). A survey of 148 UK dairy farmers found

the median dry period was 56 days (Fujiwara et al., 2018). The average RR was 30-35% in 2021 (DEFRA, 2021d). However, the optimum RR is 20-26%, with 50% of AHDB dairy farms performing within this bracket to date and 50% between 27% and 36% (AHDB, 2024a).

2.3 Annual Farm Emissions

Studies vary in their reported annual total farm carbon dioxide equivalent (CO_2e) emissions per kilogram (kg) of fat protein corrected milk (FPCM). Recent research simulated a dairy farm in Pennsylvania without carbon sequestration (CS), based on data from the Agricultural Resource Management Survey (Castaño-Sánchez, Karsten and Rotz, 2022). The authors analysed the farm CO_2e emissions against different cropping and manure management systems. The overall farm CO_2e emissions ranged from 1.11 to 1.13 (±0.01) kgs per kg of FPCM, which can be seen in Table 3. 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.

Table 3: Results from dairy farm LCAs on the average, minimum and maximum CO_2e emissions from the farm, the location of the study and the management system assessed.

Management system	Location	Average $kgCO_2e/kgMilk$	Minimum $kgCO_2e/kgMilk$	Maximum $kgCO_2e/kgMilk$	Author
Grazing	New Zealand	1.11[1]	-	-	(Rotz, 2018)
Grazing and housed	Ireland	1.21[1]	-	-	

[1] $kgCO_2e/kg$ of energy corrected milk (ECM)

Freestall housed	Pennsylvania	0.98[1]		-	-	
Free stall with anaerobic digestion (AD)	New York	0.75[1]		-	-	
Freestall and open lot	Idaho	1.04[1]		-	-	
A mixture of systems	Sweden	1.13[1]		0.94[1]	1.33[1]	(Henriksson *et al.*, 2011)
Pasture based	South Africa		-	1.17[1]	1.66[1]	(Galloway *et al.*, 2018)
Grass based	Ireland	1.26[2]		0.98[2]	1.67[2]	(O'Brien *et al.*, 2016)
A mixture of systems	Spain		-	1.21[2]	1.31[2]	(Salcedo Díaz *et al.*, 2024).
Housed	Ireland, the	1.52[2]		-	-	Sorley *et*
Mixed	UK, Spain,	1.24[2]		-	-	*al.*, 2024)
Grazing	Portugal and	1.13[2]		-	-	
	France					
Grass		1.46[2]		-	-	

[2] $kgCO_2e$/kg of fat-protein corrected milk (FPCM)

Grass with grain Housed (fed TMR)	Pennsylvania (USA)	1.15[2] 1.28[2]	- -	- -	(Rotz, Holly, *et al.*, 2020).
Mixture – using IPCC (2006)	Ireland	1.08 (0.92 with CS)[2]	-	-	Herron *et al.* (2022)
Mixture – using IPCC (2019)	Ireland	0.97 (0.81 with CS)[2]	-	-	

Rotz, Holly *et al.* (2020) also analysed the carbon offset capability, which ranged from 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 soil organic matter (SOM) accumulates, rather than a long-term ability.

Table 3 also shows how the annual emissions tend to vary according to location and production system, as a review using the Integrated Farm System Model compared the average CF of farms per kg of ECM for different locations and production systems (Rotz, 2018). The model did not include carbon sequestration (CS). Salcedo Díaz *et al.* (2024) modelled 212 dairy farms with various management strategies and found higher emissions than the other studies.

2.4 The Breakdown of emissions on dairy farms

GHGs from the dairy system consist of direct and indirect emissions. Indirect emissions being those generated from the inputs (Rotz, Stout, *et al.*, 2020; Segerkvist *et al.*, 2020), such

as the growing and transporting of animal feed for the livestock (Caffrey and Veal, 2013). Direct emissions on the other hand, are those produced on the farm (Segerkvist *et al.*, 2020), which consist of mainly CH_4 from enteric fermentation (EF; Løvendahl *et al.*, 2018; Mostert *et al.*, 2018, 2019; L. Wang *et al.*, 2019; Roque *et al.*, 2019; Drews, Czycholl and Krieter, 2020; Rotz, Stout, *et al.*, 2020) and manure management (Caffrey and Veal, 2013; L. Wang *et al.*, 2019; Mostert *et al.*, 2019; Drews, Czycholl and Krieter, 2020). CH_4 being the main contributor to the CF of the end milk product (Ibidhi and Calsamiglia, 2020). The breakdown of emissions from dairy farms, show the largest proportion of emissions from EF contributing to between 32 and 51% (Mc Geough *et al.*, 2012; Van Middelaar *et al.*, 2015; O'Brien *et al.*, 2016; Sorley *et al.*, 2024). CH_4 and N_2O from manure equated to 13 and 19%, soil and crops 28 to 29% (Mc Geough *et al.*, 2012; Sorley *et al.*, 2024), fertiliser 2% to 16% (O'Brien *et al.*, 2016; Sorley *et al.*, 2024), energy 2% (Mc Geough *et al.*, 2012), and indirect N_2O 7%.

2.4.1 Enteric Fermentation

2.4.1.1 General Introduction to Enteric Fermentation

The main cause of emissions from ruminant livestock is CH_4 from EF (Ellis *et al.*, 2010; Jose *et al.*, 2016; Roque *et al.*, 2019), which has been found to contribute to as much as 71% of GHGe from the dairy industry (Gilardino *et al.*, 2020). EF occurs in the rumen of ruminants where microorganisms breakdown feed of mainly carbohydrates into soluble molecules (Jose *et al.*, 2016), which helps balance the pH of the rumen to enable the cow to efficiently digest the feed (Løvendahl *et al.*, 2018). Ruminants and microorganisms have been evolving interdependently for 50 million years, as the rumen provides the perfect environment without oxygen for the organisms to thrive in (Løvendahl *et al.*, 2018). The microorganisms allow cattle to breakdown cellulose, the cell wall of plants (Vijn *et al.*, 2020) and convert difficult

plant material indigestible to most, to human food of high nutritive value (Niu *et al.*, 2016; Løvendahl *et al.*, 2018).

The process of breaking down feed creates CH_4 as a by-product, as it produces hydrogen and CO_2, which are collected by methanogens and combined to form CH_4 (Jose *et al.*, 2016; Roehe *et al.*, 2016; Patra *et al.*, 2017; Løvendahl *et al.*, 2018). The large contribution of EF to emissions has led to a focus on reducing EF to limit GHGe from the dairy sector (Dijkstra *et al.*, 2018), leading to more research on the impact and processes of methanogens, as the most promising strategy for reducing CH_4 emissions (Patra *et al.*, 2017). The production of CH_4 is a sign of dietary energy loss, which could impact milk productivity (Bryszak *et al.*, 2020), suggesting a low CH_4 emitting diet could also have a desired economical and productive effect, by improving milk production. Feed is the main variable that can be controlled to reduce CH_4 from EF (Weiss and Leip, 2012), explaining why several studies have identified feed as having a major potential to reduce livestock emissions (Weiss and Leip, 2012; Üçtuğ, 2019; Benaouda *et al.*, 2020; Rotz, Stout, *et al.*, 2020). Research has also highlighted dairy cows as the most influenced by feed, compared to other ruminants (van Gastelen, Dijkstra and Bannink, 2019) and thus has a large potential to limit emissions through feed. Research suggests improving the nutrition of livestock has the potential to reduce England's GHGe by 229 Kt CO_2e and it was estimated that in 2021, emissions had been reduced by 97 Kt CO_2e (DEFRA, 2021a).

2.4.1.2 Rumen microbiome

The amount of methanogens is associated with the genetics of the cow (Roehe *et al.*, 2016; Wallace *et al.*, 2019). Archaea can therefore be genetically selected to be low, to reduce the conversion of CO_2 and hydrogen to CH_4. Wallace *et al*. (2019) assessed over one thousand dairy cows, controlled the cattle's diets, and analysed the CH_4 emissions and genetic code for

the rumen microbiome of cattle from a variety of locations in Europe, including: the UK, Italy, Finland, and Sweden. They found the microbial profile in the rumen were heritable and the CH_4 emissions could be controlled for and reduced by selecting for the associated genes. It is also a practical solution to reduce emissions, as it is a cost-effective mitigation strategy for farmers (Richardson *et al.*, 2021). However, research into the area is scarce and breeding low CH_4 emitting cows is predicted to reduce CH_4 emissions only slightly from the overall industry. Researchers have also advised against prioritising lower emissions in genetic selection, due to the possible negative effect on milk production, as cattle would no longer be bred for high productivity.

2.4.1.3 Methods for Collecting Enteric Methane Emissions

There are several methods and equipment for quantifying the enteric methane emissions of cattle (Hammond *et al.*, 2016; Hristov *et al.*, 2018). The methods include indirect and direct methods, of which indirect tend to result in higher errors and lower validity (Hristov *et al.*, 2018). Various direct methods can be used to measure enteric CH_4 emissions (EME) directly from livestock, such as the respiratory chamber, sulphur hexafluoride (SF_6) tracer gas technique, ventilated hood, and the GreenFeed system (Patra, 2016). The most popular methods are long period measurements, such as the respiration chambers and the SF_6 tracer gas technique (Hristov *et al.*, 2018). There are also hood chambers, which cover the head of the cow to collect the CH_4 emissions without limiting movement, but this method is difficult to use on large scales due to time constraints, with training the animals to become used to the equipment (Hammond *et al.*, 2016; Patra, 2016).

Respiration chambers are deemed the most precise and accurate method of collecting EME at an individual animal level and at assessing the effect of diet on emissions (Hammond *et al.*, 2016; Hristov *et al.*, 2018). They are a long period measurement usually taken over 24 hours,

to assess the change in emissions over the course of the day (Arthur *et al.*, 2017). However, they require trained individuals to manage the equipment to gain accurate and replicable results (Hammond *et al.*, 2016; Patra, 2016; Hristov *et al.*, 2018). Respiration chambers are also expensive and require the animal to become accustomed to them, to reduce the probability of feed intake being impacted (Hammond *et al.*, 2016; Patra, 2016). The chambers are not without their faults, as they interfere with normal movement (Hammond *et al.*, 2016; Patra, 2016). The limited movement in the chambers lower the animal's energy usage, which could impact their emissions, especially when measuring pasture based cattle, which could affect the chambers representability of this management system (Hammond *et al.*, 2016; Patra, 2016).

The SF_6 tracer technique is also commonly used, where a tube is placed in the reticulorumen of the cow, which releases the SF_6 tracer gas at a set rate (Hammond *et al.*, 2016). The SF_6 gas mixes with the gases in the rumen, acting as a tracer for CH_4 created in the rumen. A canister collects the released SF_6 gas and CH_4 produced using the tubes placed near the mouth of the cow. The ratio of SF_6 to CH_4 is used to estimate the overall daily CH_4 production. Measurements are continued for at least five consecutive days, and it is more cost-effective than respiratory chambers. It is also less inhibiting, allowing cattle to remain in their natural environment on different production systems, making it more appropriate for use on grazing cattle, than the respiration chamber (Patra, 2016). However, when measuring emissions from cattle in pasture systems, the SF_6 technique does not include CH_4 emissions from the rectum, which equates to around three percent of the emissions (Muñoz *et al.*, 2012). The SF_6 tracer gas technique is therefore not always an accurate measurement of EME, having a ratio of standard deviation (SD) to the mean of 14%, compared to 11% for respiratory chambers (Muñoz *et al.*, 2012). In addition to this, when compared to respiratory chambers emissions, EME measured using SF_6 technique, varied by between five to ten

percentage more or less than the emissions collected from the respiratory chamber (Hammond *et al.*, 2016). Other research has found the SF_6 technique to show considerably less emissions to the respiratory chamber, overlooking as much as 15.6% of CH_4 emissions (Deighton *et al.*, 2014). However, this was using the traditional capillary tube method, which forms a vacuum to contain the gas, becoming less effective as the gas is collected and the vacuum effect diminishes. The method may therefore be inappropriate as a basis for enteric prediction equations.

However, there have been developments on the SF_6 tracer technique, which produced the same results as the respiratory chambers, by replacing the capillary tubes with orifice plates (Deighton *et al.*, 2014). The researchers favoured the SF_6 technique over the respiration chamber, as the technique is more flexible and can be used on multiple animals at once (Deighton *et al.*, 2014; Patra, 2016). The authors stated the improved SF_6 technique methodology would be suitable for genetically selecting low CH_4 emitting cattle (Deighton *et al.*, 2014). But, similar to the respiration chamber, to gain accurate emissions a trained user must manage the equipment, otherwise errors can occur (Hammond *et al.*, 2016; Patra, 2016; Hristov *et al.*, 2018). The researchers also attached the equipment to a saddle on the cow, rather than secured to the neck (Deighton *et al.*, 2014), which did not restrict movement to feed stalls and resulted in less damaged equipment. However, SF_6 usage should be limited, as it is a highly potent GHGe, over 22,000 stronger than CO_2 (IPCC, 2018).

Short-term gas collection methods, such as the GreenFeed system, are not as common as the long period methods (Patra, 2016). The GreenFeed system collects and measures emissions using sensors like the respiration chamber and an extractor fan (Huhtanen *et al.*, 2015). Feed is placed into the system to encourage the animal to visit the machine and place their head inside the hood. The time between entering the system and feed being presented and emissions being measured is set by the researcher (Hammond *et al.*, 2016). EME are

measured for short periods between three to seven minutes, throughout different periods of the day when feeding, for weeks or months, such as a full lactation, to create an average of the livestock's daily emissions. The data collection is thus, dependent on the animal voluntarily visiting the machine. However, the researcher controls when feed is available and can utilise this to measure emissions over multiple periods of the day and build a picture of the EME over time. It is a suitable method for measuring the EME of pasture-based cattle, being easily integrated into different systems.

2.4.1.3.1 Enteric Methane Prediction Equations

Measuring EME directly and reliably is time consuming, as it requires trained individuals and expensive specialised technology (Hammond *et al.*, 2016; Patra, 2016; Hristov *et al.*, 2018). Methods of collection and prediction need to be economical (Patra, 2016), which has led to the development of more cost effective methods of prediction, such as enteric CH_4 prediction equations. Prediction equations are used across the world to estimate the emissions of agricultural livestock (Hristov *et al.*, 2018). Direct measurement techniques are often used to collect EME from livestock to develop EME prediction equations. The researchers collate the data collected from livestock and commonly use general linear models to create equations to predict emissions, based on feed intake and dietary variables. However, EME prediction equations vary in complexity; most use simple readily available values, such as feed intake or GE, while more complex equations include several dietary composition variables, such as the fibre, fat and protein content of the diet (Hristov *et al.*, 2018; Benaouda *et al.*, 2019),milk composition variables, BW and energy intake (Hristov *et al.*, 2018). It is important that dietary composition variables, such as DMI, are estimated correctly for the models to accurately predict results (Hristov *et al.*, 2018).

DMI is seen as the most influential factor effecting CH_4 production (Hristov *et al.*, 2018), as DMI has a strong positive correlation to EME (Rico *et al.*, 2016). DMI can strongly predict EME in dairy cattle ($R^2 = 0.64$) and a combination of beef and dairy cattle ($R^2 = 0.69$; Ellis *et al.*, 2007). Ellis *et al.* (2007) found DMI was superior to MEI in predicting EME, as DMI generated lower RMSPE and greater R^2 values than MEI. However, the DMI of livestock is not always known in farming systems (Senga Kiessé *et al.*, 2019), which has led to the recommendation that equations are created excluding feed intake related variables (Hristov *et al.*, 2018). Therefore, studies have determined that milk factors, such as MY, ECM, milk fat and protein content are accurate predictors of feed intake to use in equations when needed (Appuhamy, France and Kebreab, 2016; Engelke *et al.*, 2018). However, research suggests that as milk factors are only used to predict DMI, DMI itself is a more accurate measure of EME (Engelke *et al.*, 2018). Engelke *et al.* (2018) assessed the goodness of fit of various EF prediction equations and found when ECM was included, the accuracy improved by a quarter. But, when DMI was included without ECM, accuracy improved by 41%, an enhancement of 16% compared to ECM inclusion. Nevertheless, Niu *et al.* (2018) found milk factors did not accurately predict EME.

Hristov *et al.* (2018) found that DMI only equations, were as accurate as more complex equations. But, DMI only equations do not allow comparison of dietary composition variables on EME (Vibart *et al.*, 2021), when fibre, fat, and protein content of feed has been shown to influence EME (Rotz, Montes and Chianese, 2010; Patra, 2013; Jose *et al.*, 2016; Niu *et al.*, 2016; Grandl *et al.*, 2019; van Gastelen, Dijkstra and Bannink, 2019; Børsting *et al.*, 2020; Arndt *et al.*, 2021). Even the inclusion of DMI in prediction equations has influenced results, due to the strong relationship between DMI and EME (Benaouda *et al.*, 2019). For instance, a review found increased fat content did not decrease EME using prediction equations (Benaouda *et al.*, 2019), in contrary to meta-analysis studies (Patra,

2013; Arndt *et al.*, 2021). It was speculated that the conflicting results were due to the high ether extract (EE) diets having a larger DMI and NDF content than the lower EE diets (Benaouda *et al.*, 2019). DMI only and simple equations are thus, not suitable for assessing dietary related mitigation strategies and are more suited for use in emission inventories (Vibart *et al.*, 2021). Benaouda *et al.* (2019) suggested that because of the large impact DMI has on EME, research into fat content should assess emissions based on grams per kilograms of DMI (CH_4/kgDMI), known as CH_4 yield. The use of CH_4/kgDMI would eliminate the effect of feed intake on EME, to isolate the effect of dietary composition on EME.

2.4.1.3.1.1 Evaluating the performance of prediction equations

Some of the studies developing EME prediction equations evaluated the performance of their equations using either R^2 values, RMSPE or both. The R^2 values reported by the individual studies for the published equations, ranged drastically from 0.04 (Ellis *et al.*, 2007) to 0.77 (Nielsen *et al.*, 2013). Ellis *et al.* (2007) developed three groups of EME prediction equations, one based on beef, one on dairy cattle, and the third set were based on a combination of dairy and beef cattle. The R^2 of the dietary variables were examined to assess how well the dietary variables predicted the EME of the livestock. EE had the highest value, strongly predicting EME for the dairy cows (R^2 = 0.84) and combined dataset (R^2 = 0.79), followed by MEI, but more so for the combined group (R^2 = 0.60), than the dairy group alone (R^2 = 0.53). NDF also predicted EME, but only moderately for the dairy database (R^2 = 0.44) and combined dataset (R^2 = 0.42). The equations were based on housed dairy cattle from respiration chamber results and a small portion of SF_6 emission results.

Few studies have evaluated and compared the performance of enteric CH_4 prediction equations. Appuhamy, France and Kebreab (2016) reviewed the performance of prediction equations for representing the EME of cattle for different regions and ranked them based on

root mean square prediction error (RMSPE) and concordance correlation coefficient. The equations showed a range in weighted RMSPE percentage from 10.97 to 18.85 and 10.71 to 19.4 when unweighted for the top ten performing equations for the different regions. In total, only 10 of the 22 top ranking equations, less than 50% (45.45%), included at least one other factor, besides DMI or gross energy intake (GEI), with only five equations containing at least three factors, which equates to less than a quarter of the top ranked equations (22.73%).

Niu *et al.* (2018) used an international dataset of EME from lactating dairy cows, to develop prediction equations for the intercontinental dataset, as well as regional equations for Europe and the United States of America. The authors measured the accuracy of the equations based on RMSPE, which ranged from 14.6 to 37.5% across the intercontinental and regional datasets. Niu *et al.* (2018) found CH_4 emissions varied per kg of DMI from 9 to 30.4gCH_4/kgDMI for the intercontinental dataset of 2,555 measurements and an average of 20.1gCH_4/kgDMI. The equation based on DMI, NDF, EE, BW and milk fat was the most accurate at predicting EME, but the second-best performing equation was NDF and DMI, which led to the authors recommending the latter, due to its simplicity and ease of access to the required data and calculation, compared to the best performing equation, which required knowledge on five variables to function.

Benaouda *et al.* (2019) reviewed the performance of 40 dairy cattle EME predictions and found EME per kg of DMI varied from 6.53 to 41.7gCH_4/kgDMI, across dairy cattle data from Europe, the USA and Australia. The RMSPE for the top 13 ranking equations for predicting EME from dairy cattle ranged from 15.6 to 27.4% and eight were based on only DMI or GEI, contributing to most of the equations (61.54%). The three reviews used a range of dietary composition factors as inputs for the equations, and a table of the range of the values can be found in Table 4 below (Appuhamy, France and Kebreab, 2016; Niu *et al.*, 2018; Benaouda *et al.*, 2019).

Table 4: The range of the dietary composition values used in the three review studies for dairy cattle in Europe. Data derived from Appuhamy, France and Kebreab (2016); Niu et al. (2018); Benaouda et al. (2019).

Descriptive statistic	BW[3]	DMI[4]	GEI[5]	CP[6]	EE[7]	NDF[8]	Methane yield[9]
Minimum	283	4.17	104	8.1	1.1	13.4	6.53
Maximum	956	33.5	605	27.4	9.4	69.7	50.4

2.4.1.4 Dietary Impacts

2.4.1.4.1 Digestibility and enteric methane emissions

Enteric emissions vary depending on the type of feed consumed (Jose *et al.*, 2016; Vetter *et al.*, 2018; Drews, Czycholl and Krieter, 2020), because they rely on the digestibility of the feed (Weiss and Leip, 2012). Diets that are lower in digestibility and thus more difficult to digest, result in higher volatile fatty acid (VFA) production to breakdown feed, resulting in larger EME (Weiss and Leip, 2012; Monteiro *et al.*, 2019). An example of a feed component low in digestibility (FAO, 2020) and high in CH_4 emissions is fibre (Rotz, Montes and Chianese, 2010; Jose *et al.*, 2016), which is found in the cell wall of plants, such as cellulose (Jose *et al.*, 2016). Pasture-based cattle and those fed grass pellets, therefore eat a high fibre diet and emit large EME (Grandl *et al.*, 2019). The larger the proportion of forage and fibre in a cow's diet, the higher the EME they produce, as Niu *et al.* (2016) found those fed a low forage quantity of 38%, released 7.2% less EME, than those fed a high forage diet of 53%, or 12.6% less per kg of ECM. A study in Ireland also found this, as cattle on a high grass diet

[3] Body weight (BW) = kilograms
[4] Dry matter intake (DMI) = kilograms per day
[5] Gross energy intake (GEI) = megajoules per kilogram of dry matter
[6] Crude protein (CP) = percentage of dry matter
[7] Ether extract (EE) = percentage of dry matter
[8] Neutral detergent fibre (NDF) = percentage of dry matter
[9] Methane yield = grams of methane per kilogram of dry matter

(384g/day or 24.9g/kg milk yield) emitted 10% more CH_4 emissions than cattle on a low grass diet (349g/day or 24.5g/kg milk yield), when CH_4 was measured using the SF_6 tracer gas technique (an extra 35 g/day, $P < 0.001$). They also assessed a low grass diet supplemented with a partial TMR, which had the lowest emissions when presented per kg of milk yield (23.9), but highest per grams per day (406; O'Neill *et al.*, 2012). Previously, a TMR (397g CH_4/day or 200g CH_4/kg fat and protein yield) was compared to a grass-based diet (251g CH_4/day or 174g CH_4/kg of fat and protein yield), which resulted in higher emissions irrelevant of the unit used, suggesting that a mixture of grass and partial TMR may reduce enteric CH_4 further than a TMR (O'Neill *et al.*, 2011).

2.4.1.4.2 Feed Concentrates

A method to decrease EME is to reduce the fibre content of dairy cattle diets by increasing the proportion of concentrate. Concentrates are high in carbohydrates, providing a reliable amount of nourishment and increase the starch content of the diet (Bell and Wilson, 2018). The substitution of fibre to starch thus, reduces the EME of cattle (Dijkstra, Oenema and Bannink, 2011; Grandl *et al.*, 2019; van Gastelen, Dijkstra and Bannink, 2019), with the potential to reduce CH_4 yield by 14%, compared to pasture and 27% per kg of milk produced (van Gastelen, Dijkstra and Bannink, 2019). Cattle fed low fibre feed also expel lower amounts of urea N, than cows on a high fibre diet (Niu *et al.*, 2016). It is important cattle receive adequate rapid fermentable carbohydrates, as they increase the efficiency of microbial protein synthesis in the rumen; an essential process that allows bacteria to breakdown feed in cattle (Niu *et al.*, 2016).

2.4.1.4.2.1 Sources of carbohydrates

There are different sources of carbohydrates, such as sugar and starch, which result in various CH_4 emissions (Børsting *et al.*, 2020). Diets high in starch have low emissions (Rotz, Montes

and Chianese, 2010; Børsting *et al.*, 2020), while high levels of sugar create large emissions, because they produce different types of VFAs (Børsting *et al.*, 2020). For instance, diets high in starch lead to propionate production, which does not convert as much hydrogen to CH_4 as butyrate that is produced from sugar. Børsting *et al*. (2020) assessed the impact of wheat; a high starch diet, against a high sugar diet; molasses, and found the molasses diet produced proportionally 4% more butyrate (19%) than the wheat diet (15%). Whereas the wheat diet produced almost 9% more propionate acid (22.6 litres/hour) than the molasses diet (20.8). The difference in carbohydrates and VFA production led to the wheat diet releasing 5.8 litres of CH_4 per day (CH_4L/day), whereas the molasses diet produced over four and a half times more CH_4, at 27.1 CH_4L/day. The EME varied across the time of day, increasing dramatically after feeding times and slowly decreasing until the next feed.

The effect of fibre digestibility was controlled in the Børsting *et al.* (2020) study, so levels of fibre could not have impacted the emissions produced. However, the wheat diet had a lower feed intake than the molasses diet, which could have caused the lower EME and led to concerns over the effect on milk production. Forage is important for the wellbeing of cattle, who are anatomically designed to digest high forage diets (Krause and Oetzel, 2006), to gain their required energy, protein and vitamin requirements (Bell and Wilson, 2018). Microbial protein synthesis is also encouraged by high forage diets, more than low forage diets, as well as needing long particles to chew to produce saliva and maintain a healthy pH of the rumen (Krause and Oetzel, 2006). Hence, there are health concerns with lowering forage quantity for grain-based concentrate, as the diet could significantly reduce the pH of the rumen, leading to acidosis; a serious health condition (Krause and Oetzel, 2006; Vallejo-Timarán *et al.*, 2020; Arndt *et al.*, 2021). In addition to the serious threat to the wellbeing of the cow, acidosis can also cause poor fertility (Vallejo-Timarán *et al.*, 2020), which would increase GHGe from the farm.

2.4.1.4.2.2 Fat Content

There is also an argument that increasing the fat content in feed can lower the EME of dairy cattle. Patra (2013) conducted a meta-analysis of 29 studies and found increased fat content in feed lowered CH_4 emissions of cattle by 15%. CH_4 emissions decreased by almost 4% (13.4gCH_4/day), for each 1% increase in fat concentration when fat levels were between 1.24 and 11.4%. Another meta-analysis found similar results, with fat and oil reducing daily CH_4 emissions by a mean of 20% and CH_4 yield by 15% (Arndt *et al.*, 2021). Theory suggests fat content reduces EME in dairy cattle because fats are not broken down in the rumen with unsaturated fatty acids (FA) restricting methanogenesis. Therefore, high fat content diets do not require the large production of acid, reducing the amount of butyrate acid produced (Patra, 2013), which converts hydrogen into large proportions of CH_4 (Børsting *et al.*, 2020). Figure 3 below shows a flow chart illustrating the impact of diet composition factors on VFAs and methane production.

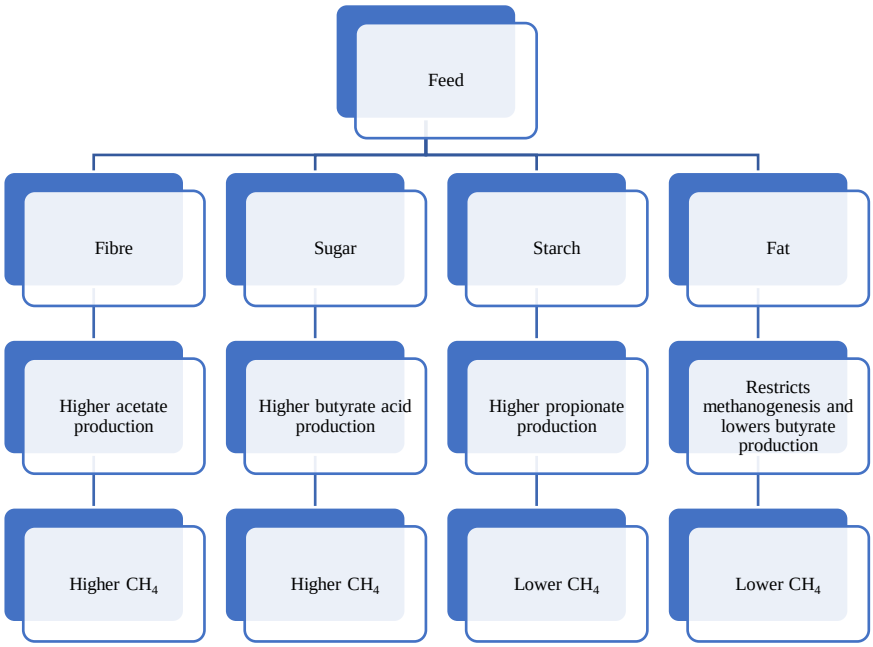

Figure 3: Flowchart illustrating the impact of dietary composition variables on volatile fatty acid production (VFA) and whether this leads to higher or lower CH_4 production. Data derived from (Børsting et al., 2020; Arndt et al., 2021).

2.4.1.4.2.3 The Environmental Impacts of the Sources of Fat in Dairy Cattle Feed

It is important the source of fat in cattle feed is considered, as in the past palm oil has been used, as it increases milk production in dairy cattle (Lunsin, 2018). However, palm oil has devastating environmental effects, by contributing to eutrophication, acidification, biodiversity loss (Saswattecha *et al.*, 2015), and deforestation (Aquilas *et al.*, 2022). In addition to health problems for those in the affected areas, due to the air pollution from large fires to clear land for palm oil production (Teng, Khong and Che Ha, 2020). After large public concern over the impacts of unsustainable palm oil, the UK government have encouraged the use of certified sustainable palm oil (CSPO) that is certified by the Roundtable on Sustainable Palm Oil (RSPO; DEFRA, 2014). In addition to this, the Agricultural Industries Confederation (AIC) swore to buy only sustainable palm oil from the autumn of 2014, improving the sourcing of palm oil to the UK.

Research into the different fats in ruminant feed also found palm oil did not result in different EME to the control group (Martin *et al.*, 2021), so the usage of palm oil did not reduce enteric emissions. However, the authors concluded that this could have been due to the low proportion of palm oil in the diet, at 1-3% of dry matter (DM). The potential for other sources of oil such as coconut and canola oil have been found to reduce CH_4 emissions (Hollmann *et al.*, 2012; Pinares-Patiño *et al.*, 2016). Coconut oil reduced CH_4 by up to 449 grams a day, per unit of milk energy produced (Hollmann *et al.*, 2012). However, it is vital that the fat content of dairy cattle diets is monitored, as excessive levels can reduce the digestion of feed and therefore negatively impact milk production (Hristov *et al.*, 2013; Patra, 2013). While a recent meta-analysis did not find the change in diet to impact milk yield, DMI was reduced by 6% on average (Arndt *et al.*, 2021) and a prior meta-analysis found fat content could

contribute to a maximum of 6% of the diet, without reducing milk production. The length of the mitigation effect was also uncertain, as the canola oil study was conducted over 12 days (Pinares-Patiño *et al.*, 2016). It was recommended if lipids were included in the diet, to contribute to a maximum of 7% of the DMI of the livestock. Other sources of fat, such as corn oil, substantially reduced CH_4 emissions by a mean of 30%, suggesting they were more suitable for use in cattle feed to increase fat content (Martin *et al.*, 2021).

2.4.1.4.2.4 Protein Content

Protein is another important component in cattle feed, which is usually measured using crude protein (CP) levels. A small study consisting of six lactating Holstein cattle were given a total mixed ration of 80% maize silage (MS) and 20% concentrate, with either 18% CP of DMI or 12% CP (Edouard *et al.*, 2016). N_2O emissions were not significantly affected by the change in protein levels, as each diet resulted in 0.76g/day of N_2O per cow. Whereas CH_4 emissions for the high CP diet were higher by 1.6g/kg when measuring per DMI, however, when g/day were considered, the low CP diet was slightly higher by 19g/day. The results were likely influenced by dry matter intake (DMI), as the high CP diet had a lower DMI, by 0.8kg DMI/day ($P< 0.001$) compared to the low CP diet (Edouard *et al*., 2016).

Protein tends to contain around 16% N, so CP is calculated as the percentage of N in feed times 6.25 (Erickson and Kalscheur, 2020). Protein intake impacts N intake, due to the N content of protein. For instance, when cattle were fed high protein (HP) diets, their N intake was raised by 115 g/day, in contrast to low protein (LP) diets (Niu *et al.*, 2016). N intake can become an issue to the health of cattle when the protein content in feed is above nutritional requirements, increasing the risk of lameness and reducing fertility (Sinclair *et al.*, 2014; AHDB, 2019). Surplus N is also excreted from the body, which can pollute the environment

(Herremans *et al.*, 2020), such as the release of NH_3 emissions (Sinclair *et al.*, 2014; AHDB, 2019).

NH_3 emissions were considerably lower for the low CP diet (1.03g/NH_3/h/per cow) than the high CP diet (1.25 g/NH_3/h/per cow). A meta-analysis of housed systems found CP and NH_3 were highly associated to each other, with an R^2 of 0.8 and lowering CP levels in cattle diets could reduce NH_3 emissions by a minimum of 4%, an average of over 40% and a maximum of 73% (Sajeev *et al.*, 2018). The NH_3 emissions included those from urine, faeces and storage. Cattle are also more likely to release N through urine as urea than stool, which is more difficult to control and prevent leaching (Dijkstra *et al*., 2011; Herremans *et al*., 2020). A 6% increase in the protein content of diets led to significantly higher N excretion from urine from 65g (N intake 415g/day), compared to 243g/day (N intake 626g/day) (Edouard *et al.*, 2016). The most efficient method suggested for reducing N emissions was limiting protein fed to lactating dairy cattle to that needed (Britt *et al.*, 2021).

2.4.2 Manure Management

Manure from dairy cows equates to around seven to ten percent of emissions from milk production (Soteriades *et al.*, 2018), consisting of mainly CH_4 and N_2O emissions (Drews, Czycholl and Krieter, 2020; Rotz, Stout, *et al.*, 2020). Manure emissions are impacted by multiple factors, such as dietary composition, soil when spread on land, storage and the weather, such as temperature (Vibart *et al.*, 2021). Research suggests the main difference effecting the emissions from manure management systems are the type of storage used and length of time it is stored. For instance, manure can be stored in liquid or solid systems, also known as dry systems (Owen and Silver, 2015; IPCC, 2019a), which produce different quantities of CH_4 (Aguirre-Villegas and Larson, 2017). They are often stored in different conditions, as solid manure tends to be collected in stockpiles and decomposes aerobically (Aguirre-Villegas and Larson, 2017). Whereas liquid manure is stored in anaerobic

conditions, an optimum environment for microbes to break down the substance, such as ponds or lagoons, leading to higher CH_4 production (Aguirre-Villegas and Larson, 2017). However, N_2O emissions are higher when solid systems or dry manure systems are used (FAO, 2020).

2.4.3 Artificial Fertilisers and Pesticides

A review of 30 papers on the environmental impacts associated with cattle, highlighted one of the focal points, as N from fertilisers (Segerkvist *et al.*, 2020), likely because fertilisers are one of the lead causes of N_2O emissions in dairy systems (Wang *et al.*, 2019). The main components of fertilisers are N, potassium, and phosphorus, as well as the macronutrients calcium, magnesium, and sulphur to improve the productivity of the soil (Caffrey and Veal, 2013). It is important that the amount of fertiliser used is monitored, as excess use can lead to poor soil quality. The organic matter in fertilisers absorb water, meaning excessive usage can lead to oversaturation of soil, leading to poor drainage and the soil becoming waterlogged, which can even lead to a reduction in micronutrients (Liu *et al.*, 2021). Fertilisers can also cause eutrophication (Evans *et al.*, 2018), where fertilisers including manure, leach into water systems negatively impacting marine life, by decreasing the quantity of oxygen in the water (DEFRA, 2023a). However, in the 2021 FPS 62% of English farmers had reported improving the precision of their N fertiliser application (DEFRA, 2021b).

To encourage high productivity and limit crop losses, pesticides are commonly used in agriculture and consist of nematicides, herbicides, fungicides and insecticides (Vetter *et al.*, 2018). These agents prevent weeds from growing to decrease competition over the area, as well as fungi and pests such as insects and rats (Vetter *et al.*, 2018; Food Standards Agency, 2021). However, the toxins can also enter the food chain, from organisms eating the plants and predators eating those animals, or by leaching into water systems (Hassaan and El Nemr, 2020; Jia *et al.*, 2020). The pesticides can increase in concentration through biomagnification

and lead to long term health problems. These chemicals are also dangerous to the bee population, as alcohol ethoxylates in fungicides have been linked to gut damage, weight loss and a 30% fatality rate in the species (Straw and Brown, 2021).

2.4.4 Energy Use

GHGe are also produced on farm from energy used, such as from housing cattle, the milking process and fuel, which is higher when obtained from fossil fuels (Rotz, Holly, *et al.*, 2020). The management system can impact the emissions generated from energy use, such as purchased feed transported to the farm has higher emissions than pasture (Rotz, Holly, *et al.*, 2020). While housed systems have the largest energy demand, from feed and housing requirements. In a study in China, the main energy use consisted of transportation and feed production, responsible for 95% of energy use (Wang *et al.*, 2019). The production of feed being the second largest contributor to GHGe in livestock, responsible for approximately 41% of emissions from global livestock (FAO, 2020). In England, increasing energy efficiency was one of the most used strategies to reduce emissions, by 79% of English farmers surveyed in 2021 (DEFRA, 2021b).

2.4.5 Transport

Considering the life cycle of milk production to the farm-gate, transportation has a minimal impact (Üçtuğ, 2019). Fuel might be the main cause of CO_2 emissions from the agriculture industry, but this accounted for less than 2% of the UK's emissions in 2019 (DEFRA, 2021a). In the dairy industry in China, feed transportation accounted for 0.7% of the total GHGe of the dairy system, having the lowest impact on emissions (Wang *et al.*, 2019). The efficiency of vehicles is also improving, so it is presumed that transport emissions will decline in the future, rather than increase or stabilise (Vetter *et al.*, 2018). In addition to this, transportation emissions from feed are often out of the farmers control (Vetter *et al.*, 2018), so it is not an easy way to reduce emissions from the system. However, LCAs past the farm-gate must

acknowledge that milk requires refrigeration, which contributes to the ozone layer depletion from chlorofluorocarbons (CFCs), which increase as miles of transportation increase (Üçtuğ, 2019). However, improving transport routes and increasing the use of low carbon vehicles will reduce transport emissions (Üçtuğ, 2019).

