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Strategies to reach zero carbon beef and sheep production on Welsh farms

McNicol, Louise

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Strategies to reach zero carbon beef and sheep production on Welsh farms

Louise Caitlyn McNicol

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Prifysgol Bangor University

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Author Name	Louise Caitlyn McNicol
Title	Strategies to reach zero carbon beef and sheep production on Welsh farms
Supervisor/Department	Dr A Prysor Williams (School of Environmental & Natural Sciences) Prof Dave Chadwick (School of Environmental & Natural Sciences) Dr David Styles (University of Galway) Prof Robert M Rees (Scotland's Rural College)
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Declaration

I hereby declare that this thesis is the results of my own investigations, except where otherwise stated. All other sources are acknowledged by bibliographic references. This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree unless, as agreed by the University, for approved dual awards.

Yr wyf drwy hyn yn datgan mai canlyniad fy ymchwil fy hun yw’r thesis hwn, ac eithrio lle nodir yn wahanol. Caiff ffynonellau eraill eu cydnabod gan droednodiadau yn rhoi cyfeiriadau eglur. Nid yw sylwedd y gwaith hwn wedi cael ei dderbyn o’r blaen ar gyfer unrhyw radd, ac nid yw’n cael ei gyflwyno ar yr un pryd mewn ymgeisiaeth am unrhyw radd oni bai ei fod, fel y cytunwyd gan y Brifysgol, am gymwysterau deuol cymeradwy.

Executive summary

In 2019, the UK was the first country to legislate the Net Zero target for greenhouse gas (GHG) emissions by 2050. To achieve this target, the Committee on Climate Change have recommended a 64% reduction in gross GHG emissions from the agriculture and land-use sector. This thesis aimed to explore strategies to reach Net Zero on Welsh beef and sheep farms.

In order to assess the effects of various GHG mitigation measures, farms must first accurately quantify their current level of emissions. There are many carbon calculators available for use on beef and sheep farms. A comparison of two of the most widely used calculators in the UK – Agrecalc and the Farm Carbon Calculator, and Bangor University's own carbon footprinting revealed the tools produced notably different emission and sequestration estimates for the same 20 farms. Therefore, while the results from different carbon calculators are not directly comparable, utilising these tools independently remains valuable for benchmarking within and between farms.

There are many mitigation and sequestration options available for farms to reduce net GHG emissions, all with varying abatement potentials and cost-effectiveness. A range of mitigation measures and afforestation were modelled on real farms to create Net Zero scenarios. Modelling work demonstrated the most efficient farms in term of emission intensities, often had the highest total emissions due to higher livestock numbers. This presents a significant challenge as although food production must be increased to feed a growing population, these increase must be made sustainability to avoid increasing net GHG emissions. Our modelling showed mitigation alone was not sufficient to achieve Net Zero at a farm level and therefore an increase in carbon sequestration (through afforestation) was required. However, care must be taken to ensure this afforestation does not displace production to less efficient systems and increase emissions overall.

With more farms changing their management practices to reduce GHG emissions, it is important now more than ever that emissions are calculated and expressed correctly. Using omega-3 as a functional unit, we demonstrated the importance of considering nutrition when expressing the carbon footprints of lambs on different finishing diets. When a mass-based functional unit was employed, the grass only finishing diet had the highest average carbon footprint, whereas when omega-3 PUFA content was accounted for, the grass diet had the lowest carbon footprint for the *longissimus dorsi* muscle cut.

Despite the range of mitigation measures available for farms to reduce their emissions, Net Zero will never be achieved unless farmers adopt these measures. Our survey highlighted many socio-economic barriers to achieving Net Zero on beef and sheep farms. For example, the majority of farmers were not aware of any additional benefits of the GHG mitigation measures listed even though most of the measures would increase production efficiencies and represent "win-win" scenarios. Moreover, the level of adoption reported in the survey would notably reduce the maximum technical abatement potential of many mitigation measures calculated in the previous modelling work. Improving uptake of GHG mitigation measures will likely require a combination of economic incentives, targeted regulation, and information provision based on individual measures to overcome these barriers.

Overall, this work highlighted the different challenges and opportunities facing the agriculture industry in meeting the Net Zero target. It also demonstrated the complexity of calculating and quantifying GHG emissions in relation to policy targets. In this thesis, Net Zero was explored at a farm level, however, Net Zero is not a farm-level target but a national-level target. Therefore, future studies should model land use that could deliver Net Zero in the Agriculture, Forestry and Other Land Use Sector at a national scale.

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Authorship Information

Two of the chapters presented in this thesis have been prepared for publication and are currently under review or published in peer reviewed journals as multi-author papers. Using the CRediT author statement system, the following describes the contribution of each author to the work.

Chapter 4 has been published in the peer reviewed journal Agricultural Systems as:

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Louise C. McNicol – Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft

Non G. Williams – Investigation, Writing – review & editing

David R. Chadwick – Conceptualization, Supervision, Writing – review & editing

David Styles – Conceptualization, Supervision, Writing – review & editing

Robert M. Rees – Conceptualization, Supervision, Writing – review & editing

Rachael Ramsey – Writing – review & editing

A. Prysor Williams – Supervision, Writing – review & editing

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Louise C. McNicol - Data curation, Formal analysis, Visualization, Writing – original draft

Lynda S. Perkins – Data curation, Project administration, Writing – original draft

James M. Gibbons - Formal analysis, Writing – review & editing

Anne P. Nugent - Writing – review & editing

Nigel D. Scollan – Funding acquisition, Supervision, Writing – review & editing

Eleri M. Thomas – Conceptualization, Investigation, Supervision

Elizabeth L. Swancott – Conceptualization, Investigation, Data curation

Colin McRoberts – Investigation, resources

Alison White – Investigation, resources

Simon Chambers - Investigation, resources

Linda Farmer – Conceptualization, Writing – review & editing

A. Prysor Williams – Supervision, Writing – review & editing

We also intend to publish **Chapter 6** in a peer-reviewed journal, however, the specific journal has yet to be selected.

McNicol, L.C., Wynne-Jones, S., Chadwick, D., Styles, D., Rees, R.M. and Williams, A.P. (In prep). Barriers and opportunities to achieving Net Zero on UK beef and sheep farms.

Louise C. McNicol – Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft

Sophie Wynne-Jones – Conceptualization, Methodology, Writing – review & editing

David R. Chadwick – Conceptualization, Supervision, Writing – review & editing

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A. Prysor Williams – Supervision, Writing – review & editing

Abbreviations

3NOP	3-Nitrooxypropanol
AFOLU	Agriculture, Forestry and Other Land Use
AN	Ammonium Nitrate
ANOVA	Analysis of Variance
AR	Assessment report
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Department for Business, Energy & Industrial Strategy
BPS	Basic Payment Scheme
C	Carbon
CAP	Common Agricultural Policy
CCC	Climate Change Committee
CFT	Cool Farm Tool
CH_4	Methane
CO_2	Carbon dioxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
DA	Disadvantaged Area
DACCS	Direct Air Capture and Carbon Storage
DEFRA	Department for Environment Food and Rural Affairs
DIAAS	Digestible Indispensable Amino Acid Score
DM	Dry Matter
dwt	Deadweight
EDS	Ecosystem Disservices
EF	Emission factor
EI	Emissions Intensity
ES	Ecosystem Services
FAME	Fatty Acid Methyl Ester
FAO	Food and Agriculture Organisation
FCC	Farm Carbon Calculator

FU	Functional unit
GHG	Greenhouse gas
GLM	Generalised Linear Mixed Model
GWP	Global warming potential
H_2	Hydrogen
HCC	Hybu Cig Cymru – Meat Promotions Wales
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
KO	Killing Out
KOH	Potassium Hydroxide
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LFA	Less Favoured Area
lwt	Liveweight
MACC	Marginal Abatement Cost Curve
MO	Mitigation Options
MUFA	Monounsaturated Fatty Acid
N	Nitrogen
N_2O	Nitrous oxide
NDS	Nutrient Density Score
NFU	National Farmers Union
NH_3	Ammonia
NI	Nitrification Inhibitor
NVZ	Nitrogen Vulnerable Zone
OM	Organic Matter
PB	Planetary Boundaries
PES	Payment for Ecosystem Services
PF	Precision Feeding
PGI	Protected Geographical Indication
PLF	Precision Livestock Farming
PUFA	Polyunsaturated Fatty Acid

SDA	Severely Disadvantaged Area
SFA	Saturated Fatty Acid
SFI	Sustainable Farming Incentive
SFI	Sustainable Farming Incentives
SRUC	Scotland’s Rural College
TAG	Triglycerides
UNFCCC	United Nations Framework Convention on Climate Change
VFA	Volatile Fatty Acids
WCC	Woodland Carbon Code

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Chapter 1 General introduction

1.1. Rationale

The effects of climate change are already being felt around the world. Extreme weather events are becoming more frequent and severe as global temperatures rise (IPCC, 2021). Rising temperatures have been undeniably driven by increasing anthropogenic greenhouse gas (GHG) emissions. Agriculture is a significant contributor to these anthropogenic GHG emissions. In 2020, the UK emitted a total of 478 million tonnes of carbon dioxide equivalent (CO_2e) gases (BEIS, 2022). It is estimated agriculture accounted for roughly 11% of these emissions as well as accounting for 48% of the UK's total methane (CH_4) emissions and 69% of total nitrous oxide (N_2O) emissions (DEFRA, 2022). A large proportion of these emissions come from livestock production systems, particularly CH_4 produced by enteric fermentation of ruminant animals (DEFRA, 2022). Nitrous oxide also contributes substantially to livestock emissions, with the majority of N_2O released from soils following urine and dung deposition by grazing livestock, manure application or synthetic N fertiliser application (Cardenas *et al.*, 2010; Chadwick *et al.*, 2018).

In 2015, the Paris Agreement was established – a legally binding international treaty to reduce global GHG emissions to a point that limited the increase in global temperature to well below 2°C (BEIS, 2022). Under the Paris Agreement, in 2019 the UK government amended the Climate Change Act 2008 to set a target of Net Zero GHG emissions by 2050. The Net Zero target refers to the government's legal commitment to reduce GHG emissions in the UK by 100% from 1990 levels by 2050 (Climate Change Committee, 2019). The agricultural sector will have to make significant efforts to reduce its emissions if the Net Zero target is to be met. However, with the global population projected to exceed 9.7 billion by 2050 (United Nations, 2022), it is estimated food production will have to increase by almost 50% from 2012 levels to meet future needs (FAO, 2018). Therefore, any increases in food production must be done sustainably to avoid further increases in GHG emissions.

In Wales, red meat accounts for 42% of total agricultural output (Welsh Government, 2023). It is estimated there was a total of 4.8 million sheep (over 1 year old) and 159,550 beef cows (over 2 years old) in Wales in 2021 (HCC, 2022) which will all contribute significantly to the country's total GHG emissions. However, the red meat sector in Wales is worth an estimated £744 million (DEFRA, 2021), producing 48,700 of lamb and 40,300 tonnes of beef in 2021 (HCC, 2022). The sector plays a vital role in providing rural employment (Armstrong, 2016), maintaining Welsh landscapes and delivering a number of ecosystem services (Zhao *et al.*, 2020), therefore, attempts to reduce GHG emissions from livestock systems in Wales should consider these wider implications.

The Committee on Climate Change (CCC) has advised a 64% reduction in GHG emissions from the agriculture and land-use sector in the UK if the Net Zero target is to be met, and whilst there is not a specific target for livestock, it is thought that a target similar to the wider sector is appropriate (CCC 2020). However, reducing GHG emissions from livestock production has natural limits due to the biological processes involved in enteric fermentation (FAO, 2013). Therefore, achieving Net Zero in the agricultural sector will only be possible by offsetting residual emissions though carbon sequestration, namely afforestation (Stark *et al.*, 2019). To meet the “balanced pathway” set out by the UK Climate Change Commission, the Welsh Government aims to plant 180,000 ha of trees by 2050 (Welsh Government, 2021). To deliver this additional woodland, it is estimated land use change equivalent to roughly 10% of agricultural land in Wales will be required (Welsh Government, 2021).

In order to move towards Net Zero, farms must first quantify their current level of GHG emissions. The biological emissions mentioned above not only make GHG emissions from agriculture hard to reduce but they also make them hard to quantify, resulting in a high level of uncertainty in farm GHG emission estimates (Rees *et al.*, 2020). There are many carbon accounting tools available to estimate whole farm GHG emissions. These tools vary notably in their input requirements and GHG emission and sequestration estimates (Sykes *et al.*, 2017; Taft *et al.*, 2018). Nonetheless, quantifying GHG emissions is an important first step towards meeting environmental targets, therefore, it is fundamental that we better understand these tools and their differences.