2.5 Methods to reduce and inhibit emissions

2.5.1 Reducing Replacement Rates

2.5.1.1 Reasons for Replacement Heifers

There are several reasons dairy cattle are lost from the herd and replacement heifers are required to replace them (De Vries and Marcondes, 2020). Cattle can be removed due to involuntary reasons, such as from suffering health problems or factors that are considered voluntary reasons, such as low productivity, low fertility (Garnsworthy, 2004; Holtsmark *et al.*, 2008; Bell and Wilson, 2018), or the failure to become pregnant. Poor fertility leads to high replacement rates (RRs; Lahart *et al.*, 2021), as successful pregnancies are critical to the lactation, output and thus profit of farms. Low fertility and high RRs then lead to higher levels of GHGe than farms with higher fertility and low RRs (Lahart *et al.*, 2021). Research assessing the impact of low fertility on total farm CH_4 emissions, highlighted that heifer replacements contributed to as much as 27% of CH_4 emissions (Garnsworthy, 2004). In addition to being responsible for 8 to 15% of NH_3 emissions. The underlining reason for RR thus tends to be economical, as it can be more cost-effective to cull low producing cattle and replace them (De Vries and Marcondes, 2020), than to address the problem, especially if heifers are reared on-farm and can easily replace the problematic cow.

2.5.1.2 Replacement Rate and Greenhouse Gas Emissions

The issue with replacement heifers is rearing, as it is an economic cost if kept on-farm from feed and housing (Beukes *et al.*, 2010), yet they do not produce milk and therefore revenue

for the first two years of their lives (De Vries and Marcondes, 2020). A German LCA study of 92 farms for the year 2013, assessed the influential variables on GHGe by conducting a sensitivity analysis. The results highlighted five influential variables, of which RR equated to 8% (Zehetmeier *et al.*, 2020), using a mean RR of 24% with a range of 11 to 45%.

A prior study investigated RRs on GHGe, using a baseline RR of 40%, an average RR for the time and Atlantic region (Weiske *et al.*, 2006). They reduced the RR to 30%, which also increased lactations per cow per lifetime. In addition to comparing the impact of keeping heifers until mature or selling them as newborns. The baseline 40% RR assumed cattle were kept on farm and resulted in a mean of 1.47kg CO_2e per kg of milk, while a 10% reduction in RR to 30% resulted in 2.72% less emissions per unit of milk (1.43 kg CO_2e per kg of milk) or 2.53% reduction in total farm emissions. When newborns were sold, emissions were also lower than when they were kept on farm, by 5.44% in the 40% RR, or 4.9% for total farm emissions, with emissions reducing even further from the baseline 40% to the 30% sold scenario, by 11.57% per unit of milk or 10.57% per total farm emissions. Emissions also reduced between the sold farms by 6.48% from the 40% RR to the 30% RR per kg of milk, or 5.96% per total farm emissions. However, the mean emissions suggested that a 40% RR where newborns were sold would result in lower emissions, than a 30% RR where heifers were reared on farm, by 2.8% per kg of milk and 2.44% per total GHGe. In total, emissions reduced by a maximum of 13% per unit of milk produced from the 40% RR to the 30% RR.

Another model found reducing RRs by 5% from 21% to 16%, could decrease CH_4 emissions by 5.62%, however, the cattle in the 16% RR had a lower DMI than the cattle in the 21% RR cattle, which may have caused the lower emissions, rather than the reduction in RRs (Beukes, Gregorini and Romera, 2011). The standard CO_2e emissions for the farm were 1.1 kg CO_2e/kgFPCM and could be reduced to 0.8 kg CO_2e/kgFPCM, by using a combination of mitigation strategies, including reducing RRs, improving genetics, standing off cows in April

and March, growing crops, reducing fertiliser usage, reducing stocking rate, and harvesting silages on-farm. While an alternative model compared different types of Holstein-Friesian cattle with varying RRs (O'Brien *et al*., 2010). GHGe reduced by 9% per kg of milk when RR reduced from 35% in the high production north American Holstein-Friesian group to 18% for the New Zealand Holstein-Friesians.

2.5.1.2.1 Why do lower replacement rates lead to lower emissions?

Prior studies have concluded that the reduction in emissions when lowering RRs is due to the reduction in heifers producing emissions and not contributing to milk production (Weiske *et al.*, 2006; O'Brien *et al.*, 2010; Zhu, Schneider and Oude Lansink, 2023). A lower RR reduces the number of animals not contributing to milk production and so increases total MY (O'Brien *et al.*, 2010). A higher MY then lowers emissions per kg of milk, as the emissions are spread further across the output, reducing emissions when expressed per yield (Van Middelaar *et al.*, 2015).

2.5.1.3 How to reduce replace replacement rates

2.5.1.3.1 Genetic Selection

The unvoluntary need to replace cattle could be reduced by improving the fertility and health of cattle. A method to improve these aspects, could be genetic selection. Currently, genetic selection is used to improve livestock performance, such as milk production (De Vries, 2020), to surpass that of prior generations (De Vries, 2017). It is a priority of the industry to breed for high producing cattle, as this leads to a higher milk supply and profit for the farm (Richardson *et al.*, 2020). However, the time between breeding genetically superior calves and their first lactation should be small, to benefit from genetic selection. The traditional method, therefore, promotes short lifespans and leads to high replacements, as the cows are

often culled and swapped with the genetically superior heifers (De Vries, 2017; De Vries, 2020).

RRs could be reduced by altering the breeding strategy of cattle, such as a focus on improving fertility levels. Over the past 40 years, fertility of dairy cows has decreased (Pryce *et al.*, 2014), which has led higher RRs and emissions. Research suggests re-establishing past fertility levels could reduce emissions from RRs by 10% and further improvements could lead to an additional 14% reduction (Garnsworthy, 2004). In addition to decreasing NH_3 emissions by 9 to 17% per herd, or 4 to 8% per individual cow. Breeding for high fertility could thus, improve the productivity of herds and reduce the voluntary removal of cattle. However, fertility has improved since 2010 in the UK, with age of first calving reducing by over two years and lower calving intervals (Hanks *et al.*, 2023). Nevertheless, there is room for improvement with the current median below set targets, as the pregnancy rate of UK dairy herds was 16% in 2023, while the set target was 21%. The median conception rate was also 6% lower than the target.

2.5.1.3.2 Length of Productive Lifespan

Breeding for higher fertility and improving the genetic worth of cattle is beneficial, however, the issue remains with cattle being quickly replaced for those genetically superior. The method leads to short lifespans and high RRs. The lifespan of cattle tends to be referred to as length of productive lifespan (LPL); the number of years the animal produces milk, which is typically between two and a half to four years in developed countries (De Vries and Marcondes, 2020). The life expectancy of dairy cattle is between four and a half to six years old, significantly lower than their natural lifespan of 20 years (De Vries and Marcondes, 2020). Researchers promote the use of strategies that expand the LPL of dairy cattle to reduce

GHGe (Van Middelaar *et al.*, 2015; Zehetmeier *et al.*, 2020; Zhu, Schneider and Oude Lansink, 2023).

Lengthening the lifespan of dairy cattle could lower emissions (Grandl *et al.*, 2019; Owusu-Sekyere *et al.*, 2023; Zhu, Schneider and Oude Lansink, 2023). The effect of increasing the LPL on RRs and emissions has been assessed in a case study in Switzerland (Grandl *et al.*, 2019). The study consisted of a small group of 30 cows and tested increasing the LPL from one to seven years. The reduction in RRs led to more than a 40% decrease in overall farm emissions, such as from EF. The increase in LPL also significantly improved the economic efficiency of the farm, reducing costs of replacements by 29% and improving milk production and thus, profits. Milk productivity tremendously increased over 400 days and continued to increase, at a smaller rate afterwards.

Modelling has shown farm GHGe to reduce by 2-3% by reducing RRs from 27% to 22.5% (Van Middelaar *et al.*, 2015). EF equated to the largest proportion of emissions (48%) followed by production of concentrates (18%), manure management (13%) and on-farm roughage production (13%; Van Middelaar *et al.*, 2015). GHGe reduced by 24kg CO_2e per tonne of FPCM using no allocation factor and 16kg using economic allocation. Lower efficiency reduced the benefit of longevity, as rearing costs compromised a low proportion compared to total costs, reducing the benefit of increased milk production and lower costs.

2.5.1.3.2.1 Parity, Health, and Milk Production

The main concern with increased lifespan is the potential issues that may arise from keeping older cattle on farm, such as their milk productivity, health, and wellbeing. Primiparous cattle tend to have a lower MY than multiparous cows (Meir *et al.*, 2019; Margerison and Geoghegan, 2022; Marumo *et al.*, 2022; Morales-Piñeyrúa *et al.*, 2022), which is thought to be due to heifers calving at 24 months old or younger when they are still developing

(Marumo *et al.*, 2022). Heifers experience puberty around 60% growth to their adult body weight (BW), which means they often calve before they reach their full BW (Boro *et al.*, 2016). Multiparous cattle are also less susceptible to heat stress, as it effects primiparous cow's milk production slightly more than multiparous cows (Marumo *et al.*, 2022), suggesting that primiparous cows might be more at risk of the effects of climate change than multiparous cattle.

Cows with a larger parity have impaired mobility compared to cows with a lower parity (Margerison and Geoghegan, 2022) and research suggests that parity one cows have a much larger BCS than other parities (Lean *et al.*, 2022). However, a study analysing pre-calving BCS across 12,168 cows from 212 study groups found that parity 2 cattle had the lowest BCS for both TMR and pasture-based cattle (Lean *et al.*, 2022), compared to parity three or above. There were no significant differences in BCS for parities 3, 4, 5 or above, suggesting parity does not influence the body condition of cattle pre-calving (Lean *et al.*, 2022). Parity 5 or above cows had a lower BCS in the TMR system but higher BCS in the pasture-based system. Pasture based cattle could therefore be a more suitable system for extending the parity and lifespan of dairy cattle to have a smaller impact on the health of the cattle.

2.5.1.3.2.2 Animal Welfare

An increased LPL of cattle, ensuring mobility and health is not impacted, could be considered higher in animal welfare (AW), as it promotes the longevity of cattle closer to their natural lifespan (De Vries and Marcondes, 2020). The strategy could be promoted as an improvement in AW, which could increase uptake of the management. The public are also highly driven to encourage these methods, as it is one of consumers top concerns when purchasing milk (Rotz, Holly, *et al.*, 2020). A survey in the United States of America (USA) of 493 individuals, not related to the agriculture industry, asked respondents to describe their

ideal dairy farm and the respondents' main concerns were the AW of the cows (Cardoso *et al.*, 2016). The public's demand for high AW when purchasing products would therefore influence the farmers decision making.

Good AW is enforced at a high level in the UK, as approximately 95% of milk made in the UK is from Red Tractor certified dairy farmers, which work to high environmental and AW standards (Countryside Online, 2018). The second highest concern from the USA survey was the quality of the milk produced for consumer health, while only 4.5% from the first survey results and 6% of the second, mentioned environmental issues, such as the sustainability and environmental consciousness of the farm. Methods for reducing emissions from the farm, could therefore be beneficial if linked to items of concern, such as improving AW, through increasing the lifespan of cattle or enhancing the milk health benefits, such as through feed.

2.5.1.3.2.3 Breeding for Longevity

Longevity is heavily shaped by the environment (Hu *et al.*, 2021), with low heritability (Hu *et al.*, 2021; Zhang *et al.*, 2022), as low correlations have been found between heritability and dairy cattle longevity traits (Zhang *et al.*, 2022). However, finding and breeding for the traits genetically correlated to the longevity of dairy cows could improve their lifespan (Hu *et al.*, 2021; Zhang *et al.*, 2022). A review found a medium correlation between longevity and reproduction (Zhang *et al.*, 2022), therefore breeding for high fertility could also benefit the longevity and emissions of the cattle. As well as selecting for health-related traits when breeding, due to the higher heritability of these variables, such as replacement survival and birth weight.

2.5.1 Reducing Soya Bean Production and Demand

The global demand for cow's milk has increased over the years, by almost 44% between 1997 and 2017 (FAO, 2020, cited in Gill, Garnsworthy and Wilkinson, 2021), which has

encouraged increases in protein, such as the use of soyabean meal (SBM) in livestock feed (Gill, Garnsworthy and Wilkinson, 2021). Soya bean (SB) production has increased 15-fold since the 1950's (Gill, Garnsworthy and Wilkinson, 2021) and was the fourth most traded commodity in the world in 2018 (IG, 2018). In 2022, 389.8 million metric tons (Mt) of SB was produced globally (USDA, 2022a), most of which was for animal consumption. In 2019 around 75% of globally produced soy was grown for animal feed (Fraanje and Garnett, 2020) and nearly all soy cake produced globally (99%) was used as animal feed, however, only 2% of this was used for dairy cattle feed (USDA, 2019, cited in Fraanje and Garnett, 2020). In 2019, the UK imported more than two million tonnes of SBM for livestock feed such as swine, poultry, and cattle (EFECA, 2019).

2.5.1.1 The Impact of Soy on the Environment

2.5.1.1.1 The Amazon Rainforest

Almost 90% of deforestation in the world is due to agriculture (DEFRA, 2023a) and particularly the large production of soy in South America (Fraanje and Garnett, 2020). The creation of soy has led to the deforestation specifically of the world's largest rainforest; the Amazon rainforest (Fraanje and Garnett, 2020). The most severely affected part of the Amazon rainforest is Rondônia, which by 2003, lost nearly 68,000km^2 to deforestation. However, it is important to note that this was not completely for the produce of soy, as land was also cleared for pasture and crops. Nevertheless, the demand for soy contributed to the deforestation, which negatively impacts the unique and diverse range of wildlife in the Amazon rainforest. Santa Cecilia in Ecuador in the Amazon rainforest alone, has 81 documented frog species, the largest amount for an individual site recorded and the same for the total frog species in the whole of the United States of America (Adler, 2013). In addition to this, the Amazon rainforest is a remarkable carbon sink, absorbing an estimated

0.56 (± 0.51) gigatonnes of carbon (GtC) annually (Rödig *et al.*, 2018). The CS potential was calculated over the 7.8 million km^2 of forestry in South America.

2.5.1.1.2 The Cerrado Savanna

It is not only the Amazon with a high biodiversity of wildlife that is affected by soy production. The Cerrado savanna contains five percent of the world's flora and fauna, containing millions of species of insects, over one thousand fish and hundreds of birds and mammals (WWF, 2022a). Deforestation in the savanna is estimated to be 50%, since the 1950s. Almost 50% of flora in the Cerrado is exclusive to the region, as well as 60 vulnerable fauna species, 12 of which are currently nearing extinction. By 2030, more deforestation is predicted due to the demand for soy and beef, of at least 10 million acres of the region's flora, when the local population depend on the savanna for medicinal purposes and nutrition. It is imperative that deforestation stops to protect the local communities and biodiversity, especially by 2030, as otherwise we risk rising above the 1.5ºC limit of the Paris Climate Agreement.

Deforestation not only impacts the environment, but the forced movement of indigenous individuals and small-scale famers, due to unmanaged and unsustainable production (WWF, 2022b). However, if production practices are improved and made sustainable, soya can have positive impacts on soil health, as it is a legume and can therefore fix N (Fraanje and Garnett, 2020). Improving the sustainability of soy is a difficult process and requires companies to monitor the sourcing of their soy products, to discourage unsustainable practices linked to deforestation and agrochemicals (WWF, 2024).

2.5.2 Protein Alternatives to Soy

2.5.2.1 Rapeseed Meal

In areas unsuited to high yields of soya, rapeseed meal (RSM) is frequently used and has long been accepted as an alternative to SBM (Huhtanen, Hetta and Swensson, 2011). Several studies have compared the effect of RSM to SBM in dairy cattle diets on milk production and composition and found rapeseed (RS) to increase milk production in comparison to SBM whilst supplying energy and protein requirements (Christen *et al.*, 2010; Huhtanen, Hetta and Swensson, 2011; Broderick, Faciola and Armentano, 2015; Rinne *et al.*, 2015; Gauthier, Swanepoel and Robinson, 2019; Pereira *et al.*, 2020; Benchaar *et al.*, 2021; Garnsworthy *et al.*, 2021).

2.5.2.2 Faba Beans

FB meal has a similar effect on milk yield (MY) to SBM (Johnston *et al.*, 2019), but less than RSM (Puhakka *et al.*, 2016; Lamminen *et al.*, 2019). MY was usually higher when extruded faba beans (FB) were used in comparison to raw FB, which is extruded at 140ºC rather than 160ºC (Mendowski *et al.*, 2019). FB are also high in starch (Halmemies-Beauchet-Filleau *et al.*, 2018), which suggests their inclusion would reduce EME (Rotz, Montes and Chianese, 2010; Børsting *et al.*, 2020). However, FB inclusion did not significantly change irrelevant of the units used, when measured using a respiration chamber (Johnston *et al.*, 2019).

2.5.2.3 Lupins

There are three main types of lupins fed to cattle: yellow, blue, and white lupins (Halmemies-Beauchet-Filleau *et al.*, 2018). Changing from SBM to lupin seed meal (LSM) did not impacted MY when compared to a typical TMR of the same ingredients of hay and maize silage, rapeseed meal, soybean meal, beet pulp and brewer's grains and wheat, excluding lupins (Bryszak *et al.*, 2020) and obtained similar MY results to FB (Mendowski *et al.*,

2019). Overall VFA production decreased with LSM inclusion, by 14.5% and the population of archaea, which likely lowered CH_4 production, by 2.36mmol/litre of ruminal fluid, to the control group (p=0.01; Bryszak *et al.*, 2020). The pH of the rumen increased by 0.1 with LSM, compared to the control group (p = 0.05), due to the plant's alkaline properties and lower starch content, which requires monitoring.

However, LSM may also add health benefits to milk, by reducing the proportion of saturated FA and increasing unsaturated FA. In addition to this, cattle wellbeing was also improved, as BCS of the dairy cows were significantly lower in the control group (2.87), than LSM group (3.13, p<0.01), likely due to an improved energy balance when feeding LSM. The researchers also calculated the cost of the feeds at the time of the study, using a database from the Netherlands. The LSM diet had a cost of 4% less per cow per day than the control diet, which contained 1 kg of wheat, 0.5 kg of RSM, and 0.5 kg of SBM more than the LSM diet. Overall, from their findings, the authors recommended feeding 100g of LSM per kg of DMI to dairy cattle for the environmental, economic and wellbeing benefits.

2.5.2.4 Red Clover

Another alternative is red clover, which is a leguminous silage high in protein (Moorby, Ellis and Davies, 2016). Being a leguminous plant, it is very efficient at fixing N in soil and has the potential to annually convert 150-250 kg N/ha (AHDB, 2024c). Clover usage in England is quite common, as the 2021 Farm Practices Survey (FPS) found 76% of farmers surveyed use clover in at least some of their temporary grassland for livestock (DEFRA, 2021b). Red clover can increase DMI and milk production of dairy cattle, whilst reducing milk protein and fat content, but not inhibiting taste (Moorby *et al.*, 2009).

2.5.2.5 Lucerne or Alfalfa

Lucerne is an alternative feed to maize and grass silage (GS) and could be a partial substitute for soya, without affecting milk performance (Sinclair *et al.*, 2015). Lucerne was increased (from 0 to 0.332kg/kgDM) in the dairy cattle diets with a constant supply of RSM and a reduction in SBM (from 0.082 to 0.064kg/kgDM) over 28 days. Irrelevant of the units used, SB and lucerne had the same enteric CH_4, but the GS diets produced more emissions than MS (Doreau *et al.*, 2014). However, SB had larger milk production than lucerne, resulting in lucerne having higher emissions per kg of milk compared to SB, but the same per day or kg/DMI.

2.5.2.6 Distiller's Grains

By-products or co-products can also be used as animal feed, which are a waste product created from a process, such as grains from the brewery or distillery industry (Kononoff and Hall, 2011; He, Allen and Huang, 2023). Feeding by-products to livestock is an efficient use of these products, which would otherwise be wasted whilst contributing to GHGe. However, there is a lack of research on using by-products as cattle feed and the effect this has on their emissions, especially when evaluating the whole system (Wang *et al.*, 2019). AnLCA study in China assessed the impact of dairy systems using by-products as feed and found EF to account for 53% of GHGe from the system. Unfortunately, there was no control group to evaluate whether the by-product feed reduced EME and it remained the highest cause of emissions from the system.

2.5.3 The Effect of Protein Alternatives on Enteric Methane and Feed Production Emissions

Few studies have compared the effect of RSM to SBM on dairy cattle EME, but a study by Christen *et al.* (2010), assessed the effect of dried distillers' grains with solubles (DDGS),

RSM and SBM on VFA production. They found the propionate to acetate ratio was similar across the diets, suggesting the fermentation patterns remained the same. The diets contained around 15.3% crude protein and aimed to provide 38% of that protein from the protein supplements investigated. The study concluded that the feeds DDGS, RSM and SBM were evenly valuable sources of protein in dairy cattle diets, resulting in comparable ECM production, N impact and feed efficiency. More recent studies also found VFA concentration was not impacted by diet, such as RSM and SBM (Rinne *et al.*, 2015; Garnsworthy *et al.*, 2021) and DDGS (Garnsworthy *et al.*, 2021). The two studies analysed seven types of VFAs, and none varied significantly between RS and SBM.

However, Benchaar *et al.* (2021) measured EME using a respiration chamber over four days. The percentage of RSM was increased from zero to 24%, SBM was reduced from 17% to zero and soybean hulls from 6.7% to zero. The results showed EME decreased from 489 to 461 grams per day. RSM inclusion also replaced VFA concentration butyrate with propionate (Benchaar *et al.*, 2021), which produces less CH_4 (Børsting *et al.*, 2020). Total VFA production also reduced, as RSM inclusion increased (Benchaar *et al.*, 2021). The RSM diet thus, had lower emissions than SBM. The study concluded SBM substituted with RSM in dairy cattle diets could benefit milk production and reduce the animal's environmental impact. Benchaar *et al.* (2021) also discovered a negative relationship between RSM inclusion in the diet and CP, as well as NDF and gross energy (GE). RSM contributed to up to 24% of dietary DM, which accounted for 56% of dietary CP.

Few studies have compared the feed production emissions of the protein sources in dairy cattle feed. A study in 2011, analysed the differences in CO_2e emissions from feed production between protein alternatives to SBM and found DDGS had the highest (0.75 CO_2e kg^{-1} feedstuff- M; Hörtenhuber *et al.*, 2011). The CO_2e emissions included those from industrial processes, such as milling, drying and distillery of the feeds. Lucerne cobs had the

second highest (0.68 CO_2e kg^{-1} feedstuff- M), followed by SBM (0.05 CO_2e kg^{-1} feedstuff- M), RS cake (0.04 CO_2e kg^{-1} feedstuff- M), RSM (0.03 CO_2e kg^{-1} feedstuff- M), and faba beans (0 CO_2e kg^{-1} feedstuff- M). However, the total emissions were also calculated based on industrial processes, fuel, pesticide and fertiliser usage and land use change, which significantly impacted the ranking of the protein alternatives. SBM had the highest emissions (3.28 kg CO_2e kg^{-1} DM), followed by DDGS (1.45 kg CO_2e kg^{-1} DM), RS cake (1.01 kg CO_2e kg^{-1} DM), lucerne cobs (0.92 kg CO_2e kg^{-1} DM), RSM (0.87 kg CO_2e kg^{-1} DM), and faba beans (0.45 kg CO_2e kg^{-1} DM).

2.5.3.1 Ammonia Emissions and Nitrogen Footprint

The effect of protein alternatives on NH_3 emissions were also assessed by multiple studies (Christen *et al.*, 2010; Huhtanen, Hetta and Swensson, 2011; Broderick, Faciola and Armentano, 2015; Rinne *et al.*, 2015; Mendowski *et al.*, 2019; Benchaar *et al.*, 2021). A meta-analysis found RSM resulted in a lower nitrogen content of ammonia (NH_3-N) than SBM (Huhtanen, Hetta and Swensson, 2011). However, RSM has also been found to result in the same or similar NH_3 emissions as SBM (Christen *et al.*, 2010; Rinne *et al.*, 2015; Benchaar *et al.*, 2021) and DDGS (Christen *et al.*, 2010). Nonetheless, Mendowski *et al.* (2019) highlighted the NH_3 content was higher for LSM than FB or SBM. CP (g/kg of DM) content for the diets were kept the same and N intake was similar between diets, suggesting another factor must impact NH_3 emissions. A study by Doreau *et al.* (2014) compared the effect of combining SBM or RSM with GS or MS and found protein type did not impact emissions, but the forage type significantly impacted the NH_3 emissions. The MS diet had higher NH_3 emissions than the GS diet, suggesting the silages used in combination with the sources of protein could be an important denominator when reducing emissions.

Substituting SBM could have a positive effect on the N footprint, as expelled urinary N was higher for SBM, than lucerne diets (Doreau *et al.*, 2014). Total N excretion was not impacted by changing from SBM to RSM, but N excretion through faeces increased and reduced from urine, as RSM content increased (Benchaar *et al.*, 2021). N excretion from urine is more difficult to control and results in higher emissions than those excreted from faeces (Herremans *et al.*, 2020). Swapping SB with lucerne or RSM might therefore not affect overall CH_4 emissions, but could increase ease of sustainable manure disposal (Doreau *et al.*, 2014).

2.5.4 Feed Additives

EME contribute to most farm emissions, which has led to the development of feed additives to reduce EME from livestock. Feeding cattle macroalgae Asparagopsis seaweed has resulted in one of the highest reductions in CH_4 emissions, by 67.2% when fed in-vivo (Roque *et al.*, 2019). Another additive is 3-Nitrooxypropanol (3-NOP) which inhibits the methanogenesis process, by preventing methyl-coenzyme M reductase (MCR) from catalysing the reaction and converting CO_2 and hydrogen to CH_4; the final process in the formation of CH_4 (Duval and Kindermann, 2012). Studies support the success of 3-NOP in limiting CH_4 production from ruminants (Romero-Perez *et al.*, 2015; Patra *et al.*, 2017; Jayanegara *et al.*, 2018; Kebreab *et al.*, 2023), by as much as 42% in-vivo, without impacting the digestibility of the feed. The studies were in-vivo, except the meta-analysis by Patra et al. (2017) that assessed both in-vivo and in-vitro. 3-NOP, when measured in-vivo,also does not impact DMI (van Gastelen, Dijkstra and Bannink, 2019), milk production (Haisan *et al.*, 2014; Arndt *et al.*, 2021), or the fat and energy content of milk (Haisan *et al.*, 2014).

A recent meta-analysis found an average CH_4 reduction of 33% from 70.5mg/kg DMI of 3-NOP. However, the type of diet could impact the effectiveness of 3-NOP on reducing emissions, as high fibre diets have been found not react to 3-NOP and thus not reduce

emissions as well as low fibre diets (Dijkstra *et al.*, 2018). The lower effectiveness in pasture-based systems, could be due to the difficultly in practice when incorporating feed additives into pasture-based cattle diets, lowering consumption (BovINE, 2020). However, 3-NOP supplements could be investigated in these systems, such as a capsule, lick blocks and devices that gradually release the additive within the rumen (Yu *et al.*, 2021). Dietary starch also increased the potential of 3-NOP to reduce methane production (Kebreab *et al.*, 2022) and could be incorporated in future interventions. 3-NOP was declared safe by the Food Standards Agency (FSA) and Food Standards Scotland (FSS) for use in the UK in 2023 (FSA, 2023). The costs of 3-NOP in the UK are currently unknown due to the recent approval but are estimated to be approximately £31 per beef cow per year in Scotland, which should be similar across the UK and for dairy cattle per (Climatexchange, 2020).

Nitrates can also be fed to cattle to reduce EME, using them as an electron sink to control the methanogenesis process in the rumen (Olijhoek *et al.*, 2016; Wenner *et al.*, 2020). Several studies have found nitrates in dairy cow diets to reduce methane emissions by a range of 6 to 23% per kg of DMI in-vivo (Van Zijderveld *et al.*, 2011; Olijhoek *et al.*, 2016; van Gastelen, Dijkstra and Bannink, 2019; Arndt *et al.*, 2021). Van Zijderveld *et al.* (2011) measured CH_4 emissions using a respiration chamber over 89 days and found dairy cows fed a corn-fed silage and a nitrate source decreased CH_4 emissions by 16% using grams per kilogram of DMI. A recent study highlighted nitrates could reduce daily CH_4 production by a mean of 17% (Arndt *et al.*, 2021). While an in-vivo review found nitrates reduced methane production by 22% per day, per kg of DMI and percent of GEI and 20% per kg of milk produced (van Gastelen, Dijkstra and Bannink, 2019).

The proportion of nitrates has also been investigated, which found the higher the nitrate levels the larger the reduction in emissions, compared to a control group using a respiration chamber. When fed 5.3g/kgDM of nitrates, methane emissions reduced 6% per kg of DMI,

which increased to 13% when fed 13.6g/kgDM and 23% when supplied 21.1g/kgDM of nitrates (Olijhoek *et al.*, 2016). However, the quantity of nitrates must be controlled appropriately, as nitrates can be poisonous to animals (Patra, 2016; Arndt et al., 2021), therefore, the levels of nitrate in forage must be known when deciding the correct proportion of nitrate to use.

Research investigating the impact of nitrates on milk production is mixed, with some studies finding no impact on milk production in-vivo (Van Zijderveld *et al.*, 2011; Olijhoek *et al.*, 2016), or the DMI of dairy cows (Van Zijderveld *et al.*, 2011; van Gastelen, Dijkstra and Bannink, 2019) and even increases in milk production (Arndt *et al.*, 2021). A positive relationship between nitrate levels and ammonia concentration was also found (Olijhoek *et al.*, 2016) and it is theorised that nitrates could increase milk production, by increasing ammonia concentrations and dietary N, if the diet did not efficiently meet their requirements (Van Zijderveld *et al.*, 2011). The theory could explain why Arndt *et al.* (2021) found nitrates increased milk production by 3%, even though DMI reduced by 2%. It is important the protein content of the diet is assessed, as if the appropriate quantity of nitrogen is met through the protein content, then excess nitrogen through nitrate will lead to nitrogen emissions (Olijhoek *et al.*, 2016). The study also highlighted that hydrogen emissions increased with nitrates, which requires further investigation, to ensure this does not lead to increased emissions elsewhere.

There are alternative sources of additives that have reduced CH_4 emissions in-vitro, such as garlic oil and essential oils (Chaves *et al.*, 2008; Patra & Yu, 2012). However, these have not reduced CH_4 emissions when measured in-vivo (Beauchemin & McGinn, 2006; van Gastelen, Dijkstra and Bannink, 2019).

2.5.5 Strategies to reduce manure emissions

2.5.5.1 Anaerobic Digestion using manure

Recycling manure is an effective strategy to reduce emissions from livestock (Aguirre-Villegas and Larson, 2017; Sefeedpari *et al.*, 2019). A study in Iran compared AD, solid liquid separation (SLS), sand separation and composting of manure and found AD was the most effective for reducing emissions (Sefeedpari *et al.*, 2019), with AD decreasing emissions by up to 83% compared to baseline emissions (Maldaner *et al.*, 2018; Sefeedpari *et al.*, 2019). AD creates renewable energy from waste (Varol and Ugurlu, 2017), such as livestock manure which has a large energy potential, making it highly suitable for AD (Im *et al.*, 2020). Bacteria breaks down the waste product into CH_4 and CO_2, known as biogas, a sustainable source of energy (Aguirre-Villegas, Larson and Sharara, 2019; Béghin-Tanneau *et al.*, 2019; Qi *et al.*, 2021). Biogas can then be used to generate electricity, fuel vehicles or be added to the grid to reduce that produced by fossil fuels (Aguirre-Villegas, Larson and Sharara, 2019).

However, AD is a costly strategy (Aguirre-Villegas and Larson, 2017; Sefeedpari *et al.*, 2019), costing a minimum of £900,000 for installation in the UK for a dairy herd of 550 cattle (Bywater & Kusch-Brandt, 2022) and economics highly influence manure management practices (Sefeedpari *et al.*, 2019). Altering manure strategies to decrease emissions has also been found to reduce profits in previous research (Dutreuil *et al.*, 2014), which means for AD to be implemented more widely, subsidies would be needed to make the technology cost-effective (Sefeedpari *et al.*, 2019). The FPS highlighted that only 8.9% of English farmers use AD, which is an increase of 7.4% since 2015 (DEFRA, 2021b). AD is therefore increasing in England but requires higher implementation to further increase the uptake and economic practicality.

Capturing the CH_4 in AD has environmental benefits, such as decreasing air and water pollution (Aguirre-Villegas and Larson, 2017) when compared to applying the manure directly to land (DEFRA, 2021a). In a study in Dubai, AD significantly reduced GHGe by 25.7%, acidification potential (AP) by 49.5%, eutrophication potential (EP) by 18% and photochemical ozone creation potential by 16% on dairy farms (Adghim *et al.*, 2020). Cattle manure is also arguably the best manure, as it contains similar GHGe to pig manure, but almost two and a half times less NH_3 emissions, releasing almost 51% less N_2O and 41% less CO_2 than pig manure (Zhuang *et al.*, 2020). Livestock manure used in AD can also contain impurities, such as antibiotics, which pollute the digestate (Qi *et al.*, 2021). Nevertheless, research has found that biochar added to the waste can improve the quality of AD digestate, by removing contaminants. It is also important the systems are managed correctly, as AD can lead to NH_3 emissions from the storage process (Aguirre-Villegas and Larson, 2017; Aguirre-Villegas, Larson and Sharara, 2019). For example, when comparing alternative scenarios, AD had the largest increase in NH_3 emissions, when covers were not included in the storage of manure (Aguirre-Villegas, Larson and Sharara, 2019).

2.5.5.2 Solid Liquid Separation

There is a huge potential to reduce the CF of milk production, by changing manure management strategies (Soteriades *et al.*, 2018). Solid manure can be separated from liquid manure, by a process known as SLS (Owen and Silver, 2015), which reduces manure emissions (Aguirre-Villegas and Larson, 2017; Aguirre-Villegas, Larson and Sharara, 2019; Sefeedpari *et al.*, 2019), such as NH_3, as the solid portion is less likely to disperse NH_3 into the atmosphere (Aguirre-Villegas, Larson and Sharara, 2019). SLS is also practical to implement as an affordable strategy (Aguirre-Villegas and Larson, 2017; Aguirre-Villegas, Larson and Sharara, 2019). However, it is debateable how much SLS reduces emissions; Aguirre-Villegas and Larson (2017) studied large dairy farms of at least one thousand

animals and found the use of SLS reduced emissions by approximately 11%. Whereas a later study by Aguirre-Villegas, Larson and Sharara (2019), collected manure samples from nine dairy farms for eight months, which showed when SLS was conducted efficiently it had the potential to decrease emissions from dairy manure by 60%.

2.5.5.3 Manure Storage

When using liquid manure management practices, the main cause of emissions from manure, which is mostly CH_4 due to anaerobic conditions (Aguirre-Villegas, Larson and Sharara, 2019), is the storage process (Sefeedpari *et al.*, 2019). However, research on the emissions from manure storage vary, as previous research found manure storage equated to low emissions (Rotz, Montes and Chianese, 2010), whereas more recent research found storage contributed considerably to manure emissions (Aguirre-Villegas, Larson and Sharara, 2019; Sefeedpari *et al.*, 2019). Storage equating to over 60% of manure emissions from the dairy systems analysed (Aguirre-Villegas, Larson and Sharara, 2019). An important factor which impacts the emissions from manure storage is the length of storage, as emissions increase with storage length (Aguirre-Villegas and Larson, 2017; Cárdenas *et al.*, 2021). However, the storage management system could impact the emissions, as separating slurry reduces the amount needed for storage and therefore GHGe (DEFRA, 2021a). SLS could reduce storage emissions by as much as 46%, by limiting the volatile solids (VS) in storage (Aguirre-Villegas, Larson and Sharara, 2019).

VS are the organic part of manure, that are converted to CH_4 emissions at high temperatures, such as in AD (Maldaner *et al.*, 2018). Previous research found VS contributed the most to manure emissions in milk production (Soteriades *et al.*, 2018). VS are proportional to 82% of dairy manure (Varol and Ugurlu, 2017), which makes the quantity of VS in manure storage a good method for estimating CH_4 emissions (Appuhamy *et al.*, 2018). However, VS vary in

degradability, likely due to the diet of cattle, which impacts the emissions from each unit of VS (IPCC, 2006), leading to no significant correlation between VS quantity and CH_4 emissions produced in systems using AD (Maldaner *et al.*, 2018).

2.5.5.4 Temperature

The temperature of manure storage can also impact GHGe (Sommer, Petersen and Møller, 2004; Maldaner *et al.*, 2018; Im *et al.*, 2020; Cárdenas *et al.*, 2021), with manure emissions being significantly higher in summer compared to winter (Cárdenas *et al.*, 2021). For instance, larger emissions have been reported from slurry stored inside during the summer months, compared to slurry stored outside, which had half the emissions (Sommer, Petersen and Møller, 2004). The authors concluded this was because storing the slurry inside led to larger quantities of VS than outside. The time of year has been found to affect the VS of manure in a UK study, with higher temperature increasing the VS proportions. A cool mean temperature of 7.3°C resulted in the lowest VS, with 43g VS kg^{-1}, while temperate conditions of an average 11°C had 49g VS kg^{-1} and warm temperatures of 17.2°C had the largest VS of 53g VS kg^{-1} (Misselbrook *et al.*, 2016).

Reducing the temperature of manure storage can therefore reduce emissions, for example a more recent study by Im *et al.* (2020), found reducing storage temperature to 15ºC could reduce emissions by 94%, and even a 5ºC reduction, from 35 to 30ºC, reduced emissions by 21%. However, it is difficult to control the temperature of storage, especially in warm weather, therefore a study investigated whether prior cool storage of manure could reduce GHGe when stored in warmer weather (Cárdenas *et al.*, 2021). The authors found that if the manure was stored in cold conditions in winter under 14ºC, then the emissions did not increase when the temperature expanded above 19. The results suggest that storing dairy

manure in low temperatures could reduce emissions from storage in the long-term irrelevant of the future temperatures (Cárdenas *et al.*, 2021).

2.5.5.5 Manure Covers

A study investigated the impact of different slurry covers for swine manure, by using a gas measuring instrument on covered and uncovered controlled slurry's, which showed covers reduced GHGe, irrelevant of the temperature (Matulaitis, Juškienė and Juška, 2015). Straw covers decreased CH_4 emissions from manure by 92%, CO_2 emissions by 71.6% and NH_3 by almost 40%. Sawdust covers reduced CH_4 emissions by as much as 100%, CO_2 emissions by the same as straw covers (71.6%), but significantly more NH_3 emissions (73.4%). Plastic film covers were also effective at limiting emissions, reducing CH_4 by 91.5%, CO_2 by 67.1% and NH_3 by 54.7% compared to uncovered slurry. Cattle slurry with crust can reduce the AP by 40% and EP by 22% compared to slurry without a crust (Soteriades *et al.*, 2018). Covers are important in manure handling to reduce emissions and avoid negative impacts (Sefeedpari *et al.*, 2019).