The metrics and functional units (FU) used to express emissions can also significantly impact the resulting carbon footprint. Recently, standard mass-based FU (e.g. kg of liveweight or kg of deadweight) have been criticised as they do not account for the nutritional quality of meat (McAuliffe *et al.*, 2023; McLaren, 2021). Using nutrient-based functional units (e.g. g of protein or protein quality) can markedly reduce the carbon footprint of meat compared to other foods than when using a mass-based FUs (Poore and Nemecek, 2018; Xu *et al.*, 2018). Although previous studies have used different FUs to compare specific foods and diets, few have compared the use of different FUs to compare different farming systems. This could be increasingly important as a growing number of farmers change their management practices to reduce GHG emissions.

There are many GHG mitigation and sequestration measures available to farmers to help them move towards Net Zero. These include measures that improve animal productivity, target nitrogen fertiliser use, use feed additives and improve manure management. Many of these represent “win-win” scenarios whereby they increase production efficiencies as well as reduce GHG emissions. Despite many of these measures making economic sense, their uptake remains low in the beef and sheep sector due to a number of other barriers affecting farmers’ behaviour (Bustamante *et al.*, 2014; Hallam *et al.*, 2012; Smith and Olesen, 2010). To achieve Net Zero, it is fundamental we understand these barriers to implementation in order to determine the most effective mechanism(s) to improve uptake. Regardless of any increases in the uptake of these measures, mitigation alone will not be enough to achieve Net Zero. Afforestation on farms will likely play a key role in offsetting residual emissions. However, this must be done in a strategic way (e.g. "the right tree in the right place") to avoid a loss of food production. If poorly planned, afforestation could lead to unintended consequences such as displacing food production to less efficient systems which could increase emissions overall.

Major innovation and changes are needed to Welsh farming systems if the Net Zero target is to be met. The sector must make significant efforts to reduce its emissions as well as offset residual emissions; however, it is not clear what this could look like in practice - at a farm level. There are many GHG mitigation and sequestration options that could help farmers move towards Net Zero, but these measures have not yet been fully explored, particularly in a Welsh context. To assess the effect of these measures, it is essential to first calculate an accurate baseline footprint. Modelling mitigation scenarios on farms could highlight the potential opportunities available for farmers to reduce their emissions. However, this modelling does not account for the true uptake of these measures, therefore, further research is needed to overcome any socio-economic barriers to implementation.

1.2. Aims and objectives

The overarching aim of this work was to assess the opportunities available for Welsh beef and sheep farms to achieve Net Zero as well as gain a better understanding of where these farms are currently in terms of emissions. The objectives of this thesis were therefore to:

1. Evaluate the existing literature surrounding GHG emissions and Net Zero in beef and sheep production systems.
2. Assess the variation in GHG emission and sequestration estimates of three widely used carbon calculators for application on Welsh beef and sheep farms.
3. Explore the opportunities currently available to reduce GHG emissions and enhance sequestration on Welsh beef and sheep farms.
4. Investigate the barriers to achieving Net Zero and assess how to improve the uptake of GHG mitigation and sequestration measures on farms.
5. Evaluate the impact of using nutrition-based functional units on the carbon footprint of lambs on different production systems, namely finishing diet.

1.3. Chapter outline

This general introduction and discussion in Chapter 8 aim to link the various independent (but interconnected) pieces of work within each chapter to meet the thesis objectives listed above (Figure 1.1).

Chapter 2 is a review of existing literature on GHG emissions from livestock systems, how they are measured and potential pathways to achieving Net Zero beef and sheep production. This chapter provides an overview of the GHG mitigation measures and sequestration measures currently available to farmers and touches on current and future policy implications.

Chapter 3 evaluates three widely used carbon calculators for application on Welsh beef and sheep farms. This chapter highlights the variation in GHG emissions estimates, sequestration estimates and sensitivity to mitigation options between three tools: Agrecalc, the Farm Carbon Calculator and Bangor University's own Carbon Footprinting Tool.

Chapter 4 uses real data from 20 farms to explore potential pathways towards Net Zero on beef and sheep farms in Wales. Scenarios were created to determine the emission reductions possible when a range of mitigation measures were implemented on each farm and the area of woodland needed to offset the residual emissions from each farm was calculated. These findings highlight the different challenges and opportunities the industry faces if it is to achieve this target.

Chapter 5 investigates the barriers and opportunities to achieving Net Zero on UK beef and sheep farms. This chapter identifies factors farmers feel influence their uptake of GHG mitigation and sequestration options and assesses how these barriers can be overcome to increase adoption rates. The maximum technical abatement potential of each GHG mitigation measure calculated in the previous chapter are then compared to the measure's actual abatement potential (abatement potential which considers current and future uptake of each measure).

Chapter 6 evaluates the effect of using different functional units on the carbon footprint on lambs on different finishing systems. This chapter compares the carbon footprint expressed with the use of a traditional mass-based functional unit (kg CO_2e/kg of deadweight (dwt)) and a nutrition-based functional unit (kg CO_2e/g omega-3) for 444 carcases from 33 farms on one of four distinct diets: forage crops, grass, concentrates, and grass and concentrates.

Chapter 7 summarises the generated results and discusses the wider implications of the findings. This general discussion also highlights limitations of the presented work as well as identifying areas for future research.

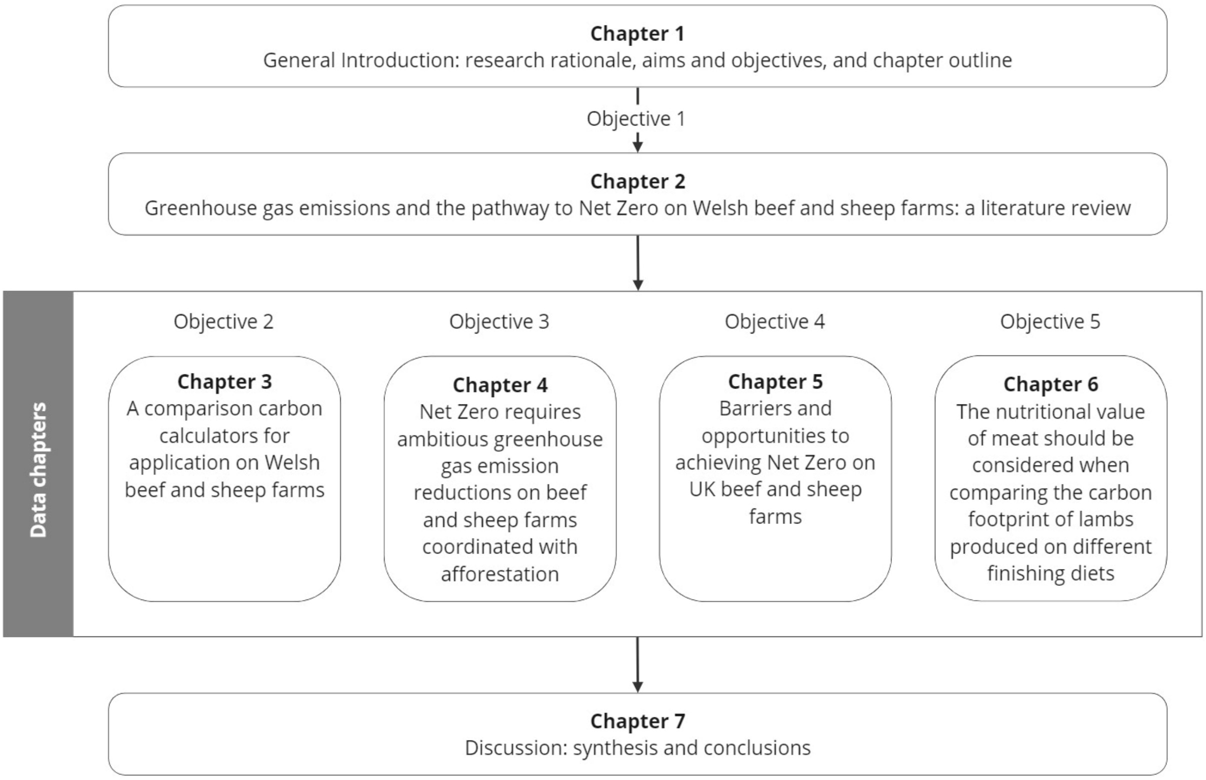


Figure 1.1. Thesis flowchart illustrating how the different chapters meet each thesis objective.

Table 1.1. Publication status of each data chapter and the journals in which they have been published.

Chapter	Publication status	Journal
A comparison of carbon calculators for application on Welsh beef and sheep farms	In preparation	TBD
Net Zero requires ambitious greenhouse gas emission reductions on beef and sheep farms coordinated with afforestation	Published	Agricultural Systems
Barriers and opportunities to achieving Net Zero on UK beef and sheep farms	In preperation	TBD
The nutritional value of meat should be considered when comparing the carbon footprint of lambs produced on different finishing diets	Published	Frontiers in Sustainable Food Systems

Chapter 2 Greenhouse gas emissions and the pathway to Net Zero on Welsh beef and sheep farms: a literature review

2.1. Background

2.1.1. The red meat sector in Wales

Red meat production is one of the biggest agricultural sectors in the UK, accounting for approximately 23% of agricultural production by value (DEFRA, 2023a). The UK is the world's sixth largest producer of sheep meat (Colby, 2015), producing 275,800 tonnes of lamb and mutton in 2022 as well as 906,400 tonnes of beef (DEFRA, 2023b). In 2020, the UK was estimated to be 110% self-sufficient in sheep and lamb and 86% self-sufficient in beef and veal (DEFRA, 2021).

In Wales, red meat accounts for 42% of total agricultural production by value, almost double the figure for the rest of the UK (Welsh Government, 2023a). In 2021, Welsh Government (2022) estimated a total of 4.8 million sheep and 159,550 beef cows in Wales, generating 48,700 tonnes of lamb and 40,300 tonnes of beef. Welsh red meat production was worth an estimated £744 million in 2020 (DEFRA, 2021), playing a vital role in supporting rural communities, maintaining Welsh landscapes and providing other cultural and wellbeing benefits.

2.1.2. Agriculture and Planetary Boundaries

Over recent years, livestock systems have been under increasing pressure both economically and environmentally. Agriculture can impact on the environment in a number of ways, for example, land use change, greenhouse gas and ammonia emissions, water quality and biodiversity (Campbell *et al.*, 2017). Research suggests the Earth is entering the 'Anthropocene' – an era in which human activities significantly impact the Earth System's functioning (Crutzen, 2006). Rockström *et al.* (2009) introduced the concept of "planetary boundaries" (PBs). PBs are intended to represent Earth System processes and quantify a boundary for each process that should not be surpassed to avoid unacceptable global environmental change. The PB framework was recently revised by Richardson *et al.* (2023) who concluded six out of the nine PBs assessed have been transgressed. Agriculture affects almost all of these PBs. Biosphere integrity and biochemical flows are at high risk, and agriculture has been a major driver in this (Campbell *et al.*, 2017). Agriculture has also been a driver of three zones of uncertainty (increasing risk): land system change, freshwater use and climate change. Mainly through the use of nitrogen fertilisers, agriculture also affects areas that are considered to be in the "safe" zone such as ocean acidification, stratospheric ozone depletion and atmospheric aerosol loading (Richardson *et al.*, 2023).