2.5.5.6 Applying manure to land as fertiliser

The dairy industry provides manure, an organic fertiliser (Gilardino *et al.*, 2020), that can reduce the emissions from fertilisers and decrease the demand for artificial fertilisers to be imported (Petersen, 2018). Manure is a brilliant fertiliser as it provides soil with beneficial nourishment for growing crops and keeping land healthy (Aguirre-Villegas, Larson and Sharara, 2019; Wang *et al.*, 2019). The digestate is created from AD, which can be used to fertilise soil as it is high in N (Adghim *et al.*, 2020; DEFRA, 2021b). Adding digestate created through AD, also aids the sequestration of soil, and compared to MS, had a 27% lower CF (Béghin-Tanneau *et al.*, 2019). However, the process can lead to NH_3 emissions, therefore, previous research has highlighted the importance of measuring the NH_3 content of

digestate, to limit that applied to soil (Evans *et al.*, 2018). Measuring the NH_3 levels and controlling the emissions avoids trading CH_4 emissions for N_2O and negatively impacting different parts of the environment, such as through eutrophication and acidification from NH_3 (Evans *et al.*, 2018).

It is also crucial that manure is applied to land appropriately, as the method used to apply the manure to land, can decrease the CF of milk production (Soteriades *et al.*, 2018), by reducing N_2O emissions (Aguirre-Villegas, Larson and Sharara, 2019). Most emissions from manure management in small farms have been found to be from the application to land (Aguirre-Villegas and Larson, 2017). Injecting manure instead of applying it to the surface is an encouraged method, as it can reduce NH_3 emissions by 22% (Aguirre-Villegas and Larson, 2017). As well as applying fertilisers where needed, using precision farming (IPCC, 2007) to reduce N leaching, which is increasing in uptake. In the 2021 FPS, 62% of English farmers had reported improving the precision of their N fertiliser application (DEFRA, 2021b). However, dairy manure also contains high amounts of nitrates (Amaly *et al.*, 2021), which can leach into water systems and have been linked to severe health conditions, such as birth defects (Stayner *et al.*, 2022). However, research has shown nitrates can be removed using a cost-effective nanofiber membrane (Amaly *et al.*, 2021), which would reduce the risks of using dairy manure as a fertiliser and support the usage of AD and digestate.

2.6 Carbon Offsetting through woodlands

2.6.1 Land shortage in the UK

There is a land shortage in the UK and livestock use more land than any other activity, accounting for 40 to 50% globally (IPCC, 2007). A heightened demand for dairy products could increase demand for land further (OECD-FAO, 2018). Therefore, it is not only important to reduce GHGe, but to prevent land shortages, it is also imperative that

agricultural land is used efficiently. Efficiency can be achieved by increasing product yield, whilst decreasing land use, which is one of the objectives of sustainable intensification of livestock (Dumont, Groot and Tichit, 2018). Thus, a requirement is increasing the efficiency of management systems and animal productivity in the agricultural industry, which could also help reduce emissions of the output produced (IPCC, 2007).

Additionally, agriculture's large land usage means there is a huge potential to offset emissions, through grasslands, hedgerows, and forestry, which store carbon and provide vital habitats for wildlife (IPCC, 2007). In addition to positively impacting the surrounding landscape, by improving the aesthetic of the land (Dumont, Groot and Tichit, 2018). Pasture-based cattle can also be beneficial for declining wildlife, such as in Wales, where the golden plovers are a priority species (Royal Society for the Protection of Birds, 2021a). In a survey in 2007, only 36 pairs were reported, however, cattle are helping to increase habitats suitable for the bird, by grazing the coarse vegetation to increase the bird's ability to nest and feed.

2.6.2 Introduction to Carbon Offsetting

Carbon offsetting can assist with removing carbon emissions from the atmosphere and is essential for the UK to reach Net Zero (Royal Society and Royal Academy of Engineering, 2018). There are various methods for offsetting emissions on the farm, such as through soil, forestry, and hedgerows. Soil and flora can absorb and store carbon, acting as a natural carbon sink. The carbon in soil is often measured by the soil organic carbon (SOC) stocks in soil. In the UK, agricultural land accounts for over 70% of land use (CPRE, 2021), thus the industry has a huge potential to optimise carbon storage and assist the UK to Net Zero. The agriculture industry stores carbon across the UK and the Net Zero goal encourages the maintenance and efficiency of carbon sinks (NFU, 2019). Improving the storage of carbon in soil alone, could reduce emissions in the UK by 5 $MtCO_2e$ annually.

2.6.3 Woodlands and Forestry

There was 3.24 million hectares of woodlands estimated in the UK in 2022 (Forest Research, 2022). It is estimated that between 1.3 and 22 kg CO_2 per year can be absorbed per tree, with an average of five kg CO_2/year/tree (Cooper, Dubey and Hawkes, 2022). While encouraging woodlands on farms could capture 0.7 MtCO_2e annually (NFU, 2019). Hedgerows and trees are also useful for wildlife, with oaks being particularly beneficial for providing insects with habitats. Older trees are also more likely to have holes in, providing more nests for birds, owls, and bats (Royal Society for the Protection of Birds, 2021b).

When evaluated, afforestation was the most effective method for removing CO_2e emissions, compared to bioenergy with carbon capture and storage, direct air capture and enhanced weathering (Cooper, Dubey and Hawkes, 2022). Afforestation requires minimum equipment, such as transportation, planting tools and tree protection. Experts therefore view the technology as more economically viable than carbon capture and storage strategies, and financing renewable sources (Shrestha *et al.*, 2022). Human ecotoxicity was also considered for the various methods of which afforestation had the least risk. The only factors that could lead to potential toxicity were those from plastics used, such as to protect the tree, metals used in the power saw when managing the forest and any non-renewable transportation of the saplings to the area of plantation. However, the process can take between 10 and 100 years, which is considerably longer than direct air capture and bioenergy with carbon capture and storage which are practically instant, and enhanced weathering which takes between 23 and 62 years. Afforestation also requires large areas of land to sequester carbon, being a considerable investment in space and time as a mitigation method. However, that is one of the reasons farmlands are an ideal area for the method, as they tend to have large areas of land to plant trees, and they can also be used for fruit or as borders between areas of land.

Restoring vegetation can have benefits to farmers, as reforestation offers protection against extreme weather events such as flooding and storms (UNEP, 2020).

2.6.4 Tree Species

There are also large varieties of tree species that could be planted. A study in China conducted a literature review to investigate the CS potential of the afforestation of pure woodlands of one species of tree compared to a mixed woodland of diverse tree species (Yu *et al.*, 2023). The review found mixed species of woodlands had a larger CS rate of 0.89 Mg ha^{-1} yr^{-1} than monoculture woodlands with 0.32 Mg ha^{-1} yr^{-1} ($p < 0.05$). The review also assessed the CS rate for various tree species, which was 0.97 Mg ha^{-1} yr^{-1} for a mixture of arborvitae (arbor) shrubs, 0.85 Mg ha^{-1} yr^{-1} for diverse arbor species, and significantly lower for the pure arbor at 0.34 Mg ha^{-1} yr^{-1} and pure shrub at 0.2 Mg ha^{-1} yr^{-1} ($p < 0.05$). Increasing tree diversity has also been linked to lower rates of disease and pests in trees, improving the resistance of trees in the UK (Roebuck, Hurley and Slater, 2022). The research suggests that woodlands would therefore have a higher CS rate and offsetting potential (Yu *et al.*, 2023), and lower vulnerability (Roebuck, Hurley and Slater, 2022), if a diverse mixture of species are planted, rather than one species.

2.6.5 Restrictions for tree plantation

There are various restrictions limiting plantation of trees in the UK, from physical and environmental to policy limitations (Burke *et al.*, 2021). Physical restraints where land already contains forestry, infrastructure, or a body of water, which prevents the planting of trees. Environmental restrictions, where planting trees could damage the land, such as marshes and peatlands. Finally, policy issues, refer to areas which could be high quality land and used for tree plantation, but includes restrictions such as protected land areas and requires planning permission.

It is estimated that 65% of the land in England is high quality but contains restrictions (8.5million ha). The land in Scotland is predicted of lower quality, with 19% rated highly. However, the major restriction being protected areas contributing to over 30% of the land, peatlands, and marshes 15% (over 1 million ha). Northern Ireland also has environmental restrictions, constituting to 14% of land. However, across the UK, policy limitations contribute to the largest restrictions for afforestation, with an estimate of just below 16 million ha.

Burke *et al.* (2021) highlighted the physical, environmental and policy restrictions on afforestation across the UK, and showed the difference in available land for afforestation, if it was presumed trees could or could not be planted on agricultural land (Burke *et al.*, 2021). When the assumption that agricultural and protected land would be unavailable for afforestation, land vacancy was significantly limited, especially in England. Under this scenario, 4.7 million ha of land was available for afforestation in the UK, enough to meet the CCC aimed coverage. However, only 1.2 million ha (9%) of land in England was marked as available, with Northern Ireland and Scotland having the largest land availability, which could cause political issues. Scotland also currently has 19% forestry coverage, whereas England has 10%, Wales 15% and Northern Ireland 9% (Forest Research, 2022). Using this land would also dramatically limit land availability for other functions, such as housing, with a predicted increasing population (FAO, 2015).

The more optimistic view, that agricultural land would be available for afforestation, resulted in a dramatic increase of over two-fold, to 10.4 million ha of land. Land in England increased to 5.5 million ha which was 2.3 million hectares more than Scotland (3.2 million ha). It is essential agricultural land is used for afforestation to meet Governmental woodland growth targets (Wynne-Jones, 2013). The study highlighted the power and necessity for the

agriculture industry in reaching Net Zero, as the industry's large land area has the potential to support tree plantation and CS.

The Committee on Climate Change (2020) estimated that tree cover in the UK will need to be increased by a minimum of 4% by 2050, to meet the Net Zero goal. The coverage equates to a minimum of 90 million conifer or broadleaved trees, over 30,000ha of land each year. Strategies such as the "The Big Farm Tree Planting campaign" by the NFU in the Northwest, were launched in 2021 with an aim of planting 2,000 UK grown trees (NFU, 2021). The equipment needed and trees were free to NFU members, offering a huge incentive to farmers in the area to increase their environmental image and tree coverage.

The UK government 25 Year Environment plan is to increase forestry cover to 12% by 2060, requiring the annual plantation of 7,200 trees per hectare from 2025, using 208,485ha of land (DEFRA, 2022b). If reached, it is estimated that 19.5 $MtCO_2$ would be saved and 113.7 $MtCO_2$ by 2100. Working towards 2050 instead of 2060, would require further trees being planted each year, to 9,900 per hectare, using 276,415ha of land. It would result in larger savings of 24.1 $MtCO_2$ by 2050 and 150.2 $MtCO_2$ by 2100. However in 2023, DEFRA released an upgraded version of the 25 Year Environment plan called the Environmental Improvement Plan 2023, which will be reviewed in 2028 (DEFRA, 2023a). Currently the aim is to increase woodland cover in England to 16.5% of land by 2050 and a short-term goal of increasing woodland cover by 0.26% by the end of January 2028, corresponding to 34,000 hectares. To reach the short-term target, 6,800 hectares of trees will need planting each year until the 2028 goal. The Environmental Improvement Plan also aims to increase hedgerows in England by 2050, by 45,000 miles each year, but has a shorter goal of 30,000 miles each year until 2037 (DEFRA, 2023a). The overall goal is to restore hedgerows in England to 360,000 miles. As well as increasing biodiversity, by investing in creating and repairing habitats for a range of wildlife, for 500,000 hectares of land by 2042. The aim will be to increase the

number of species above 2022 records and 10% more than 2030. The plan also aims to increase the sustainability of agricultural soil in England by 40% by 2028 and 60% by 2030 (DEFRA, 2023a).

2.6.6 Funding for woodlands

The Government launched the Farming in Protected Landscapes (FiPL) programme in 2021, to provide funding for farmers protecting landscapes (GOV, 2021), which has been extended with the Improved Environmental Plan until March 2025 by ten million pounds funding made available (DEFRA, 2023a). The programme provides funding to different projects, such as increasing carbon storage, enhancing biodiversity, and improving land resistance to climate change (GOV, 2021). However, to reach England's Net Zero requirements, 16,700 trees would need to be planted annually per hectare from 2035, over an area of 420,395ha to offset 32.8 $MtCO_2$ by 2050 and 226.4 by 2100 (DEFRA, 2022b).

To improve the survival of tree saplings, plastic covers can be used to provide protection. A study investigated the environmental footprint of various tree cover materials to protect tree saplings. Tree covers made from polypropylene, produced less GHGe than bio-based alternatives Polylactic acid blend (PLA) and bio-polypropylene (bio-pp; Chau *et al.*, 2021). However, covers increased GHGe compared to cover free tree samplings, but reduce the risk of eutrophication, water shortages and ozone weakening. Still, covers increased GHGe by 3-4-fold compared to tree samplings without covers and therefore, the results suggested the reduced mortality rate did not justify their usage, due to the large emissions generated at the manufacture process. The least environmentally impacting disposal methods most suitable for the covers were recycling, followed by incineration with energy recovery, landfill and lastly incineration without energy recovery. Economic factors play a large role in afforestation in agriculture, as losses in production and profit negatively impact tree planting, whereas

benefits from schemes such as carbon credits increase incentives and the probability of planting trees (DEFRA, 2022b).

2.6.7 Benefits of shade to cattle

Trees can also offer shade, which provides benefits to cattle (Palacio *et al.*, 2015). An eight-week study in Canada using 24 lactating Holstein cattle, half with access to shade and half without, found that access to shade reduced time spent at the water trough (6.5-fold). While cattle grazed more (1.5-fold) and spent more time lying down (1.8 times) than the control group without access to shade. Milk production was not impacted. In New Zealand, aggressive interactions increased with less access to shade, by over 3-fold from 9.6m shade per cow to 2.4m of shade per cow (Schütz *et al.*, 2010). Respiration rate also increased by 11-18% with less or no shade. Providing shade in pasture systems may improve cattle comfort, behaviour, and welfare.

2.6.8 Carbon credits

It is important that the carbon offset on farms is considered, to show recognition to encourage maintenance of carbon sinks. Carbon sinks not only store carbon, but encourage scenic natural landscapes, such as woodlands and fields (IPCC, 2007). Research assessing the emissions of pig farms with access to large outdoor areas, concluded the importance of including the CS of soil, to ensure a holistic view of the farm is captured (Monteiro *et al.*, 2019). A strategy to promote carbon offsetting in the agriculture industry is by using carbon credits, which farmers can obtain from CS of soil, capturing their emissions and the maintenance of forestry (IPCC, 2007). Carbon credits in the UK can be obtained from the Woodland Carbon Code (WCC), which is supported by the UK government (Koronka, Ovando and Vergunst, 2022; The Woodland Carbon Code, 2022).

Organisations can offset their own emissions by compensating the WCC, which then pays individuals and projects to plant trees which sequester carbon, through carbon credits (Koronka, Ovando and Vergunst, 2022). The value of the credits is then based on the estimated carbon offset, benefit to wildlife and diversity, public engagement, and employment created. In 2019, the UK Government initiated a £50 million UK Woodland Carbon Guarantee to encourage the planting of trees, to sell the carbon captured using certified carbon credits, known as Woodland Carbon Units (GOV, 2022). The UK Woodland Carbon Guarantee promised a set price from the Government for the credits every five to ten years until 2056, to assure a continued revenue for the preserved forestry and carbon sink. The landowners pertained the option to sell to the government or the public market. Optimally farmers would convert poor quality grazing areas to forestry (Koronka, Ovando and Vergunst, 2022), to support efficient use of land.

However, it is important that carbon credits and carbon offsetting are used to assist the journey to Net Zero and that they are not used as an excuse to continue releasing emissions and business as usual (The Climate Change Committee, 2022). Planting trees is economically viable (Shrestha *et al.*, 2022) and is a popular choice for reducing emissions from businesses (The Climate Change Committee, 2022). But emissions also need to be reduced where possible to reach Net Zero, as it cannot be completed with carbon offsetting alone. Carbon credits can also be ingenuine and double counted, where the emissions offset are counted twice, which is avoided and against the rules in the WCC registry (The Woodland Carbon Code, 2023). It is therefore important that credits are sold to and bought from a verified source, using a comprehensive auditing system, such as those in the Verified Carbon Standard programme (VERRA, 2023) and Quality Assurance Standard certified (Quality Assurance Standard, 2023).

2.6.9 Uncertainty measuring carbon sequestration.

However, there is a large amount of uncertainty when determining CS figures (Weiss and Leip, 2012). The carbon in soil is constantly changing (Nave *et al.*, 2019), making it difficult to measure. Research is lacking on CS of soil, and it is difficult to find the operations for current research, as the methodology for calculating CS differs widely, resulting in different values across studies (Monteiro *et al.*, 2019). However, with growing interest on the topic, research has called attention to the demand for more accurate measures of CS, particularly pastoral soils (Monteiro *et al.*, 2019).

2.6.10 Government Assistance and Encouragement

However, the maintenance of flora on farms has additional benefits to improving the carbon storage potential of land, such as improving air quality and biodiversity, which the UK Government encourage through economic incentives (DEFRA, 2023a). The Sustainable Farming Incentive (SFI) standards by DEFRA, provide income to farmers that maintain and support nature on their land, such as the quality of soil, grassland, trees, and hedgerows. In 2023, the Government announced an expansion for the SFI of six items, including hedgerows and grasslands. In addition to hedgerows, farmers can also receive payment for improving biodiversity, soil, water and air quality, and carbon offsetting by incorporating flowers in grass margins and in-field strips.

2.7 Life Cycle Assessment

There are different types of modelling approaches, such as LCA and inventory based models, empirical and statistical models, and process-based and mechanistic models (Ouatahar *et al.*, 2021). The LCA model is a well-accepted approach used to analyse the environmental impact of a product (Caro, 2019; Gilardino *et al.*, 2020; Segerkvist *et al.*, 2020) from the emissions produced, to the resources needed for manufacturing and waste created. Alternatives to LCA include an environmental impact analysis (EIA), which assesses the environmental costs and benefits of a project, to limit the impact. However, this method is more useful after conducting an LCA, where a mitigation strategy has been developed and can be fully investigated before implementation. It is intended for new projects, as an environmental risk assessment, rather than a project to improve sustainability of an existing entity (International Organization for Standardization, 2006; Komínková, 2016).

An LCA is a popular tool for calculating the CF of livestock (McClelland *et al.*, 2018; Mostert *et al.*, 2019; Paramesh *et al.*, 2019; Vibart *et al.*, 2021), being deemed one of the leading approaches for reliably evaluating the environmental footprint of the dairy production system (Wang *et al.*, 2019; Tarighaleslami *et al.*, 2020). For instance, organisations such as the Food and Agriculture Organization of the United Nations (FAO), use a Global Livestock Environmental Assessment Model (GLEAM), based on a LCA approach, which has been used locally and globally, focussing on the emissions produced from livestock; mainly manure and feed (FAO, 2015). The benefits of an LCA are that they can apply different scenarios to a model, to calculate the impact of the changes on the environment (Curran, 2016; Caro, 2019). LCAs consider the complete life cycle of the item, by examining the direct and indirect emissions emitted from the process, creating a holistic overview (Leip and Uwizeye, 2019). It is an important tool when deliberating new policies (FAO, 2015; Curran, 2016; Caro, 2019; Leip and Uwizeye, 2019), by providing evidence to determine the best

strategies for future legislation and goals within the sector (Weiss and Leip, 2012; Üçtuğ, 2019).

2.7.1 Weaknesses of the application of LCAs and scope

The scope of an LCA can be overgeneralised, by having a limited scope of application, as they are determined by the investigator (McClelland *et al.*, 2018). For instance, project investigators might choose to assess the CF of a product, which does not evaluate the whole significant impact of that product, such as biodiversity, the water footprint and or the N footprint. A review investigated this by analysing 173 peer-reviewed studies on the impact of products on GHGe and global warming (McClelland *et al.*, 2018). They found climate change was the most popular impact category, evaluated in 96% of the papers assessed. Other environmental issues were neglected, such as biodiversity, which was one of the least examined impact categories, with only 3% of the studies including the topic. Figure 4 shows a selection of impact categories and the percentage of articles in the meta-analysis that considered them in their study (McClelland *et al.*, 2018).

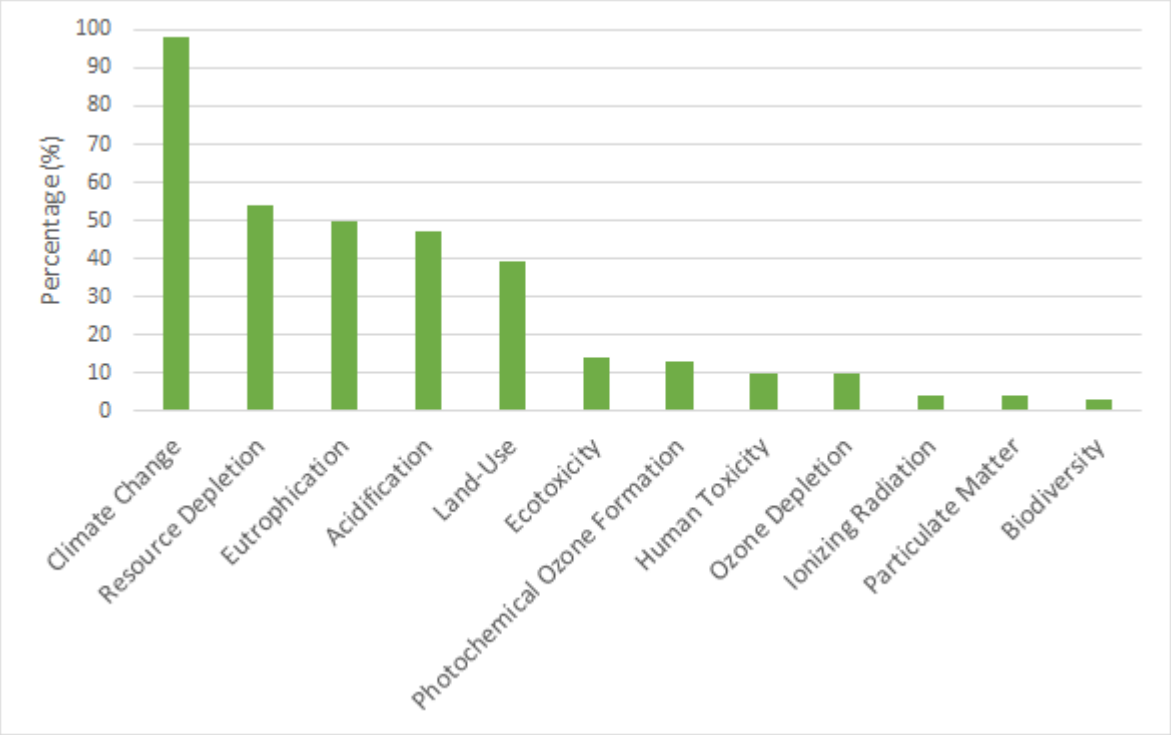

Figure 4: The percentage of articles in the meta-analysis by McClelland et al. (2018) that included the above impact categories.

2.7.2 The importance of a well-developed scope

The length of LCAs can vary (McClelland *et al.*, 2018), starting at "cradle" and often ending at "grave" (Curran, 2016). But in the agricultural industry, LCAs are also assessed on-farm, from cradle to the farm-gate, evaluating the emissions of inputs and those generated on-farm. However, emissions not formed on-farm are sometimes discounted using this method, such as imported feed, as the emissions are formed off-farm (Beukes *et al.*, 2010). Studies can fail to consider the cultivation of feed within their scope, even though whether feed is imported or grown on-farm significantly impacts the CF of feed (Mogensen *et al.*, 2014), as does cultivation through fertiliser and pesticide use (FAO, 2020). For instance, a previous LCA of feed production did not consider whether the feed was imported, where it was imported from and therefore the emissions associated with the transportation of the feed or impact on the area's environment and land use (Park, Lee and Yang, 2015). However, the LCA method does allow for import emissions to show an accurate overview of emissions (Bertrand and

Barnett, 2011). The issue resides with the scope design, rather than the LCA methodology, as poor planning can lead to the neglect of another area or impact (McClelland *et al.*, 2018). The scope needs to be developed appropriately to gain a holistic view of a product, to avoid a narrow scope that would negatively impact another area of the environment. Nevertheless, a benefit of an LCA can be to focus on a particular area, provided further research on the potential impacts is acknowledged prior to implementation.

There is also limited data on the emissions from importing feed from different countries, which effects the accuracy of GHGe results (Weiss and Leip, 2012; McClelland *et al.*, 2018). The lack of data led to one study using an average to represent all import emissions, irrelevant of the transport distance (Weiss and Leip, 2012). Insufficient data can also require tweaking boundaries for defining terminology (McClelland *et al.*, 2018). For instance, McClelland *et al*. (2018) aimed to assess the impact of imported feed against feed grown on-farm but found a very restricted number of farms studied were self-sufficient, that would create the baseline for the data. It was decided to overcome this issue, that studies using less than 10% of imported feed, would be categorised as "self-contained" to form the baseline. However, this instability in boundaries could lead to errors in the results and cause difficulty between comparisons. The Agibalyse dataset contains emission factors for several locations of a variety of livestock feeds, which would be suitable for comparing the emissions from imported feed across locations (Litskas *et al.*, 2020),

2.7.3 Functional Units

There are various forms of functional units for how GHGe are reported, such as per hectare of land, per animal, per unit of energy or output produced, such as milk or protein. It is vital that the functional units used in an LCA are declared and standardised, as they are not accurately comparable, suggesting different systems or feeds as more environmentally friendly (Little *et al.*, 2017). For instance, when two forages were compared, corn-silage

appeared to result in higher emissions than lucerne, when measured per kg of CO_2 per hectare, but less per kg of protein. The same can occur in production systems, as they have different aims, with housed systems aiming for high efficiency, favouring large MY per cow and per area, whereas pasture-based systems favour high MY per hectare of grassland (Lorenz *et al.*, 2019). There is a tendency for housed systems to use GHGe per unit of milk produced, whereas pasture-based tend to favour GHGe per hectare of land, as the area tends to be larger to stretch the GHGe (Rotz, Holly, *et al.*, 2020). There is also a preference for smaller cattle in pasture-based systems, leading to lower MY and efficiency. The unit GHGe per hectare of land lacks consideration for the milk output of cattle. It is beneficial to base functional units on production, to improve efficiency and measure GHGe based on the output of the farm.

2.7.4 Economics in an LCA

Farming is a career and source of income for those in the industry, making the costs and profit of different systems and mitigation strategies a key factor in decision-making (Caffrey and Veal, 2013; Hristov *et al.*, 2013). Strategies that have not been thoroughly evaluated to show a profitability return after investment are unlikely to be implemented on-farm (Hristov *et al.*, 2013). Nevertheless, there are a limited number of LCA studies evaluating the economic factors of dairy production systems (Rotz, Holly, *et al.*, 2020; Ruviaro *et al.*, 2020; Segerkvist *et al.*, 2020). Not only are the economics important, but it is critical to include economic, environmental, and social aspects to holistically assess the sustainability of a product (Segerkvist *et al.*, 2020). Yet, LCAs generally do not analyse the social or economic properties of a product (International Organization for Standardization, 2006) and very few LCAs have assessed both emissions of the dairy system, milk production and profits (Jayasundara *et al.*, 2019).

Significant trade-offs have also been identified, when both the environmental and economic implications of systems have been assessed. For example, grass-based systems in Pennsylvania showed larger profits, but higher emissions per milk produced than housed systems (Rotz, Holly, *et al.*, 2020). Researchers have highlighted the need for LCA studies to incorporate the economic costs of different production systems, as well as emissions, to aid policy (Parajuli, Dalgaard and Birkved, 2018). The vital research would inform the government of the required subsidies to make changes in practices and limit emissions. Without this research, policy makers would not have the knowledge to financially help the industry reach the required emission targets, creating a huge barrier between decision makers and farmers.

2.7.5 Modelling Approaches

LCAs, and inventory-based models tend to be based on emission factors, standard values, or empirical models to calculate emissions from each component, which are useful for building national inventories and large models (Ouatahar *et al.*, 2021). Conversely, empirical, and statistical models are apt for experiments assessing mitigation measures, determining the deviation in emissions and for emission calculators at the farm level that need little input measures. Models that are based on a whole farm level, can evaluate several mitigation strategies at one time and the longitudinal effect of climate change. Ouatahar *et al.* (2021) created a decision tree based on set objectives to aid the decision-making process of choosing a modelling approach, which showed whole farm models (WFMs) to be the used approach for evaluating different mitigation strategies at the farm scale.

2.8 Farm Simulation Models

2.8.1 The importance of a holistic model

GHGe from different parts of the farm system are often analysed separately, using equations such as enteric CH_4 from feed and manure emissions, however, farm simulation models are fitting for holistically evaluating the environmental, economic, and technical repercussions of changing management methods (O'Brien *et al.*, 2010; Vibart *et al.*, 2021). The models consider the possible negative consequences of improving one area across the system (Schils, De Haan, *et al.*, 2007; Schils, Olesen, *et al.*, 2007; Crosson *et al.*, 2011; Vibart *et al.*, 2021), to avoid compromising the efficiency of the farm (Kiefer, Menzel and Bahrs, 2014). Thus, simulation farm models are the best approach for showing a holistic view of the operations, to consider these factors and the environmental impacts of the strategies (Rotz, Holly, *et al.*, 2020; Segerkvist *et al.*, 2020). The models are valuable and mostly used in research for analysing the effectiveness of mitigation schemes (Vibart *et al.*, 2021) and economic viability (Crosson *et al.*, 2011), to capture the impact on the complete system (O'Brien *et al.*, 2010). Models can also vary in the level of detail they require and portray (Vibart *et al.*, 2021), to be modified to suit the aim and objectives of the study.

It is important mitigation strategies are evaluated on the system as a whole, shown in a study using the Holos model, to compare the whole farm emissions between corn silage and alfalfa/lucerne silage (Little *et al.*, 2017). The model showed corn silage reduced EME and CH_4 from manure by 6% each, N_2O from manure by 17%, soil N_2O by 2% and N_2O from indirect sources by 5% compared to lucerne silage. However, the lucerne silage had lower CO_2 emissions from energy by 91%, from liming by 168% and the importation of feed by 8%. In total, the difference in silage only resulted in 10kg CO_2e less for the lucerne silage, than the corn silage per cycle. Nonetheless, if the EME were analysed alone, the corn silage diet would appear to be the most favourable silage to reduce CH_4 emissions. Even though

enteric CH_4 was the main cause of emissions from the sector, contributing to 46 and 44% of GHGe, the difference was not the largest between the silages. FPCM was not significantly different between the silages, but the corn silage diet had a lower CP content than lucerne, which meant it needed supplementing with SBM The study highlights the importance of an efficient model, to ensure the suitability of the approaches and prevent possible consequences (Patra *et al.*, 2017).

Models allow the input of data to fit individual farms and assess mitigation strategies, which are more accurate than using a universal mitigation approach, which would not represent all farms given the large variety in production systems (Jose *et al.*, 2016). Tailored strategies are more valuable than universal mitigation strategies, that are implemented nationally (Rotz, Stout, *et al.*, 2020). Models offer a cost-effective process for evaluating emissions, rather than directly measuring GHGe. Therefore, predicting emissions is the preferred method, but must be accurate to be beneficial, as simulation models are used both in government, to deliberate new approaches to reduce emissions, and on-farm (Ibidhi and Calsamiglia, 2020). Models are also a useful tool to show farmers how the mitigation schemes work, as they are straightforward for farmers to understand, being used at a familiar agricultural level. They can therefore be used to convince farmers to apply the suggested strategies on-farm (Schils, De Haan, *et al.*, 2007; Schils, Olesen, *et al.*, 2007).

2.8.2 Existing whole farm simulation models

There are several whole farm simulation models used to predict GHGe from dairy and other livestock across the world, as seen in Table 5 below, which tend to be from cradle to farm-gate (Crosson *et al.*, 2011). However, current WFMs lack consideration for the level of uncertainty associated with the emission factors used (Schils, Olesen, *et al.*, 2007). Existing simulation models also do not tend to include a CS component. Out of 31 WFMs found in the literature, only eight included CS, namely: Farm Sim (Schils, Olesen, *et al.*, 2007), Hoofprint

(Sise *et al.*, 2010), The GHG Model (O'Brien *et al.*, 2010), Holos (Mc Geough *et al.*, 2012), AgreCalc (Agrecalc, 2014), Farmscoper (Gooday *et al.*, 2015), the Valio Carbo® Farm calculator (Valio, 2020), and FarmAC (FarmAC, 2023). Teagasc have developed a Sustainability Digital Platform AgNav (Teagasc, 2022). Agnav has been developed in collaboration with Teagasc, the Irish Cattle Breeding Federation (ICBF) and Bord Bia. Agnav has been piloted on farmers, which began in March 2023, and is limited to farmers taking part in the Signpost advisory program.(Teagasc, 2023) Teagasc aim to incorporate CS and biodiversity into the tool in the future (Teagasc, 2022; Today's Farm, 2023). In total out of the tools analysed, less than 30% included CS in their simulation model.

Table 5: List of worldwide simulation models used to examine the environmental impact of livestock and the areas they cover, adapted from Schils, Olesen, et al. (2007). CH_4 = methane, CO_2 = carbon dioxide, N_2O = nitrous oxide, CS = carbon sequestration, AW = animal welfare, EME = enteric methane emissions, H2 = hydrogen, VFA = volatile fatty acids, OMD = organic matter digestibility, N = nitrogen, DM/DMI = dry matter/intake, CP = crude protein, VS = volatile solids.

Model Name	Animal	CH_4	CO_2	N_2O	CS	NH_3 and NO_3	Economics	AW	Biodiversity	EME measurement	Manure Measurement	Country	Reference
DairyWise	Dairy	✓	✓	✓		✓	✓			CH_4 EF × DMI (Schils *et al*., 2006) & updated (Bannink *et al*., 2020)	Emission factor	Netherlands	(Schils, De Haan, *et al.*, 2007; Bannink *et al.*, 2020)
FarmGHG	Dairy	✓	✓	✓		✓				Kirchgessner *et al*. (1995)	IPCC Tier 2	Europe	(Olesen *et al.*, 2004, 2006)
SIMS Dairy	Dairy	✓	✓	✓		✓	✓	✓	✓	Giger-Reverdin *et al*. (2003)	IPCC & Chadwick and Pain (1997) &	UK	(Del Prado *et al.*, 2011)

									Yamulki *et al.* (1999)		
DairyGEM	Dairy	✓	✓	✓		✓		Mills (2003)	IPCC (2006) Tier 2 & Sommer (2004)	USA	(Rotz *et al.*, 2015)
Holos	Dairy	✓	✓	✓	✓	✓	✓	IPCC	IPCC	Canada	(Mc Geough *et al.*, 2012)
WFM	Dairy	✓						H_2 balance and VFA profile	Estimates OMD and N excretion, not N_2O or CH_4 from manure	New Zealand	(Beukes *et al.*, 2010; Beukes, Gregorini and Romera, 2011)
The GHG model	Dairy	✓	✓	✓	✓	✓		(Mills *et al*., 2003; IPCC, 2006)	Emission factors	Ireland	(O'Brien *et al.*, 2010)
Dairy Tier 3	Dairy	✓		✓				Rumen H_2 based on VFA stoichiometry	IPCC Tier 2	Netherlands	(Bannink, van Schijndel and Dijkstra, 2011;

									Jan Dijkstra *et al.*, 2018)
NorFor	Dairy	✓	✓	✓		✓		(Nielsen *et al.*, 2013)	(Nielsen *et al.*, 2013)
D-GAF	Dairy	✓	✓	✓			Livestock numbers, DMI, DM digestibility, milk metabolic rate increase, liveweight, liveweight gain and milk production	VS, DM digestibility, emission potential (0.24), ash content, methane conversion factor	Australia	(The Primary Industries Climate Challenges Centre (PICCC), 2023)
D-GAS	Dairy	✓	✓	✓			Based on DM, DM Digestibility and CP	Emissions factor	Australia	(Dairy Australia, 2023)

HolosNor	Dairy & Beef	✓	✓	✓		✓		IPCC (2006) Tier 2 & digestibility of the diet	IPCC (2006)	Norway	(Bonesmo *et al.*, 2013)
Integrated Farm System Model (IFSM)	Dairy & Beef	✓	✓	✓		✓	✓	Mills 2003	IPCC 2006 Tier 2 & Sommer (2004)	USA	(Rotz *et al.*, 2014, 2022)
FarmSim	Cattle	✓	✓	✓	✓	✓		IPCC Tier 1 and 2	IPCC Tier 2	France	(Schils, Olesen, *et al.*, 2007)
Grange Dairy Beef Systems Model	Cattle	✓	✓	✓			✓	Based on real measurements			(Ashfield, Crosson and Wallace, 2013)
BEEFGEM	Beef	✓	✓	✓		✓	✓	IPCC (2006)	Husted (1994), Chadwick (2000) & Oenema (1997)	Ireland	(Foley *et al.*, 2011)

Karoline	Beef	✓						Rumen H_2, VFA stoichiometry, CH_4 formation in hind gut	manure N and P output	Denmark/Sweden, & Finland	(Danfær *et al.*, 2006)
Hoofprint	Sheep and beef	✓	✓	✓	✓	✓		Energy intake * number of animals	Energy intake *number of animals	New Zealand	(Sise *et al.*, 2010)
OVERSEER	Ruminants	✓	✓	✓		NO_3		EF (21.6 g CH_4 kg−1 DMI) * animal intake (IPCC, 2006)	NZ inventory EF and IPCC Tier 2	New Zealand	(Wheeler *et al.*, 2008)
CAPRI	Ruminants and non-ruminants	✓		✓			✓	Data Coefficients		EU	(Kesting and Witzke, 2021)

FarmAC	Ruminants and non-ruminants	✓	✓	✓	✓	✓			Not specified	Not specified	Denmark	(FarmAC, 2023)
GLEAM	Ruminants and non-ruminants	✓	✓	✓					IPCC Tier 2	IPCC Tier 2	-	(Gerber *et al.*, 2013)
REPRO	Ruminants and non-ruminants	✓	✓	✓				Aim for future module	IPCC - conversion factors	IPCC	Germany	(Küstermann, Kainz and Hülsbergen, 2008)

Cool Farm Tool	Various livestock	✓	✓	✓		✓	✓	IPCC and FCR	IPCC Tier 2	-	(Hillier *et al.*, 2011)
Valio Carbo® Farm calculator	Various livestock	✓	✓	✓	✓			(Ramin and Huhtanen, 2013)	Sommer *et al.* (2004), (Elsgaad (2016), Petersen (2016), IPCC (2006) & (Gronroos *et al.*2017).	Finland	(Valio, 2020)
INRA method	Various livestock							Sauvant and Nozière (2016)	IPCC Tier 2 & Eugene 2019	France	(Eugène *et al.*, 2019)
GAS-EM	Various livestock	✓		✓		✓		Kirchgessner *et al.* (1994)	IPCC Tier 2	Germany	(Vibart *et al.*, 2021)
Arla Global Climate	Various livestock	✓		✓				IPCC 2006	IPCC 2006	Sweden/Denmark/Germany/UK	(Vibart *et al.*, 2021; Arla, 2023)

Check Carbon tool												
Farmscoper	Various livestock	✓	✓	✓	✓	✓	✓	✓	IPCC 1996	IPCC Tier 2 (1996)	UK	(Gooday *et al.*, 2015)
Agrecalc	Various livestock	✓	✓	✓	✓			✓	IPCC 2006 Tier 2	IPCC Tier 2	UK	(Agrecalc, 2014)
Sustainability Digital Platform – in development	Various livestock		✓	NU E	✓	✓		✓	-	-	-	(Teagasc, 2022)
The Ruminant Farm Systems Model (RuFaS)	Dairy	✓	✓	✓	✓		✓		Choice of three: (1) Niu *et al*. (2) Mills *et al*., Mitsherlich Model 3, or (3) the IPCC Tier 2 model.	Based on animal and dietary characteristics and IPCC Tier 2	USA	(Hansen *et al.*, 2021)

DairyMod	Dairy	✓			Australia	(Johnson *et al.*, 2003)
DyNoFlo	Dairy	✓	✓	Estimates manure N excretion using milk production from milking cows and book values for dry cows, heifers, and steers.	USA - Florida	(Cabrera *et al.*, 2005)

Previous models mostly neglect to examine the economics of different mitigation strategies, due to limited data on costs and investments (Lie *et al.*, 2018). Out of the worldwide models investigated, economic inclusion was 32% of the models and the CS component was in 29%. Production costs significantly influence decision-making, therefore, if profitable, economic inclusion could encourage low emission strategies and their uptake (Finnegan *et al.*, 2018).