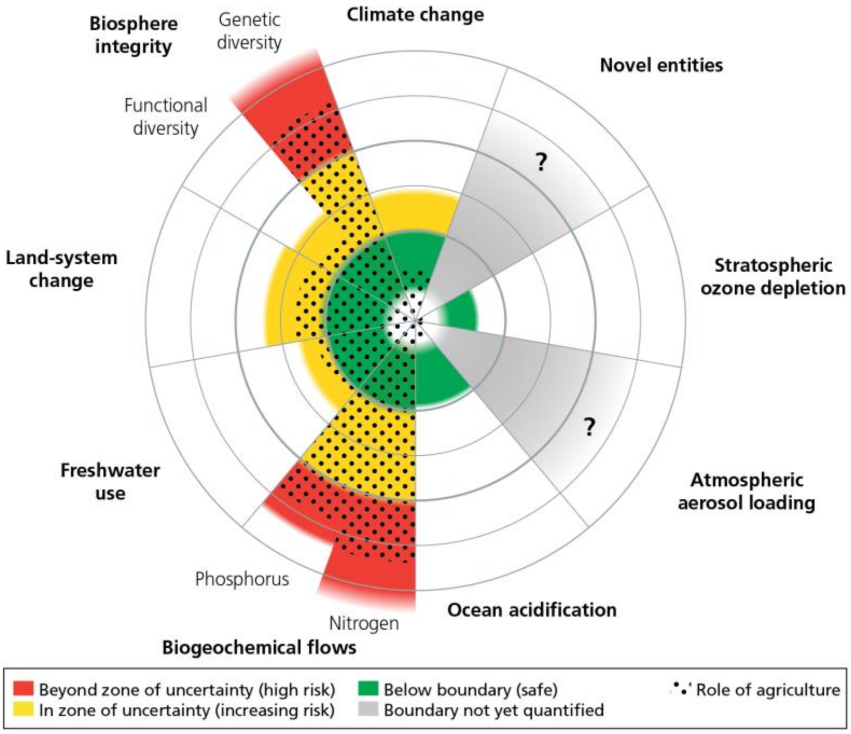


Figure 2-1. The status of the nine planetary boundaries (PBs; green, yellow, red) overlaid with our estimate of agriculture's role in that status. PBs based on Steffen *et al.* (2015), with modification for freshwater from below boundary (safe) into zone of uncertainty (Gerten *et al.*, 2015), and an estimate for functional diversity based on (Newbold *et al.*, 2016) (Campbell *et al.*, 2017).

2.1.3. Greenhouse gas emissions from agriculture

Agriculture contributes around 47 Mt CO_2eq per year to the UK's anthropogenic greenhouse gas (GHG) emissions, equating to 11% of total GHG emissions in 2021 (BEIS, 2021). The largest source of GHG emissions from livestock is methane (CH_4) primarily from the enteric fermentation of ruminant animals, which accounts for roughly 58% of the sectors emissions (BEIS, 2021). Methane is also produced from manure management and deposition of animal excreta on pasture, alongside nitrous oxide (N_2O). Nitrous oxide is emitted from soil following excreta deposition on grazing land, as well as application of manure and synthetic fertiliser, which together represent 28% of the sector's GHG emissions (BEIS, 2021). A relatively small amount of carbon dioxide (CO_2) is also produced by agriculture (14% of total UK GHG emissions) - mainly from land use change, feed and fertiliser production, and energy use.

2.1.3.1. Methane emissions

Methane is the most important GHG emitted from livestock agriculture, not only because it is produced in the highest quantities, but it is also 27 times more potent than CO_2 over a 100-year timeframe (IPCC, 2019). However, the impacts of CH_4 are still under debate (see Section 2.2). The main source of CH_4 on livestock farms is from the enteric fermentation of ruminant animals. Enteric fermentation is a multistep process, which starts with the hydrolysis of dietary polysaccharides into hydrolysable sugars by the enzymatic activity. These hydrolysable sugars are then fermented to volatile fatty acids (VFA) - acetate, propionate, and butyrate that are used for energy. During the process, hydrogen is produced and converted into CH_4 with the help of methanogens (Bhatta and Enishi, 2007). Most CH_4 is released through eructation, with a small proportion released as flatulence. A range of factors affect CH_4 emissions in ruminant animals including feed intake and type, management practices, genetics, health and geographical regions (Thompson and Rowntree, 2020). A small amount of CH_4 is also produced from manure management; the amount of which depends on how manure is stored, for example, manure stored as liquid slurry in a tank will produce more CH_4 due to the anaerobic conditions (Broucek, 2018).

2.1.3.2. Nitrous oxide emissions

Nitrous oxide also accounts for a large proportion of GHG emissions generated by livestock systems. Nitrous oxide is predominantly released from soils following the application of synthetic nitrogen (N) fertiliser (Cardenas *et al.*, 2010), manure applications (Thorman *et al.*, 2020) and urine and dung deposition by grazing livestock (Chadwick *et al.*, 2018a). Sheep and cattle convert organic N in plant biomass to reactive N which is excreted mainly in the urine (Chadwick *et al.*, 2018a). As N intake increase, N excreted in the dung remains relatively constant, whereas N excreted in the urine will increase (Koenig and Beauchemin, 2013). When the N applied to soil is beyond the plants requirement (which is often the case in urine patches), the excess is lost through various soil microbial processes, one resulting in N_2O emissions from nitrification and denitrification (Selbie *et al.*, 2015). Urine patch N loading will depend on the protein content of the sward, livestock type, age and stage of lactation (Selbie *et al.*, 2015).

2.1.4. Other environmental impacts

As well as GHGs, livestock systems have several other environmental impacts. For example, agriculture accounted for 87% of total ammonia emission in the UK in 2021 (DEFRA, 2023c). Ammonia is a gas which is emitted from excreta deposited by grazing animals, manure management and use of urea-based fertilisers (Misselbrook *et al.*, 2023). Ammonia has a negative effect on air and water quality which can then have knock on effect on biodiversity and human health (Guthrie *et al.*, 2018; Wyer *et al.*, 2022). Ammonia causes acidification of ecosystems (Durand *et al.*, 2011) and disrupts the nutrient balance in soils and water sources (Withers *et al.*, 2014).

Another way in which livestock can cause water pollution is through nitrate leaching (Wang and Li, 2019) and phosphorus runoff (Pericherla *et al.*, 2020) from animal excreta and use of fertiliser. This could give rise to eutrophication and negatively impacts aquatic biodiversity (Smolders *et al.*, 2010; Withers *et al.*, 2014).

In grasslands, changes have also occurred due to increased stocking rates. A reduction in grass composition and decline in bird and arthropod species have been reported in upland grazing (Barzan *et al.*, 2021; Wang and Tang, 2019). In the longer term, sheep grazing has also been shown to affect the plant species present with grasses, mosses and liverwort declining and shrubs, sedges and herbs increasing (Milligan *et al.*, 2016). Soil quality can also be affected by grazing animals. Higher stocking rates result in soil degradation leading to greater compaction and erosion (Bengtsson *et al.*, 2019). If cattle grazing is not managed appropriately (e.g. too high a stocking density in wet conditions), the resulting soil compaction can cause a decline in readily-available water for plants as well as drive a decline in soil pore size and total porosity (Houlbrooke and Laurenson, 2013).

However, livestock can also deliver many environmental benefits such as improving soil health and biodiversity. Soil health can be significantly improved by deposition of animal excreta. Manure can fertilise soils to support the growth of grasses or arable crops, which could reduce the need for synthetic fertiliser. This is particularly important with modern arable farming's heavy reliance on synthetic fertilisers. Additionally, livestock grazing can accelerate nutrient cycling by promoting the decomposition of residual aboveground biomass (Teague and Kreuter, 2020). Grazing livestock can also maintain biodiversity and deliver a range of ecosystem services by maintaining habitats such a grasslands, heathland, wood pasture and costal marches for birds, insects, and mammals (Bailey *et al.*, 2019). Grazing controls plant species and alters plant structure to optimise habitats for different species (Nugent *et al.*, 2022). Livestock can also prevent scrub encroachment in sensitive habitats and control certain undesirable species (Laborde and Thompson, 2015)

2.1.5. Carbon sequestration from livestock systems

Unlike other sectors, agriculture has the potential to sequester CO_2 from the atmosphere on a large scale into biomass and soils. Farms in the UK are already likely to be removing significant quantities of

CO_2 from the atmosphere as well as contributing to ecosystem biodiversity by hosting habitat such as hedges, woodlands and permanent pastures. All plants play a vital role in removing CO_2 from the atmosphere via photosynthesis. Plants make carbohydrates, which enter into the soil through their roots, as well as storing some in its leaves and stems. In soil, carbon compounds become organic matter (OM). Soil contains OM from animals, insects, plants and fungi which is decomposed by a vast array of micro-organisms (Khatoon *et al.*, 2017). Around half of all OM is carbon and in this form it is very stable (Lehmann *et al.*, 2020). This can only be released as CO_2 if significant oxidation occurs, for example, cultivation (Rutledge *et al.*, 2014). Agricultural soils can be huge carbon sinks. Soil which is high in OM has improved fertility and structure, generating greater crop yields and increased carbon sequestration (Lal *et al.*, 2015). Globally, soils contain about three times the amount of carbon in vegetation, and twice that in the atmosphere (IPCC, 2000). In Wales, it is estimated that soils store 409 million tonnes of carbon (Detheridge *et al.*, 2014). Livestock play an important role in carbon sequestration from grasslands. Deposition of dung on permanent pasture returns organic carbon to the soil and therefore increases carbon sequestration (Ostle *et al.*, 2009). Manure returns nutrients to the soil and promotes biomass growth and related accumulation of above-ground carbon (Dawson and Smith, 2007). However, studies have found intensive livestock production led to losses in soil carbon (Powlson *et al.*, 2012). Therefore, livestock must be grazed at a suitable level (i.e. the correct number and type of livestock at the appropriate time of the year) to avoid losses in soil carbon.

The C sink saturation effect is widely recognised, indicating that soils under grassland can no longer sequester carbon at previous rates (Smith *et al.,* 2014). This occurs because soil C reaches a new equilibrium following significant changes in land use. These land use changes initially increase soil C sequestration rates, but over time, rates decrease and stabalise. Soil respiration plays a key role in this process. As soil C increases, microbial activity and root respiration also increase, leading to higher CO_2 emissions. This balance between C inputs and outputs ultimately determines the soil's C storage capacity.

2.2. Quantifying greenhouse gas emissions

2.2.1. IPCC greenhouse gas inventory methodologies

To quantify GHG emissions accurately, standardised equations and modelling are essential. Since 1996, the Intergovernmental Panel on Climate Change (IPCC) has published guidelines for countries to report GHG emissions to the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (IPCC, 2019). Inventory reporting in the Land Use, Land Use Change and Forestry (LULUCF) sector covers all GHG emissions and removals from both maintaining and converting land.

The LULUCF sector differs from other sectors as it includes both GHG sources and sinks. The sources - gross CO_2 emissions and sinks - CO_2 removals/sequestration (the process of storing C in pools), with net GHG emissions equalling gross CO_2 emissions minus CO_2 removals. The IPCC have classified methodical approaches in three different Tiers relating to the degree of complexity of emission factors and information available as ruminant production systems vary hugely in terms of management practices, breeds, feeds, geographic location and environmental conditions (IPCC, 2019).

A simple Tier 1 approach is sufficient for initial estimations in most regions. Tier 1 employs a gain-loss method and uses default emission factors (EF) provided by the IPCC. Tier 1 uses fixed methane EFs per head of livestock so requires only the number of animals per cohort for calculation, however, this may lead to some simplifying assumptions about carbon pools. IPCC Tier 1 methodologies may also be combined with spatial activity data from remote sensing (IPCC, 2019).

The IPCC Tier 2 approach uses similar methodology as Tier 1; however, it is more detailed and uses country-specific EFs. For land use, Tier 2 uses EFs which are more appropriate to the soils, forests, climatic regions and land use systems in that country. Similarly with livestock, Tier 2 EFs relate more to the breeds, herd structure and feeds used in that country. More stratified activity data such as yields, feed quantity and feed characteristics are needed for the Tier 2 approach. Using subcategories of livestock allows a better reflection on actual production conditions and their impact on GHG (IPCC, 2019).

Tier 1 and 2 are used to estimate larger areas such as continents and nations, whereas Tier 3 is often applied on restricted areas (Marino *et al.*, 2016). Tier 3 uses higher-order methods like models and can utilise plot data to address site specific circumstances in climate, soil, livestock and management. If implemented correctly, Tier 3 estimates provide a higher certainty than lower Tiers and can also provide a closer link between biomass and soil carbon dynamics (IPCC, 2019).

2.2.2. Global warming metrics

The IPCC reports all GHGs as CO_2 equivalent (CO_2e) using a metric known as Global Warming Potential (GWP). GWP is a relative measure of how much heat, relative to CO_2, a GHG traps in the atmosphere. GWP is expressed over 100 years so to convert a non-CO_2 gas, it is multiplied by its gas specific GWP_{100} factor. For CH_4, the value of GWP_{100} is 27 and for N_2O the value is 273 (IPCC, 2021), however, this can vary depending on which assessment report GWP values are taken from (Table 2.1). GWP_{100} gives globally applicable values that are easy to communicate and understand, but modelling GHG emissions still involves some uncertainty (Röös *et al.*, 2011).