The IPCC methodology is very popular in existing models, such as Holos (Mc Geough *et al.*, 2012), HolosNor (Bonesmo *et al.*, 2013), FarmSIM (Schils, Olesen, *et al.*, 2007), OVERSEER (Wheeler *et al.*, 2008), GLEAM (Gerber *et al.*, 2013), REPRO (Küstermann, Kainz and Hülsbergen, 2008), Cool Farm Tool (Hillier *et al.*, 2011), Arla Global Climate Check Carbon tool (Vibart *et al.*, 2021; Arla, 2023), Farmscoper (Gooday *et al.*, 2015) and Agrecalc (Agrecalc, 2014). The IPCC methodology is also programmed into models as an optional methodology for either predicting manure, enteric emissions or both, similar to The GHG model (O'Brien *et al.*, 2010), DairyWise (Schils, Olesen, *et al.*, 2007), DairyGEM (Rotz *et al.*, 2015), SIMSDAIRY (Del Prado *et al.*, 2011), Integrated Farm System Model (IFSM; Rotz *et al.*, 2014, 2022), Valio Carbo® Farm calculator (Valio, 2020), GAS-EM (Haenel *et al*., 2020 cited in, Vibart *et al.*, 2021), the INRA method (Eugène *et al.*, 2019), FarmGHG (Olesen *et al.*, 2004, 2006), Dairy Tier 3 (Bannink, van Schijndel and Dijkstra, 2011; Jan Dijkstra *et al.*, 2018) and BEEFGEM (Foley *et al.*, 2011).

2.8.3 IPCC Guidelines

The IPCC Guidelines are the most representable containing steady values for creating a nation-wide GHG record and comparing emissions internationally (Crosson *et al.*, 2011). There are multiple tiers in the IPCC guidelines for calculating the GHGe of the agricultural industry, to allow the option of including more detail if available (Crosson *et al.*, 2011), from Tier 1 to Tier 3, with Tier 2 being the most used strategy (IPCC, 2006). The Tier 1 methodology is the simplest form, to allow estimation of emissions with little needed inputs,

to allow ease of use. The calculation of emissions can be conducted with a minimum input of the number of livestock on-farm. Tier 2 is an enhanced version of Tier 1, where additional inputs are required, such as type of livestock, manure management, diet and production system used. However, the methodology has been criticised, as it lacks consideration for variations in farms, such as the type of location and management system (Crosson *et al.*, 2011). But, if sufficient detail is available, IPCC also offer a Tier 3 approach, which is the most advanced of the methodologies, requiring the manure and enteric CH_4 calculation methodologies, dietary information and the calculations used for energy requirements (IPCC, 2006). The methodology incorporates country-specific data to accurately predict emissions for the region, but data is needed for this function.

Nevertheless, the IPCC methodology still has flaws, as the approach is deficient in information to compare emissions between management systems and farms across the tiers (Crosson *et al.*, 2011; Ouatahar *et al.*, 2021). The methodology was built for use as a national inventory and not to be used as a tool to predict an individual farm's emissions and evaluate mitigation strategies (Ouatahar *et al.*, 2021). The approach also does not differentiate between imported and locally sourced feed, presuming a mixture of the two, which might not reflect emissions or compare farms accurately (Crosson *et al.*, 2011). WFMs are used to overcome these issues, as inputs and emissions can be adjusted as needed to accurately reflect the individual farm and their emissions. A method that incorporates the complete system is needed to precisely evaluate the GHGe of the agricultural system (Ouatahar *et al.*, 2021).

2.9 Summary of knowledge gaps, aims and objectives of the PhD and thesis structure

The project aimed to address the knowledge gap of which strategies are available to UK dairy farming systems to holistically reduce GHGe while remaining profitable and productive.

Chapter 3 assessed the variation between equation results and their ability to capture the effect of dietary composition factors on GHGe. Previous research has not quantified the large variation in enteric CH_4 prediction equations, their prediction results, or their lack of dietary composition detail to compare the emissions of an array of diets. The Chapter 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 the measurement method used, cow type and their stage of lactation, which previously published equations have not accounted for.

A knowledge gap is the quantification of the impact of altering RRs on a UK dairy farm system on GHGe and milk productivity, to find a 'sweet spot' for reducing GHGe through RRs, without substantially impacting milk production to ensure feasibility and economic viability. Chapter 4 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 CH_4 and feed production. Research tends to focus on only milk quantity and quality and occasionally EME, not combined with the feed production emissions. Chapter 5 holistically evaluated the effect of alternative sources of protein to soya on EME 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 requires a roadmap and information on how to reach their set target, with limited research holistically investigating a combination of strategies and the practicality of how this goal can be achieved in the UK dairy industry. Chapter 6 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.

2.9.1 Aims of PhD

The aim of this project was to assess mitigation strategies for reducing the GHGe of dairy cattle farms. The project utilised and adapted an existing WFM, capable of simulating scenarios and calculated the CO_2e emissions of a typical UK dairy production management system. The model assessed emissions associated with feed, fertilisers, fuel, energy use, manure storage and handling, EF, as well as management and fertility, whilst evaluating the potential to offset emissions through CS of forestry. To achieve the primary aims, initial steps were required to adapt the existing LCA model associated with the WFM to simulate the components of the dairy system from cradle to farm-gate. The aims of adapting the LCA were for the future use in the assessment of management and mitigation strategies in Chapters 3-6. To meet the aims a scope was established for the LCA and representable databases for the data components were located. Additionally, due to the high variability between existing enteric CH_4 prediction equation results, we sought to collate predictions from previously published equations to create a combined prediction equation based on the most influential dietary composition variables (Chapter 3).

2.9.2 Objectives

1. Find and determine the most appropriate scope to represent the GHGe of the REMEDY model.
2. Adapt and utilise the WFM to accurately predict the impact of mitigation strategies on reducing a UK dairy farms GHGe.

Chapter 3: Enteric Prediction Equations

Chapter 3: Enteric Prediction Equations

3.1 Introduction

Enteric CH_4 prediction equations are a cost effective method of estimating the emissions of agricultural livestock (Hristov *et al.*, 2018). There are several prediction equations and sources of variability between them, as the studies used to develop the equations vary in their methodologies, from the measurement methods used, such as the respiration chamber, SF_6 technique, ventilated hood, or the green feed system, to the size of the study population, the region the study was conducted, and the farming system used. There are also unexplained sources of variability in CH_4 emissions, such as cow type and their stage of production, which are not regarded in published prediction equations, raising considerable concerns regarding their generalisability. However, few studies have evaluated and compared the performance of enteric CH_4 prediction equations. Prediction equations are also not commonly developed and compared across multiple diets, with most being based on emission data from a total mixed ration diet, or limited concentrate or forage intake (Hristov *et al.*, 2018). Further research is needed into the degree of variation beyond simple measurements of dietary composition, using a large selection of diets (Hristov *et al.*, 2018).

Previous reviews have not evaluated the degree of variation in predicted CH_4 emissions between enteric equations or assessed which dietary composition variables within the prediction equations have the greatest influence (Appuhamy, France and Kebreab, 2016; Niu *et al.*, 2018; Benaouda *et al.*, 2019). There is a demand for efficient methods that report realistic results to compare carbon reduction strategies (Hammond *et al.*, 2016), as current models are created using restricted data sources. New models are needed based on accurate enteric emissions, from large scale studies to increase representability (Hristov *et al.*, 2018).

Globally, it would be beneficial to have an ‘average’ equation to use universally, based on dietary characteristics, which is not currently available.

3.2 Aims and Objectives

Chapter 3 aimed to collate existing prediction equations, assess their ability to account for dietary composition variables on EME and investigate their variability. The equations would then be refined to create a combined equation based on the results of those that account for dietary composition variables on EME.

Chapter objectives:

1. To investigate the variation between existing enteric prediction equation results.
2. To create a prediction equation based on dietary composition variables.

3.3 Methodology

3.3.1 Sourcing the prediction equations

Equations predicting emissions from EF were identified using the databases Science Direct, Google Scholar and PubMed, by searching for peer reviewed scientific publications in English. The terms: “dairy cattle”, “prediction”, “equation(s)”, “methane” and “enteric fermentation emissions” were searched, which after removing duplicates, resulted in 239 papers. The article titles and abstracts were screened to remove those irrelevant, before they were examined for international equations, predicting EME from dairy cattle. The search resulted in 25 articles being selected, from which the prediction equations were extracted, giving a total of 132 enteric methane prediction equations. From the equations, 101 were chosen, as the required dietary data was available to calculate the CH_4 emission results. The equations were coded as functions, into R statistical programming language, version 4.3. Some equation outputs were reported as megajoules per day, which were converted to the same functional unit of CH_4 grams per day (gCH_4/day). They were converted by dividing CH_4 emissions predicted in megajoules per day, by 0.05565 (0.05565 megajoules of energy is equivalent to one gram of CH_4; De Haas *et al.*, 2011; Appuhamy, France and Kebreab, 2016 and Niu *et al.*, 2018). Eleven equations from the 101 equations were removed, as they obtained zero results, resulting in 90 equations. The equations were then divided by DMI, to produce CH_4 emissions as grams per kg of DMI, to allow comparison between diets with dissimilar DMI.

3.3.2 Defining the Diets

In consultation with a specialist dairy cow nutritionist, the authors complied a dataset of 15 individual dairy cow diets commonly used in commercial UK dairy farms. The choice of diets was intended to be representative of different cow stages of production, MY, production

system types and seasons common in the United Kingdom and Europe, as well as some more extreme variations in dietary compositions. Diets 1, 2, 3, 6, 7, 8, 9, 11, 12, 13, 15, 16, 18 were lactating dairy cows, and diet 4 was for dry cows, these are detailed further in Appendix 1. Nutrition values for each dietary component were sourced from the reference feed values, from the most up to date feed into milk (FIM) database (Thomas, 2004).

3.3.3 Building the combined prediction equation

3.3.3.1 Refining the equations and diets

The equations were refined by removing those that included other ruminants, such as sheep and goats, and milk factors, such as MY, milk fat and milk protein content, as they were cow type specific and did not function on dry cow diets. The equations were further refined to remove simplistic equations, such as those based on only DMI or GEI, as they could not distinguish between diets, which resulted in 32 remaining enteric equations, from five papers as shown in Table 6. The diets were used to analyse the correlations that exist between the various dietary characteristics, to avoid significant associations between variables, which would bias the combined equation results. A correlation plot was created in R programming language, which was also converted to a data frame and table to view the units of each correlation.

Table 6: 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
Moate *et al*. (2011)	2	CH_4g/day = [24.51 - 0.788 × EE] × DMI
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

3.3.3.2 Descriptive analysis model predictions

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 7. The dietary composition variables were used in the equations and included: BW, DM, GE, ME, CP, FA, EE, NDF, and ADF.

Table 7: The range of enteric methane emissions in grams per kilogram of DMI 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 (CH_4g/kgDMI)	
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	28.50
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

3.3.3.3 Evaluating the variability between enteric methane prediction equations

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.

Highly correlated variables, such as NDF and ADF (1.00), GE and ME (1.00), GE/ME and EE (0.86), GE/ME and CP (0.77) were identified and only one dietary characteristic from each was considered for inclusion in the models. After this, all combinations of variables were considered, and twelve combinations of dietary characteristic variables were selected using the variables: ME, GE, NDF, EE, CP, and FA, which are shown in Table 8 below. The eight nutritional values in the twelve models were univariately screened for significant statistics and low error. 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.

Table 8: The twelve combinations of dietary characteristics that were reviewed, after analysing the correlations between the dietary variables. ME = metabolised energy, NDF = neutral detergent fibre, GE = gross energy, FA = fatty acids, EE = ether extract, CP = crude protein.

Model Number	Variable Combination	Number of Variables
1	ME and NDF	2

2	GE and NDF	2
3	NDF and EE	2
4	ME, NDF and FA	3
5	ME, NDF and EE	3
6	ME, CP and NDF	3
7	GE, CP and NDF	3
8	GE, NDF and FA	3
9	GE, NDF and EE	3
10	CP, NDF, FA and EE	4
11	GE, CP, NDF, FA and EE	5
12	ME, CP, NDF, FA and EE	5

3.3.3.4 Analysing the performance of the equations

The performance of the twelve equations were analysed against the variation in the published equations and the fifteen diets, using boxplots.. The results of the combined equation were compared to the median and range of the published equations.

3.4 Results

3.4.1 Diet composition

A summary, such as the mean and range of the dietary composition variables, across the fifteen formulated diets used in the equations, can be seen below in Table 9. The details of the individual diets are available in Appendix 1.

Table 9: The summary of the mean and range of the different diet composition variables in the 15 diets used in the study. MEI = metabolized energy intake as megajoules per day, CP = crude protein, FA = fatty acids, EE = ether extract, NDF = neutral detergent fibre, ADF = acid detergent fibre, all reported as percentage of dry matter.

Dietary Variable	Mean	Minimum	Maximum
MEI (MJ/day)	214	125.3	271.7
CP (%)	17.13	12.58	22.05
FA (%)	3.18	0	7.5
EE (%)	4.85	2.74	6.4
NDF (%)	39.37	32.5	52.5
ADF (%)	32.27	26.65	43.05
Forage (%)	57.86	50	81.89

3.4.2 Analysing the variability between enteric equations

The study resulted in 32 refined international equations that estimate EME from dairy cattle, which produced large variability in their predicted CH_4 emissions between the equations, even when the same inputs were used. Figure 5 shows the variation in emission results between the 32 refined equations, with simplistic equations, such as percentage of forage intake only removed and those that included milk factors. The list of equations utilised are presented in Table 6. Figure 5 also reflected the consistency of equations in reflecting differences in dietary nutritional composition, as they were consistent in their ranking of the

diets from most to least emitting, per kg of DMI. The refined equation results ranged from 12.49 to 34.27gCH_4/kgDMI.

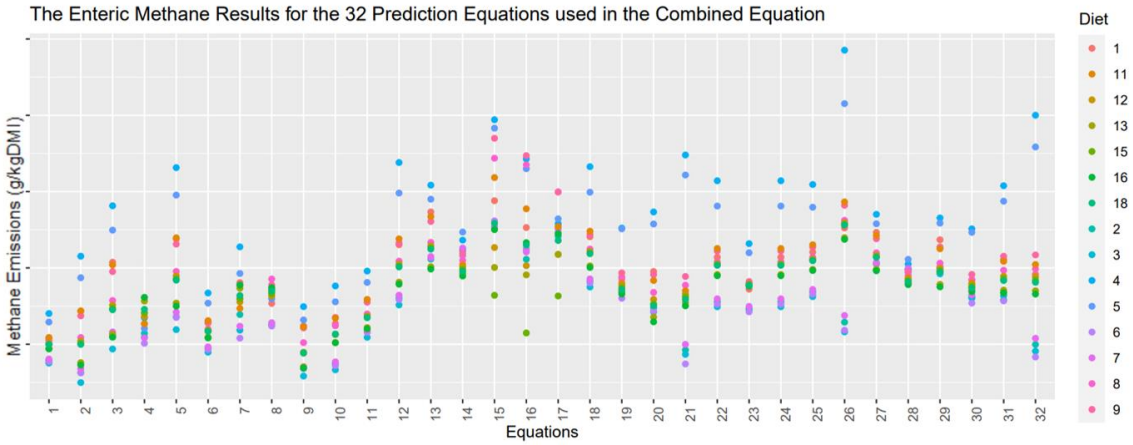

Figure 5: The variation in the results obtained from the 32 prediction equations against 15 dairy diets, as grams of methane per kilogram of DMI.

3.4.3 Choosing the combined prediction equation dietary variables

Table 10 shows the correlations between the dietary composition variables, which was used to assess the associations between the factors and whether multiple variables could be used in a single equation, without biasing the results. The table highlights the strong correlations between the variables GE/ME and EE (0.86) and GE/ME and CP (0.77), which would bias the results if used in the same equation, limiting their usage.

Table 10: The correlations between the dietary composition variables, using the 15 diets. The dietary variables consist of: GE = gross energy, ME = metabolized energy, CP = crude protein, FA = fatty acids, EE = ether extract, NDF = neutral detergent fibre, ADF = acid detergent fibre, starch, sugar and DMI = dry matter intake.

	GE	ME	CP	FA	EE	NDF	ADF	Starch	Sugar	DMI
GE	1.00	1.00	0.77	0.10	0.86	-0.68	-0.68	0.32	0.06	0.09
ME	1.00	1.00	0.77	0.10	0.86	-0.68	-0.68	0.32	0.07	0.09
CP	0.77	0.77	1.00	0.18	0.67	-0.62	-0.62	0.22	0.00	0.17
FA	0.10	0.10	0.18	1.00	0.37	-0.48	-0.48	0.08	-0.15	0.32
EE	0.86	0.86	0.67	0.37	1.00	-0.57	-0.57	0.12	-0.10	-0.05
NDF	-0.68	-0.68	-0.62	-0.48	-0.57	1.00	1.00	-0.76	0.19	-0.66

ADF	-0.68	-0.68	-0.62	-0.48	-0.57	1.00	1.00	-0.76	0.19	-0.66
Starch	0.32	0.32	0.22	0.08	0.12	-0.76	-0.76	1.00	-0.43	0.66
Sugar	0.06	0.07	0.00	-0.15	-0.10	0.19	0.19	-0.43	1.00	0.12
DMI	0.09	0.09	0.17	0.32	-0.05	-0.66	-0.66	0.66	0.12	1.00

3.4.4 Analysing the performance of the equations

The performance of the equations used to choose the factors for the combined equation are shown in Table 11, such as R^2, root mean square error (RMSE) and the residuals for the 12 possible equation combinations. The fixed effects model showed significant results for all the variables included in three of the tested combined equations. Namely, equation 1: ME and NDF, equation 2: gross energy (GE) and NDF, and equation 4: ME, NDF and FA, seen in Table 11. The results were similar between the models, but based on the model performance, simplicity, 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 6.

Table 11: Presents the performance of the 12 possible character combinations for the combined prediction equations, such as the R^2, root mean square error (RMSE; $gCH_4/kgDMI$), 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
		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		Intercept	19.23	0.42	46.06	0.80	1.46	1.00	2.30
	EE	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	GE, CP, NDF, FA		Intercept	19.23	0.42	46.06	0.80	1.46	1.00	2.30
	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,		Intercept	19.23	0.42	46.06	0.80	1.46	1.00	2.30
	FA and EE	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.

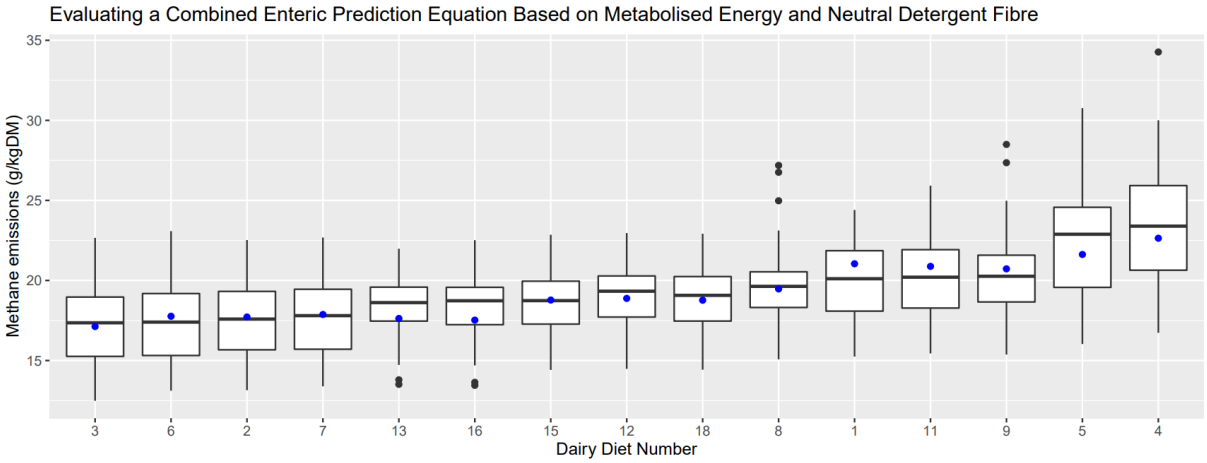

Figure 6: The performance of the combined prediction equation based on metabolised energy (ME) and neutral detergent fibre (NDF) including the random effect, against the variation in results between equations represented by the boxplots and the median of the equations, signified by the line extending through the middle of each boxplot. Methane emissions as grams per kilogram of dry matter intake (DMI).

The distribution of random effects for the 32 chosen equations are shown below in Figure 7.

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.

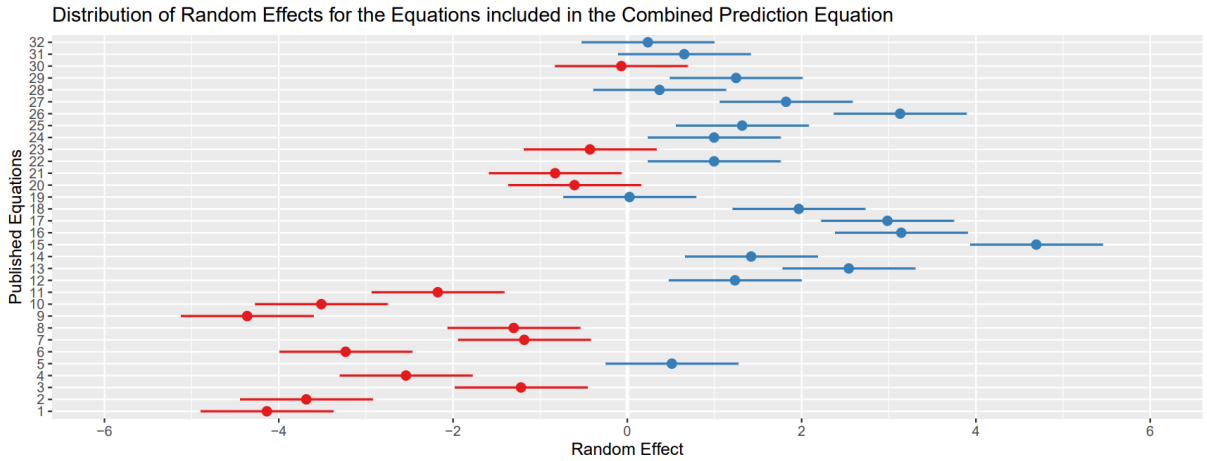

Figure 7: The distribution of random effects for the 32 refined equations used in the combined prediction equation.

3.5 Discussion

The enteric prediction equations from existing literature were compiled and the variability between the equations evaluated, utilising dietary composition and intake. There were 101 international prediction equations, which produced large variation in their EME projections, demonstrating the uncertainty when comparing varying research on dairy cattle emissions. The equations were refined to 32 prediction equations and twelve possible dietary combination factors for a universal equation were deliberated. A fixed effect with random effects model and a range of 15 hypothetical diets representable of different types of dairy cattle in the UK, such as lactating, dry cows and youngstock diets, were used to create an equation, that could be used universally across cow types. The diets were used to generate predictions from each equation, and a combined EME prediction equation was successfully defined, which accounted for the dietary proportions of energy and fibre and the unexplained sources of variability from numerous studies, used to generate the predictions.

The EME varied from 6.13 to 35.15gCH_4/kgDMI for the 90 collated equations using the 15 diets. The results showed a larger variation than those found by Niu *et al.* (2018) of 9 to 30.4gCH_4/kgDMI with an average of 20.1gCH_4/kgDMI. However, the current study included diets for a variety of cow types, such as dry cows, which would cause larger variation in emissions, whereas Niu *et al.* (2018) only assessed lactating dairy cows. While Ellis *et al.* (2007) obtained a larger variation in their EME results from 4.76 to 42.21 gCH_4/kgDMI for the combined dataset (beef and dairy), the dairy group showed a lower variation in EME from 6.2 to 35.8gCH_4/kgDMI, similar to the current study's findings. Benaouda *et al.* (2019) review showed an even larger variation of 6.53 to 41.7gCH_4/kgDMI across the dairy cattle data from Europe, the USA and Australia, highlighting the difference equations and the dataset used can cause. However, the refined data in the current study, had a much lower variation in their results, by 7.24gCH_4, with a range of 12.49 to 34.27gCH_4/kgDMI.

The variation between previously defined equations, could be due to the studies varying in methodology when creating the equations, which Hristov *et al.* (2018) highlighted in their review of prediction equations. The studies differed in their country of origin and size, from small-scale studies of 16 cow records, to worldwide meta-analyses of over 5,000 cow records. The method of collection also varied for the EME, from respiration chambers to more variable long period methods, such as the SF_6 technique, which varies by between 5 - 10% (approximately 14.3 to 29.1gCH_4/day), when compared to respiratory chamber emissions (Hammond *et al.*, 2016). Niu *et al.* (2018) generated 49 equations and 23% of the EME results obtained to develop these equations were using the Green Feed system, of which 15 equations were used in the creation of the combined prediction equation. EME vary considerably over a 24 hour period (Børsting *et al.*, 2020), which also highlights dairy cows have higher emissions during feeding, than other points of the day. EME are taken at different points of the day (Patra, 2016), however, they may not be representative of emissions, as the cattle were feeding during this time, which could have misled the results and caused some of the variations in the equations.

Importantly, some of the studies included a variety of livestock, such as goats and sheep, which may vary considerably in their emissions (Benaouda *et al.*, 2019). However, while the equations used in the combined prediction equation were refined to those that included dairy and beef cattle only, other factors such varying cow type, stage of production, study design and measurement methodology, were combined in the random effects estimated in our analysis. The partitioning of this variation was not conducted in the current study and would have been difficult to include. The combined prediction equation derived in the study was based on the results from 32 existing equations, from only five studies, which may have limited the results. However as previously stated, existing equations derived from single studies are restricted, as they do not account for the random effect of animals or studies.

The diets used in the study showed a range of dietary composition values for UK based lactating and dry dairy cattle diets. The range of BW values for the formulated diets (550 to 703kg) were lower than those in the European dataset (283 to 956kg) used by Appuhamy, France and Kebreab (2016), Niu *et al.* (2018) and Benaouda *et al.* (2019), which could have been due to the variation across Europe, compared to UK dairy cattle. The larger BW also likely caused a higher required DMI (4.17 to 33.5kg/day) to the current study (13.55 to 25.32kg/day). The larger BW and DMI could have also led to the larger range in EME for the reviews (6.53 to 50.4gCH_4/kgDMI), compared to the current study (6.13 to 35.15gCH_4/kgDMI). The reviews also contained a larger range in their dietary composition variables, such as EE (1.1 to 9.4), CP (8.1 to 27.4) and NDF (13.4 to 69.7) to the current study (EE = 2.74 to 6.4, CP = 12.58 to 22.05 and NDF = 32.5 to 49.16). However, the diets were formulated for use in the study to represent different dairy cattle systems in the UK, rather than across Europe, so cannot be compared flawlessly. But the diet composition range across the reviews, show the current diet composition values are within previously used diets, to support their applicability and usage.

RMSPE has been used in previous studies to evaluate the performance of equations (Ellis *et al.*, 2007; Appuhamy, France and Kebreab, 2016; Niu *et al.*, 2018; Benaouda *et al.*, 2019), so was deemed a suitable measure in addition to the R^2 values, residuals of variation and significant t-values from the fixed effect results. The equations assessed in the current study for use in the combined prediction equation had a low RMSE of an average of 1.47, compared to Appuhamy, France and Kebreab (2016) findings of a range from 10.71 to 19.63% RMSPEs for the published equations they analysed. Benaouda *et al.* (2019) had an even higher RMSPE range of 61 to 90.8% for their top 13 ranking equations for predicting EME from dairy cattle. The large error could be due to the large range in BW and dietary composition factors used in the equations, as the equations were aimed for across Europe,

North America, Australia or internationally, which could have reduced the effectiveness of the equations. The R^2 values for the combined equation were also very high, with an average of 0.79. The value was higher than the R^2 values reported from the individual studies, that created the published equations, as the highest was 0.77 (Nielsen *et al.*, 2013). The results suggest the equations had low error and would be suitable equations for predicting the EME of dairy cattle.

The published equations included a variety of predictor variables, but demonstrated consistency in their ranking, to reflect differences in dietary nutritional composition. The combined EME equation defined in the current study is consistent with previous findings in the literature, highlighting the importance of energy and fibre content in influencing EME (Hristov *et al.*, 2018; Benaouda *et al.*, 2019). However the final equation did not contain the effects of fat and protein content on EME predictions, when they have been linked several times in the literature (Rotz, Montes and Chianese, 2010; Patra, 2013; Jose *et al.*, 2016; Niu *et al.*, 2016; Grandl *et al.*, 2019; van Gastelen, Dijkstra and Bannink, 2019; Børsting *et al.*, 2020; Arndt *et al.*, 2021), and previously EE very strongly predicted EME for dairy cows (R^2 = 0.84) and combined dairy and beef cattle (R^2 = 0.79; Ellis *et al.*, 2007). The current study finding EE not to predict EME, could have been due to the high correlation between the variables GE and ME with EE (0.86) and CP (0.77). The correlations were commonly observed in the diets used in this study, limiting the use of these combinations of factors in the creation of prediction equations. Equation one was chosen based on NDF and ME which were highly correlated to each other (-0.68). However, the fibre content is linked to the energy content of the diet, which cannot be avoided, as it has long been known that as fibre intake increases, energy intake decreases (Beauchemin, Farr and Schaalje, 1994). More recently ADF was also negatively correlated to energy intake in horses (Sharpe, 2019). Thus, it was deemed acceptable to use these dietary variables in a single equation.

The equations were evaluated based on RMSPE and R^2 and performed similarly to each other, such as equation four that included FA, as well as fibre and energy content of the diet. However, when inspected, only three prediction equations of the 32 equations included FA, h suggesting a small influence on the accuracy of equation predictions if included. The selection of the most parsimonious model containing ME and NDF was considered the most appropriate and in agreement with Hristov *et al.* (2018), who stated that the trade-off between model complexity and prediction accuracy should be considered, when creating a prediction equation. Niu *et al.* (2018) also recommended the simple equation of DMI and NDF, compared to the better performing equation that included five variables. The current study chose ME rather than DMI, due to the strong correlation between DMI and EME, that could suppress the effect of dietary variables on EME (Rico *et al.*, 2016; Benaouda *et al.*, 2019). To minimise the impact of DMI influencing the predictive ability of dietary composition on EME, the emissions were also evaluated based on grams of CH_4 per kilogram of DM, as suggested by Benaouda *et al.* (2019). DMI was not included in the potential combined equations, as shown in Table 11. ME is also the principal factor impacting milk production (AHDB, 2021b), so it is an important variable to consider when measuring emissions and allows consideration of performance. Previous research by Ellis *et al.* (2007) found DMI superior to MEI in predicting EME, with lower RMSPE and greater R^2 values, however, MEI and NDF content of dairy diets also predicted EME in the study, which the current results support.

Milk factors were not considered in the combined equation, as previous research has found DMI a more accurate predictor of EME, than milk variables (Engelke *et al.*, 2018; Niu *et al.*, 2018). The combined equation was also built to suit all cow types, to provide a universal equation across the dairy farm. Eleven of the milk factor equations tested, resulted in zero emissions for the two dry cow diets. Previous equations have been built for lactating dairy

cows and failed to consider their suitability for use on dry cows and across the herd, to provide a holistic view of EME across the dairy farm.

3.6 Conclusion

The evaluation of the equations highlighted consistency in the ranking of the diets from most to least emitting, suggesting the equations are suitable for comparing the EME of the diets. However, current EME prediction equations show a range in predictions of 21.78g CH_4/kgDMI in their results and this large variation causes difficulty when generalising the results of any individual equation. There are several methods for directly measuring EME of livestock, which leads to large discrepancies between prediction equations. The variation and mass of available equations causes difficulties when choosing an equation and comparing strategies and emissions, to develop long-lasting effective mitigation strategies and governmental legislation to assist the industry towards Net Zero. The combined prediction equation provides a mean of the currently available equations and data, accounting for unexplained variation, to generate a universal equation to compare across farm systems and countries. The combined equation is based on existing published equations and fifteen representable dairy diets, based on dietary composition factors ME and NDF. The equations showed high accuracy and low error with an R^2 of 0.79 and RMSE of 1.47gCH_4/kgDMI. The equation provides a compromise solution allowing easier comparison between studies, until further research establishes new factors or improved measurement methods, that allow greater accuracy predicting the impact of dietary variables on EME than the current widely used IPCC methodology (IPCC, 2006; IPCC, 2019) and DMI only equations (Vibart *et al.*, 2021).

Chapter 4: Replacement Rates

Chapter 4: Replacement Rates

4.1 Introduction

An important aspect of dairy farming is maintaining herd size, as a stabilised herd size allows an efficient supply of milk to meet demand. Farmers maintain herd size from the vital management group known as heifers (Samsonstuen *et al.*, 2019), through either raising heifer replacements on-farm or purchasing them off-farm, to succeed any losses in dairy cows (Nor *et al.*, 2015). The heifers can then calve and join the herd as milking cows. Cattle can be replaced due to voluntary and involuntary reasons, from issues such as illness or low productivity. Although not adding to the milk output, the heifer replacements still contribute to the farms GHGe (De Vries and Marcondes, 2020).

Studies that have examined the relationship between GHGe and RRs have shown lower RRs can lead to lower farm emissions (Garnsworthy, 2004; Weiske *et al.*, 2006; Beukes *et al.*, 2010; O'Brien *et al.*, 2010; Beukes, Gregorini and Romera, 2011; Van Middelaar *et al.*, 2015; Grandl *et al.*, 2019; Lahart *et al.*, 2021; Zhu, Schneider and Oude Lansink, 2023), varying from 2% to over a 40% decrease in farm emissions. In 2021, the average RR in the UK was 30-35% (DEFRA, 2021d). Poor fertility can increase RRs and GHGe (Lahart *et al.*, 2021). CH_4 emissions from heifer replacements alone can contribute to as much as 27% of total CH_4 emissions, when fertility levels were compared from a conception rate of 38% to 65% (Garnsworthy, 2004). Yet, there are a lack of studies investigating the effect of RR on the total farm emissions through whole farm simulation modelling (O'Brien *et al.*, 2010). Simulation farm models are the best approach for showing a holistic view of the farm operations, to consider the environmental impacts of the strategies (Rotz et al., 2020; Segerkvist et al., 2020). A simulation model is needed to analyse the complete farm

emissions to find the optimum RR for UK dairy farms, to reduce the environmental impact without negatively affecting milk production and farm income.

4.2 Aims and Objectives

The aims of Chapter 4 were to utilise the University of Nottingham (UoN) REMEDY model (UKRI, 2020) to simulate the effect of RRs on the CO_2e emissions of the whole system and total annual milk production. A medium RR of 22% for the representable farm was compared to a low RR of 10% and a high RR of 40%, by increasing the number of removals and cull rate of the farm.

Chapter Objectives:

1. To use the REMEDY model to investigate the optimal RR of UK dairy farms, to reduce total CO_2e emissions without negatively impacting total milk production.
2. To evaluate the accuracy of the REMEDY model for simulating the change in RRs, cull rate, milking herd, and youngstock herd size.

4.3 Methodology

4.3.1 Creating a Scope for the project

To conduct an LCA for the current project, the official International Organization for Standardization methodology (ISO 14040: 2006) were followed, as highlighted in Figure 8 below. The first step was to determine the aim and scope for the LCA, by conducting a literature review on previous LCA studies in the dairy industry, to compare between. The project overall aim was considered throughout the scope planning process. Science Direct, Google Scholar and PubMed were used to search for relevant articles, using the terms “Life cycle assessment”, “life cycle analysis”, “dairy cattle”, “milk production”, “greenhouse gas emissions”. From the LCAs researched, the scope was decided, which can be seen in Figure 9 below.

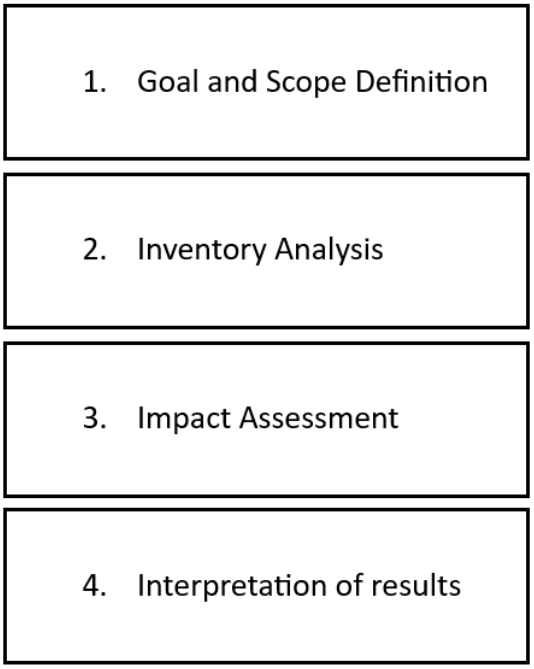

Figure 8: The stages of a life cycle assessment methodology, derived from the official International Organization for Standardization methodology (ISO 14040: 2006).

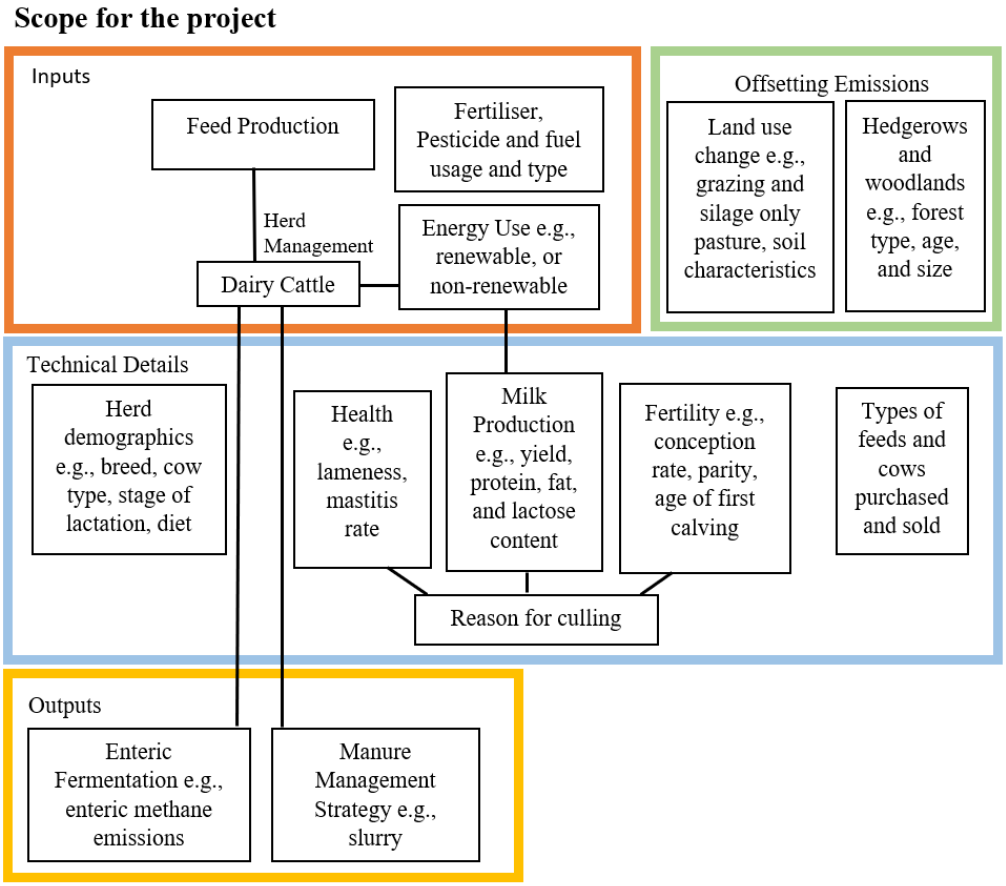

Figure 9: The decided scope for the project from birth to farm-gate.