Although the IPCC (2021) method for calculating GWP from GHG emissions is the international standard and is generally accepted, it has been questioned (Allen *et al.*, 2018; Cain *et al.*, 2019; McAuliffe *et al.*, 2023; Ridoutt and Huang, 2019). Some studies have suggested GWP_{100} misrepresents the impact of short-lived GHGs like CH_4, it masks the fact that although methane has a strong warming influence when it is emitted, it will diminish rapidly over a few decades (Allen *et al.*, 2018; Cain *et al.*, 2019). If CH_4 emissions were held constant, temperature will remain constant because atmospheric concentrations remain unchanged as CH_4 is broken down as quickly as it is emitted. However, stable CO_2 emissions lead to an accumulation of CO_2 in the atmosphere. If methane is treated as CO_2 it would create a warming pathway instead of a stable temperature (Cain *et al.*, 2019). Moreover, if methane emissions were reduced, this would lead to cooling.

A new metric called GWP* relates CH_4's warming potential more closely to its half-life in the atmosphere and expresses emissions as CO_2e, which relates much more closely to temperature response. GWP* relates cumulative CO_2 emissions with the current rate of emissions of shorter lives GHG (Lynch *et al.*, 2020). However, more recently, GWP* itself has been criticised, with some studies highlighting the metric could be unfair to developing countries as it depends on past emissions (Rogelj and Schleussner, 2019). Moreover, although GWP* better represents future warming, GWP_{100} still reflects the average climate potency of GHGs emitted in a given year or from a given process and enables attribution of GHGs, which is the aim of most of its applications.

Global Temperature Change Potential (GTP), is an alternative end-point metric which assesses the relative temperature change over a specified time period, typically 100 years (GTP_{100}). The coefficient for biogenic CH_4 under GTP_{100} is notably lower than under GWP_{100} at 4.7 CO_2e. Although not as significant, GTP_{100} also reports a lower value for N_2O than GWP_{100} at 234 CO_2e (IPCC, 2021). The main advantage of employing GTP_{100} over GWP_{100} is that it is more directly related to surface temperature change (IPCC, 2007). McAuliffe *et al.* (2023) argue using a single impact assessment is insufficient to account for the complexity of how our food systems influence climate change, and recommend utilising a range of metrics.

Table 2.1. Global Warming Potential values for greenhouse gases over 100 years taken from the various IPCC Assessment Reports (AR; IPCC, 2021).

Greenhouse gas	GWP values for 100-year time horizon					
	AR1 1990	AR2 1995	AR3 2001	AR4 2007	AR5 2014	AR6 2021
Carbon dioxide (CO_2)	1	1	1	1	1	1
Methane (CH_4) biogenic	21	21	23	25	28	29.8
Methane (CH_4) fossil						27.2
Nitrous oxide (N_2O)	290	310	296	298	265	273

2.2.3. Life cycle assessments

To quantify GHG emissions at a farm level, a life cycle assessment (LCA) approach can be used. LCAs are frameworks used to calculate the environmental impact of food (Guinée *et al.*, 2011). The emissions and resource use over a product's full lifecycle are measured from production, transportation, use or consumption to its final disposal. The environmental impact is calculated in relation to multiple impact categories. Carbon footprints and GWP are only one impact category in an LCA, alongside others like Acidification potential and Eutrophication potential. These LCAs include all major sources of CH_4, N_2O and CO_2 emissions both on farm and off farm. This means that livestock emissions and fuel combustion on farm are accounted for, but also emissions related to imported feed and associated land use change, as well as fertiliser production. The goal and scope of an LCA provides information of a product system in terms of its system boundaries and functional unit (Silva, 2021). LCA application is subject to international standards defined by the International Organization for Standardization (ISO) which define the requirements and guidelines LCA studies must follow (ISO 14040) (International Organization for Standardization, 2006).

The environmental impact of a product is dependent on the system boundary and allocation method in which it is assessed. For example, with beef and lamb systems the system boundaries tend to be from "cradle to farm gate" meaning all direct and indirect emissions from the animals birth up until the animal leaves the farm are included (Edwards-Jones *et al.*, 2009; Nguyen *et al.*, 2010; Jones *et al.*, 2014; Hietala *et al.*, 2021). This includes upstream emissions from fertiliser, feed and bedding production. With some products, the "cradle to grave" approach is used – this also includes emissions from transportation and slaughter, however, the "cradle to farm gate" system boundary is more appropriate for comparing management practices and efficiencies of different agricultural systems (Figure 2.2). There is currently no standardised evaluation framework for LCA methodologies, however, Goglio *et al.* (2023) defined various criteria such as transparency and reproducibility, completeness, fairness and acceptance, robustness, applicability and accuracy, which could provide a robust framework to assess LCA methodology for livestock systems.

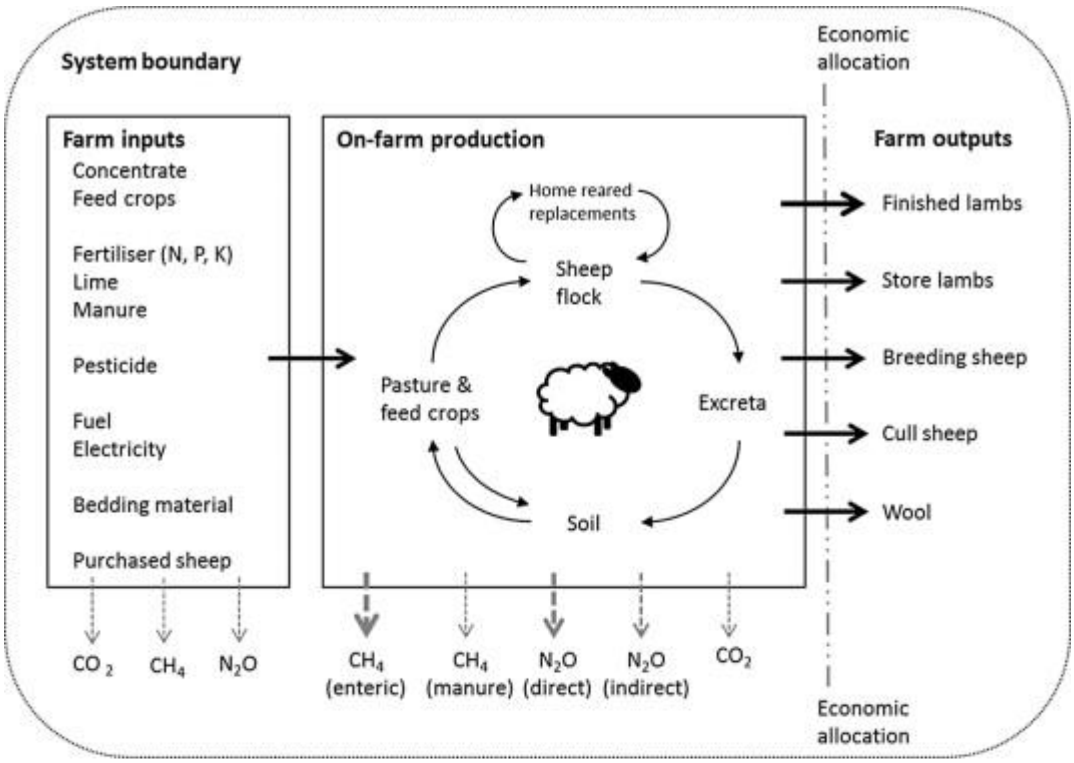


Figure 2.2. Schematic representation of the carbon footprint of a sheep farming system and the cradle to farm gate system boundary (Jones *et al.*, 2014).

2.2.3.1. Functional units

LCA's then express the environmental footprint within these system boundaries in relation to a defined functional unit (FU); for beef and lamb this is typically by mass, for example per kg liveweight (lwt) or per kg deadweight (dwt) (Edwards-Jones *et al.*, 2009; Jones *et al.*, 2014; Ripoll-Bosch *et al.*, 2013). When trying to reduce the environmental impact from agricultural production on a given area of land, results can also be presented on a per hectare basis (Browne *et al.*, 2011; Schils *et al.*, 2007). However, these functional units do not account for the nutritional quality of red meat. Recently there has been a shift from simpler mass and area-based FUs towards more nutritionally driven LCAs (McAuliffe *et al.*, 2020; McLaren, 2021).

LCA studies that consider nutrition can have different degrees oJf complexity. Previous studies have used protein as a FU, which markedly reduces the carbon footprint of meat compared to other foods than when using mass-based FUs (Poore and Nemecek, 2018; Xu *et al.*, 2018). However, this approach could be too simplified, as it does not account for the full nutritive value of meat. Multiple nutrients can be assessed in a single FU. Saarinen *et al.*, (2017) developed a novel nutrient index for protein rich foods to compare their quality. The index included multiple FUs from individual nutrients as well as a novel nutrient score. The study found the choice of FU affected the interpretation of results considerably, for example, beef had the largest GWP using the common mass-based FU, however, this was overtaken by cheese and lamb when a novel nutrient FU designed for protein-rich foods was applied (Saarinen *et al.*, 2017). More novel approaches to LCA involve diet-level assessments that account for a foods' effect on human health. Stylianou *et al.* (2016) developed the Combined Nutritional and Environmental Life Cycle Assessment (CONE-LCA). CONE-LCA uses a traditional LCA approach but predicts health outcomes using epidemiological data based on the nutritional quality of food; such as the work by Stylianou *et al.* (2016), who used a serving of milk as a case study. They showed that although having an additional serving of milk increased GWP, milk consumption was beneficial for long-term health, which outweighed the negatives in three different scenarios in an average US diet (adding a serving of milk with no other dietary changes, adding a serving of milk while subtracting equal caloric quantity from the overall diet and adding a serving of milk while subtracting an equal caloric quantity of sugar-sweetened beverages). The application of such a metric would likely yield very different results depending on the starting diet and nutritional status of individuals. Moreover, the traditional "product-based" approach is not without its limitations, particularly when applied to organic farming systems. Product-based LCAs often favour high-yielding, intensive farming systems and neglects the broader environmental benefits of organic farming, such as enhanced biodiversity and reduced pesticide use, which are more accurately reflected by an area-based approach (van Der Werf *et al.,* 2020).

2.2.3.2. Allocation and types of LCA

LCAs provide additional challenges when applied to agriculture, as agricultural systems often produce more than one output (co-products). The environmental footprint then needs to be divided for each product in a process called allocation. Different allocation methods can be used, for example: economic allocation, mass allocation, and allocation based on product properties like protein. Although economic allocation is the most commonly used (Aldama *et al.*, 2023), ISO recommend using mass and protein allocation. On dairy farms, where milk production is the main focus and meat is a co-product, the International Dairy Federation recommend using physical allocation methods such as energy-based allocation (IDF, 2015). The method of allocation can be subjective and can strongly affect the results of the LCA studies (Aldama *et al.*, 2023). Different allocation methods alongside different system boundaries, and functional units create uncertainties in LCAs therefore studies require a thorough sensitivity analysis (Igos *et al.*, 2019).

LCAs can be either attributional or consequential. The attributional approach assesses the environmental burden of existing situations, directly attributable to the system delivering the primary functional unit of interest. However, consequential LCA considers potential consequences of changes in production and relies on system expansion to allocate impacts of co-products (Schaubroeck *et al.*, 2021). More recently, Hardaker *et al.,* (2022) created a framework for incorporating ecosystem services into LCA. The framework quantifies the endpoint damage to ecosystem services from a product alongside existing LCA methodologies for modeling impacts on ecosystem quality (biodiversity), human health, and natural resources.

2.2.4. Carbon accounting tools

To meet environmental targets, appropriate tools are needed to carbon footprint farms and model the impacts of mitigation scenarios at a farm level. 'Carbon calculators' allow the measurement and modelling of GHG emissions at current baseline levels and under potential mitigation options. Taft *et al.* (2018) evaluated a number of different GHG calculators and identified three that were most suitable for use in Welsh agriculture. These tools included Agrecalc, Farm Carbon Calculator (CFF) and the Cool Farm Tool (CFT). Agrecalc gives the most comprehensive set of summary metrics, presenting emissions at a whole farm, enterprise and product level whereas the Cool Farm Tool only presents results at an enterprise and product level and the CFF at the farm level only. All tools provide total emissions, sequestration and net emissions within the output or as a separate calculation. Despite this, estimations between calculators vary substantially using the same data as well as varying substantially from LCA literature (Taft *et al.*, 2018; Sykes *et al.*, 2017).

Each tool uses different calculation and allocation methods, and has different levels of detail for breaking down carbon emissions and sinks. The CFF tool was the most basic, using only Tier 1 EFs for enteric and manure CH_4, while Agrecalc and CFT use Tier 2. Livestock N_2O are also not included in the CFF, with the others using Tier 2 methods. Both the CFF and CFT also lack information about animal purchases and sales, so it is unclear how animal numbers across the year are calculated. This is a particular problem for livestock farms as animals are in flux throughout the year as they are born/purchased/sold.