4.3.2 Collecting data inputs

To obtain data on the inputs for the LCA, as part of the second stage of the ISO 14040:2006 methodology, namely the inventory analysis, the OpenLCA software was downloaded. Free databases were downloaded from OpenLCA Nexus, named: Agribalyse, EcoInvent as part of Agribalyse, the Global Feed LCA Institute (GFLI) and openLCA LCIA methods (OpenLCA, 2020). The data was then examined from each database to find that appropriate to the study, namely: different cattle feeds, manure spread as fertiliser and artificial fertilisers. Fertilisers were chosen to be included in the LCA model, as it was in all 30 papers of a review, analysing the emissions of the dairy system using a LCA approach (Segerkvist *et al.*, 2020).

The Agribalyse dataset contained emissions from cattle feed, fuel and fertiliser and has been used in prior literature assessing the LCA of products (Litskas *et al.*, 2020). The impact

assessment methods from OpenLCA nexus were then downloaded into the Agribalyse dataset in OpenLCA. A new process was created in OpenLCA named “Feed” and the most common cattle feeds were selected and entered as inputs into the new process. The feeds were then analysed using the software and impact assessment method IPCC 2013 for GWP 100a and 20a (IPCC, 2013). IPCC (2013) was the most current IPCC methodology on the database. We extracted all emission factors available from the Agribalyse and GFLI databases for feed, fuel and fertiliser using a Python script that produced a comma-separated value file as an output. The relevant emission factors were then included in the simulation model.

4.3.2.1 Farm Data

Farm data, from a farm known to the research team, was used as an example “test farm” for scenarios. The demographics and management were considered typical of a possible UK dairy farm (summarised in Figure 10). The farm is a semi-seasonal system, holding 140 dairy cows, containing mainly the most common breed of cattle, Friesians (AHDB, 2020b), but also Norwegian red and Normandy cross breeds, which have been increasing in the UK due to productivity benefits (AHDB, 2020b). The actual “test farm” demographics were used to represent the baseline scenario for simulation. The cows were fed forage, consisting of mainly grass and dairy concentrate. Average annual yield was approximately 7,000 litres per cow. The farm had a total land area of 124 hectares of which 92% is grazing pasture and the remaining; silage only pasture. 20 hectares of the land has been converted in the past 20 years, from arable maize to grass. The farm had around 500 trees, with a mixture of willow, ash, oak, elm species over 50 years old, 30 mature orchard apple trees over 100 years old and13km of hedgerows over 30 years old. The parity of the cows ranged from one to nine, with a RR of 20% and an average culling age of seven years old, after five lactations. The average age of first calving was 25 months. The fertiliser usage was 8.2 tonnes per year of calcium ammonium nitrate (27% N) and fuel usage 94 litres of diesel per hectare. The faeces

from the cows were stored in a slurry over winter with straw to form a crust. The slurry was spread via a dribble bar, while the solids were removed every two weeks and spread across the grasslands. April to November the cows grazed and defecated on pasture.

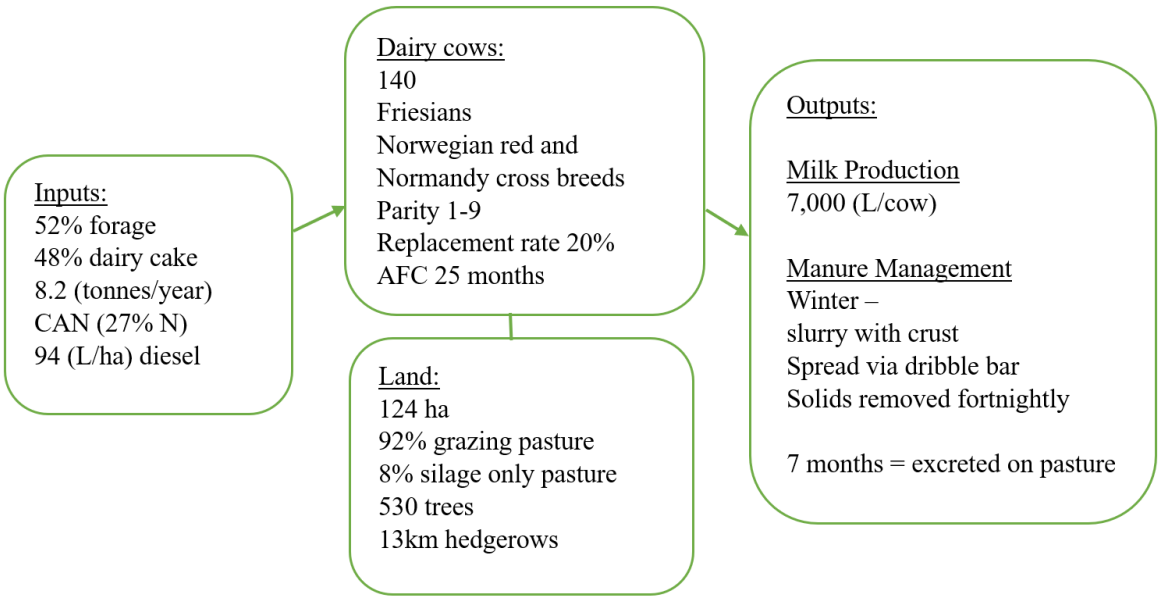

Figure 10: Summary of the typical UK farm represented in the simulation model.

4.3.3 The REMEDY Model

The REMEDY model (UKRI, 2020) developed at the UoN, was a simulation model programmed to aid farmers in their decisions across the system. The model provides a holistic view of the farm by showing the environmental and technical impacts, as shown in Figure 11. The model simulated the GHGe created on the farm, as well as the impacts on cow performance and milk output by comparing different inputs and herd demographics, based on data from a typical UK dairy farm. The model allows comparison between farms, changes on-farm, their inputs, and the effect of these on the farms' milk outputs, economics and environmental footprint at low cost compared to measuring emissions directly on-farm. The model was coded in Python (Python, 2021) using object-oriented programming to represent animals, land, and diets. The project utilised the simulation model to evaluate various scenarios.

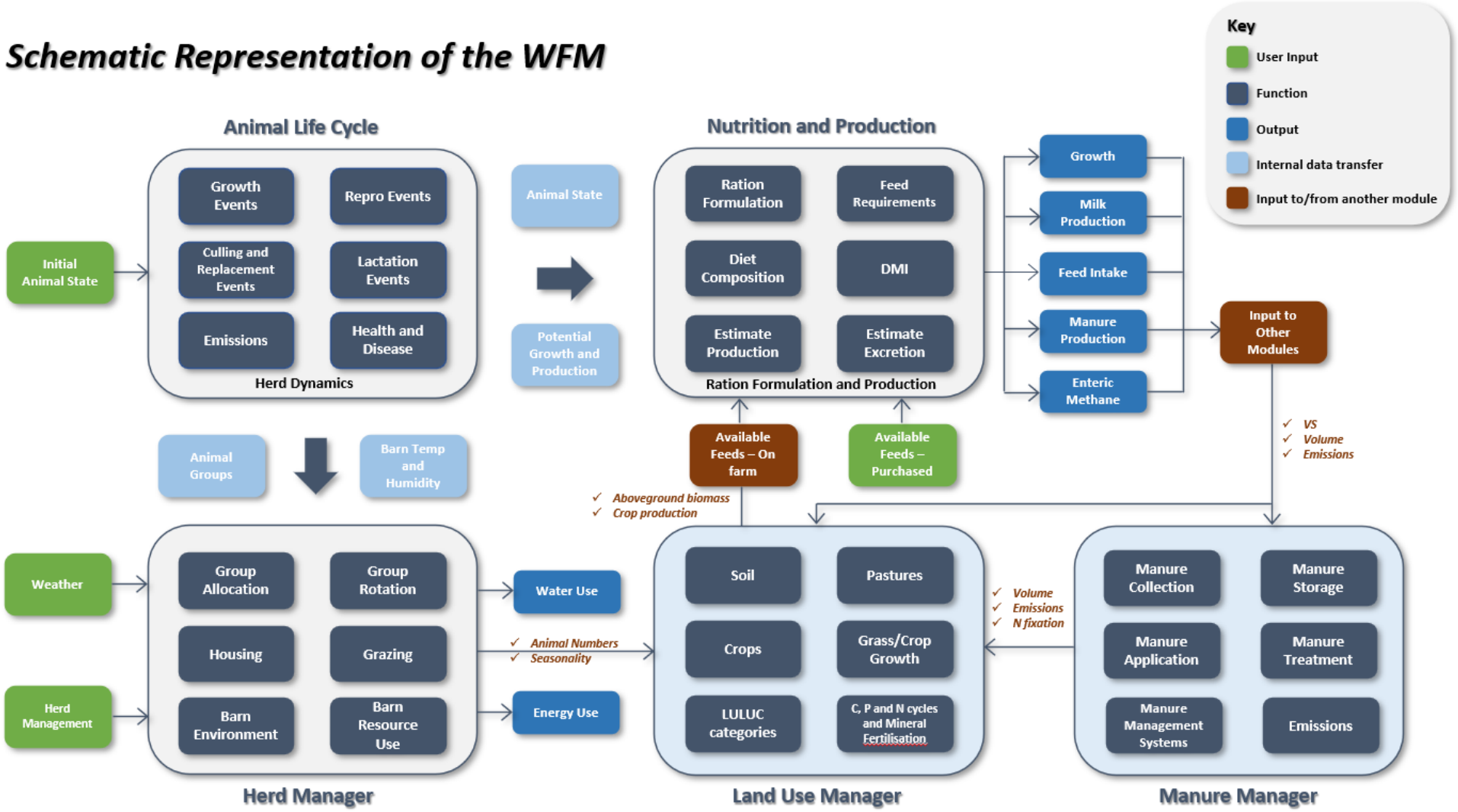

Figure 11: The diagram of the complete REMEDY Model (UKRI, 2020).

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.

Enteric emissions were predicted using the IPCC (2006; 2019) Tier 2 enteric CH_4 prediction equation emission factor for weaned, breeding heifers, and steers. For dairy cows using the IPCC methodology for comparison to the combined equation, a CH_4 conversion factor (Ym^3) of 6.3% was used from IPCC (2019) Table 10.12 for medium producing cattle. Ym^3 is the fraction of gross energy in dairy cattle feed converted to CH_4 to estimate enteric fermentation The combined equation highlighted in the results in Chapter 3 was used to predict enteric CH_4 for milking and dry cows, based on the dietary variable NDF and ME. There was also an option to overwrite the default values and equations and choose an equation for use in the model. Preweaning calves were assumed to have zero EME, based on the IPCC methodology, as the rumen is inactive at this stage and the calf does not emit significant CH_4 emissions (IPCC, 2019b). The model converted output emissions to their CO_2e based on GWP100 (see Table 2 for conversion factors), assuming no annual changes on-farm.

4.3.3.1 Animal Life Cycle

The life cycle of the animals was simulated such as reproduction cycle, including oestrus, insemination, pregnancy, and calving. The culling and RRs were simulated, based on probabilities using typical UK dairy farm parameters, to vary per simulation to suit the farm. The dry period was simulated at a fixed rate of 60 days per production cycle.

4.3.3.2 Nutrition and Production

Diets used within the simulation were developed for milking and dry cows in conjunction with a dairy nutritionist. The updated IPCC (2019) DMI equations, which are shown below,

were used to determine the DMI of the management groups. The BW used were 230kg for weaned cattle, 400kg for heifers and 600kg for milking cows, dry cows, and bulls. The nutritional content of the rations in the feed were calculated based on the INRA nutritional feed database. The emissions associated with the production of feed were collected from the Agribalyse feed database per kilogram 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 to obtain the average herd feed production emissions.

DMI was estimated using the IPCC (2019) 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 (2019) 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 DMI and milk production of grazing dairy cattle at an individual animal and herd level during pasture (O'Neill *et al.*, 2014). The model used parity, milk quality, age, the BCS of the cow and peak MY.

Milk production was estimated based on the nonlinear MilkBot Lactation Model (Ehrlich, 2011), which previous research has shown to accurately predict MY 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 includes the effect of management strategies and health on MY. The model uses parameters based on scale, ramp, decay and offset. Milk production could also be adjusted within the model, as required.

4.3.3.3 Herd Management

There are six management groups for the herd demographics in the model: preweaning calves, weaned calves, breeding heifers, milking cows, dry cows, and bulls. The IPCC (2006; 2019) methodology allowed for the modification of climatic zones on CS potential for a typical UK climate. Static weather was simulated in the model, with the effect of temperature assumed at 11ºC to be representative of the UK, to predict the effect on manure emissions from storage and CS potential.

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.

4.3.3.4 Land Use Management

CS 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 Tier 1 methodology

presumes no change in dead organic matter and mineral soil carbon stocks for forest land and zero for dead organic matter for non-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.

There were two IPCC (2006) methodologies, based on "Forest Land Remaining Forest Land", and "Land Converted to Forest Land". It was assumed that forest land remained forest land in the simulation model. The equations used in the IPCC (2006) tier 1 methodology are shown below. There is limited data available on estimating the uncertainties of emission factors for CS.

4.3.3.4.1 Forest Land Remaining Forest Land

Equation 2.9 from IPCC (2006) was used to calculate the annual increase in biomass carbon stocks (Gain-Loss Method).

$$\Delta C_G = \sum (A * G_{TOTAL} * CF)$$

ΔC_G = the annual increase in biomass carbon stocks due to biomass growth in land remaining in the same land use category (tonnes/carbon/year $^{-1}$), A = area of and remaining in the same land use category (ha), G_{TOTAL} = average annual biomass growth (tonnes/ha^{-1}/year $^{-1}$), CF = carbon fraction of dry matter (tonnes carbon^{-1})

Equation 2.10 Tier 1 was used to calculate the average annual growth in biomass.

$$G_{TOTAL} = \sum \{G_W * (1 + R)\}$$

G_{TOTAL} = average annual biomass growth (tonnes/ha^{-1}/year $^{-1}$), G_W = mean annual above-ground biomass growth for a specific woody vegetation type (tonnes/ha^{-1}/year^{-1}), R = ratio of below-ground biomass to above-ground biomass for a specific vegetation type (tonnes). If no change, then R equals zero.

Equation 2.7 calculates the annual change in carbon stocks in biomass in land remaining in a set land use type (Gain-loss method).

$$\Delta C_B = \Delta C_G - \Delta C_L$$

ΔC_B = annual change in carbon stocks in biomass (the sum of above-ground and below-ground biomass) for each land sub-category, considering the total area (tonnes/carbon/year^{-1}), ΔC_G = the annual increase in carbon stocks due to biomass growth for each land sub-category, considering the total area (tonnes/carbon/year $^{-1}$), ΔC_L = annual decrease in carbon stocks due to biomass loss for each land sub-category, considering the total area (tonnes/carbon/year $^{-1}$)

4.3.3.4.2 Land Converted to Forest Land

Equation 2.16 was used to calculate the initial change in biomass carbon stocks on land converted to another land type.

$$\Delta C_{CONVERSION} = \sum_i \left\{ \left(B_{AFTER_i} - B_{BEFORE_i} \right) * \Delta A_{TO_OTHERS_i} \right\} * CF$$

$\Delta C_{CONVERSION}$ = initial change in biomass carbon stocks on land converted to another land category (tonnes/carbon/year $^{-1}$), B_{AFTER_i} = biomass stocks on land type i immediately after the conversion (tonnes/ha^{-1}), B_{BEFORE_i} = biomass stocks on land type i before the conversion (tonnes/ha^{-1}), $\Delta A_{TO_OTHERS_i}$ = area of land use i converted to another land use category in a certain year (ha/year^{-1}), CF = carbon fraction of dry matter (tonnes/carbon^{-1}), i = type of land use converted to another land use category.

4.3.3.5 Manure Management

Manure emissions were simulated based on the IPCC Tier 2 methodology, which calculates the CH_4 and N_2O emissions from manure separately (IPCC, 2006). The emissions were simulated on a daily step to account for the change in manure management system from

slurry (2nd November to 31st March) to pasture (1st April to 1st November) during the year. The emissions could then 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. Typical animal mass (TAM) varied per management group: milking, dry and bulls were predicted to be 600kg, preweaning and weaned cattle were 230kg and breeding heifers 400kg. Default factors used in the manure equation were region specific to the UK or Europe. 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).

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

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 CH_4 emissions from manure, the VS excretion rates were calculated using the IPCC (2006) equation 10.24 below, based on feed digestibility, GEI, 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 kilogram 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 CH_4 conversion factors were based on mean annual temperature of 11ºC for the region. The maximum CH_4 producing capacity for manure produced by dairy cattle was 0.24 m^3/CH_4/kg of VS excreted. 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 kilograms 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).

Direct N_2O emissions from livestock manure were calculated using the updated Equation 10.25 (IPCC, 2019). The AWMS was presumed to be one for the daily emissions, the Nex calculated from Equation 10.30 was used, the emission factor (EF_3) was 0.004 (kgN_2O-N/kg N) for pasture from Table 11.1, Chapter 11 from the IPCC (IPCC, 2019b) and EF_3 was 0.005 (kgN_2O-N/kg N) 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 N 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, 2019). The Nex calculated was used, AWMS equalled one, the

amount of N co-digestates added to biogas plants was not used, as this was not relevant to the represented dairy farm. The fraction of managed manure N for livestock was 0.11 for pasture and 0.3kg/N for liquid slurry.

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

$N_{volatilization-MMS}$ = 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, 2019). The emission factor for N_2O emissions (EF_4) was 0.01kg N_2O-N for pasture and slurry.

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

$N_2O_{G(mm)}$ = 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 N that is lost due to leaching, as seen below (IPCC, 2019). Nex calculated using Equation 10.30 was used per management system and AWMS equalled one. The amount of N co-digestates added to biogas plants was again ignored. The fraction of managed manure N for dairy cattle that is leached from the manure management system was 0 for slurry, as it is presumed no N is leached from this manure management system, whereas the value was 0.24 kg/N 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, 2019). The result from Equation 10.27 was used, in addition to the emission factor for N_2O emissions from N leaching and runoff (EF_5), which was 0.011 kg N_2O-N/kg N for pasture and leaching was zero kg N_2O-N/kg N 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) $^{-1}$, $N_{leaching-MMS}$ = 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.

NH_3 emissions were simulated in the model, using the N excretion rate (IPCC, 2006, 2019b), and based on the Tier 2 NH_3 excreta emission factor (IPCC, 2006). As well as the Ireland National Inventory and informative inventory report to the United Nations (Duffy, Hyde, Hanley and Dore, 2011; Duffy, Hyde, Hanley, Dore, *et al.*, 2011), Inventory of NH_3 emissions from UK Agriculture – 2021 (Misselbrook, T.H., Gilhespy, Carswell and Cardenas, 2023) and a study on the mass-flow model of NH_3 emissions from UK livestock production (Webb and Misselbrook, 2004). The NH_3 options were included for slurry and pasture. The NH_3 excreted pasture, manure spreading, slurry summer spreading, slurry autumn spreading, fertiliser spreading, cattle housing, and milking unit.

An EF of 0.47 (standard error ±0.09) g NH_3–N $animal^{-1}$ h^{-1} was used for concrete dairy cow-collecting yards and dairy cow-feeding yards from an improved large UK National Inventory of NH_3 emissions (Misselbrook, Webb and Gilhespy, 2006). EF NH_3 excreta were based on IPCC (2006). The emission factor and standard error for Total NH_3 N (TAN) was collected for cattle in a housed system using a slurry management system and those using a deep litter straw-bedded housing generating farmyard manure from the inventory of NH_3 emissions from UK Agriculture 2021 (Misselbrook, T.H., Gilhespy, Carswell and Cardenas, 2023). They were chosen as the most current methods for estimating NH_3 emissions.

4.3.4 Simulating the replacement rate scenario

Dairy farm data was entered into the model using a farm data gatling file from the University of Nottingham, containing individual cow records, establishing the initial model population at an individual animal level. Individual animals were then simulated daily based on their management group from November 1st, 2021, to October 31st, 2031. As the model is stochastic, 50 repetitions of each scenario for 10 years were simulated. To compare scenario results, only result from the last three years (from 01 November 2028 to 31 October 2031) were used to compare stable means and SD for all outcome variables. The last three years were chosen to allow a burn in period for any change in herd demographics to stabilise. A typical UK dairy diet of grazing, dairy cake, and straw (Diet 2 in Appendix 1) was used in the model for the RR 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 BWs. It was assumed that heifers were reared on farm from birth, as the baseline farm.

All factors were kept constant and a baseline RR of 22% was used and compared to a lower rate of 10% and a higher rate of 40% on the overall farm CO_2e emissions over the 10-year period. The current study analysed a reduction in RR of 30% (high to low RR), 18% (high to

medium RR), and 12% (medium to low RR). The output data was compiled into comma-separated values (CSV) files in two forms. The first was an animal level dataset on parity, milk production, and days in milk (DIM). The second was a herd level dataset, which included the N_2O and CH_4 emissions from manure and the EME. Both datasets included total herd animal numbers to enable conversion of emissions to individual and herd level.

The enteric emissions for the milking and dry cows used in the total farm GHGe results were calculated using the combined equation (Chapter 3), as stated in the methods for the REMEDY Model (Chapter 4, Page 120), while the other four management groups were calculated using the IPCC (2006) equation. For comparison to the combined equation, the enteric emissions for the milking and dry cows were also calculated using the IPCC (2006) equation.

The CSV files were imported into R programming language (R, 2022) for analysis, where the data was subset by RR and each of the five runs of 10 years and the ten simulation repeats.. The annual sum was calculated for total animal numbers, milk production, average calving's per parity, EME, CO_2e emissions from manure and total CO_2e emissions for the complete farm. The sum was calculated for each of the 50 farm simulations for the last three simulation years (November 1st, 2028, to October 31st, 2031).

The sums were then merged into an individual data frame, per RR, to create an overall mean and SD for each of the variables analysed. The data was merged and the annual mean and SD were calculated for the enteric and manure emissions, the number of animals in the herd, total milk production, average calving's per parity and total farm emissions as CO_2e, based on GWP100. Scatterplots were created to visualise the data. The total CO_2e emissions for the whole farm were plotted against the milk production, where a trend line was added to the data, to find the optimum RR for low emissions and high milk productivity.

The emissions from feed production were included in the GHGe results, 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. GHGe from energy use were calculated using emission factor 0.21 $kgCO_2e/kWh$, fuel for diesel (average biofuel blend) as $2.48kgCO_2e/L$ (DEFRA, 2023) and fertiliser usage at $2.32kgCO_2e/kg$ were also included in the total farm CO_2e emissions from Agibalyse. The model outputs were then used to complete stage three to assess the impact of the system and stage four to interpret the results, using the official LCA methodology (ISO 14040: 2006).

4.4 Results

4.4.1 Animal Numbers

The average total number of animals per management group for the last three simulation years, were analysed from November 2028 to October 2031 per RR. The dairy farm consisted of mainly milking cows, followed by weaned calves, breeding heifers, dry cows, preweaning calves and lastly bulls. The main difference in livestock numbers was between heifers for the three RRs. Table 12 shows the annual total of the overall number of livestock on farm per management group, which shows the higher RR also had a larger annual average of animal numbers on the farm.

Table 12: 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 (10%)	Preweaning calf	10	±3
	Weaned calf	53	±6
	Breeding heifer	26	±5
	Milking cow	127	±5
	Dry cow	22	±5
	Bull	2	±1
Medium (22%)	Preweaning calf	12	±4
	Weaned calf	57	±6
	Breeding heifer	39	±6
	Milking cow	130	±4
	Dry cow	22	±4
	Bull	2	±2
High (40%)	Preweaning calf	13	±3
	Weaned calf	66	±7
	Breeding heifer	60	±8
	Milking cow	132	±3
	Dry cow	21	±4
	Bull	3	±2

4.4.2 Milk Production

Total annual milk production (litre of FPCM) per RR scenario was analysed, shown in Table 13. 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 RR 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 13: 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	±32,479
Medium	1,225,702	±22,327
High	1,200,650	±16,973

4.4.3 The Combined and IPCC Enteric Methane Prediction Equation

The enteric emissions for the milking and dry cows calculated by both the IPCC (2006) and combined equation for comparison, are shown in Table 14 below.

Table 14: The total annual average enteric methane emissions for milking and dry cows at the herd level, comparing predictions using the combined equation created in Chapter 3 and the IPCC (2006) equation.

Equation	Replacement rate	Dry cattle	Milking cattle
Combined	Low	1,424 (±56)	20,030 (±324)
	Medium	1,488 (±49)	20,475 (±291)
	High	1,514 (±45)	20,960 (±153)
IPCC[10]	Low	1,241 (±44)	17,199 (±205)
	Medium	1,284 (±31)	17,705 (±151)
	High	1,302 (±33)	18,107 (±117)

[10] Intergovernmental panel on climate change (IPCC)

4.4.4 Total Farm carbon dioxide equivalent emissions

The annual CO_2e emissions from GHG emitting sources included fertiliser usage, fuel, electricity, and CS on-farm across the whole dairy enterprise, which are shown in Table 15 below. The emissions are based on the typical UK dairy farm (described on pages 118-119, summarised in Figure 10), simulated in the model.

Table 15: The annual emissions from fertilisers, fuel, and electricity at the dairy enterprise as carbon dioxide equivalent (CO_2e), as well as the carbon sequestration (CS) ability of the land ($kg/CO_2e/herd/year$)

	Fertiliser	Fuel	Electricity	CS of Land
CO_2e emissions	17,557.62	18,225.07	13,410.00	-243,464.40

The breakdown of the CO_2e emissions from each source of emissions can be seen in Table 16 below. The total CO_2e emissions are also highlighted in Table 16 with and without CS. The total emissions include enteric CH_4, CH_4 and N_2O from manure and the emissions from fertilisers, fuel, feed production, and electricity, presented as CO_2e. The average emissions irrelevant of the source and total annual average were highest for the high RR, followed by the medium RR and lastly the low.

Table 16: The total carbon dioxide equivalent (CO_2e) emissions of each source on farm with and without carbon sequestration (CS) for the three replacement rate scenarios and standard deviation.

Replacement rate	Enteric	Manure	Feed Production	Total	Total with CS	Total standard deviation
Low	689,925 (±16,348)	201,156 (±5,614)	578,240 (±13,176)	1,518,511	1,275,047	±21,771
Medium	732,879 (±12,178)	217,708 (±5,180)	597,184 (±7,066)	1,596,963	1,353,498	±17,163
High	782,752 (±12,809)	238,710 (±5,666)	609,454 (±5,304)	1,680,107	1,436,642	±18,320

The CO_2e emissions were 9.62% greater for the high RR scenario than the low RR scenario and 4.91% higher for the medium RR, than the low RR. The mean CO_2e emissions between the high and medium RR varied by 4.95%. The ranking of the RRs was the same when CS was included in the values, but the percentage variation in CO_2e emissions between RRs was greater when CS was included. The high RR had 11.25% greater emissions than the low RR scenario and the medium RR 5.8% greater than the low RR. The difference between the high and medium RR was 5.79%. The average CO_2e emissions per kg of FPCM are shown in Table 17 below. CO_2e emissions from EF contributed to the largest proportion of total CO_2e emissions, followed by feed production, CS of land (when included), manure, fuel, fertiliser and lastly electricity.

Table 17: The average kilogram of carbon dioxide equivalent (CO_2e) emissions per kilogram of fat-protein corrected milk (FPCM) for the various sources of emissions.

Replacement rate	Enteric	Manure	Feed Production	Fertiliser	Fuel	Electricity	Land
Low	0.59	0.17	0.49	0.01	0.02	0.01	-0.21
Medium	0.60	0.18	0.49	0.01	0.01	0.01	-0.20
High	0.65	0.20	0.51	0.01	0.02	0.01	-0.20

4.4.5 Milk Production and carbon dioxide equivalent emissions

Milk productivity was analysed against CO_2e emissions for the three RRs, which can be seen in Figure 12 and Figure 13 below. The results are based on the 50 simulation repetitions and show the relationship of balancing low emissions without impacting milk production. The figure shows the high RR had the highest emissions and medium milk production, whereas the low RR had the lowest emissions and lowest milk production.

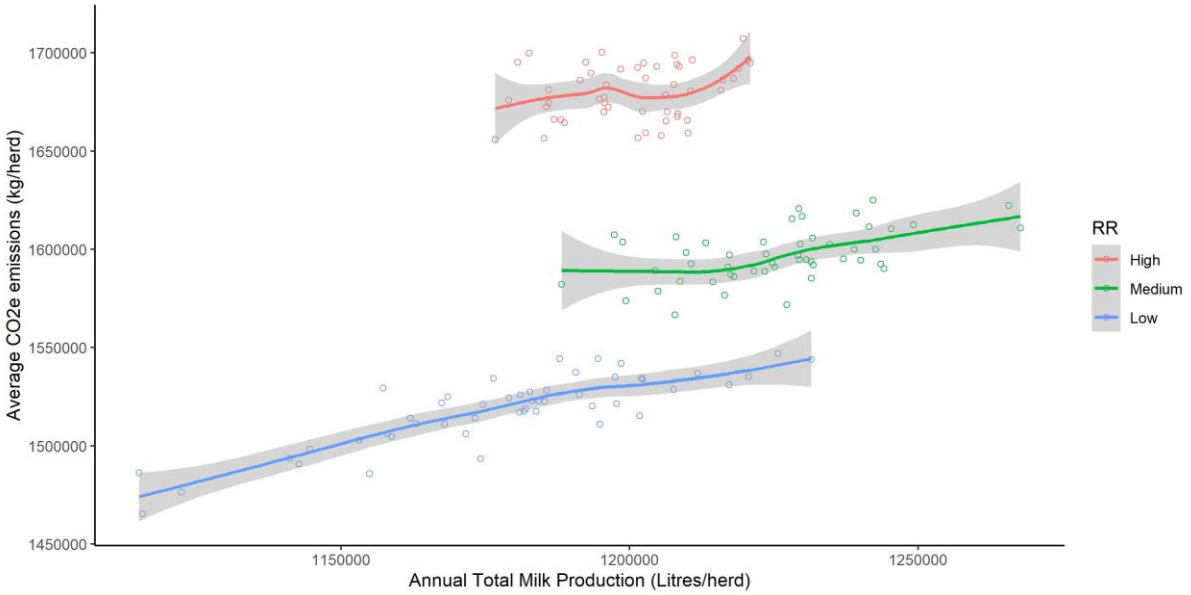

Figure 12: The total annual average milk production and the total average annual carbon dioxide equivalent (CO_2e) emissions for the herd per replacement rate, without carbon sequestration (CS). The figure shows the mean points for the 50 simulation repetitions, as well as the trend line per replacement rate.

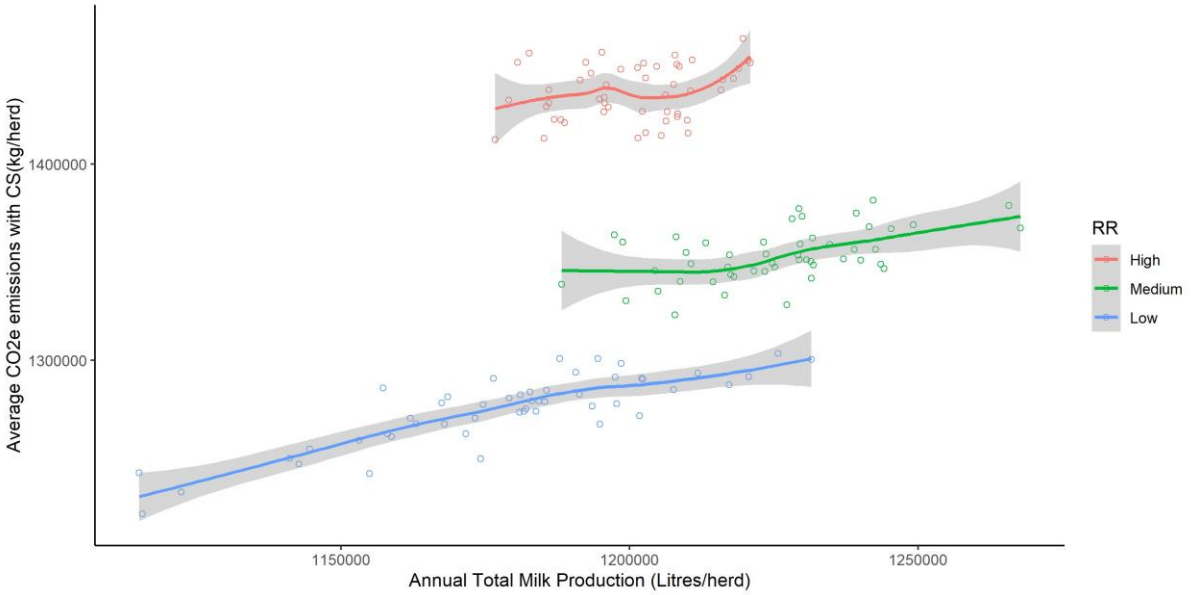

Figure 13: The total annual average milk production and the total average annual carbon dioxide equivalent (CO_2e) emissions for the herd per replacement rate, including carbon sequestration (CS). The figure shows the mean points for the 50 simulation repetitions, as well as the trend line per replacement rate.

The CO_2e emissions per RR scenario remained the same ranking of most to least emitting, as high, medium and low, when converted to per litre of FPCM with and without CS, shown in Table 18. The percentage reduction was greater when CS was included in the values. The high RR had 9.93% more emissions than the low RR, or 12.16% when CS was included. The

high RR had 8.51% more emissions than the medium RR or 9.17% including CS. The low RR had 1.55% less emissions than the medium RR or 1.84% including CS. The figures and Table 18 highlight the optimum RR for milk production as the medium RR, which also produced the medium GHGe of the three scenarios. The low RR had the lowest emissions, but only by 0.02kg of annual CO_2e emissions per litre of FPCM yet reduced annual milk production by almost 47,000 litres of FPCM. The medium RR thus, lowered GHGe compared to the high RR, without negatively impacting milk production.

Table 18: The mean carbon dioxide equivalent (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

4.4.6 Average Parity per Calving

The average parity per calving was analysed and the annual average parity per calving for each of the RRs can be seen below in Figure 14. The number of calvings was highest for parity one and lowest for parity 14. The effect of RR was that a high RR had a larger amount of calvings in the lower parities (1- 4), which reduced in parity 5 and 6, which were the highest parities experienced in the high RR scenario. The medium RR had the highest parity of 12 and the low RR had milking cows reach up to parity 14. Parity as high as 20 has been recorded in a dataset of almost 8 million dairy cows, across 28 states of America on 24 different cattle breeds (Schambow *et al.*, 2021).

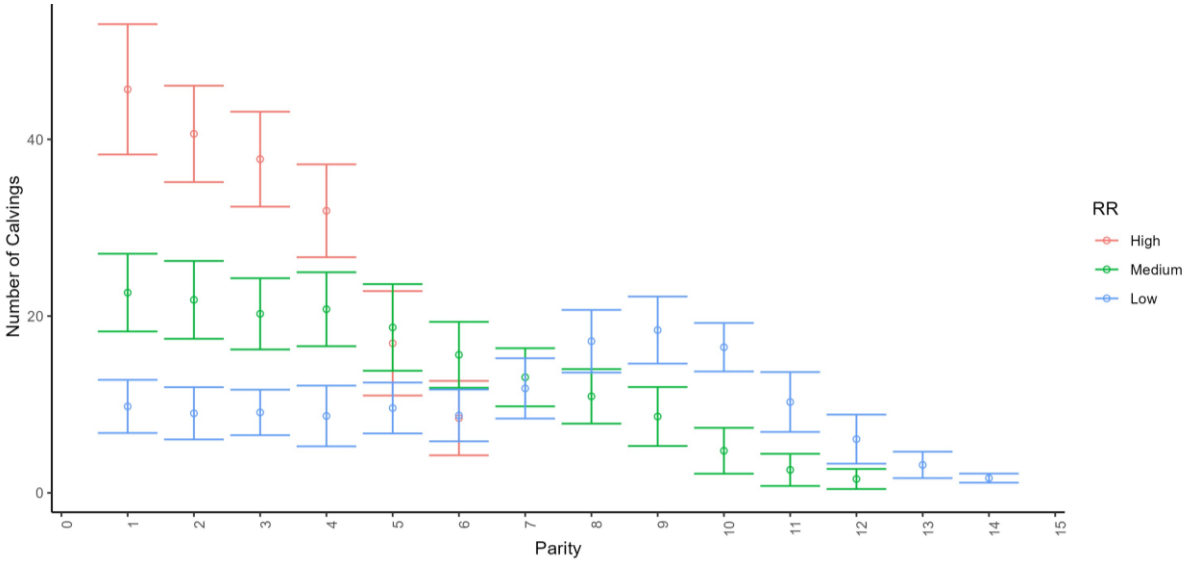

Figure 14: The average total amount of calving's per parity (1-14) for the three replacement rates over the final year simulated (01 November 2030 – 31 October 2031).

4.5 Discussion

An average UK dairy farm with a 22% RR and 140 dairy cows was simulated into the model, based on the farm described on pages 118-119 and summarised in Figure 10. The RR was compared to a high RR of 40% and low RR of 10%. Six management groups were used in the model to simulate a usual working dairy farm, and the numbers varied over the days and years to simulate normal events, such as the culling rate. The simulation ran over three years, from the 1st of November 2028 to the 31st of October 2031 and the results showed the herd numbers during this period, as well as their CO_2e emissions, calving parity, and milk production.

4.5.1 Replacement rate and greenhouse gas emission findings

The RRs ranked as high, medium, and low for the highest total farm emissions to the lowest total farm emissions. The results support previous research of a positive correlation between RR and GHGe (Zhu, Schneider and Oude Lansink, 2023). The farm emissions were highest for the largest RR of 40% as expected, which was likely due to an increase in the number of heifers needed as replacements, creating emissions for two years (Beukes *et al.*, 2010), before they became milking cows (De Vries and Marcondes, 2020). The reduction in RR decreased total CO_2e emissions from the farm by an average 10% in the current study from a high RR to a low RR, 5% from high to a medium RR or a medium to a low RR. The percentage reduction was slightly greater when CS from the farm was included, likely due to the small differences when rounded to whole numbers. This reduction in RR decreased total CO_2e emissions from the farm by an average 11% in the current study from a high RR to a low RR, 6% from high to a medium RR or a medium to a low RR. The current study therefore supports previous research that lower RR can lead to lower farm emissions (Garnsworthy, 2004; Weiske *et al.*, 2006; Beukes *et al.*, 2010; O'Brien *et al.*, 2010; Beukes, Gregorini and

Romera, 2011; Van Middelaar *et al.*, 2015; Grandl *et al.*, 2019; Lahart *et al.*, 2021; Zhu, Schneider and Oude Lansink, 2023).