An assessment by Taft *et al.* (2018) found that the highest performing of these tools only scored 54% overall for use on Welsh farms (based on a multi-criteria analysis of key features such as practicality, usability, enabling, rigor and completeness). This assessment highlighted that none of these tools were fully suited for immediate use in Welsh agriculture (Taft *et al.*, 2018). Although the calculators discussed detect the majority of mitigation options (MOs) directly or indirectly, there are some exceptions for example: the change of timing to manure or fertiliser use, MOs in which new EFs are required or MOs that involve LUC and sequestration, which is still poorly understood. Taft *et al.*, (2018) concluded tools for use in Welsh agriculture should use the highest available Tier as well as Wales-specific EFs detailed in Brown *et al.* (2019).

2.3. Net Zero and policy in the UK

Several countries have signed the Kyoto Protocol to the United Nations Framework Convention on Climate Change, an international treaty in which countries have agreed to reduce GHG emissions to levels equivalent to those of 1990 (Breidenich *et al.*, 1998). In 2019, the UK was the first country to legislate the Net Zero target by 2050 in line with the 2015 Paris Agreement, a legally binding international treaty to hold the increase in global temperature to well below 2.2°C. (BEIS, 2022). The Net Zero target is defined by the IPCC as the point at which “anthropogenic emissions are equal to anthropogenic removals” over a specified timeframe (IPCC, 2018). The new laws are revised from the 2008 Climate Change Act, which aimed at an 80% reduction in GHG emissions from 1990 levels.

In their most recent Sixth Carbon Budget (the legal limit for UK emissions from 2033-37) the UK Climate Change Committee (CCC) have set a target of 965 $MtCO_2e$ equating a 78% reduction from 1990 to 2035 alongside a pledge to reduce emissions by at least 68% by 2030 (Climate Change Committee, 2020a). The CCC have acknowledged that not all areas of the UK have equal opportunities to achieve Net Zero. For example, the CCC report that “Wales has less opportunity for CO_2 storage and relatively high agricultural emissions that are hard to reduce” (Climate Change Committee, 2019). For this reason, Wales has its own legislative framework with the current legal target of 95% reduction (Climate Change Committee, 2020b).

2.3.1. Policy changes needed to achieve Net Zero

Many key changes are needed if the targets of the Sixth Carbon Budget are to be achieved. Low-carbon farming practices, peatland restoration and bioenergy crops should also be supported. The CCC urge the government to set out a clear path to incentivise the take-up of zero emission options for agricultural machinery and incorporate it in an existing strategy (Climate Change Committee, 2020a). Funding for such measures could come through the forthcoming Sustainable Farming Scheme (see next section) (Welsh Government, 2022). However, regulatory change may also be necessary; though recent measures such as the all-Wales designation as a Nitrate Vulnerable Zone and the restrictions in ammonia emissions required under the Clean Air Strategy (DEFRA, 2019) will also likely inadvertently lead to reduced emissions if farmers are obliged to reduce their livestock numbers to comply.

2.3.2. Current and future agricultural policy post-Brexit

Previously, farmers receive subsidies from the EU's Common Agricultural Policy (CAP) to support their income (Borrell and Hubbard, 2000). However, this system has been criticised as some think it encourages practices that harm the environment. In light of Brexit, the Government have introduced the new UK Agriculture Bill which aims to reward farmers for contributing to "public good" and reducing their GHG emissions (Pe'er *et al.*, 2020) . Under the Agriculture Bill, Wales have proposed a new scheme called the Sustainable Farming Scheme (SFS) which pays farmers for delivering environmental benefits (Welsh Government, 2022). The new policy has the potential to support the major transition in land use and agricultural systems needed to achieve Net Zero.

2.3.3. Ecosystem services and policy design

With the new Agriculture Bill, there will be a shift from current subsidies to support for providing environmental benefits. To integrate these benefits into agri-environmental policy, a suitable sustainability assessment will be required (the details of which are currently unannounced). The ecosystem service (ES) concept is now well established and provides a framework to define and analyse environmental impacts to aide policymakers' decisions (Grêt-Regamey *et al.*, 2017). Environmental impacts depend on individual farm characteristics like the use of on-farm and off-farm resources, degree of intensification, species, and many others (Bernués *et al.*, 2017). Pasture-based livestock systems in particular provide a number of ES however they can also cause negative environmental impacts or ecosystem disservices (EDS) (Blanco *et al.*, 2019). Many relationships exist between agricultural practices and a number of ES that can be utilised at a farm level to help with their integration into policy. Bernués *et al.* (2017) introduce the Payment for Ecosystem Services system to reward farmers for the delivery of ES supporting the principle of "public money for public good". PES are voluntary transactions given for one or more well defined ES and can be based on either the ES outcome (target orientated) or by the land management associated with the ES (practice orientated) (Reed *et al.*, 2014). Some examples of ES in farming include maintaining grasslands, managing forestry, grazing in semi-natural habitats and maintaining semi-natural vegetation. The ranking of such farming practices is dependent on specific policy targets.

The Welsh Government's proposal for the new SFS revealed the scheme is designed in a similar way to support farmers deliver a number of "Sustainable Land Management objectives". These objectives are to "produce food in a sustainable manner, mitigate and adapt to climate change, maintain and enhance the resilience of ecosystems and the benefits they provide and conserve and enhance the countryside and cultural resources, promoting public access and engagement with them" which must be delivered together and can be delivered on the same land. The SFS takes a land sharing approach that "delivers environmental and social outcomes through the adoption of sustainable farming practices". One of the specific actions listed in the scheme is reducing GHG emissions through better use of inputs and increasing production efficiencies.

2.3.4. Forest carbon sequestration policy

The CCC recommend support should be made available for more costly measures like afforestation and agroforestry schemes (Climate Change Committee, 2020c). Investment in increasing forest carbon provides a low-cost opportunity in climate policy, but policies will require careful design. In Wales, the Glastir Woodland Creation Scheme intended to increase woodland cover from 14% to 20% by 2030 to offset the GHG emissions from agriculture, however, landowner engagement has been relatively low. If the majority of woodland creation is to take place on farms, farmers' attitudes towards forestry should be crucial to policymakers' decisions. Many farmers in Wales believe forestry will generate little economic benefit (Wavehill Consulting, 2009). Other economic influences such as concerns over the loss of EU Single Payments, cost of the land use change and the greater perceived profitability of farming have also been reported (Leach *et al.*, 2012). New woodlands on farms provide ecosystem services like water management, habitat creation and timber production and therefore should be presented as an important farm diversification strategy (Wynne-Jones, 2013). A number of studies identify grants as a key element in landowners' decision-making, with one study noting that 82% of woodland owners would commercially manage their woodland if financial assistance was available (Sharpe *et al.*, 2001). However, studies have found economic incentives alone are not enough (Ryan and O'Donoghue, 2016) and a greater integration between farming and forestry practices is needed for these schemes to succeed. Future policy frameworks should move towards a more integrated ecosystem approach and work within a wider strategy to reduce the carbon footprint of food production.

The design of carbon sequestration policies is more complex than other emission mitigation policies. Carbon sequestration is site-specific and depends on factors such as soil quality, tree species, and local climate, therefore policy must take this heterogeneity into account and be designed efficiently (Gren and Aklilu, 2016). As well as the heterogeneity of landowners, uncertainty exists from weather conditions affecting biomass growth and therefore sequestration, errors in measuring, monitoring, and verifying carbon sequestration and permanence of created sinks from natural causes such as wildfires or pathogens. Further uncertainty can be created from asymmetric information between buyers and sellers e.g. on baseline emissions, costs of carbon sequestration and intentional harvesting of planted trees before the end of the project period (Gren and Aklilu, 2016).

Carbon trading schemes could be safe guarded in the UK by schemes such as the Woodland Carbon Code – a voluntary standard for woodland creation projects that provides reassurance on how much carbon a project will sequester. In 2019, the area of woodland certified under the Woodland Carbon Code rose by 60%, driven by woodland carbon (Woodland Carbon Code, 2020). Woodland carbon has attracted new clients to woodland creation. Companies and organisations interested in reducing their carbon footprint can invest in land for planting to offset their emissions while embedding sustainable practices into their own value chain in a process known as carbon insetting. This usually involves farmers who practice agroforestry and provides them with additional income. However, there are concerns by some in the farming industry that the sector cannot then (also) claim sequestration if the credits have been sold to another party (Welsh Government, 2023b).

2.4. Options for achieving Net Zero beef and sheep production in the UK

2.4.1. Mitigation and reducing emissions

To reach the Net Zero target in the UK, the CCC have estimated that the AFALOU sectors must reduce its emissions by 64% (Climate Change Committee, 2020c). Although there is not a specific target for the livestock sector, it is presumed this should be in line with the wider agricultural sector. A 64% reduction from 2017 livestock emissions would mean emissions would require a 37.12 Mt CO_2eq reduction. How this is achieved depends on the uptake of mitigation measures and carbon sequestration strategies (CIEL, 2020). A range of mitigation options are currently available, all with different abatement potentials and cost-effectiveness (Eory *et al.*, 2015; Moran *et al.*, 2011). Marginal abatement cost curves (MACCs) for agriculture have been developed in the UK to calculate the cost of avoiding emission of, or sequestering, an additional unit of CO_2 equivalent for a series of GHG mitigation measures (Figure 2.3; Moran *et al.*, 2011; Jones *et al.*, 2015; Eory *et al.*, 2020). Many mitigation measures can be implemented at a low cost and can even result in a net profit (MacLeod *et al.*, 2010; Moran *et al.*, 2011). These so called “win-win” options have co-benefits such increasing productivity as well as GHG abatement. Overall, key mitigation measures fall under four main categories: animal management, nutrition and feed additives, manure management and land management.

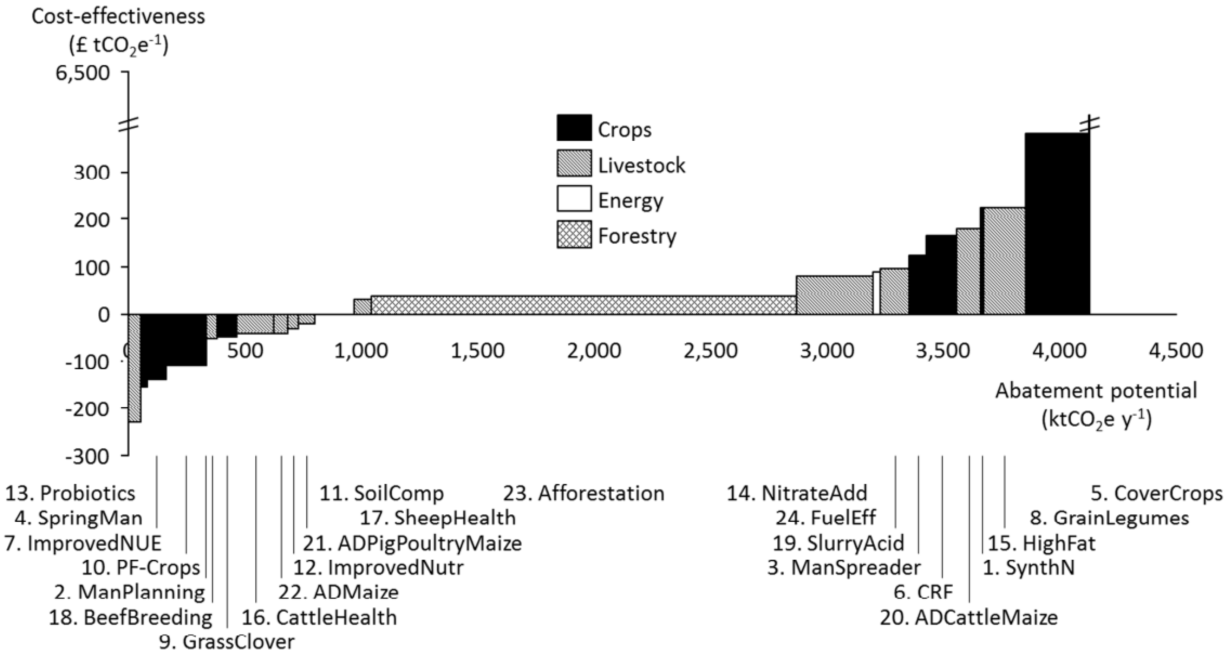


Figure 2.3. Marginal abatement cost curve for UK agriculture (with interactions and assuming 45% uptake), at a C price in 2030 of £78 t CO_2e^{-1} (Eory *et al.,* 2015).

2.4.1.1. Improving production efficiency

Increasing production efficiency on UK farms offers a win-win solution for reducing emission whilst simultaneously reducing costs and potentially increasing welfare (Bustamante *et al.*, 2014; Verspecht *et al.*, 2012). When efficiencies are increased, fewer animals are required to produce the same level of output. Animals also take less time to reach target weight so they are on farm for shorter periods and therefore emit less GHGs (FAO, 2013). The most efficient farms tend to require fewer inputs as well as reduced associated waste. Hyland *et al.* (2016) found the most efficient farming systems to be the lowest emitters and if all enterprises were to reach the efficiency levels of the lowest emitting farms, product-level carbon footprints could be reduced by 15% and 30% for beef and lamb, respectively. Production efficiency can be achieved by a number of interacting approaches by improving breeding, nutrition and health (Kumari *et al.*, 2020). However, animal numbers may also be higher on the most efficient farms, leading to higher total emissions (despite lower emissions per kg of product). This is known as the “Jevons Paradox” whereby increases in efficiency generate an increase (rather than a decrease) in resource consumption (Giampietro and Mayumi, 2018).

2.4.1.2. Breeding

Improving breeding management could be a sustainable way to reduce CH_4 emissions both directly and indirectly. Firstly, cattle which emit less CH_4 can be bred for directly by selecting for heritable traits which are responsible for emissions (de Haas *et al.*, 2011). Pinares-Patiño *et al.* (2013) found there is likely a genetic variation between animals for CH_4 emission traits, even when results were adjusted to exclude other related traits. However, this can be impractical as these traits are hard to measure. Animals could also be bred for phenotypes which enhance productivity such as feed efficiency, feed intake or N excretion (Hegarty and McEwan, 2010; Roehe *et al.*, 2016). Feed efficiency has been highlighted as the main indirect selection index for reducing CH_4, with Waghorn and Hegarty (2011) estimating a potential 15% reduction in CH_4 emissions when feed efficiency is used as the main breeding goal. Reduction in CH_4 emissions through feed efficiency should also apply to N_2O emissions as animals will use nitrogen more efficiently (Gerber *et al.*, 2013). However, potential deleterious effects can occur when genetically selecting for higher production and feed efficiencies through impairing biological functioning (Fraser *et al.*, 2013). Feed efficiency traits can cause a range of fertility and metabolic disorders and therefore pose a threat not only to production but also health and welfare (Bell *et al.*, 2011). To avoid these unintended negative consequences, farmers should consider herd-level efficiency rather than individual animal performance when selecting for breeding (Weigel and Lin, 2000).

2.4.1.3. Animal health

Improving animal health could also play a key role reducing GHG emissions from livestock, and presents another potential win-win scenario. Unhealthy animals have reduced production efficiencies therefore will take longer to reach target weights and will also require more inputs to achieve the same output as a healthy animal, all increasing GHG emission intensities (Lanzoni *et al.*, 2023). Reductions in mortality can also reduce CH_4 and N_2O by reducing the emissions associated with animals that die before they are able to reproduce or produce output e.g. meat (Shields and Orme-Evans, 2015). Controlling endemic diseases such as liver fluke, nematodes and Johne's disease has been highlighted as a promising strategy to reduce GHG emissions from beef and sheep production (Skuce *et al.*, 2016). Implementation of cost-effective measures that focus on cow/ewe fertility, abortion rates, calf/lamb mortality, growth rates and finally feed conversion ratios have been shown to be successful in reducing GHG emission intensity (Bartley *et al.*, 2016). Gastrointestinal nematodes are one of the most important parasites, particularly in sheep; therefore, controlling them could have a significant effect on emissions. Kenyon *et al.* (2013) found that when lambs were treated before showing clinical signs, they took less time to reach target weights and GHG emission intensities were reduced by 10%. Similar has been seen in cattle, however, to a lower magnitude. ADAS (2014) found under a scenario where there was a 50% movement from the baseline towards a healthy cattle population, there would be an estimated 6% reduction in GHG emission intensity. The main benefit of this scenario is seen in the reduction in replacement numbers (19%) and reduction in mortality and morbidity that would mean 28% fewer cows would be required.

2.4.1.4. Grazing management

Grazing management is another strategy that could help improve production efficiencies. When pasture quality is improved, so too is animal productivity which enables earlier slaughter and decreases GHG emissions. Improving grassland management has the potential additional benefit of increasing soil organic carbon and therefore increasing carbon sink capacity (Abdalla *et al.*, 2018). Although the use of concentrates and total mixed rations are often associated with increased yields, in some cases, grazing has been found to have lower GHG emissions. For example, Cameron *et al.* (2018) found grazing cattle had 39% lower CH_4 emissions than cattle fed total mixed rations. Similarly, Rotz *et al.* (2009) found grazing systems reduced net GHG emissions by 8-14% as well as other environmental benefits. Management practices like rotational grazing can increase the utilisation of pasture by partitioning fields and allowing grass time to recover from grazing. The growth rates with pasture improvement and better management allow animals to reach target weights faster (Mazzetto *et al.*, 2015). Other studies have suggested continuous grazing practices have lower CH_4 and N_2O emissions but also lower carbon sequestration rates (Soussana *et al.*, 2007).

2.4.1.5. Precision livestock farming

Precision Livestock Farming (PLF) technologies are another way in which farmers could reduce their carbon footprint. PLF is a term used for a range of smart technologies which can monitor, model and manage animal production to make livestock farming more economically and environmentally sustainable (Tullo *et al.*, 2019). New advances in phenotyping and genotyping such as understanding the rumen microbiome, precision feeding and precision animal surveillance could all play a part in reducing emissions (CIEL, 2020). Many studies have highlighted the importance of PLF as a tool for reducing animal agriculture's environmental impact (Llonch *et al.*, 2017; Shields and Orme-Evans, 2015; Tullo *et al.*, 2019). One important way PLF could be part of the solution is in early detection of disease using real-time technology (e.g. sensors, microphones, diagnostic tools) where farmers can be alerted when there is a change in normal patterns/behaviour, e.g. rumination (Dominiak and Kristensen, 2017). This can reduce disease, mortality and allows farmers to treat animals before they show clinical signs, which will not only increase production efficiencies and reduce emissions but also improve welfare (Van Hertem *et al.*, 2017). This technology has been applied to detect many conditions such as lameness, subacute rumen acidosis, impaired rumen functionality and mastitis (Humer *et al.*, 2018; King *et al.*, 2018; Zhang *et al.*, 2018; Zhao *et al.*, 2018). PLF tools have also been used in the management of herd and flock fertility. Timing of insemination of cows and sheep is critical to production and can be detected through devices and algorithms to increase conception rates (Alhamada *et al.*, 2017; Arcidiacono *et al.*, 2018). Feed efficiency is key to increasing production levels and reducing GHG emissions. PLF has be applied in an approach called precision feeding (PF) to achieve nutrition that is more effective. Using information technology and management processes, individual animals or groups of animals nutrient requirements can be met more accurately, reducing losses, improving product quality and optimizing available resources (González*et al.*, 2018).

2.4.1.6. Novel and alternative feeds

Optimising feed production and utilisation by designing diets and feed ingredients or additives offers a promising approach to increasing efficiency and reducing GHG emissions. For example, the use of soya as cattle feed has become increasingly common. However, this demand has driven extensive land use change overseas, which results in significant environmental impacts such as habitat loss, biodiversity decline, and increased GHG emissions (Castanheira *et al.,* 2013). Simple measures like farmers growing their own protein sources or using by-products in livestock feeds could reduce reliance on imported feeds and reduced the associated environmental impacts (Ma *et al.*, 2022; Yang *et al.*, 2021). Increasing diet digestibility improves nutrient use efficiency and has been shown to decrease CH_4 production by up to 30% (Gerber *et al.*, 2013). Increasing concentrates in animal diets has also been proven to be an effective mitigation strategy through a reduction in ruminal pH (Fouts *et al.*, 2022), though those concentrates will of course have other upstream impacts. A review by van Gastelen *et al.* (2019) found an average increase of 386 g/kg dry matter (DM) in concentrates decreased CH_4 production by 6% in sheep and 26% in beef cattle.

More research and a greater understanding of the rumen microbiome will present additional opportunities to lower CH_4 emissions through the manipulation of the rumen microbial populations (Beauchemin *et al.*, 2020). This can be done through gut microbial programming or dietary supplements that inhibit methanogens. Many rumen modifiers have been tested in recent years, with varying results. One of the most widely tested are antibiotic ionophores such as monensin, which increases acetate-to-propionate ratio and decrease CH_4 production. A meta-analysis by Ahvanooei *et al.* (2023) found addition of monensin at doses of 19-16 ppm reduced CH_4 emissions 8.12 – 33.31

g/day/cow, however, the use of antibiotics as feed additives are banned in the EU. More recently, yeast, *Saccharomyces cerevisiae* in particular, has been studied as a feed additive for its beneficial effects on digestion and animal performance (Nagpal *et al.*, 2015). However, a meta-analysis by Darabighane *et al.* (2019) found yeast had no significant effect on daily CH_4 production or CH_4 production per dry matter intake in dairy or beef cattle. Moreover, Benchaar *et al.* (2024) reported that active dry yeast *Saccharomyces cerevisiae* increased in CH_4 production by 18% *in vitro*. Further work is therefore needed to ascertain the potential benefits of including yeasts in ruminant diets. Another feed additive that has been well established is nitrate. Methane is produced in the rumen by archaea from H_2 produced during fermentation; nitrate competes for H_2 and electrons, leading to a reduction in CH_4 production of up to 50% (Troy *et al.*, 2015). However, nitrate must be considered cautiously due to its potential toxicity at higher doses. Similarly, dietary lipids can act as a hydrogen sink. Increasing levels of dietary unsaturated medium chain fatty acids like coconut oil inhibit rumen methanogens and reduce the proportion of energy supply from fermentable carbohydrates and therefore reduce CH_4 production through multiple mechanisms (Palangi *et al.*, 2022). The efficacy of lipids to reduce CH_4 depends on the level of inclusion in the diet and fatty acid profile (Patra, 2013). A meta-analysis by Yanza *et al.* (2021) found coconut oil to be the most effective medium-chained fatty acid in reducing CH_4, reducing CH_4 production by 28%. Polyunsaturated fatty acids (PUFA) can also reduce CH_4, for example, Wang *et al.* (2017) found safflower seeds and hemp reduced CH_4 yields *in vitro* by 21% and 18%, respectively. However, most sources suggest excessive lipid supplementation could negatively impact cattle health (Hristov *et al.*, 2013). Currently, the most promising methane inhibitor appears to be 3-nitrooxypropanol (3NOP). Similarly to the previously mentioned feed additive, 3NOP is a chemical that reduces the rate at which rumen archaea convert hydrogen released from ingested feed into CH_4 (Duin *et al.*, 2016). A review by Yu *et al.* (2021) found 3NOP reduced enteric CH_4 production by an average of 30%, with some studies reporting reductions as high as 82%. However, there is little research on the effects of 3NOP in sheep. It is also unclear how 3NOP would be administered to grazing animals, although 3NOP has been shown to be effective when administered as a bolus, little literature exists on its effectiveness in these conditions (Rooke *et al.*, 2016).

Other novel dietary approaches have been identified as successful CH_4 mitigation options. Red seaweed is among the many studied due to its effect on livestock production performance through its retention of bioactive compounds including bromoform, with antimethanogenic properties (Machado *et al.*, 2016). When Asparagopsis was supplemented at just a level of 0.2%, a reduction in CH_4 of up to 98% was reported (Kinley *et al.*, 2020). However, sustainable supply of seaweed on the scale needed could lead to its own environmental impacts (Abbott *et al.*, 2020). Moreover, there have been concerns raised over the toxicity of bromoform (Glasson *et al.*, 2022).

Another natural and sustainable feedstuff that has become increasingly of interest is tree fodder. Tree fodder contains tannins and saponins which modify ruminal fermentation by suppressing ruminal protozoa and selectively inhibiting some bacteria (Ramos-Morales *et al.*, 2017). Additionally, tree fodder is also thought to work via another mechanism in which saponins enhance flow of microbial protein from the rumen, increasing feed efficiency and utilization and therefore reducing methanogenesis (Goel and Makkar, 2012). Saponins have been shown to reduce CH_4 emissions by between 6-50%, however, this depends on the source and dose of saponins (Króliczewska *et al.*, 2023). Methane reductions from tannins have also been reported to be highly source and dose-dependent (Aboagye and Beauchemin, 2019). Jayanegara *et al.* (2012) found a linear decrease in CH_4 production with increasing tannin concentrations in both *in vitro* and *in vivo* across 30 studies; however, some of this reduction was due to a decrease in digestibility of organic matter. If found to be reliably effective, tree fodder and plant extracts could present a win-win scenario due to the opportunity for agroforestry and carbon sequestration.