4.5.2 Emissions per kilogram of fat-protein corrected milk.

The current results for the represented farm varied compared to previous carbon audits completed at the dairy farm. The results were compared to the results calculated by the Arla Climate Check tool for the representative dairy farm used in the model, which were obtained from the farm. The methods used in the tool are described in Table 4. The Arla tool CF reported 1.08 $kgCO_2e$ per kg of FPCM, using the medium RR. The Arla tool used by the farm does not currently include CS, so the current findings without CS, of 1.29±0.02$kgCO_2e$ per kg of FPCM, were high compared to Arla's findings.

The contribution of the sources of emissions were broken down, where enteric emissions (0.6 $kgCO_2e$/kg FPCM) were slightly higher than the Arla results (0.52 $kgCO_2e$/kg FPCM), using the combined equation in the current study. The emissions from manure storage (0.18 $kgCO_2e$/kg FPCM) were double the emissions from the Arla Climate Check tool (0.09 $kgCO_2e$/kg FPCM). The emissions from feed production were slightly higher in the current study, which may have been due to the feed used having slightly higher emissions, as the whole ration was assumed to be purchased off-farm in the simulation. The CO_2e emissions from energy, including fuel and electricity were the same for both tools (0.03 $kgCO_2e$/kg FPCM). The Arla tool (Tier 1) states the results should not be compared to different methodologies and highlights the variation between these methods.

The percentage reduction in GHGe produced between RR scenarios were different when expressed per litre of FPCM to total CO_2e emissions. Total CO_2e emissions per litre of FPCM reduced by 9.93% from a high to low RR, 8.51% from a high to medium RR, and 1.55% from a medium to low RR. The results support previous findings in GHGe reduction from

reducing RRs (Beukes *et al.*, 2010; O'Brien *et al.*, 2010). A New Zealand study found that the baseline farm had CO_2e emissions of 1.1 kg CO_2e/kgFPCM but could be reduced to 0.8 kg CO_2e/kgFPCM, by using a combination of mitigation strategies, including reducing RRs, improving genetics, standing off cows in April and March, growing crops, reducing fertiliser usage, reducing stocking rate, and harvesting silages on-farm (Beukes, Gregorini and Romera, 2011).

A 2010 study on a pasture-based system in New Zealand found RR had the potential to reduce overall GHGe by a mean of 5.98% per kg of FPCM (Beukes *et al.*, 2010), between the 2% and 12% decrease found in the current study. While another study from 2010 analysed a large reduction of 17% in RR from 35% to 18% on GHGe and found GHGe reduced by 9% per kg of milk (O'Brien *et al.*, 2010). Similarly, the current study found a 9% mean reduction in CO_2e emissions per litre of FPCM from the high RR to the medium RR (18% reduction in RR). The current results support O'Brien *et al.* (2010) findings, with very similar findings, supporting the accuracy in the simulated reduction. The reduction in RRs in the current study reduced total CO_2e emissions without CS by a mean of 1.55% to 9.93% per year, depending on the RR. When CS was subtracted from the emissions the total CO_2e emissions reduced by between 1.84% and 12.16% by lowering RRs.

Previous research found emission reductions to vary from 2% to over a 40% decrease in farm emissions, a larger difference than the current study. However, the difference in RR analysed also varied between previous studies. The current study analysed a reduction in RR of 30% (high to low RR), 18% (high to medium RR), and 12% (medium to low RR). Weiske *et al.* (2006) also analysed a 40% RR, but against a smaller difference of 10%, to a RR of 30% for a conventional Atlantic European dairy model farm using FarmGHG, examining GHGe across the whole farm, with a slurry manure system. The results were similar to the current study of 1.47 kg CO_2e per kg of milk (Weiske *et al.*, 2006), compared to a CF of 1.41kg

CO_2e per kg of milk for a 40% RR without CS. Their results showed a decrease in mean total emissions of 2.53% for heifers reared on farm and a mean reduction of 2.72% kg CO_2e per kg of milk. The largest decrease Weiske *et al.* (2006) highlighted was 13% per unit of milk, larger than the current study, however, this was due to the reduction in emissions comparing heifers being kept on farm and sold, which was not evaluated in the current study.

The percentage reduction due to reducing RRs was similar to previous research showing that CH_4 emitted reduced by 5.62% when replacements were decreased by 5% (Beukes, Gregorini and Romera, 2011). Beukes, Gregorini and Romera (2011) only analysed a 5% RR reduction compared to a 18% reduction in the current study yet found a similar GHGe reduction. They only examined CH_4 emissions, whereas N_2O from manure was also included in the current study. The prior study found DMIs to vary which could have impacted the results, however DMIs in the current study were kept constant, thus not directly contributing to the present results, suggesting the reduction in replacement heifers must have played a significant role in the reduction of overall emissions. However, it could also be argued that the variation in DMI in Beukes, Gregorini and Romera (2011) may have caused the larger reduction in GHGe, thus explaining the difference to the current study.

The total annual farm emissions per kilogram of milk was higher than previous findings highlighted in Table 3 (Henriksson et al., 2011; Galloway et al., 2018; Rotz, 2018; Herron *et al.*, 2022). It was similar to the average emissions for the Irish housed system (1.26 $kgCO_2ekgFPCM$; O'Brien *et al.*, 2016), the TMR housed system in the USA (1.28$kgCO_2ekgFPCM$; Rotz, Holly, *et al.*, 2020) and within the range between a mixed and housed European dairy farm (1.24 to 1.52$kgCO_2ekgFPCM$; Sorley *et al.*, 2024) and mixed Spanish study (Salcedo Díaz *et al*., 2024). The reason for most of the farm LCAs being lower than the current study, was likely due to differences in metric, such as total $kgCO_2ekgECM$ instead of FPCM, differences in location, management system, feed, measurement method

and the combined equation creating higher enteric emissions than the IPCC (2006; 2019) equations, which was highlighted in Table 14. The IPCC being used commonly across dairy farm carbon tools globally (Schils, Olesen, et al., 2007; Küstermann, Kainz and Hülsbergen, 2008; Wheeler et al., 2008; Hillier et al., 2011; Mc Geough et al., 2012; Bonesmo et al., 2013; Gerber et al., 2013; Agrecalc, 2014; Gooday et al., 2015; Vibart et al., 2021; Arla, 2023).

4.5.3 Length of productive lifespan, replacement rates and greenhouse gas emissions

The effect of RR on GHGe has also been analysed alongside varying the LPL of cattle on farm. A RR of 22.5% was compared to 27% in a previous study analysing LPL from around 4 to 5 years of age (total age 6 to 7 years; Van Middelaar *et al.*, 2015). GHGe reduced by around 2 to 3% depending on efficiency, similar to the difference between the low and medium RR in the current study (2% per kg/FPCM), even though the RR only reduced by 4.5% compared to a 12% difference in the current study. The results suggest a lower RR than 22% does not have a large reduction effect on farm CO_2e emissions.

The efficiency of the farm can also impact GHGe, with high efficiency reducing GHGe by almost 7% compared to low efficiency farms. The efficiency also impacts the effectiveness of LPL and RRs on reducing GHGe, as research has highlighted a lower efficiency farm having 1.9% reduction in total GHGe compared to 2.9% in the high efficiency farm when lifespan was increased. Milk production and profit also increased, but had a lower impact on low efficiency farms, as costs were higher, limiting the benefit of the reduction across the whole farm.

The proportion of contribution from the various sources was similar to previous research, EF equated to the largest proportion of emissions in both studies, between 45-55% in the current study and beyween 32 and 51% in previous research (Mc Geough *et al.*, 2012; Van

Middelaar *et al.*, 2015; O'Brien *et al.*, 2016; Sorley *et al.*, 2024). Manure management (13-19%), contributed to a similar 13-17% in the current study. The larger proportions were when CS was included in the results, which was not considered in the previous study. Feed production was measured as production of concentrates (18%) and on-farm roughage production (13%) in a previous study (Van Middelaar *et al.*, 2015), equating to 31% in total, which was lower than the current study, which could have varied due to the diet and that the complete production of feed was included in the current study, as purchased off-farm, rather than on-farm roughage production in the previous study.

4.5.4 Need to reduce replacement rates

The results, therefore, support the theory that RRs should be minimalised to reduce the environmental impact of the farm and costs. RR reduction means that from an environmental perspective, cows should not be voluntarily culled early to replace them with genetically superior higher milk producing cattle, as currently encouraged (De Vries, 2017; Richardson *et al*., 2020). The reduction in voluntary culling could arguably increase AW, such as reducing the cull rate and lengthening the lifespan of cattle to nearer their natural life expectancy (Holtsmark *et al.*, 2008; Richardson *et al*., 2020).

4.5.5 Milk productivity and replacement rates

The research suggests that lower RRs should be chosen over high RRs, therefore the breeding strategy of replacing cattle for those genetically superior should be discouraged to improve RRs of the farm and lower emissions. However, from a productivity perspective, enhancing the genetics of dairy cattle has been found to increase milk production, by 11.68%, which was 9.6% more than the lower RR simulation (Beukes *et al.*, 2010).

Milk production was also assessed in the current study for the three RRs. Cattle with a low RR of 10% had a lower average total milk productivity than a 22% RR (by 3.83%), and the

40% RR scenario (by 1.82%). The medium RR of 22%, therefore, had the largest total milk production of the three scenarios, suggesting too low a RR could negatively impact milk production and therefore emissions, when considered per litre of FPCM produced.

Previous research found a reduction in RR increased milk production by 2.08% per hectare and the potential increase of 11.68% (Beukes *et al.*, 2010), supporting the current study results of a 2.04% increase in milk production from the high RR to the medium RR, but emissions were considered per litre of FPCM in the current study, rather than per hectare. The current study did not find a high increase in milk production, with the maximum difference between the medium and low RR of almost 4%, of which the medium RR had a higher MY than the low RR. Previous research found a similar increase of 2 to 3.2% in milk production, however, the RR only varied by 4.5% from a RR of 22.5% compared to 27% (Van Middelaar *et al.*, 2015).. The previous study also found an increase of €77 per unit change per year per cow. However, the results showed small differences in milk production between RRs, suggesting small differences in profit, supporting previous research that RR does not significantly impact profit (Zehetmeier *et al.*, 2020; Zhu, Schneider and Oude Lansink, 2023). Nevertheless, the relationship between farm CO_2e emissions and milk productivity, suggested an optimum replacement of the baseline; 22%, to reduce emissions compared to a high RR, but also increase milk productivity and avoid negatively impacting farm profit, even if the difference was not significant.

4.5.6 How to reduce replacement rates

To reduce RRs further, it would be beneficial to re-establish past fertility levels in cattle, which could decrease replacement emissions by 10% and NH_3 emissions by up to 8% per cow (Garnsworthy, 2004). The number of voluntary cullings on farm and thus, demand for RRs can also be reduced by increasing the LPL of dairy cattle, to reduce emissions and increase perceived AW. However, older cattle could also have lower levels of fertility, which

would limit the benefit of increasing LPL and negatively impacts emissions. In addition to this, higher parity of dairy cattle has also been linked to offspring producing lower levels of milk (Van Eetvelde *et al.*, 2020), lowering the efficiency of the farm and thus, increasing emissions per proportion of milk generated. It is thus, a complex balance to reduce RRs, especially by improving LPL, whilst maintaining milk production, feed efficiency and fertility. The research suggests improved genetic merit should be encouraged, but not at the expense of the RR and lifespan of the farm cattle (Garnsworthy, 2004), ensuring the cattle are healthy.

Heifers were reared and kept on farm for the representative farm simulated in the model. However, research suggests that total farm emissions could be reduced by an approximate 6% further, if heifers are sold rather than kept on farm (Weiske *et al.*, 2006). Their results suggested that whether heifers were kept on farm or sold could have a larger impact on emissions than reducing RR. The outcome of heifer placement was not analysed in the current study, but the RRs examined were not as drastic as the current study, which may have led to the larger impact of heifer placement over RR.

4.5.7 Parity

Another important aspect stated in the literature suggests that it could be beneficial to increase parity and convert to using more multiparous cattle than primiparous. The reason for this is that multiparous cattle are less susceptible to heat stress, as it effects primiparous cow's milk production slightly more than multiparous cows (Marumo *et al.*, 2022). Heat stress is likely to become a more frequent issue in the UK, so it would be beneficial to breed cattle that are less susceptible to the effects on milk production to ensure demand can be met. Multiparous cattle also have larger milk production than primiparous cattle (Meir *et al.*, 2019; Margerison and Geoghegan, 2022; Marumo *et al.*, 2022; Morales-Piñeyrúa *et al.*, 2022).

In particular, the percentage of milking cattle in parity seven or above for the typical UK dairy farm used in the model was 6.48%, which is slightly higher than previous research, with 3.9% from parity seven or above (Van Eetvelde *et al.*, 2020). However, the current study and Van Eetvelde *et al*. (2020) both reported a low proportion of cattle with a high parity (>6), suggesting the results were representative, and most cows are culled before this stage (Van Eetvelde *et al.*, 2020). Van Eetvelde *et al.* (2020) also found that cattle born from those of a higher parity had a lower MY. The results suggest increasing the parity of cattle might increase their MY but lower the efficiency and output of their offspring. However, it was theorised that this might be due to the higher parity cattle at the time having a lower genetic merit for milk production, which could have impacted the results.

4.6 Conclusion

In conclusion, a medium RR was considered the optimum level to reduce emissions without compromising milk production. A low RR of 10% emitted the least emissions from the herd (1.27 kgCO_2ekgFPCM/year), however, it also resulted in the lowest milk production (1,178,766 litre/FPCM) of the three RRs. The high RR scenario of 40% led to the highest emissions (1.41 kgCO_2ekgFPCM/year), and medium milk production (1,200,650 litre/FPCM), whilst the medium RR of 22% resulted in the medium emissions (1.29 kgCO_2ekgFPCM/year) and the highest milk production (1,225,702 litre/FPCM). The research suggests RRs should be limited to reduce emissions, by improving fertility rates and reducing the number of voluntary culls, but a very low RR could also negatively impact milk productivity. The results were based on a typical UK dairy farm, and emissions and milk production may vary when different management systems are modelled and thus, potential optimum RRs. Further research should investigate the rearing of heifers on and off farm on GHGe results, to analyse whether heifers were kept on farm or sold has a larger impact on emissions than reducing RRs.

Chapter 5: Alternative Sources of Protein to Soya Bean

Chapter 5: Alternative Sources of Protein to Soya Bean

5.1 Introduction

Protein is usually measured by CP levels (Erickson and Kalscheur, 2020) and accounts for around 14% of a dairy cow's diet (AHDB, 2021b). Protein is important for general body maintenance and milk production (Garnsworthy *et al.*, 2021), as there is a positive relationship between MY and CP levels (Yang, Ferris and Yan, 2022). SB is a universally popular source of protein in dairy cattle diets (Huhtanen, Hetta and Swensson, 2011; Rinne *et al.*, 2015), due to its high dietary nourishment and crop growth affordability (Gill, Garnsworthy and Wilkinson, 2021). In 2023, the UK imported 2,150 metric tons (MT) of soyabeans, an increase of 66.8% since 1990 and 8.42% since 2016 (Index Mundi, 2024).

Global demand for SB has led to the deforestation of highly diverse wildlife habitats (Fraanje and Garnett, 2020), the removal of a pivotal carbon sink (Rödig *et al.*, 2018) and the forced movement of indigenous people (WWF, 2022b). Although dairy contributes to only a small portion of soy use, population growth and demand for livestock and their products, will increase SB demand and therefore deforestation (Aquilas *et al.*, 2022). DEFRA announced a £12.5 million funding pot for research and development of sustainable farm-based proteins to reduce the industry's environmental impact, reliance on imports and increase food security (DEFRA, 2022a). There are several possible alternative sources of protein in dairy cattle diets that can be used to reduce reliance on SBM, which include grain legumes such as FBs, lupins, peas, and RS (Halmemies-Beauchet-Filleau *et al.*, 2018; Kuoppala *et al.*, 2021) and forages, such as lucerne (Sinclair *et al.*, 2015). Yet, the UK experienced a reduction in RS production in 2022 (USDAb, 2022). Few studies have holistically compared the environmental impact of multiple sources of protein in dairy cattle feed. Studies also tend to

focus on one emission source, such as EME or those from feed production, rather than the overall environmental impact.

5.2 Aims and Objectives

Chapter 5 aimed to simulate the effect of different sources of protein in dairy cattle diets on enteric CH_4, feed production emissions and milk production. The proteins RSM, brewers' grain, wheat distillers' grain, beans, red clover, lucerne, lupins and peas to SBM were compared. The proteins brewers' grains, beans, wheat distillers, clover, lucerne, lupins and peas were supplemented with RSM to complete the nutritional requirements of the diet, as these could not have been reached with the alternatives alone.

Objectives:

1. To compare the effect of substituting the source of protein in lactating dairy cattle feeds on overall farm CO_2e emissions for the milking herd.
2. To compare the average CO_2 emissions from the production of sustainable SBM within the UK and externally produced SB linked to deforestation.

5.3 Methodology

In consultation with a dairy nutritionist, 13 diets were formulated using different proportions and mixtures of the protein alternatives to SBM: RSM, brewers' grain, distillers' grain, beans, red clover, lucerne, lupins and peas, without impacting the milk quantity or quality, the palatability of the feed or the health of the cow. The dietary composition of the complete diets can be seen in Table 19 below. 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%), BW per cow type (703kg), body condition score (2.75), and average daily gain (0.164 kg/day). DMI, ME, 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 GS, MS, dairy minerals, sugar beet unmolassed with the protein and in some diets rolled barley and wheat. The GS was assumed to be good quality.

Table 19: the dietary composition of the 13 complete diets for the protein alternative to soya bean (SB) scenarios. DMI = kg/day, ME/GE = MJ/kg, CP, FA, EE, NDF and forage = percentage of dry matter. Peas version 1 (V1) did not contain soya hulls, while peas version 2 (V2) did contain soya hulls.

Diet	DMI	ME	CP	FA	EE	NDF	Forage
Baseline - beans rape	22.91	11.03	15.63	2.95	3.28	33.23	53.42
Beans rape	22.70	11.13	15.70	2.94	3.28	32.82	57.36
Mixed - no soya	22.85	11.16	16.07	3.51	3.88	32.94	57.00
Baseline - RS	22.82	11.09	16.24	3.16	3.90	33.09	52.41
Soya	22.69	11.16	16.31	3.15	3.28	33.80	57.38
Baseline - 50-50 SB RS	22.71	11.13	16.44	3.19	3.46	33.40	57.35
Peas V1 and rape	22.84	11.21	16.54	3.04	3.41	31.73	57.01
Peas V2 and rape	22.84	11.11	16.69	2.98	3.36	32.28	54.24
Lupins and rape	22.76	11.32	16.88	3.86	4.35	33.29	57.22
Clover and RS	22.97	11.01	16.89	3.71	5.15	31.38	52.38
Lucerne and rape	22.78	11.14	17.04	3.32	5.34	31.56	57.13

Baseline - w-distillers RS	22.73	11.16	17.07	4.33	4.67	33.34	53.83
Baseline - Brewers RS	22.96	11.10	17.57	4.41	5.18	32.85	52.54

The alternative protein scenarios investigated the environmental impact of the milking cattle management group only. The combined equation was used to predict the EME of the cattle and the IPCC (2006) and (2019) methods were used to calculate the manure emissions. The results were simulated using the REMEDY model, over a 10-year period from 01 November 2021 to 31 October 2031. The model simulated 10 years, but the results from the last three years were used when the effect and data stabilised, from 01 November 2028 to 31 October 2031, as stated in Chapter 4. GHGe from energy use, fertiliser usage and fuel were also included in the total farm CO_2e emissions.

The emissions from feed production were included in the GHGe results for the sources of protein, which were collected from the Agribalyse dataset inventory in OpenLCA, including 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 UK data was unavailable for the feed. The emissions associated with SBM linked to deforestation were also obtained from Agribalyse for SBM sourced from France. The diet, milk production, enteric CH_4, 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 economic costings for the diets 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 grown on-farm.

5.4 Results

5.4.1 Enteric fermentation emissions

The results showed the diet with the lowest EF emissions was lucerne with RS, and the highest was the baseline beans diet with RS, converted from CH_4 to CO_2e emissions, as shown in Figure 15.

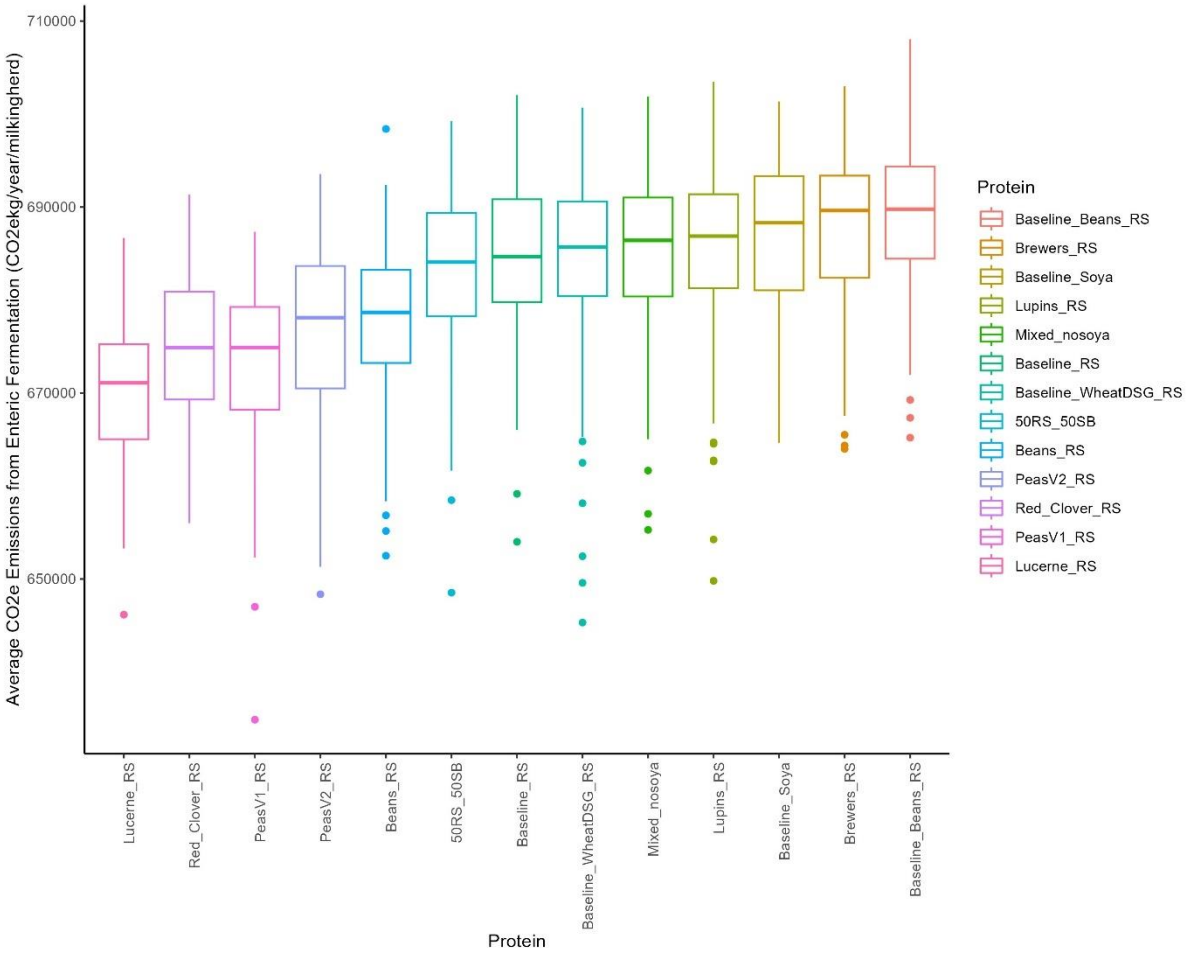

Figure 15: The average total annual carbon dioxide equivalent (CO_2e) enteric fermentation emissions for the milking herd across the 50 simulation runs and 13 protein alternative diets.

5.4.2 Feed production emissions

The ranking of the diets for most to least emissions from EF, did not correspond to the ranking of the feed production emissions of the diets, as shown in Figure 16. The diet with the highest feed production emissions was the soya bean meal (SBM) diet with deforestation,

and the lowest was the diet peas version one with RS, which did not contain soya hulls. Feed production emissions varied significantly for the different sources of protein.

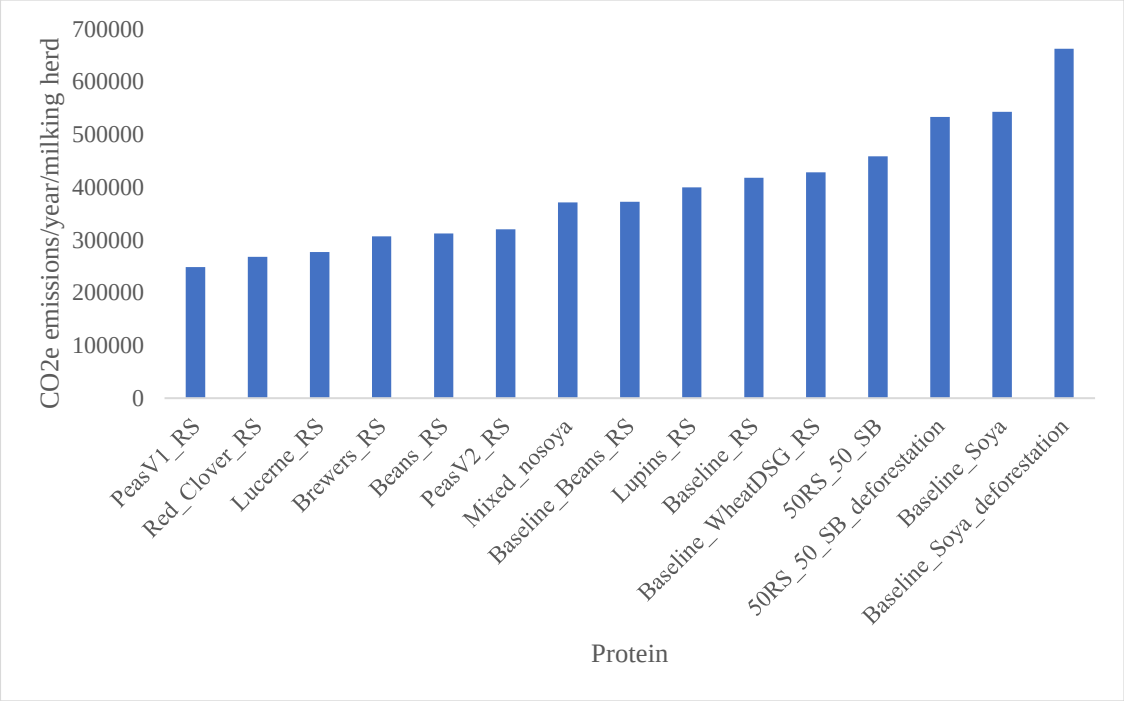

Figure 16: The average annual CO_2e emissions as kilograms (kg) from feed production for the milking herd, based on UK sourced feed or national average, if UK figures were not available.

5.4.3 Manure emissions

The manure emissions from the 13 protein alternative diets are shown in Table 20 below. SB had the lowest manure emissions for the milking herd and red clover with RS the highest, but results remained relatively consistent.

Table 20: The mean annual CO_2e manure emissions per herd and standard deviation for the 13 protein alternative diets.

Protein	Mean manure emissions (CO_2e kg/milking herd/year)	Standard deviation
Red_Clover_RS	126,100	±1,868
Brewers_RS	125,688	±1,649
Baseline_Beans_RS	125,477	±1,721
Mixed_nosoya	124,721	±2,001
Baseline_RS	124,602	±1,825
PeasV2_RS	124,591	±1,984
PeasV1_RS	124,488	±1,998
Lucerne_RS	124,435	±1,694

Lupins_RS	123,705	±2,075
50RS_50SB	123,688	±1,992
Baseline_WheatDSG_RS	123,631	±2,150
Beans_RS	123,538	±1,948
Baseline_Soya	123,498	±1,871

5.4.4 Total Farm carbon dioxide equivalent emissions

The annual emissions for the dairy enterprise, such as from fertilisers, fuel, and electricity, can be seen in Table 21 below. In addition to the estimated CS potential of the land. The total farm CO_2e emissions for the protein alternative scenarios with and without CS, can be seen in Figure 17 and Figure 18 below. Figure 19 shows the breakdown of the emissions from each source and total CO_2e emissions for each of the protein alternative scenarios. Peas with RS had the lowest total CO_2e emissions, SB linked to deforestation the highest, and SB without deforestation was the second highest scenario. The figure highlights that feed production had the largest impact on the ranking of the protein sources, very similar to the final ranking, except for brewers' grain being two positions higher for the total farm emissions to feed production only.

Table 21: The annual emissions from fertilisers, fuel, and electricity at the dairy enterprise as carbon dioxide equivalent (CO_2e), as well as the carbon sequestration ability of the land (kg/ CO_2e/herd/year).

	Fertiliser	Fuel	Electricity	Land
CO_2e emissions	17557.62	18225.07	13410.00	-243,464.40

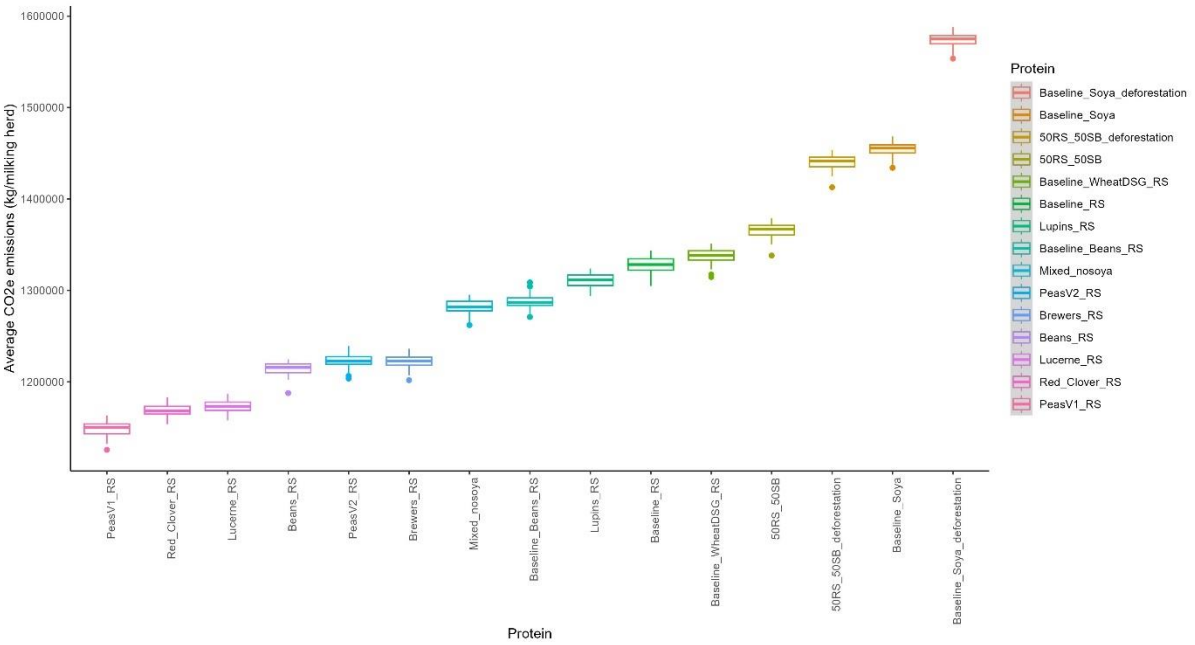

Figure 17: The annual average total farm CO_2e emissions and standard deviation for the 15 protein alternative diets in kilograms (kg) per the milking herd.

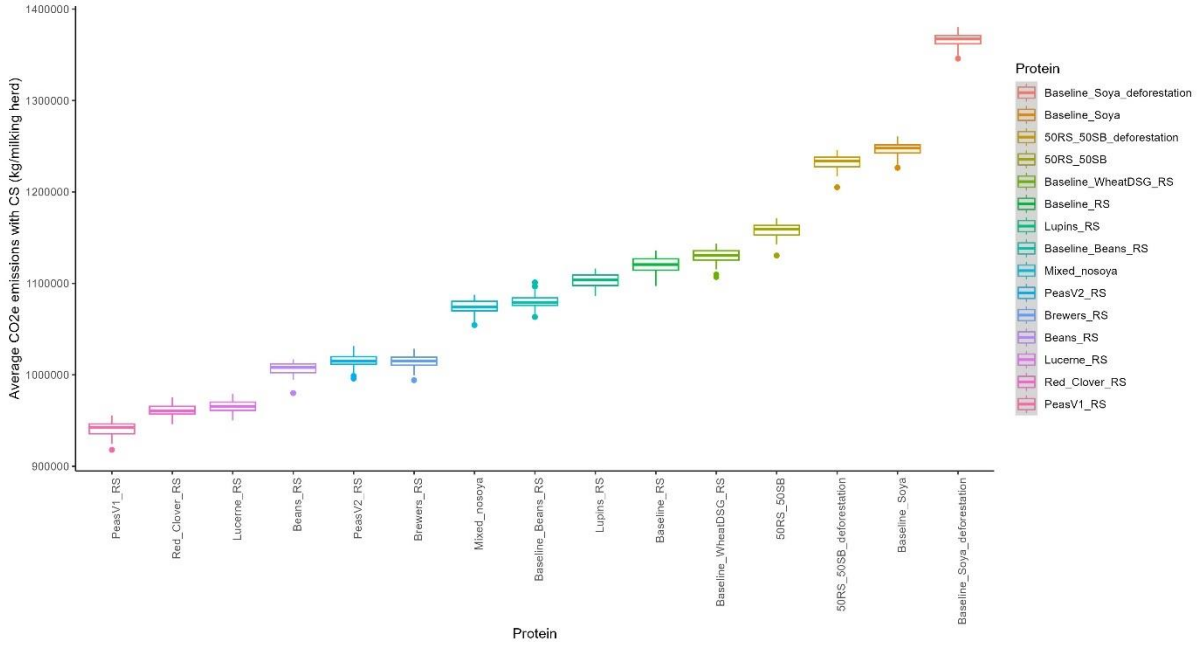

Figure 18: The annual average total farm CO_2e emissions for the milking herd and standard deviation with carbon sequestration (CS) for the 15 protein alternative diets in kilograms (kg).

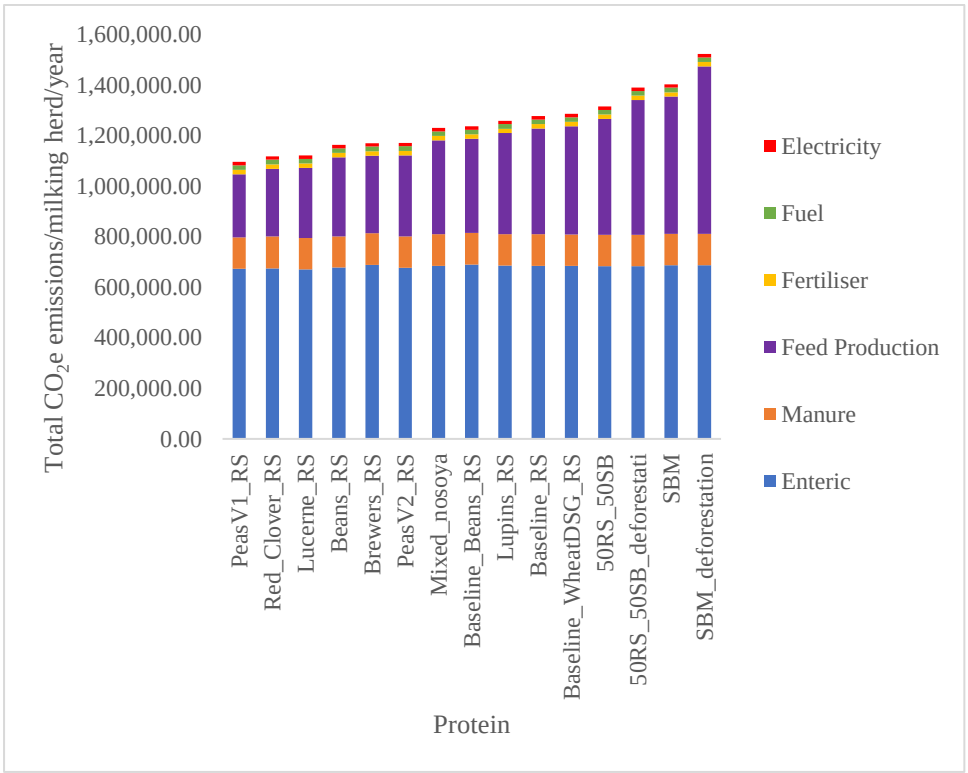

Figure 19: Stacked bar chart of the breakdown of the total milking herd emissions per protein source.

The NH_3 emissions associated with each scenario were also estimated using the simulation model and can be seen in Figure 20 below. Each scenario showed large variability in their NH_3 emissions, suggesting little significant change between proteins.

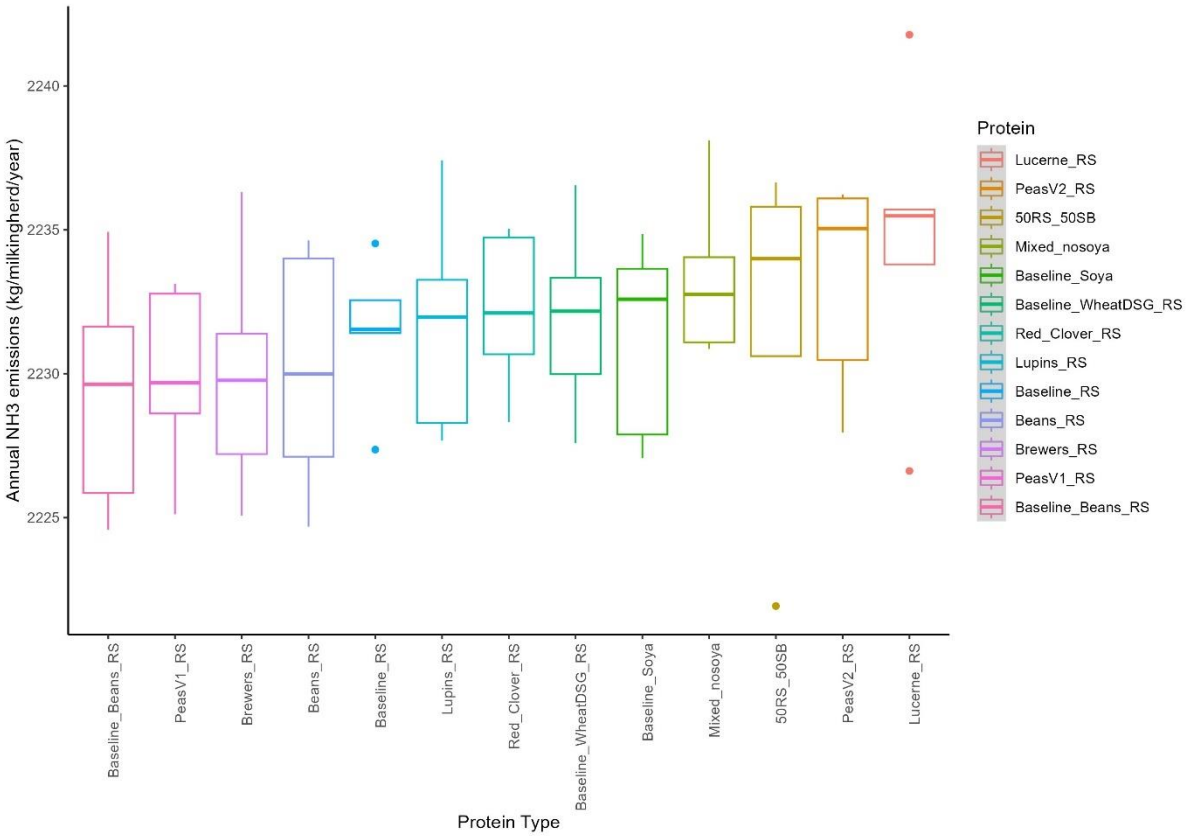

Figure 20: The mean annual kilograms (kg) of ammonia (NH_3) emissions (kg/milking herd/year) for the 13 protein diets with standard deviation.