2.4.1.7. Targeting nitrogen fertiliser use

Most of the previously described measures are aimed at reducing methane emissions; however, N_2O can be a big contributor to a farm's total GHG emissions. The key mitigation strategy to reduce N_2O emissions will be to reduce N fertiliser use and optimise manure management practices. To achieve this, a combination of changes will be necessary such as nitrification inhibitors, improved timing and rates of application, improved soil management and introduction of nitrogen fixing species (legumes such as clover). Better timing and reducing excessive fertiliser application could have the additional benefit of economic savings as well as reducing N_2O emissions (Snyder *et al.*, 2009). Precision farming technologies and N planning tools could prove useful to calculate grass and soil requirements so excessive inputs can be avoided and N can be utilised more effectively (Balafoutis *et al.*, 2017). Remote sensing also has the potential to guide precision application of fertilisers and manure so "emission hotspots" can be avoided (Radočaj *et al.*, 2022).

Simple changes such as the way animal manure is handled and spread can significantly reduce N_2O emissions. Covering slurry has been suggested as an option for reducing GHG from manure management; this has been proven to reduce NH_3 emissions and therefore indirect N_2O emissions, however, it is unclear how effective it is in reducing net GHGs (Berg *et al.,* 2006). Petersen *et al.* (2012) found covering a slurry with either a solid cover, straw or natural surface crust reduced CH_4 emissions, increased N_2O emissions but overall a reduction in GHGs. Cooling of manure could be a cost-effective way to reduce CH_4 emissions if the heat exchanged can be utilised especially in cold climates. This has been shown to have a significant reduction in CH_4 emissions of up to 46% (Groenestein *et al.*, 2011). As with N fertilisers, correct timing of manure application can also be an effective mitigation strategy for both direct and indirect N_2O emissions (Thorman *et al.*, 2007). Manure application methods could also have action via direct and indirect N_2O. Although choice of application techniques has been seen to have little impact on overall N_2O emissions, a reduction in N losses have potential to increase yields and therefore reduce product emissions (Petersen *et al.,* 2012). Chemical additives have also been evaluated to reduce emissions from slurry storage. Acid is the most widely used and effective slurry additive. Acidification is likely to have effect through inhibition of sulphur transformation and has been reported to reduce CH_4 emissions and NH_3 emissions by up to 98% (Kavanagh *et al.*, 2019) and 75% (Misselbrook *et al.*, 2016), respectively. However, application of large quantities of acidified slurry could lead to a reduction in soil pH. Langley (2022) found slurry acidification temporarily reduced soil pH by up to 0.75 units. Therefore, any reductions in soil pH should be compensated by liming (Loide *et al.*, 2020).

Strategies also exist which target plants and soils to mitigate N losses. Nitrification inhibitors (NIs) have been shown to have a significant effect on N_2O emissions from urine and slurry. NIs slow the nitrification process and promote plant N uptake, reducing losses through leaching and denitrification. Misselbrook *et al.* (2014) found a 56% reduction in N_2O emissions from fertiliser, cattle urine and cattle slurry in the UK. However, the effectiveness of NIs has been shown to be dependent on temperature and soil types (Chadwick *et al.*, 2018b). Additionally, other negative effects have also been noted, such as contamination of milk (Marsden *et al.*, 2015).

One of the most promising emission reducing approaches across all mitigation strategies is the introduction of novel and alternative forage species mixtures, particularly varieties that are deep rooted or fix atmospheric N. The key N fixing grass swards are leguminous clovers, they are thought to act via two pathways. Firstly, through their interaction with rhizobium bacterial species to increase N fixation, reducing N losses and reducing the need to N fertilisers, and secondly, by increasing productivity (Jensen *et al.*, 2012). From 12 studies analysed in a study for Farming Connect, legumes reduced N_2O emissions by on average 39% in Wales (Cutress and Williams, 2021). Another species that has been investigated to reduce N_2O emissions is plantain (*Plantago*). Plantain can produce and release bioactive compounds which inhibit nitrification (Gardiner *et al.*, 2016). Simon *et al.* (2019) found a significant reduction in N_2O emissions from urine patches with increasing proportion of plantain in both animal diet and sward. Using multi-species grass mixtures could further reduce GHG emissions as different plant species can affect nitrification through different pathways (Bracken *et al.*, 2022). Cummins *et al.* (2021) found N yield-scaled N_2O emissions of a six-species mixture were 41% lower than from those animals grazing a monoculture. Multi-species swards may also provide other co-benefit such as increased DM yield production and improved animal performance (Jerrentrup *et al.*, 2020; Moloney *et al.*, 2021).

2.4.2. Enhancing sequestration

2.4.2.1. Afforestation

Some level of GHG emissions will always exist from livestock production due to biological processes involved in enteric fermentation and soil emissions (FAO, 2013), therefore to achieve Net Zero, residual emissions must be offset through GHG sequestration. There are numerous GHG removal options, but afforestation is the key strategy in the UK agriculture. Trees absorbs CO_2 from the atmosphere and store it in their biomass, organic matter and soils. In the "balanced pathway" scenario set out by the UK CCC, the national target in Wales was to plant 180,000 ha of trees by 2050, which equates to approximately 10% of agricultural land in Wales. Woodland on farms can include anything from commercial forestry to semi-natural or agroforestry. Commercial forestry involves growing and harvesting trees, often in place of agricultural production, whereas agroforestry involves the combination of trees and agricultural production on the same land. Agroforestry exists in many forms including silvopasture, hedgerows, shelterbelts and row systems allowing sequestration without affecting farm productivity (Nair *et al.*, 2021). Semi-natural forests are native woodland that have developed gradually or accidentally over time, as opposed to planted. Effective management of existing woodland is also important for sequestration to be maximised. Commercial forestry could extend the duration of CO_2 removal by harvesting fast growing trees and using their wood in the bioeconomy (Forster *et al.*, 2021). If implemented appropriately, tree planting has a high carbon capture potential at a relatively low cost as well as providing additional benefits in the form of biodiversity, flood management and animal welfare (Burgess, 2017).

2.4.2.2. Land sparing and land sharing

In theory, if production efficiencies are increased and animal numbers remain constant, less land will be needed for the same level of output, leaving more land available for offsetting. This is referred to as a "land sparing" approach in which sustainable intensification takes place on agricultural land and "spared" areas are restored for other ecosystem services such as offsetting or for biodiversity (Balmford, 2021; Lamb *et al.*, 2016; Phalan *et al.*, 2011). Alternatively, a "land sharing" approach can be fostered, where the needs of both agriculture and conservation are targeted on the same area of land. This requires farmland to be more suitable for wildlife which may mean reducing fertiliser and pesticide inputs or promoting habitats by maintaining trees, hedges and ponds (Green *et al.*, 2005). Whether a land sparing or sharing approach is best is subject to ongoing debate, and an optimised approach to land use has yet to be determined. This balance of food production and conserving biodiversity is an important issue facing land use in the UK and Wales. Recently, Bateman and Balmford (2023) argue a land sharing approach could risk driving food imports and causing biodiversity loss overseas. The authors highlight an important issue that afforestation must be done in a strategic way (e.g. "the right tree in the right place") to avoid the loss of food production. Decreasing production in this country could lead to importing more food from countries that could have higher GHG emission intensities and lower standards than the UK. Moreover, even within the UK, if more efficient farms decrease their production to plant trees, production could be displaced to less efficient systems and increase emissions at a national level.

In general, more land will be needed for the sum of food production and C sequestration, and achieving carbon neutrality will likely require less land being used for food production (particularly on land where production is inefficient). The potentially significant socio-economic consequences of this to the huge number of rural communities that rely on farming as their primary source of income needs consideration. Therefore, farmers may need to be paid for C sequestration as well as food production. Payment could come from further down the food production chain such as retailers reducing their Scope 3 emissions under the "Retailer Net Zero Collaboration Action Programme" (WRAP, 2023), and/or the public sector through payment for public goods or ecosystem services (such as the forthcoming Sustainable Farming Scheme (2025) in Wales).

2.4.2.3. Soil carbon sequestration

Another option for GHG removal is increasing soil carbon sequestration. A soil's potential for sequestering additional carbon depends on the soil type, texture, clay content and pH as well as management practices (Smith *et al.*, 2015). Changing management practices e.g. fertiliser usage and tillage or improving grazing management could increase soil carbon content (Conant *et al.*, 2017). Carbon stored in soils is not permanent, continuous turnover of soil organic matter makes soil sensitive to management, and climatic factors mean soils can either be a carbon source or carbon sink. The key in this removal strategy will be to identify land where soils have been depleted by farming practices and that have potential to be restored by changes in management practices that foster carbon sequestration. Increasing soil carbon stocks will improve soil health, structure and aerobic microbial processes so more nutrients will be taken up into biomass, increasing productivity and reducing inorganic inputs (Lal, 2016). There are numerous management options that can enhance sequestration of carbon in soils, however, the capacity to make significant further gains may be limited in many agricultural soils (Poulton *et al.*, 2018), particularly under permanent grasslands as they are often likely be at a state of carbon equilibrium (Smith, 2014).

2.4.2.4. Other options for carbon sequestration

Alternative carbon sequestration options are available; however, they are not as well researched, especially in the UK. Additional carbon can be stored in soils via the application of biochar (Gupta *et al.*, 2020). Biochar involves growing biomass that is then burnt in the absence of oxygen to create a charcoal-like substance that can stabilise organic matter when added to soil (Lehmann *et al.*, 2009). The potential for carbon capture from biochar is high, however, so is the cost. It is also not clear if this is a viable option for use in the UK without adverse effects (Hilber *et al.*, 2017). However, biochar has other co-benefits, for example, it has been shown to reduce CH_4 emissions in soil (Yu *et al.,* 2013). Moreover, biochar has been shown to be effective as a methane inhibiting feed additive for cattle (Winders *et al.,* 2019). However, the mechanism of action for CH_4 reduction in cattle is poorly understood and there is a large variation in abatement potentials in the literature (Honan *et al.*, 2021).Another option to enhance GHG removals is enhanced weathering, which involves crushed silicate rocks like basalt to speed up the weathering process. Silicate rock fragments are spread on land and react with CO_2 to remove it from the atmosphere (Renforth, 2012). This is another method that is not well researched for use in the UK yet and is relatively expensive.

Bioenergy with carbon capture and storage (BECCS) is another promising new technology for enhancing sequestration. BECCS involves the burning of biomass to convert it to bioenergy; this burning is considered to be carbon neutral but the carbon emitted in BECCS is captured and stored (Donnison *et al.*, 2020). Similarly, direct air capture and carbon storage (DACCS) captures CO_2 directly from the air and is stored permanently in deep geological formations (Gambhir and Tavoni, 2019). Carbon dioxide is captures by engineered processes and can be done as liquid or solid (Erans *et al.*, 2022). BECCS and DACCS both have a high potential for sequestering carbon; however, they are expensive and have not been deployed at scale in the UK. BECCS could potentially require large areas of agricultural land to be converted to biomass production, however, this could be avoided if existing forestry residues or hedgerow biomass were utilised (Smith *et al.*, 2016). Forestry residues generally have a lower environmental impact than other feedstocks but they are also limited in availability and more difficult to collect (Brack and King, 2021). On the other hand, DACCS requires little to no land and could be used as an alternative carbon sink without increasing the competition for land.

2.5. Concluding remarks

Major innovation is needed on UK and Welsh farms to reach Net Zero. The sector will have to make significant efforts to reduce its emissions, however, emission reductions alone will not be enough to achieve Net Zero due to the natural limits of reducing enteric methane emissions. Therefore, large-scale land use change may be needed to offset residual emissions. There are many mitigation measures and sequestration options to help farms move towards Net Zero, all with varying abatement potentials and cost-effectiveness. However, many have not yet been fully explored, particularly in a Welsh context. It is important to note the Net Zero target is a national target set across all sectors, so it does not require individual sectors to reach the target on its own. However, it is likely the Agriculture, Forestry and Other Land Use sector will be relied upon to offset emissions from other industries. This literature review has highlighted the scale of the challenges faced by farmers to reach environmental targets while maintaining food production but also highlighted the range of opportunities available to farmers to achieve Net Zero.

Mitigation options include measures which relate to increasing production efficiencies (e.g. breeding and health), novel and alternative feeds (e.g. feeding by-products and increasing digestibility of feeds), feed additives (e.g. 3NOP and red seaweed) and targeting N fertiliser use (e.g. N planning and nitrification inhibitors). Many of these measures deliver co-benefits and therefore represent “win-win” scenarios, for example, introducing legumes not only reduces N_2O by reducing the need for N fertiliser, but they are also likely to increase digestibility and crude protein of grass therefore increasing animal production efficiencies (Jensen *et al.*, 2012).