5.4.5 Milk Production

Milk Production was maintained between the protein alternatives, only slightly differing between the protein scenarios. The mean total annual fat-protein corrected milk (FPCM) for the milking herd with SD for the protein scenarios can be seen in Table 22 below. Lupins with RS had the largest mean total FPCM and peas version 2 (with soya hulls) and RS the lowest production.

Table 22: The average total annual milk production as fat-protein corrected milk (FPCM) for the milking herd with standard deviation.

Protein	Mean total milk production (FPCM/litres/milking herd)	Standard deviation
PeasV2_RS	1,224,478	±21,701
Mixed_nosoya	1,224,546	±21,300
Baseline_Beans_RS	1,225,874	±22,020
PeasV1_RS	1,226,062	±19,593
Red_Clover_RS	1,227,358	±18,278
Beans_RS	1,227,664	±21,519
Baseline_Soya	1,228,267	±21,801
Baseline_RS	1,228,649	±19,961
50RS_50SB	1,229,125	±20,015
Brewers_RS	1,229,300	±18,396
Lucerne_RS	1,229,459	±20,028
Baseline_WheatDSG_RS	1,229,921	±23,322

Lupins_RS	1,230,129	±21,590

5.4.6 Total Farm carbon dioxide equivalent 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 21 and with CS in Figure 22 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 RS, lucerne and RS, beans and RS, brewers and RS, peas with soya hulls (version 2), mixed protein without soya, baseline beans with RS, lupins and 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.

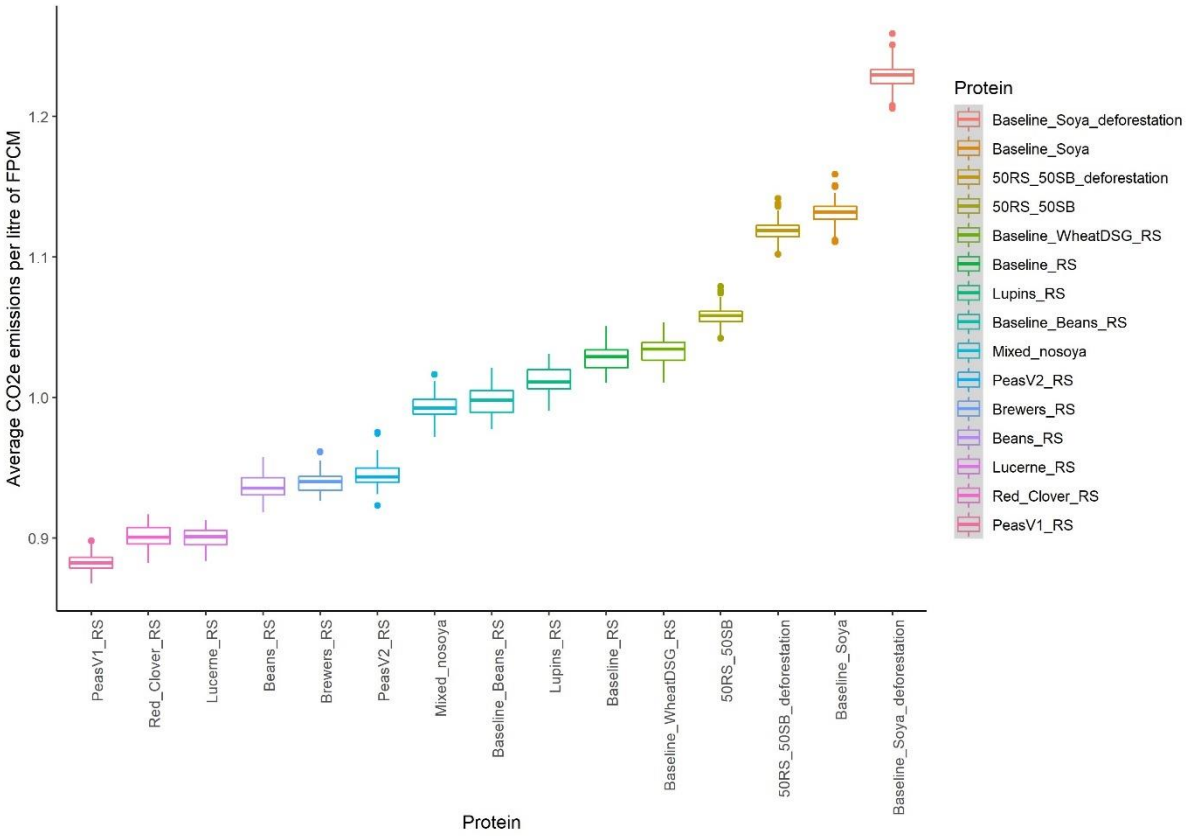

Figure 21: The average total annual farm carbon dioxide equivalent (CO_2e) emissions as kilograms (kg) for the milking herd per litre of fat-protein corrected milk (FPCM) for each of the five simulation runs and 15 protein alternative diets.

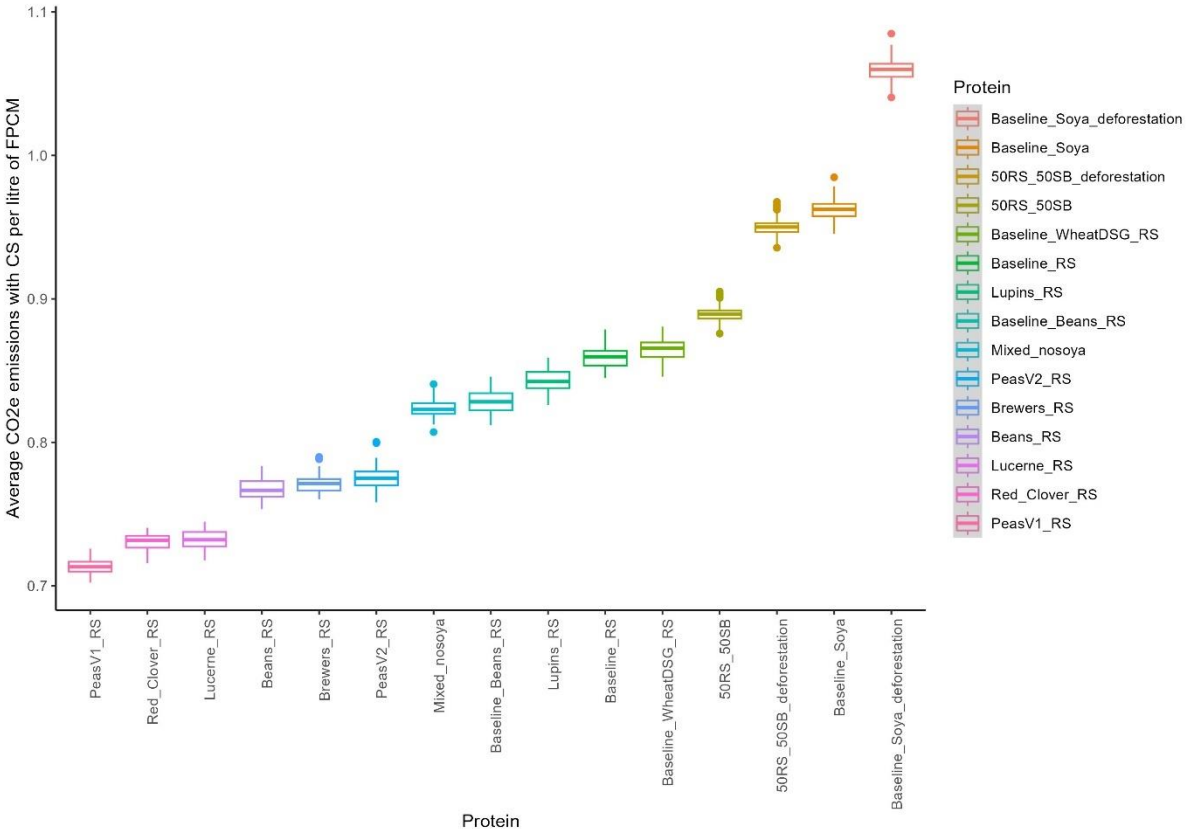

Figure 22: The average total annual farm carbon dioxide equivalent (CO_2e) emissions (kg) for the milking herd with carbon sequestration (CS) included, per litre of as fat-protein corrected milk (FPCM) for each of the five simulation runs and 15 protein alternative diets.

The CO_2e emissions per kilogram of FPCM from each source of emissions, such as EF, manure management and feed production for the milking herd, are presented in Table 23 below. EF equated to the largest emissions (0.56kg CO_2e/kg FPCM), followed by feed production (0.32), manure management (0.1), energy and fuel usage (0.03) and the CS potential of land offset CO_2e emissions (-0.2).

Table 23: The carbon dioxide equivalent (CO_2e) emissions per kilogram of fat-protein corrected milk (FPCM) from each source of farm emissions for the milking herd.

Protein	Enteric	Manure	Feed Production	Fertiliser	Fuel	Electricity	Land
Red_Clover_RS	0.55	0.10	0.22	0.01	0.01	0.01	-0.20
Lucerne_RS	0.56	0.10	0.25	0.01	0.01	0.01	-0.20
PeasV2_RS	0.56	0.10	0.30	0.01	0.01	0.01	-0.20
PeasV1_RS	0.56	0.10	0.30	0.01	0.01	0.01	-0.20
Beans_RS	0.56	0.10	0.34	0.01	0.01	0.01	-0.20
50RS_50SB	0.55	0.10	0.26	0.01	0.01	0.01	-0.20
Baseline_RS	0.55	0.10	0.20	0.01	0.01	0.01	-0.20
Baseline_WheatDSG_RS	0.54	0.10	0.23	0.01	0.01	0.01	-0.20
Mixed_nosoya	0.56	0.10	0.33	0.01	0.01	0.01	-0.20
Baseline_Soya	0.56	0.10	0.37	0.01	0.01	0.01	-0.20
Baseline_Beans_RS	0.56	0.10	0.35	0.01	0.01	0.01	-0.20
Brewers_RS	0.55	0.10	0.25	0.01	0.01	0.01	-0.20
Lupins_RS	0.56	0.10	0.44	0.01	0.01	0.01	-0.20

Baseline_Soya_deforestation	0.56	0.10	0.54	0.01	0.01	0.01	-0.20
50RS_50SB_deforestation	0.56	0.10	0.43	0.01	0.01	0.01	-0.20

5.4.7 Economic Costs of Feeds

The most expensive diet at the time of the study, was lucerne and RS and the least was the brewers' grains-based diet with RS. The diets varied by 22%, between the most and least expensive, and can be seen in Figure 23 below.

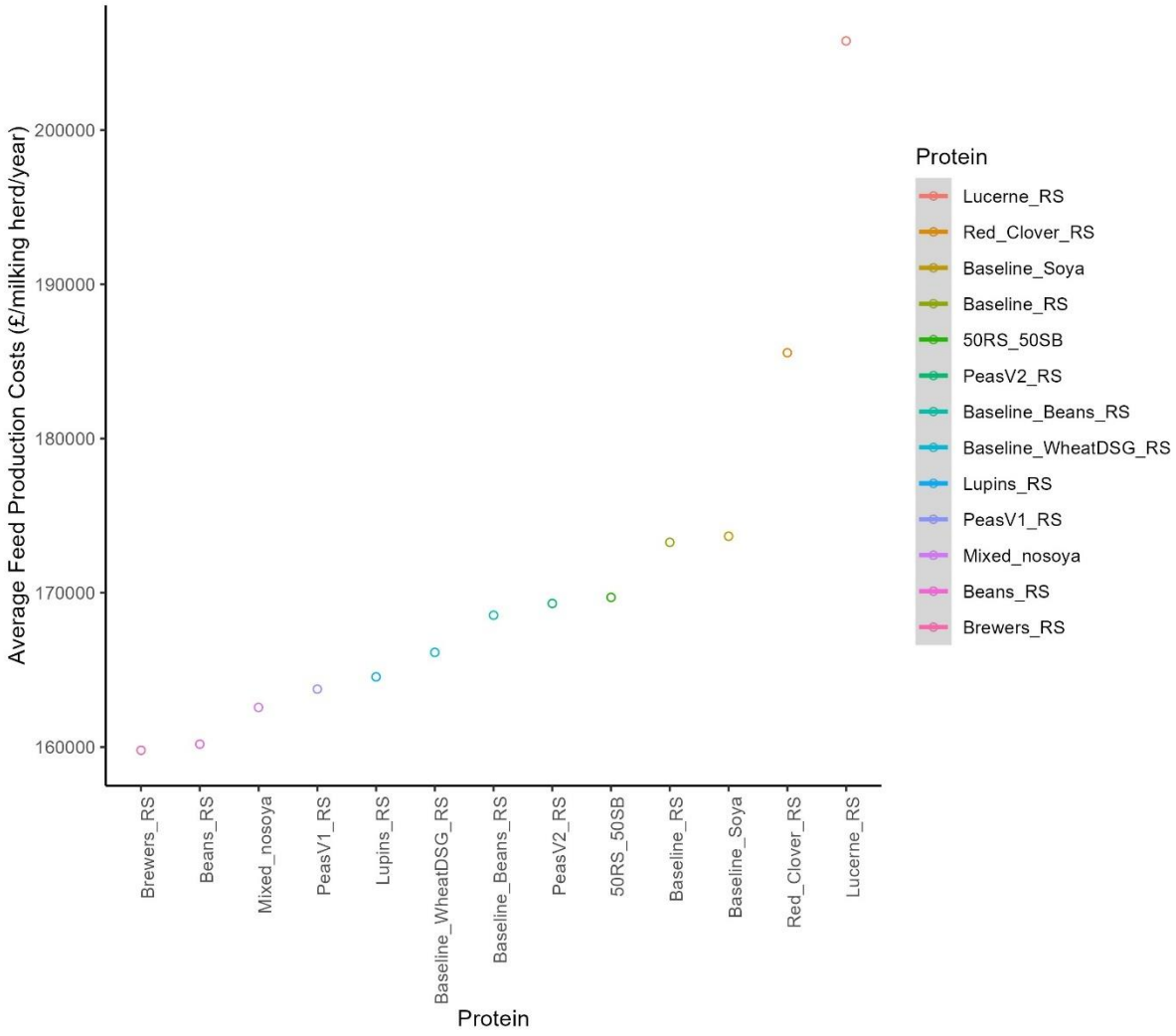

Figure 23: The estimated annual cost of the protein alternative diets in British sterling pounds (£/milking herd/year).

5.5 Discussion

The study simulated 13 protein alternative diets in a farm simulation model, on the total average annual farm CO_2e emissions. The two SBM diets were replicated in the study, with alternative feed production emissions, which were either linked to deforestation or not (totalling 15 diets). The diets were selected to show a range of possible protein alternatives to SBM in the UK, formulated with a dairy nutritionist to ensure maintained milk production, health of the rumen biome and the cow requirements were met. The results showed that SBM had the largest total average annual CO_2e emissions per litre of FPCM and peas without soya hulls (version one), had the least CO_2e emissions per litre of FPCM. The results suggest substituting SBM in dairy cattle diets will reduce overall farm emissions and shows multiple possible protein alternatives.

Switching from a deforestation linked SBM source to a non-deforestation source, reduced total farm emissions by around 7%. Substituting SBM from a non-deforestation linked source for a protein alternative, reduced total overall farm emissions by between 2% and 22% and 8% and 28% when from a deforestation linked SBM source.

Substituting SBM linked to deforestation, will have multiple benefits, by preventing deforestation, such as in the Amazon rainforest and Cerrado savanna, to restore these carbon sinks, which offset GHGe and preserve biodiversity of flora and fauna. Steps to halt the demand for deforestation, will also help to reach the 2030 1.5ºC warming limit of the Paris Climate Agreement.

SBM whether from a deforestation linked source or not, resulted in the highest total farm CO_2e emissions. The feed production emissions associated with SBM increased the overall emissions, explaining why the diet was highest even when not linked to deforestation. It is

therefore suggested that dairy cattle diets should be based on alternative proteins to SBM, irrelevant of the deforestation status.

Feed production was the second largest contributor after EME. Feed production has had a large contribution in previous studies, such as finishing pigs, contributing to 50 to 52% (Van Zanten *et al.,* 2015). However, feed production is often the second largest contributor in ruminants, due to the high production of CH_4 from enteric fermentation of feed making the largest contribution (Ellis *et al.,* 2010; Jose *et al.,* 2016; Roque *et al.,* 2019). Feed production is responsible for approximately 41% of emissions from global livestock (FAO, 2020). The current study found the contribution of feed production from the protein sources varied depending on the source but contributed to between 23 and 44% of the total emissions of an LCA.

The reason feed production emissions had a large influence on the emissions and ranking of the protein sources, was likely due to the feeds being sourced off-farm. Although the emission factors were mainly based on sourcing within the UK, there were some protein emission factors that were unobtainable for the UK. The emissions factors used for those sources, were either based on the European or national average, which could have increased and influenced the ranking of the total farm emissions for the protein sources. However, the SBM linked to deforestation was sourced from France and the SBM not linked to deforestation was sourced from within the UK yet had high CO_2e emissions, suggesting it was not the importation of the feed that increased the emissions of SBM. The emissions would have also been influenced by the different forms of cultivation.

The differences in cultivation demands are the likely source of large variation in feed production emissions and contribution to the overall protein sources CO_2e emissions. SBM is an intensive crop, requiring lots of inputs, such as high rates of pesticides (Sasu-Boakye *et*

al., 2014). In the USA, 98% of grown SBM was applied with herbicides in 2020 (USDA NASS, 2020). Peas are not as intensive and do not require N application, as they are very efficient at fixing N and even improving the soil for the next crop planted (Teagasc, 2017). However, rapeseed can require a large quantity of fertiliser to produce high yields (Lehuger *et al.*, 2009; Sasu-Boakye *et al.*, 2014), which has been reported almost four times higher than SBM (Lehuger *et al*., 2009). In contrast to the current study, RSM had the highest overall feed production emissions, however, SBM was sourced from Brazil in the previous study and the emission factors were from 2009, which are now outdated. In a 2015 study, SBM had higher feed production emissions in the study on swine than rapeseed, but only by 0.8% (Van Zanten *et al.*, 2015). Whereas a recent study showed GHGe linked SBM production (4.42 kg CO_2e per kg of feed) were 7.5 times higher than RSM (0.59 kg CO_2e per kg of feed) for weaned pigs (Wilke *et al.*, 2023), supporting the current study's ranking of the diets based on feed production.

The feed production emissions have also been compared in an Austrian dairy system for sources of protein, which were ranked like the current study, with SBM as the highest, followed by DDGS. However, the current study ranked lucerne as one of the lowest feed production emitting diets, only higher than peas version one (without soya hulls) and red clover. Yet, the prior study ranked lucerne higher than RSM and faba beans. However, lucerne cobs were analysed in the prior study rather than forage, which could have caused the variation in results, as the current study assessed lucerne as a dried roughage, not a concentrate. Apart from lucerne, the protein sources were ranked similarly to the current study, supporting the results.

However, DDSG's and brewers grains are waste products of a former process in the distillery and brewery industry, that would be created and wasted if not fed to cattle (Kononoff and Hall, 2011; He, Allen and Huang, 2023). Feeding by-products is an efficient process to

reduce waste and it is thus, debateable whether the feed production emissions should be included in the total emissions of the farm. It could be argued that the production emissions should be attributed to the brewery or distillery industry. The feed production emissions were included for all the sources of protein in the current study, but their inclusion could make a significant difference to the ranking and overall emissions. DDSG's were heavily influenced by the feed production emissions and could be one of the lower emitting diets and reduce waste. There needs to be a universal methodology on where the emissions should be counted, to ensure they are accounted for and both systems do not exclude the associated emissions.

5.5.1 The comparability of the model results

The current modelling study produced comparable results to existing literature. Overall farm CO_2e emissions ranged from 0.88 to 1.22 $kgCO_2e$/kg FPCM for the milking herd without CS, while previous research ranged from 0.75 (Rotz, 2018) and 1.9 $kgCO_2e$/kg FPCM for the farm (Rotz, Stout, *et al.*, 2020), of which the latter diet consisted of a protein mix and SBM as the protein component. The results overlapped with the grazing housed system in Ireland (1.21 $kgCO_2e$/FPCM), which would be the most similar located farm to the current study. In addition to the results overlapping for a grass-based system in Ireland (0.98 kg to 1.67 $kgCO_2e$/kgFPCM), but slightly lower than the mean 1.26 $kgCO_2e$/kgFPCM (O'Brien *et al.*, 2016). However, the prior study did not evaluate protein sources. Sorley *et al.* (2024) examined management systems, which showed the grazing system as the lowest emitting (1.13 $kgCO_2e$/kgFPCM), which overlapped with the current findings. The mixed system was slightly higher (1.24 $kgCO_2e$/kgFPCM) than the current study, which was based on a mixed UK farm.

The model produced slightly lower results than several previous studies that did not report the protein used in the diets (Rotz, 2018; Castaño-Sánchez, Karsten and Rotz, 2022; Salcedo Díaz *et al.*, 2024; Sorley *et al.*, 2024) and that which used mostly RS and SBM diets

(Henriksson *et al.*, 2011). However, the current study only included the milking herd of the farm, which would lower the total CO_2e results, compared to previous studies that included all management groups. Other influential variables between studies, could have been the varying milk production and sourcing of feed.

Previous studies lack inclusion of CS in their reported CO_2e emissions, with the current study's overall farm CO_2e emissions ranging from 0.71 to 1.05 $kgCO_2e$/FPCM with CS. The carbon offset potential being 0.2 $kgCO_2e$/FPCM. Another study that assessed the offsetting potential of grassland, found between 0.6 and 1.3 $kgCO_2e$/kg FPCM total offsetting potential (Rotz, Holly, *et al.*, 2020). However, they estimated the potential during the transition period of converting cropland to perennial grass, when SOM accumulates, rather than the long-term ability. The study also only included grassland, whereas the current study included all sources of land type sequestration on the farm.

The protein alternatives consisted of several leguminous plants, such as FB, lupins, peas, and RS (Halmemies-Beauchet-Filleau *et al.*, 2018; Kuoppala *et al.*, 2021), which are known for their N fixing properties (Van Kessel, & Hartley, 2000). The plants improve the nitrogen levels in the soil, enhancing fertility of the soil, without the need for artificial fertilisers, which can equate to between 2% to 16% of dairy farm emissions (O'Brien *et al.*, 2016; Sorley *et al.*, 2024). Fertilisers are also considerably expensive in the UK and have increased by an average of over £150 per tonne since 2020 (AHDB, 2024b). Improving the quality of soil is also an aim of DEFRA's Environmental Improvement Plan 2023, to increase the sustainability of agricultural soil in England by 40% by 2028 and 60% by 2030 (DEFRA, 2023a). To help achieve this goal, it is expected that the UK government will offer economic subsidies, which could aid the industry in transitioning to protein alternative diets. The transition would have multiple benefits, by reducing dairy cattle methane emissions, demand for fertilisers and improve the quality of the farms soil.

5.5.2 Rapeseed meal and Soybean Meal

The current study supports previous research that a RSM dairy diet resulted in lower emissions than SBM (Benchaar *et al.*, 2021). The previous study examined various proportions of RSM and SBM in a diet, using a respiration chamber to measure the CH_4 emissions, rather than an estimation based on an equation. Benchaar *et al.*, (2021) also investigated the effect on daily EME, which reduced by almost 6% when SBM was substituted with RS (Benchaar *et al.*, 2021). The current study supports this, as EME from the 50-50RS and RS only had lower emissions than the SBM diets. The reduction in emissions from feeding dairy cattle RSM, rather than SBM, is likely due to the reduction in total VFA concentration and change from butyrate to propionate acid (Benchaar *et al.*, 2021), which produces less CH_4 (Børsting *et al.*, 2020). Research proposes that RSM would lower emissions compared to SBM, without affecting the pH and microbiome of the rumen and therefore the efficiency of digestion or rumen health of cattle (Rinne *et al.*, 2015).

5.5.3 Red Clover

Red clover is very efficient at fixing N in soil (AHDB, 2024c), has the potential to increase milk production (Moorby *et al.*, 2009) and is very common on farms in England (76%; DEFRA, 2021b), meaning it would not be a large transition to incorporate into dairy cattle diets or to produce. It had the second lowest emissions for the protein alternative diets per kg of milk, suggesting it did not negatively impact milk production and may have increased milk productivity. However, dietary N is thought to increase with red clover in a dairy cattle diet (Moorby, Ellis and Davies, 2016). Dietary N was not evaluated in the current study, but N_2O from manure emissions were converted to CO_2e emissions and red clover had the second lowest emissions of the diets. The low total CO_2e emissions from the red clover diet, suggests that dietary N did not impact overall total farm emissions, however, equations that use dietary N to predict emissions may be more suitable to evaluate this. Unfortunately, clover is not a

universal solution, as it cannot be used on some soil types (DEFRA, 2021a), however, this would encourage a diversity of plant growth in the UK. A diversity of protein sources should be encouraged and grown, especially with climate change, to improve food security should a disease or pest strike the food source.

5.5.4 Lupin

In the current study, lupins ranked ninth for the overall total farm emissions compared to the other protein alternatives, Previous research has reported lupin seed meal to reduce EME by up to 17% compared to a TMR of SBM and RSM (Bryszak *et al.*, 2020). The current study included manure and feed production emissions, not just EME. However, the study supports the current results as the lupin diet had lower CO_2e emissions than SBM, RSM, wheat distillers' grains with RS and 50-50 RS and SBM.

=Lupins was a less expensive diet and ranked 5th out of the 13 diets assessed in the current study. Lupins has also been linked to health benefits to milk consumers, by lowering unsaturated FA in milk (Bryszak *et al.*, 2020). It has been recommended that due to these benefits, diets should be supplemented with lupins to benefit wellbeing and the environment. The health benefits should be evaluated to ensure no health and environment trade-offs.

5.5.5 Ammonia Emissions

The mean annual NH_3 emissions were also assessed, however SBM ranked 5th out of the 13 protein sources, emitting slightly less NH_3 than the baseline RS diet (6th). The results contrasted previous research (Huhtanen, Hetta and Swensson, 2011), but supported research of emitting similar NH_3 emissions (Christen *et al*., 2010; Rinne *et al*., 2015; Benchaar *et al*., 2021). NH_3 emissions were lower for FB and SBM than lupins, supporting previous research (Mendowski *et al.*, 2019). Previous research found that the protein type did not impact

emissions, but the forage type did (Doreau *et al*., 2014), however, the current study opposes this finding, as the protein of the diets did impact NH_3 emissions.

5.5.6 Costs of Feeds

The costs were based on purchased feeds and could be reduced by growing the feeds on-farm. The costings provided are a rough estimate of the time of the study due to fluctuations in costs. The costs would need to be analysed at the time and geographical area to gain accurate results. The costs suggest that the least emitting diet (peas version one) would be the fourth least expensive feed to purchase. Lucerne also had low emissions but was the most expensive feed. From emissions and cost, it can be concluded that peas version one (no soya) seemed the most viable protein from the 13 alternative protein diets analysed.

5.5.7 Proportions of carbon dioxide equivalent emissions

The proportion of contribution from the various sources in the current study and previous research were similar. EF equated to the largest proportion of emissions in both studies, between 46 and 62% in the current study, and between 32 and 51% in previous studies (Mc Geough *et al.*, 2012; Van Middelaar *et al.*, 2015; O'Brien *et al.*, 2016; Sorley *et al.*, 2024). Manure management (13-19%), contributed between 8 and 12% in the current study. The larger proportions were attributed when CS was included in the results, which was not considered in the previous study. Feed production was measured as production of concentrates (18%) and on-farm roughage production (13%) in a previous study (Van Middelaar *et al.*, 2015), equating to 31% in total, which was between the range found in the current study (23 to 44%). There was large variation in the contribution of feed emissions to the total farm emissions, which was likely due to the change in diets. It was also assumed that the feed was purchased off-farm, whereas the previous study included on-farm roughage production and concentrates.

5.6 Conclusion

In conclusion the study highlighted multiple suitable protein replacements for SBM in dairy cattle diets, that reduced GHGe by between 2 and 28%. The study also highlighted that the highest farm emissions were those using SBM linked to deforestation, increasing emissions by approximately 7%, compared to SBM not linked to deforestation. Substituting SBM with an alternative protein, would reduce the demand for SBM linked to deforestation, improving biodiversity and habitats for wildlife. The results suggest that milk demand can be met with the protein alternative diets. Feed production emissions had the largest influence on the ranking of the diets. From the 13 alternative protein diets analysed, peas (version one) were determined as the optimum diet, as it resulted in the least total CO_2e emissions and was the fourth least expensive for purchased feed. It should be noted that before a dairy cattle diet is modified and an alternative protein source is used, the rations would need to be developed by a dairy nutritionist, to ensure the diets meet the animal requirements to safely maintain milk production and the rumen biome. Additional combinations and proportions of protein sources in dairy cattle diets, should be assessed in future studies. Policy should also clarify whether feed production emissions from waste products fed to livestock, should be included in the farm system.

Chapter 6: Net Zero

Chapter 6: Net Zero

6.1 Introduction

The National Farmers Union (NFU) have set a goal of becoming carbon zero by 2040, for all agricultural sectors in England and Wales, to support the Government's 2050 carbon zero target (NFU, 2019). Yet, there is a lack of knowledge on how farmers can reduce their GHGe, with contrasting research and advice (DEFRA, 2021b). One of the biggest challenges facing the industry is how the sector will reach their Net Zero target. There has been lots of research into mitigation strategies for reducing GHGe from the agriculture sector, but not a combination of mitigation strategies. There is currently no single method to reach Net Zero, so an assessment of multiple mitigation strategies is needed, to evaluate how UK farms can plan to reach Net Zero. A reliable method for achieving this is through modelling different scenarios, as this assesses how different variables interact (Bertrand and Barnett, 2011). It can also aid decision planning when developing legislation (Bertrand and Barnett, 2011; Sefeedpari *et al.*, 2019; Ibidhi and Calsamiglia, 2020), as it provides blueprints to create a foundation for carbon reducing grant schemes (Sefeedpari *et al.*, 2019). Grant schemes are likely to increase, as interest in climate change continues to grow and the Net Zero target nears, intensifying pressure on the Government to implement more incentives and legislation to reduce the dairy sectors environmental impact (Mostert *et al.*, 2018).

6.2 Aims and Objectives

The aims of Chapter 6 were to utilise the farm simulation model to simulate a combination of mitigation strategies to explore the possibility of achieving Net Zero in the UK dairy industry within an estimated timeline. The scenarios were analysed both together and with each strategy removed to assess whether the farm could reach Net Zero without one of the strategies to allow flexibility in choice to the farmers.

Objectives:

1. Assess whether Net Zero is possible in UK dairy farms by utilising the UoN REMEDY model and an estimated timescale of reaching Net Zero.
2. To assess whether the combination of all the mitigation strategies is required to reach Net Zero, or whether Net Zero could be reached without one of the strategies.

6.3 Methodology

An extreme scenario was simulated in the UoN REMEDY simulation model to examine whether a typical UK dairy farm can reach Net Zero. Multiple mitigation measures were simulated on the farm: afforestation to offset emissions, feed additives to reduce enteric CH_4, 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. See the methodology in Chapter 4 on pages 118 to 132, for further details on the mechanical workings of the model. The farm was based on the representative UK dairy farm described on page 118-119 and summarised in Figure 10, with a 22% RR, but adapted to minimalize GHGe.

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 in the methodology of Chapter 4, on pages 127 to 132 were used, with the CH_4 emission factor of $3.2 g CH_4 kg VS^{-1}$, CH_4 conversion factor (MCF) of 3.55% to represent a high-quality AD management system, with minimal leakage, and open storage. Zero fertiliser usage and renewably sourced electricity resulted in zero CO_2e emissions from electricity and fertiliser. The dairy diets were supplemented with 3-NOP and an enteric CH_4 reduction of approximately 30% was presumed based on the literature (van Gastelen, Dijkstra and Bannink, 2019; Arndt *et al.*, 2021), to avoid overestimating thepotential of feed additives and to be representative of alternative feed additives, such as seaweed (Roque *et al.*, 2019).

The mitigation strategies were also simulated with the option of one removed, such as the 30% 3-NOP reduction, anaerobic digester replaced with a slurry tank and the scenarios

without CS for comparison. The results were simulated over a 10-year period from 01 November 2021 to 31 October 2031. The model simulated 10 years, but the results from the last three years were used when the effect and data stabilised, from 01 November 2028 to 31 October 2031, as stated in Chapter 4. There is limited data available on the CS 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 CS ability of woodlands was based on the IPCC Tier 1 (2006) methodology. The potential of birch (*Betula spp.*) was -4,040.32kgCO_2e/ha, beech (*Fagus spp.*) -6,185.92kgCO_2e/ha, and oak (*Quercus spp.*) -9,688 kgCO_2e/ha. The potential was then multiplied by the hectares of land for the total CS 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 RSM, forage and dairy cake. Dry cows were fed 13.6 kg of DMI of straw and concentrates (diet composition shown in Appendix 1 as diet 4). Heifers were fed 9.08kg/day, 6.59kg/day for weaned cattle, and 13.48kg/day for bulls, based on the presumed BW of 600kg for milking cattle, dry cattle, and bulls, 230kg for weaned calves and 400kg for heifers. The number of milking cows in the herd was approximately 100 for the farm, which was reduced by 10% and 20% to approximately 90 and 80 cows to simulate reducing the milking herd size as a mitigation strategy.

Feed production emissions were calculated based on the Agribalyse database results for each of the rations of the diet for milking and dry cows. The emissions for the milking cattle diet were 8.61kgCO_2e/cow/day and 3.01 kgCO_2e/cow/day for the dry cattle diet. The emissions were then multiplied by the average animal numbers for each scenario, and the average DIM,

which were 305 days and the average dry period which was 60 days per year. GHGe from energy use, fertiliser usage and fuel were also included in the total farm CO_2e emissions.

6.4 Results

The results show that with the mitigation systems in place, excluding CS, the farm had low CO_2e emissions of 0.75kg CO_2e/kgFPCM. The inclusion of CS 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 24. The reduction in milking cattle herd size only reduced CO_2e emissions per litre of FPCM, when CS was subtracted from the total. The feed additives removed, or AD replaced by a slurry tank for manure storage, only reached Net Zero when oak trees were planted.

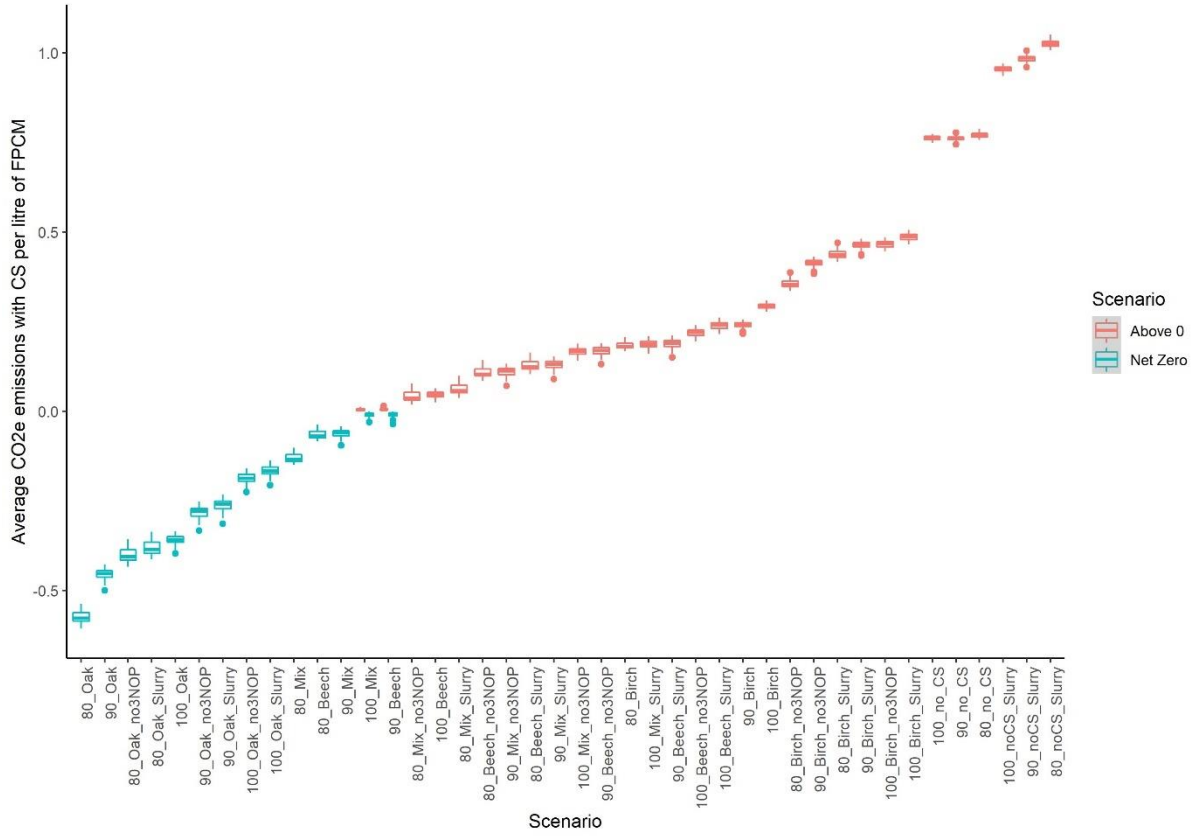

Figure 24: A boxplot of the scenarios with the various mitigation strategies that reached Net Zero or minus emissions per litre of FPCM. The scenarios that reached Net Zero are shown in blue, while those that did not reach Net Zero are presented in red. 100, 90 and 80 refer to the milking cow herd size numbers, "no3NOP" mean the scenarios where the 30% reduction in enteric methane 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 were higher than 0, so the scenarios were mixed in whether they reached Net Zero using the model.

6.4.1 Tree Species

The tree species influenced the CS 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 24. 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 24. 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 24: 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 (CO_2e) emissions as total kgCO_2e/year.

Tree Species	Milking herd size scenario	Land CS	Total CO_2e	Total CO_2e with CS	Total CO_2e standard deviation
Birch	100	-501,274.2	807,746	306,472	±4,238
	90	-501,274.2	740,429	239,154	±11,290
	80	-501,274.2	647,840	146,566	±5,321
Beech	100	-767,054.08	807,746	41,912	±4,238
	90	-767,054.08	740,429	-26,545	±11,290
	80	-767,054.08	647,840	-117,963	±5,321
Oak	100	-1,201,312	807,746	-392,346	±4,238
	90	-1,201,312	740,429	-460,803	±11,290
	80	-1,201,312	647,840	-552,221	±5,321
Mixture (1/3 each)	100	-823,121.5	807,746	-14,155	±4,238
	90	-823,121.5	740,429	-82,612	±11,290
	80	-823,121.5	647,840	-174,030	±5,321

6.4.2 Reducing Total Miking Herd Numbers

The total animal numbers for each of the management groups for the three total cattle number scenarios can be seen in Table 25. 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. The MY can be seen in Table 26. The total annual farm GHGe were converted to CO_2e emissions per kilogram of FPCM, as shown in Table 27. Enteric CH_4 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 25: 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 26: 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) and Standard Deviation
100	1,071,741 (±18,051)
90	963,817 (±15,897)
80	853,895 (±15,155)

Table 27: The average kilograms of carbon dioxide equivalent (CO_2e) emissions per kilogram 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

6.4.3 Feed Additives

The average EME as CO_2e were compared for the herd, against an approximate 30% reduction in EME by substituting the diet with feed additives. The EME can be seen in Table 28 below.

Table 28: The annual enteric methane emissions as carbon dioxide equivalent (CO_2e) as kilogram 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	431,748 (±348)	616,783 (±348)
90	387,446 (±340)	553,494 (±340)
80	344,119 (±329)	491,599 (±329)

6.4.4 Manure Management

The average manure emissions were compared using AD and a slurry tank. The AD significantly reduced total manure emissions from the farm, by around 70%, which can be seen in Table 29 below.

Table 29: The annual manure carbon dioxide equivalent (CO_2e) emissions from anaerobic digestion compared to all year slurry.

Milking herd size scenario	Slurry (total CO_2e/year)	Anaerobic Digestion (total CO_2e/year)
100	293,586 (±7,117)	87,047 (±2,397)
90	263,240 (±7,038)	78,047 (±2,347)
80	233,975 (±6,833)	69,377 (±2,291)

6.5 Discussion

A farm simulation model showed the potential to reduce and offset GHGe from UK dairy farms and meet Net Zero. The results suggest that multiple mitigation strategies are needed for UK dairy farms to reach Net Zero, including woodlands to offset GHGe. Oak had the largest offsetting potential, compared to beech and birch woodlands. The scenarios that had the potential to reach Net Zero included those with oak trees, without the use of feed additives, or with a slurry tank rather than an AD, with all milking herd sizes examined. The mixture of tree species with 80, 90 and 100 milking herd size and beech trees with a 10-20% reduction in milking herd size. The reduction in the milking herd only reduced CO_2e emissions per litre of FPCM when CS was subtracted from the total, due to the reduction in milk production. The scenarios would take 20 years for the woodlands to stabilise and farm to reach Net Zero, which would be after the 2040 NFU Net Zero goal.

6.5.1 Feed additives

The presumed 30% reduction in enteric CH_4 from feed additives aided the farm in reaching Net Zero, as when the effect was removed, the total farm emissions exceeded the Net Zero threshold, except when only oak trees were planted on-farm. It is safe to assume from the current results, that a type of feed additive fed to at least the milking herd is required for UK dairy farms to reach Net Zero. Feed additives are an extra cost to farmers (SRUC, 2022) and thus economic incentives and legislation will be required to aid farmers in this management transition.

6.5.2 Anaerobic Digester and Slurry Tank Manure Emissions

Currently, less than 10% of farms in England use an anaerobic digester (DEFRA, 2021b), possibly due to their high expense and maintenance (Aguirre-Villegas and Larson, 2017; Sefeedpari *et al.*, 2019). It is therefore unlikely that AD plants can be incorporated on all

farms across the UK. The total annual farm CO_2e emissions using an anaerobic digester were thus, compared against a slurry tank on farm. The results showed the possibility of alternative manure storage on farm to anaerobic digesters to reach Net Zero, depending on the woodland area and tree species. It was possible for the farm in the current study to reach Net Zero without the anaerobic digester, using a slurry tank for the whole year, provided the land was converted to oak trees.

AD should be encouraged where possible, as it leads to low pollution levels (Aguirre-Villegas and Larson, 2017; DEFRA, 2021a) and cattle manure results in lower NH_3 emissions than swine (Zhuang *et al.*, 2020). The management system should also be monitored, such as using biochar to reduce the risk of contamination (Qi *et al.*, 2021).Depending on the farm's electricity consumption, the AD might also allow surplus renewable energy to be sold to the grid to offset emissions further and provide another source of income.

The change in manure management reduced emissions without CS, with an average 0.76 $kgCO_2e$/kg FPCM for the farm, which supports literature of 0.75 kg of CO_2e/kg of ECM for a freestall system with an anaerobic digester in New York (Rotz, 2018). AD had low manure emissions of 0.08 $kgCO_2e$/kg FPCM. The manure emissions from AD (0.08 $kgCO_2e$/kg FPCM) were only slightly lower than those reported by the farm's Arla Climate Check tool (0.09 $kgCO_2e$/kg FPCM), which calculated slurry for 5 months and pasture-based manure management for 7 months. The results suggest that the Arla Climate Check tool may be underestimating the emissions from the manure slurry and pasture management system. The Tier 1 tool may have failed to consider the complete emissions from CH_4, and N_2O from direct, indirect, and leaching, which was considered in the current model. Another possibility is that the tool might be deliberately underestimating CO_2e emissions to compensate for the current absence of CS in the tool.

The CO_2e emissions were lower for the CS scenario in the current study, than the representable farm emissions using the Arla Climate Check tool from enteric, manure management and feed production. The total farm CO_2e emissions were 1.08 for the Arla tool and 0.69 in the CS scenario. The fuel emissions were equal to the energy (electricity and fuel) emissions reported by the Arla tool.

6.5.3 Do we need to reduce the milking herd?

The results show that Net Zero can be reached without reducing milking herd size, in extreme afforestation scenarios, using oak or a mixture of tree species that include oak. However, a 10-20% reduction in milking herd size aided the transition to Net Zero and shows Net Zero can be reached without significantly reducing the herd and milk supply.

6.5.4 Tree Species

The tree species dramatically impacted the CS potential and whether the farm met Net Zero. The farm reached Net Zero without reducing milking herd size when farmland was converted to oak or an even mixture of birch, beech, and oak trees. Converting the farmland to birch woodland offset the farms emissions, by an average -62.06% per year (-501,274.2 $kgCO_2e$/year). Beech woodlands offset more emissions than birch, with an average -94.96% (-767,054.08 $kgCO_2e$/year), followed by a mixture of birch, beech, and oak, evenly split a third each, contributing to -101.9% (-823,121.5 $kgCO_2e$/year) of the farm emission offset. Oak had the largest offsetting potential of a mean of -148.72% (-1,201,312 $kgCO_2e$/year) of the total farm emissions. It is important to note that the REMEDY model used IPCC Tier 1 based on the default emission factors, which were not country specific and are therefore, associated with higher uncertainties than the Tier 2 and 3 methodologies.

6.5.5 The benefits of diversity in tree species

Oak had the largest sequestration potential to aid the farm to Net Zero. However, it would be harmful to plant a monoculture species, as it would negatively impact the biodiversity of the land and reduces the resistance of the woodlands. Research suggests it may be beneficial to plant a range of tree species to increase diversity, as it can lower disease and pests, as well as contribute to the resistance of UK trees (Roebuck, Hurley and Slater, 2022). Previous research has suggested that a diversity of trees increases their CS potential (Yu *et al.*, 2023), which was found in the current study compared to a woodland of only birch or beech tree species. But oak alone was found to have a higher offsetting potential than the mixture of tree species. However, it is not feasible or environmentally optimum to plant oak trees across UK farmlands alone, and thus, a scenario where only the sequestration of oak trees allows the farm to reach Net Zero is impractical.

The long-term offsetting abilities of woodlands are vague with large uncertainty in CS abilities and lengths (IPCC, 2006). However, the SOC is thought to remain stable for at least 150 years (Johnston, & Poulton, 2008). It is important that the woodlands offsetting potential is considered after 20 years, to incentivise their presence and avoid removal before the end of the tree species lifespan. The planted trees will also aid wildlife, especially as they age, providing an array of habitats (Royal Society for the Protection of Birds, 2021b)..

The average size of dairy farms in England were 129 hectares in 2019 (DEFRA, 2019), similar to the current farm size of 124 hectares, which suggests the scenarios tested are feasible across typical dairy farms in England to reach Net Zero. The herd size (140) was also very close to the average UK dairy herd size (160) in 2021 (AHDB, 2023b). It is a controversial scenario to encourage the use of a 100% housed system in the UK, with concerns over AW and management, in addition to the practicality of widespread adoption. There is the option for cattle to pasture in the woodlands, which would need further research,

however, the trees provide shade, which can improve cattle comfort (Palacio *et al.*, 2015) and temperament (Schütz *et al.*, 2010). However, forest management can be intensive for farmers, including the paperwork, suggesting the need for economic incentives to encourage the adoption of afforestation. Land availability would also need to be monitored to ensure food production and security is not traded for forestry, to ensure sufficient forage can be produced on-farm.

6.5.6 Implementing a combination of measures

The simulation included implementing multiple mitigation measures together, which may have feasibility issues. For instance, the measures are an additional economic cost, with 3-NOP having an additional cost of £31 per year per cow (SRUC, 2022) and AD having a minimum cost of £900,000 for UK installation (Bywater & Kusch-Brandt, 2022). It would be difficult for farmers in the UK to implement these measures without economic incentives, when 44% of English farmers surveyed lacked motivation to mitigate GHGe from their farm (DEFRA, 2021b). It is important that the UK government supports farmers that can incorporate anaerobic digesters, through subsidies, to make the technology cost-effective (Sefeedpari *et al.*, 2019). AD and afforestation also require large land usage, which needs to be evaluated to ensure demand can be met with current availability without negatively impacting food security.

There is also the possibility of silvopastoral systems for cattle to remain on pasture with planted trees. However, this would also impact manure management, such as the amount collected for AD and the application of feed additives into the cattle diets. There is the possibility for 3-NOP lick blocks on pasture-based systems, however, the amount of 3-NOP digested by each cow can be difficult to monitor (Yu *et al.*, 2021). An alternative is a device that gradually releases the additive within the rumen. However, this could increase costs and labour to the farmer, requiring additional incentives for implementation. Manure would be

difficult to collect for AD on pasture but would be a natural fertiliser. It would also have higher NH_3 emissions, than injecting the manure into the ground (Aguirre-Villegas and Larson, 2017). The emissions associated with the manure management system and the length of time on pasture, would need to be evaluated to ensure Net Zero could be met with an alternative manure system to AD.

6.6 Conclusion

In conclusion, the model showed blueprints towards reaching Net Zero, by combining mitigation strategies. The strategies included: converting manure storage to AD, renewable electricity, removing fertilizer usage, reducing milking herd size, and increasing cow milk productivity, improving RRs, afforestation and reducing EME by supplementing the dairy cattle diets with feed additives. The model highlighted Net Zero could be reached without an expensive anaerobic digester or by reducing milking herd size, but feed additives would be required. Legislation and economic subsidies will be required to aid farmers with the implementation of feed additives in UK dairy farms.

The simulation results also suggested carbon offsetting was a necessity to reach Net Zero in UK dairy farms. The current model showed a high offsetting potential by transitioning the system to a fully housed system and converting farmland to forestry. The carbon offsetting potential varied depending on the tree species of the forest, with oak having the largest ability, followed by a mixture of the three species, beech and lastly, birch. However, due to the 20 years it takes for trees to reach maturity, it is unlikely that dairy farms will reach Net Zero by the NFU's 2040 goal, unless afforestation has already begun. Further research should investigate the potential for cattle to graze in woodlands, or the potential of silvopastoral systems to diversify the potential of Net Zero management practices. In addition to a Tier 2 or 3 methodology for evaluating the CS potential of UK specific farms to reduce uncertainty in prediction results.

Chapter 7: Discussion and Conclusions

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7.1 Discussion

Farmers are unsure how to reduce their CF and reach Net Zero without impacting production (DEFRA, 2021b). UK farmers and the government may therefore benefit from research and education to aid prioritisation of mitigation strategies to aid the industry and country on their Net Zero journey. The current project utilised a whole farm simulation model linked to a LCA model covering the various aspects of a dairy farm (including feed, manure management, EME, health, milk production and reproduction) 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 influence legislation on how the government can support the transition to more sustainable practices.

7.1.1 Total farm emissions in relation to combustion vehicles

In practical terms, to a widely used vehicle in the UK, 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.To simplify the results, based on the average car emissions, the annual emissions from the high RR were the equivalent of the annual emissions from 1,032 cars. While the medium RR was the equivalent of 981 cars and the low RR 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 RR, therefore, produced the equivalent of almost 100 more cars than the low RR and over 50 more than the baseline. There was a similar difference between the medium and low RR of 48 cars. Emissions could thus, be reduced by changing RR, 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.

In practical terms, UK averages estimate farm emissions for SBM as the equivalent of 853 annual car emissions. The lowest emissions from the pea version one (no soya hulls) diet on the other hand were equivalent to 665 cars, and the highest SBM alternative of wheat distillers' grain with RS equivalent to 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. A larger reduction in GHGe than reducing RRs of the farm.

SBM linked to deforestation had the largest annual total farm emissions equivalent to 927 petrol vehicles. Thus, switching from SBM linked to deforestation to a protein alternative 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.

7.1.2 Working towards Net Zero

It is likely with the interest in alternative proteins, such as the funding for research from DEFRA (DEFRA, 2022a), that dairy diets in the UK will diversify and current EME prediction equations may not fully represent the change in diets. The SF_6 tracer gas technique offers a more inclusive method for testing the prediction equations accuracy in comparison to direct emissions than the respiration chamber, as it allows movement of the cow and is effective on pasture-based cattle (Deighton *et al.*, 2014; Patra, 2016). However, the SF_6 gas used in the methodology is a highly potent GHGe, over 22,000 stronger than CO_2 (IPCC, 2018). Using the technique to measure emissions to aid mitigation measures, could thus be counterproductive. The usage of SF_6 should be minimalised and the EU aims to phase out

usage of the GHG by 2030 (European Commission, 2024). The GreenFeed system, although a short period measurement, offers a flexible approach to measuring emissions in multiple management systems over weeks or months, without the need for SF_6 to test the equations accuracy.

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. Chapter 6 addressed the question, by combining multiple mitigation measures to explore 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, 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.

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%. CS 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.

Converting the farmland to birch woodland offset the farms emissions, by an average -62.06% per year (-501,274.2 $kgCO_2e$/year). Beech woodlands offset more emissions than birch, with an average -94.96% (-767,054.08 $kgCO_2e$/year), followed by a mixture of birch, beech, and oak, evenly split a third each, contributing to -101.9% (-823,121.5 $kgCO_2e$/year) of the farm emission offset. Oak had the largest offsetting potential of a mean of -148.72% (-1,201,312 $kgCO_2e$/year). The model results highlight the need and potential of offsetting

emissions; however, it also showed the limitations for offsetting emissions and differences tree species and age can have. CS is not a silver bullet for climate change, and it is crucial emissions are reduced as extensively as possible to treat the cause of climate change. Offsetting should only be used as an extra measure and not as an excuse to continue business as usual.

An important aspect not covered in the scope of the study or model, but important when considering the environmental impact, is biodiversity. Encouraging biodiversity is vital to reduce risk to food security, from disease, parasites, and climate change if the weather becomes unsuitable for growing certain feeds or trees. Chapter 6 showed the tree species significantly impacted the offsetting potential, with oaks having the largest (-1,201,312 $kgCO_2e$/year). Chapter 5 also highlighted peas (version one) resulted in the lowest overall CO_2e emissions (0.88 $kgCO_2e$/kgFPCM without CS and 0.71 $kgCO_2e$/kgFPCM with CS). There are a variety of pea species that can be grown for cattle feed. However, for these reasons above, it would be unwise to conform to one feed or tree type. A diverse range of crops should be grown to enhance biodiversity, and mixed cropping can improve pest resistance and soil quality (Permaculture Association, 2024). It is also important a polyculture of trees is planted to promote diversity, increase resistance to pests, disease, and changes in the climate. For instance, oak trees are particularly susceptible to climate stress and are currently suffering acute oat decline in the UK (The Woodland Trust, 2024) and thus, promotion of sole plantation of oak, could lead to significant losses in tree coverage. A mixture of tree species also promotes habitats for diverse ranges of wildlife.

The UK imported over two million tonnes of SBM in 2019 for livestock feed (EFECA, 2019). Climate change is estimated to reduce the security of reliance on importation of food (DEFRA, 2021c). Thus, it is important that the industry transitions from SBM to an alternative diet to increase food security, reduce GHGe and prevent deforestation. Increasing

farm grown forage also reduces costs of purchased forage (AHDB, 2020a). Although transportation was not included in the scope of the current study to assess GHGe, to increase food security, it is advised that cattle feed is grown locally either on farm or within the UK to improve food security. Trees could also be used to feed cattle, such as willow trees which may also reduce methane emissions (Agrecalc, 2024a), but require further investigation.

RSM was used in the current study to complete the protein alternative diets; however, RS yields have been unpredictable with the changing climate and particularly vulnerable to cabbage stem flea beetle (Leybourne *et al.*, 2024). The UK is also aiming to limit pesticide usage that protects crops from pests, by a minimum of 50% by 2030, to reverse insect decline (UK Parliament, 2024b). A concern associated with this change in practices is lower yield, which could lead to an increase in price of UK grown crops, which would make importations more economically viable, where these dangerous pesticides are utilised. It is vital that measures are in place to promote local produce at an economically viable rate to work towards more sustainable farming strategies and improve food security.

The availability of agricultural land for planting trees dramatically increases land availability by over 120% (Burke *et al.*, 2021), to reach the UK tree cover targets. Afforestation of agricultural land could also be used to aid the country in DEFRA's 2042 biodiversity goal to restore habitats for wildlife for 500,000ha of land (DEFRA, 2023a). It is important agricultural land is utilised, to allow other types of available land to be converted to housing with a predicted increasing population (FAO, 2015). England has a low forestry cover of 10%, compared to 19% in Scotland (Forest Research, 2022). Agricultural land availability significantly improves the potential of England to meet DEFRA's 2050 goal of increased woodland cover to 16.5% of land and planting 34,000ha by the end of January 2028 (DEFRA, 2023a). In addition to 360,000 miles of hedgerows by 2050. Equal tree coverage

across the UK would also be possible to avoid political issues over responsibility and land availability.

However, as mentioned, the UK has a land shortage with an increasing population (FAO, 2015). It is important land is used efficiently. Food production and security need to be maintained without competing with feed for livestock or afforestation of land. It is important that afforestation, maintenance of woodlands and CS are encouraged and incentivised, but not at the expense of food production. It is vital food is produced in the UK and imports are limited to increase food security. Arable and livestock farming need to be prioritised to meet the country's needs. Tree coverage, arable and livestock farming should also be equal to population and land size, between England, Scotland, Wales, and Northern Ireland, to provide necessary production to each area and limit political disagreements. Polycultures of crops and trees should be chosen with a higher resistance to climate change and the forecasted extreme weather conditions.

The results showed that AD was not a necessity for a typical UK dairy farm to reach Net Zero. An important finding, as AD are an expensive energy system in the UK costing at least £900,000 for installation in the UK (Bywater & Kusch-Brandt, 2022). The high expense is the likely reason for the low uptake of the system, as less than 10% of farms in England used an anaerobic digester in 2021 (DEFRA, 2021b). It would be difficult to encourage widespread use of AD across England, especially across small scale farms. It also allows cattle to graze where manure is difficult to collect for AD. However, AD limits leakage and thus leads to low pollution levels (Aguirre-Villegas and Larson, 2017; DEFRA, 2021a) and cattle manure is a particularly beneficial manure, as it contains lower NH_3 emissions than alternatives, such as swine (Zhuang *et al.*, 2020). AD can also provide renewable electricity generation for the farm and surplus to be sold to the grid as an additional income. AD from agriculture could then be used to power part of the national energy system and be a huge

solution to converting to renewable power and reducing energy security concerns. AD usage in agriculture could gain positive environmental attention and change the public perception of the industry, which is often portrayed negatively in the media (Duley *et al*., 2022). However, AD also has a large land usage, which must be considered before implementation to ensure it is the most efficient use of land in that area.

The results highlighted a need for feed additives in dairy cattle diets to reach Net Zero in UK dairy farms. Feed additives are an additional farming cost (SRUC, 2022) and require subsidies or economic incentives to aid farmers in their implementation, especially with the cost-of-living crisis in the UK, such as high energy costs (UK Parliament, 2024a). Feed additive 3-NOP has recently been approved for use in the UK (FSA, 2023), which means a lack of knowledge on the national costs for the additive (SRUC, 2022). 3-NOP could have an additional annual cost of approximately £31 per cow (SRUC, 2022), which could be difficult to encourage, when a large proportion of farmers (44%) lack motivation to mitigate their farm GHGe (DEFRA, 2021b). However, there are alternative sources of feed additives, such as macroalgae Asparagopsis seaweed that has had similar and even higher CH_4 reductions to 3-NOP (Roque *et al.*, 2019) that could be more widely encouraged in the UK.

Nevertheless, the new introduction of feed additives in the UK may also lead to apprehension regarding the use of feed additives, as farmers may worry about the impact on cattle and milk quality. The public might also have the same apprehensions about milk quality, taste and whether ingesting the milk may have health complications for them as the consumer. Education and awareness are needed on the benefits of feed additives and safety of their use for cattle, milk quality and the consumer. Policy and legislation are also needed that subsidise and incentivise farmers to use feed additives, AD, convert land to woodland and reduce their GHGe from farm.

7.2 Limitations

7.2.1 The Equations used in the Model

The model and combined equation was developed based on pre-existing research, such as the IPCC methodology and published enteric CH_4 prediction equations. The equations used could be outdated, as research is constantly advancing and might not accurately represent current dairy farms, dairy diets, and their emissions. The model used GWP 100, which is starting to reduce in usage, as interest grows towards GWP*, such as the Agrecalc carbon tool offering the metric alongside GWP100 (Agrecalc, 2024b) and the assessment of CH_4 as a short-lived gas. The results may therefore reduce in validity as the uptake of this method is increased and GWP100 could become outdated, as research develops.

The enteric CH_4 prediction equations also varied considerably in their reported results. The combined equation only found the dietary variables ME and NDF to influence the enteric emissions, when multiple dietary variables impact enteric CH_4, such as fat content (Patra, 2013; Arndt *et al.*, 2021) and the source of carbohydrate (Børsting *et al.*, 2020). The combined equation therefore is limited, as it does not consider the effect of these variables on enteric CH_4, as this is very difficult to predict.

7.2.2 Replacement Rates

A few assumptions had to be made in the simulation model, which could limit the results. It was assumed that cattle remained in the herd for the entire year, which would be doubtful in the real world, especially in the higher RR scenario. The assumption was the likely cause of the higher animal numbers in the higher RR, which could have increased the GHGe, as cattle would not have been on the farm for the entire year in real life and not contributed to as many GHGe. It was also assumed that heifers were reared on farm, when heifer management has

had a significant impact on GHGe in previous research, larger than RRs (Weiske *et al.*, 2006). The GHGe for the farm if heifers were sold was not assessed.

7.2.3 Diet composition

Dietary N content was not assessed in the current study, which may lead to larger N emissions and trade-offs between GHGe and the optimum dairy diet. Forage and fat content of the protein alternatives diets were not controlled for in the current study, so it cannot be guaranteed that the forage content did not influence the results. The fat content of the diets varied to maintain milk production across the protein alternative diets. SBM has a very high energy density, which means high supplementation is needed with substitution. Milk production was stabilised to assess the total CO_2e emissions associated with the protein alternatives against a consistent milk output, so the effect of the protein alternatives on milk production were not assessed. The milk output can therefore not be certain and is a limitation of the results but was within the expected range for the system type analysed. Nutrition values for each dietary component were sourced from the feed into milk (FIM) database (Thomas, 2004). Although this was the most up to date source, it is still outdated and a limitation of the study, as feeds and nutritional quality have improved over time.

7.2.4 Cost analysis

A cost analysis was not conducted for the RRs in Chapter 4, to assess the economic viability of the three scenarios. However, milk production was assessed as a method of measuring the economic costings, by ensuring profits were maintained and not negatively impacted. The costs of the protein alternative feeds were estimated based on the time of the study and as fluctuations constantly occur, the costings are likely to be outdated, limiting the accuracy of the economic costings. The costings are therefore unlikely to aid farmers' decision-making for an alternative protein.

7.2.5 A representative farm

The results were based on outputs from the simulation model for a typical UK dairy farm. However, management systems vary considerably across the UK, and one typical farm could misrepresent several production systems in the country. The results could therefore be inapplicable to numerous UK farms, creating a huge limitation to the study guidelines for reaching Net Zero.

7.2.6 A partial life cycle analysis

Due to time constraints, a partial LCA of the project was conducted to the farm-gate, excluding emissions from bedding and past the farm-gate such as transportation, storage, and waste treatment. The partial LCA led to the total farm emissions excluding emissions past the farm gate, associated with the product. The results, therefore, cannot offer mitigation advice for that stage of the life cycle, limiting the application of the results. The total emissions and woodlands required to offset emissions would thus be higher, if associated with the farm and included in the LCA.

7.2.7 Static Parameters

Models require static parameters, such as the animal BW and DMI assumed in the REMEDY model, which could be considered mid-point figures. The GHGe of the dairy system are complex, such as the variation in EME over a 24-hour period. It is difficult to model this complex system and the fluctuations that occur. Stochasticity was used to model part of this variation; however, the results were based on assumptions from the simulation model and will therefore have limitations. The model was also unable to simulate the complexity of a silvopastoral system. The system has strict requirements on the wide-spacing between trees in rows to qualify as a silvopastoral system. The total land area for the representative farm was known, but not individual areas to determine the possible number of trees that could be

planted. The Net Zero scenario therefore, led to a housing system with woodland conversion of the land.

7.2.8 Feasibility

There were assumptions made in the simulation scenarios that could have feasibility issues in vivo. For instance, it was assumed for the Net Zero chapter that zero fertiliser was applied to the farm and feed was purchased off farm. An increase in leguminous plants could improve the nitrogen levels in soil properties (Van Kessel, & Hartley, 2000), however, it does not necessarily mean zero artificial fertiliser would be used. Manure can be used as a natural fertiliser from slurry or digestate from AD, which should be increased in the UK. Orange peel powder is another natural alternative, that has a nitrogen content of 7.2 mg/g (San, 2021). When tested it doubled N (0.18%) and phosphorus content (0.40%) and trebled potassium content of soil (1.01%). Usage is currently small, but awareness of the effectiveness and high cost of artificial fertiliser (AHDB, 2024b) may increase usage.

It was also assumed that feed was purchased off farm and the study did not assess the trade-off for land availability to meet both food security and afforestation requirements. Although feed production emissions were included in the study, the limitation of not assessing feed produced on farm could lead to future farm carbon audits associating emissions with the source and not the farm. There is also the issue that sufficient land may not be available to grow and meet feed requirements and afforestation. A current concern is the trade-off between afforestation and crop production, reducing incentives to grow crops and limiting food security in the UK, in prioritisation of biodiversity. It is important this trade-off is evaluated, and incentives do not reduce food production and security.

The farm was also assumed to be a housed system, where manure could be collected for AD and feed additives could be monitored and applied in feed, rather than a capsule in the rumen.

A pasture-based system would require additional monitoring and labour to incorporate a capsule into the rumen to release the feed additive. It would also limit manure management strategies, such as manure collected for AD.

7.3 Further research

7.3.1 Multiple Livestock

The study assessed the GHGe of the dairy industry, however, it could be adapted to suit different livestock and those commonly used in different areas. The model was dairy cow specific, but could be modified to beef cows, as feed has different effects on reducing dairy emissions to beef cattle (van Gastelen, Dijkstra and Bannink, 2019). The scenarios could then be compared across a multi-species farm and evaluate the costings and environmental footprint of reducing RRs in the dairy system on meat production and earnings received from beef to limit trade-offs on the beef sector

7.3.2 Replacement Rates

The RR scenario encouraged increasing the LPL of dairy cattle, which requires further research before implementation, to ensure milk production and profitability are not impacted (Grandl *et al.*, 2019). A higher parity lowers BCS, mobility and increases the BW of cattle (Margerison and Geoghegan, 2022) and should not be amplified past a healthy amount. Further research should also investigate the difference in heifer management on GHGe, such as whether they are reared on farm or sold. Heifer management had a significant impact in previous research (Weiske *et al.*, 2006), having a larger impact than the 10% difference in RR. Future research should assess whether heifer management still has such a large impact on GHGe.

7.3.3 Protein Alternatives

It is important that the prediction equations are evaluated against a large dataset of feed and cattle, including the new diversified dairy diets and proteins in direct measurement systems, such as the respiration chamber, to check their representability. Future research should assess more sources of protein, such as vetches and different combinations of proteins in a dairy cattle diet. The nutrition values for each dietary component in the FIM database should also be updated to reflect current nutritional quality (Thomas, 2004). In addition to different species of protein sources, such as pea varieties, on milk production, quality, nutrition and GHGe. Including substitutions from RS to complete the dairy diets, to improve biodiversity in potential feed. In addition to investigating the impact of forage and fat content of the protein alternative diets on GHGe, milk production and quality. Research could develop new equations that represent the new diversity in diets in the UK. Dietary N content could also be incorporated into the equation to ensure there are no trade-offs between various GHGe and this can be used to estimate the dietary impact on manure emissions.

7.3.4 Climate Change Resistant Crops

Global warming is changing the climate of the country, impacting rainfall and temperatures, which could impact the plants suited to grow in the UK and therefore the feed we are able to produce and feed to cattle. Thus, it would be beneficial for research to investigate which crops for feed, mixed cropping species and cattle breeds will be most suitable for the changing climate to ensure future food security and assess their environmental impact.

7.3.5 Land Availability

Further research should also assess land availability in the UK and the proportions that can be reasonably designated for forestry, without impacting current and forecasted livestock and human feed demands. In addition to whether there is the necessary available land to become

self-sufficient in the UK, to reliably increase food security and grow feed on-farm to reduce feeding costs, such as purchased forage (AHDB, 2020a). Further research into feeding livestock tree branches, such as willow trees (Agrecalc, 2024a), could also help reduce land demand for feed, EME and increase forestry targets. Incentives also need to be managed and adjusted where needed to ensure forestry is not prioritised over food production to maintain food security. In addition to the CS potential of silvopastoral systems and the possibility of cattle grazing in woodlands. The achievability of these systems would increase the amount of land available for woodland and CS, without restricting the production system of the farm.

7.3.6 Feed Additives

Now 3-NOP has been approved for usage in the UK (FSA, 2023), research should evaluate public opinion on consuming milk from cattle fed methane reducing additives. Whether the public would purchase the milk or have concerns over the safety or quality of the milk. In addition to whether farmers would worry about the health of the cattle or milk production and invest in 3-NOP and the subsidies required to improve cost-effectiveness of the strategy. Further research is also required on the most practical methods for incorporating additives into pasture-based systems.

The model could be adapted to include feed additives to assess the emissions associated with their production and enteric CH_4, such as 3-NOP, seaweed, and nitrates. However, future research should conduct in-vivo studies on the effect of multiple dietary mitigation strategies when used together, to assess the safety of mixing methods on livestock health (Arndt *et al.*, 2021). The model could then simulate the various methods and quantities of the additives within the safe proportions tested, with the dietary strategies currently known, such as increased starch content. The studies could also test the mitigation measures such as 3-NOP longitudinally, as the longest specified study was 146 days (Romero-Perez *et al.*, 2015). The

studies need to assess 3-NOP reduces EME overtime, such as a full lactation of an average 315 days for UK dairy systems (AHDB, 2021c).

7.3.7 A Full Life Cycle Analysis

Further research should expand the scope of the project and assess the emissions of a complete LCA of dairy milk. An enlarged scope would include emissions from bedding, and past the farm gate, such as transportation, storage, and waste treatment to gain an accurate figure of total emissions associated with milk. The total required CO_2e required to be offset could then be calculated for the complete LCA, as a larger proportion of land may need to be converted to woodland to achieve Net Zero dairy milk. A larger scope would also allow analysis of how emissions can be reduced past the farm gate and increase the potential to reduce emissions associated with the product.

7.3.8 Multiple Farms

The current study was based on a representable UK farm due to limited available data, however, farms across the UK are very high in diversity and future research should include multiple baseline farms. Previous research has highlighted the differences efficiency can have on GHGe of farms and the effectiveness of mitigation measures (Van Middelaar *et al.*, 2015). Therefore, future research should include a larger range of management systems and baseline farms in the UK, to accurately account for the reductions in UK dairy farm CO_2e emissions. The range of management systems would include pasture-based systems, where the emissions from manure management could be analysed and the feasibility, labour requirements, costs of feed additives and CS of silvopastoral systems with livestock in woodlands. Multiple manure management systems could be compared to establish whether Net Zero can be reached with AD and with cattle on pasture. The time length on pasture could be assessed, to establish the length of time cattle could graze on pasture to still reach Net Zero and provide sufficient manure for AD, as a mixed system.

7.3.9 The Wider Environmental Impacts

The current project focussed on the impact of the dairy industry on climate change, although, other areas such as eutrophication were mentioned, there was not the opportunity to examine this in detail. There are several environmental impacts to investigate, such as biodiversity, eutrophication, acidification, ecotoxicity, photochemical ozone formation, land use, particulate matter, and resource depletion, such as fossil fuel and water usage. Future studies should assess the mentioned areas in detail, to give a holistic view of the impacts of the industry to ensure there are no negative trade-offs when implementing a strategy. The model could be expanded to include biodiversity by using similar systems to SIM_{SCORE} in the $SIMS_{DAIRY}$ model (Del Prado *et al.*, 2011). The popularity and credibility of the GWP factors should also be considered and updated to those recommended in the future, such as GWP*.

The water footprint was not analysed in the current study; however, water scarcity could be a larger issue and higher priority when the model is applied elsewhere. The default emissions and parameters used in the model, such as temperature can be modified to be applied to other areas across the globe, to suit their climate and production systems. The REMEDY model should be used in future research to assess production systems outside the UK and if conducted, it could also be useful to include the water footprint of the system. The model could then be utilised to ensure any changes in management system would not negatively impact the water footprint of the industry.

Research has highlighted a need for increased awareness to farmers for reaching Net Zero, this could include workshops, virtual and in-person events and conferences, as well as through newsletters such as the NFU, to support farmers in their journey to Net Zero.

7.4 Overall conclusions

The REMEDY simulation model developed at the University of Nottingham accurately represented GHGe for UK dairy farms. The combined equation used in the model, acted as a suitable compromise for predicting EME from dairy cattle based on current literature, based on dietary variables ME and NDF. It is presumed that research will continue, and the equations used in the model will be updated for those most suitable, as diets diversify and as the literature develops.

The research recommended a ‘sweet spot’ for RRs to limit GHGe without compromising milk production. A guideline of 22% was advised based on the represented farm, however, the most suitable RR must be tailored to the individual farm. The LPL could be further investigated to examine the extent to which the RR can be reduced, and LPL increased without impacting the welfare of cattle, such as BCS, BW and the milk productivity of the cow.

Protein alternatives to SBM were also investigated and had a larger potential to reduce total farm GHGe than RRs. SBM should be phased out, as it had the largest CF of the proteins investigated and even larger when linked to deforestation. Peas without soya hulls were determined as the optimum protein source for lowering emissions. Further research should investigate a variety of species on the rumen microbiome, milk production and GHGe. RSM was used as the substitute for SBM to maintain energy and milk production, however, further substitutes should be investigated, as RSM can be unpredictable, and a polyculture of crops should be grown.

The current project highlighted that Net Zero is possible for UK dairy farms, but not by the NFU 2040 goal. It is more likely that UK farms will reach the UK Government 2050 Net Zero target. The study highlighted the requirement for offsetting through woodland to reach

Net Zero. However, it is important the cause of climate change is addressed rather than the symptoms, by reducing emissions as much as possible, in addition to offsetting emissions. The study showed the large variation between tree species and CS potential, however, a mixture of species was advised to limit pest and climate change resistance, as well as promote biodiversity of flora and wildlife habitats. In addition to a mixture of protein sources and mixed cropping systems to promote healthy and fertile soils. Future research should investigate the potential of silvopastoral systems to offset GHGe and cattle in woodlands to allow for a variety of production systems.

Introducing mitigation strategies that reduce GHGe will help to limit the frequency of extreme weather events and their impact. Otherwise with expected increased population (FAO, 2015) and GHGe to rise, events such as floods, the devastating effects and the economic damage followed will only increase. The study showed a variety of potential strategies to reduce GHGe from altering RRs, protein in feed, adopting AD, feed additives and increasing the efficiency of lactating cows. The results demonstrate the potential strategies for farmers to investigate and trial to reduce their CF.

It is important that the strategies are disseminated to increase education on how to reduce dairy farm emissions, as we work towards Net Zero. In addition to legislation and subsidies to incentivise their implementation and cost effectiveness. Feed additive 3-NOP was recently approved for usage in the UK and will be an additional expense to UK farmers. It is important that economic subsidies are implemented to encourage the uptake of 3-NOP in UK farms. AD is also an expensive mitigation strategy, which was not required for the typical dairy farm to reach Net Zero, however, it should be encouraged as a renewable energy source and to limit leakage and pollution from manure management.

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9 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	Diet description	MEI	CP (%)	FA (%)	EE (%)	NDF (%)	ADF (%)	Forage (%)
1	Low input and output grazing ration	202.3	18.08	3.41	4.32	46.11	37.81	81.89
2	Organic moderate output farm TMR with grazing	262.6	15.6	4.33	4.14	34.87	28.59	69.2
3	High input and output TMR	271.7	17.98	3.56	4.12	32.78	26.88	53.36
4	High input and output herd TMR	125.3	13.97	1.73	3.41	52.5	43.05	81.44
5	Transition cow high input and output TMR	136.5	12.58	1.58	2.74	49.16	40.31	73.86
6	VMS high output TMR	268.9	16.05	3.74	4.7	35.15	28.82	50.51
7	Autumn calver, moderate input and output TMR	255.2	17.43	3.91	4.07	35.47	29.09	57.69
8	Grazing and average dairy compound feed	222.3	19.25	0	5.1	38.85	31.86	50
9	Grazing and high NDF dairy compound feed	207	16.95	0	4.55	43.85	36	50

11	Big bale grass silage and high NDF dairy compound feed	196.2	15.2	2.5	5.45	45	36.9	50
12	Grass silage and high NDF dairy compound feed	203.4	19.75	4.5	5.65	38.05	31.20	50
13	Grass silage and average dairy compound feed	218.7	22.05	4.5	6.2	33.05	27.10	50
15	High acid grass silage and high NDF dairy compound feed	207	16.2	7.5	5.85	37.5	30.75	50
16	Low acid grass silage and average dairy compound feed	222.3	18.5	3	6.4	32.5	26.65	50
18	Poor grass silage and average dairy compound feed	210.6	17.4	3.5	6	37.25	30.55	50