However, mitigation alone will not likely be enough to reach carbon neutrality due to the biological process involved in enteric fermentation. Achieving Net Zero on farms will therefore require residual emissions to be offset through GHG removal mechanisms and afforestation will likely be key in removing GHGs from the atmosphere. Increasing soil C sequestration is another GHG removal option, however, it is likely soils under grasslands have a low potential to make any further significant gains (Poulton *et al.*, 2018). Alternative GHG removal options include biochar, BECCS and DACCS; however, they have not yet been deployed at scale in the UK.

In order to assess the effect of various mitigation measures on farms, it is essential we first calculate accurate baseline carbon footprints. There are many carbon accounting tools available for farms to calculate their carbon footprint. These tools vary notably in their input requirements and GHG emission and sequestration estimates. However, quantifying current levels of GHG emissions on farms is the first step in moving towards Net Zero, therefore, it is important we understand these tools and their differences. Moreover, the FUs used to express emissions can also have a significant impact on resulting carbon footprints. Many studies have compared the use for different FUs to compare specific foods and diets, however, few studies have compared the use of different FUs to compare different farming systems.

Modelling mitigation scenarios on real farms could highlight the realistic opportunities available for farmers to move towards Net Zero. However, these scenarios do not reflect the true uptake of these measures. In the beef and sheep sector, the uptake of mitigation measures remains low due to the various economic, social and psychological factors that influence farmers' decision-making. It is therefore vital to understand the barriers to implementation of specific GHG mitigation and sequestration options in order to determine how to improve the uptake of these measures to move towards Net Zero.

Chapter 3 A comparison of carbon calculators for application on Welsh beef and sheep farms

L.C. McNicol, D. Chadwick, D. Styles, R.M. Rees and A.P. Williams

Abstract

Quantifying greenhouse gas (GHG) emissions from livestock production systems is an important first step towards meeting the Net Zero by 2050 target. Many carbon accounting tools are available to quantify GHG emissions at the farm level, however, different tools have been shown to produce notably different results for the same farms. Of the current, commercially available tools, Agrecalc and Farm Carbon Calculator (FCC) have been shown to be amongst the most appropriate for use on UK farms. As well as commercially available tools, other bespoke tools such as Bangor University's own carbon footprinting tool are well established.

Using data from 20 beef and sheep farms selected to be representative of typical livestock systems found in Wales, we compared the results from Bangor University's own carbon footprinting tool and some of the highest performing commercially available tools, Agrecalc and the FCC. The tools were compared in terms of their emission estimates, sequestration estimates and sensitivity to mitigation options.

The three carbon calculators produced notably different results for the same 20 farms. The FCC had the least detailed data collection process and did not provide separate estimates for each GHG. Agrecalc required a higher level of detail in its input data and appeared to mirror Inventory reporting more accurately which could be an important factor when looking at footprints in relation to government targets. However, the Bangor Tool outperforms Agrecalc in other areas such as sequestration, calculating sequestration rates more accurately where the data is available. All tools had a low potential sensitivity to detect the impact of mitigation options.

Despite the two tools resulting in notably different farm and product footprints, their use separately is still valid when benchmarking within (over different years) and between farms. Caution should be exercised when comparing footprints from different tools due to the inherent differences between the tool's emission factors and assumptions.

3.1 Introduction

Agriculture is responsible for 10% of the United Kingdom (UK)'s total greenhouse gas (GHG) emissions (Climate Change Committee, 2020). Livestock contributes substantially to these emissions, mainly in the form of methane (CH_4) from enteric fermentation of ruminant animals. Globally, CH_4 accounts for 50%, carbon dioxide (CO_2) 26% and nitrous oxide (N_2O) 24% of overall livestock GHG emissions (FAO, 2013). CH_4 is primarily produced as a by-product of enteric fermentation, but also from manure. N_2O emissions mainly come from soils following nitrogen fertiliser and manure application. In pasture-based systems a significant proportion of N_2O comes from deposition of excreta onto grassland soils (FAO, 2006). Most CO_2 emissions on farm come from energy use and the embedded emissions associated with feed and fertiliser production as well as embedded emissions associated with bought in stock.

In 2019, the UK was the first country to legislate the Net Zero GHG emissions by 2050 target, which will require considerable mitigation efforts from livestock production (Climate Change Committee, 2020). Quantifying GHG emissions from livestock production systems is an important first step towards meeting these environmental targets. Many carbon accounting tools are available to quantify GHG emissions at the farm level. Of the current, commercially available tools, Agrecalc, Cool Farm Tool and Farm Carbon Calculator (FCC) have been shown to be amongst the most appropriate for use in UK farming systems (Sykes *et al.*, 2017; Taft *et al.*, 2018; DEFRA, 2024). The advantages of these tools are they are free to users, provide a complete account of GHG emissions at both farm and enterprise levels, and allow comparison with previous years and other similar farms. This means that benchmarking similar farms is possible, which can highlight opportunities for mitigation measures and sharing of good practise. These tools still have limitations as even the "highest performing" tool, Agrecalc, only scored 54% for overall performance (Taft *et al.*, 2018) based on assessment components devised by Hall *et al.* (2010) and Whitaker *et al.* (2013). Key areas of uncertainty affecting this performance include representation of embedded emissions, especially bought-in stock and land use emissions. Aside from commercially available tools, other bespoke as Bangor University's own carbon footprinting tool are well established (Edwards-Jones, Plassmann and Harris, 2009; Jones *et al*., 2014; Hyland *et al.*, 2016). Whilst this tool is also suited to quantifying GHG emissions from UK farms, it was designed as more of a research tool. Tools vary in their inherent calculations, and the choice of tool depends on users' specific needs and aims. When calculating the carbon footprint of a farm, the choice of tool can have notable effects on the results, therefore it requires careful selection to match the intended aims of the carbon audit.

In 2020, Hybu Cig Cymru (HCC) commissioned research form Bangor University in collaboration with the University of Limerick to use the Bangor University carbon footprinting tool to analyse the carbon footprint of 20 beef and sheep farms in Wales that reflected the different farm types commonly found in Wales. The aim of this study was to compare the results from the Bangor University carbon footprinting tool and some of the highest performing commercially available tools, Agrecalc and the FCC (Sykes *et al.*, 2017; Taft *et al.*, 2018; DEFRA 2024) - for the aforementioned beef and sheep farms. This study assessed any variation emission estimates between the tools for CO_2, embedded emissions, CH_4 and N_2O as well as sequestration estimates to better understand how and why these differences in results occur.

3.2 Methods

3.2.1 Farm data collection

Twenty farms were contacted to take part in the initial study. These farms were selected to be representative of agricultural systems typical of those found across Wales including hill, upland and lowland, and those keeping sheep, cattle or both. Participating farms were categorised into hill (*n*=11), upland (*n*=6) and lowland (*n*=3) based on the area where the majority of their land fell. The majority of farms were a mixture of both beef and sheep enterprises, with 3 being only sheep. Enterprise types varied between farms for cattle; for example, a mixture of spring/autumn calving suckler and breeder/finishers. Similarly, with sheep systems there was a mixture of early and late lambing and store/finishers.

Data were collected through a detailed self-reported Excel spreadsheet for the Bangor Tool and, in most cases, follow up emails and calls to participants were used for verification of this data. Data were collected over 3 years for 8 farms, 2 years for 3 farms, and across 1 year for a further 9 farms. Datasets from multiple years were then averaged for each farm before calculating individual carbon footprints. In cases where data were difficult to obtain, or where any data were missing, recently published UK data or standardised estimates were used in their place (Craig, 2018; Redman, 2018). When inputting data into Agrecalc and the FCC, data were converted or calculated from existing data where necessary. Any information required from Agrecalc or the FCC which was not provided in the questionnaire was sourced from national averages from the Farm Management Handbook (Craig, 2018). The FCC did not provide seperate estimates for each GHG therefore a full comparison could not be completed on this tool. Therefore, total emissions, sequestration and net emissions were evaluated across all three tools, but individual GHG estimates were only compared between Agrecalc and the Bangor Tool.

3.2.2 Tool descriptions

3.2.2.1 Bangor University Tool

An updated version of the Bangor carbon footprinting tool was used in this study. This tool uses a combination of revised IPCC (2019) Tier 1 guidelines as well as improved Tier 2 methods which give more accurate N_2O and CH_4 estimates as well as incorporation of UK animal feeding system models and agricultural practices. All livestock and manure management estimates uses consolidated Tier 2 emission factors (EFs) for Wales (Brown et al., 2017). Energy use emissions from electricity and fuel use DEFRA (2007) EFs and Carbon Trust (2006) EFs for renewables. Embedded emissions from feeding are calculated using Carbon Trust (2011) EFs. The Bangor Tool has also been validated to PAS2050 standards which takes into account both GHG emissions and carbon sequestration with the "farm gate" system boundary. Carbon footprints were quantified at both a farm and product level for all 20 farms using the Bangor Tool.

3.2.2.2 Agrecalc tool

Agrecalc - Agricultural Resource Efficiency Calculator was developed by Scotland's Rural College and has been found to be amongst the highest performing carbon accounting tool in terms of transparency, methodology and allocation for use on UK farms (Sykes *et al.*, 2017). The tool uses a combination of IPCC (2006) Tier 1 and Tier 2 methodologies and conforms to PAS2050 standards. Energy use emission estimates are calculated using EFs from DEFRA (2011) conversion factors for company reporting. IPCC (2006) Tier 2 calculations are employed for livestock and manure emissions. Embedded fertiliser and pesticide emissions are calculated using Carbon Trust (2010) EFs and feed and bedding EFs from Kool *et al.* (2012), whereas N_2O emissions from fertiliser and crop residues uses IPCC Tier 1 methods. IPCC Tier 1 methodology is also used to estimate carbon sequestration from woodland. Carbon footprints were quantified at both a farm and product level for all 20 farms using Agrecalc.

3.2.2.3 Farm Carbon Calculator tool

The Farm Carbon Calculator (FCC) is a tool created by the Farm Carbon Toolkit (Farm Carbon Toolkit 2021). It claims to be suitable for use on livestock and arable farms on any scale or soil in the UK. The FCC uses IPCC (2019) Tier 2 UK specific methodology to calculate emissions from livestock. The tool also uses data from the GFLI database (Blonk, 2020) for animal feeds. Nitrous oxide emissions from crop residues and manures are calculated using IPCC (2019) Tier 1 methodology. The majority of the FCC fuel and electricity calculations use DEFRA (2019) conversion factors. Fertiliser emission calculations are based on improved UK specific IPCC (2019) EFs. Finally, carbon sequestration is calculated using a range of sources. Soil and hedgerow sequestration is estimated using the FCC own calculations whereas sequestration from trees and woodland uses figures from the Woodland Carbon Code. The FCC's methodology is also PAS2050 compliant but takes a broader approach and includes indirect emissions.

3.3 Results

Total emission calculations from Agrecalc ranged from 365-2428 kt CO_2eq, with an average for all farms of 1078kt CO_2eq (Table 3.1). For the Bangor Tool, overall total emissions estimates were lower, ranging from 232-2182 kt CO_2eq (Table 3.1) with an average of 863 kt CO_2eq across all farms (Figure 3.1). The FCC had the lowest total emission estimates ranging from 36-1458 kt CO_2eq (Table 3.1) with an average of 590 kt CO_2eq (Figure 3.1).

Sequestration estimates were also different between the models, Agrecalc estimating sequestration rates between 13-762 kt and averaging 128 kt CO_2eq, with the Bangor Tool estimating higher sequestration rates between 82-418 kt CO_2eq (Table 3.1) with an average 234 kt CO_2eq (Figure 3.1). The FCC sequestration estimates were the lowest at 8-588kt CO_2eq (Table 3.1) averaging 93kt CO_2eq (Figure 3.1).

When accounting for the total greenhouse gas emissions (expressed as CO_2e) and sequestration, i.e. net emissions, Agrecalc therefore had higher net emissions with net farm emissions ranging from 179-2412 kt CO_2eq for all farms and an average of 956 kt CO_2eq. The Bangor Tool estimated 150-1970 kt CO_2eq net emissions (Table 3.1) and average 720 kt CO_2eq across all farms (Figure 3.1). The FCC had the lowest net emission estimates ranging from 36-11458 kt CO_2eq (Table 3.1) and averaging 590 kt CO_2eq (Figure 3.1).

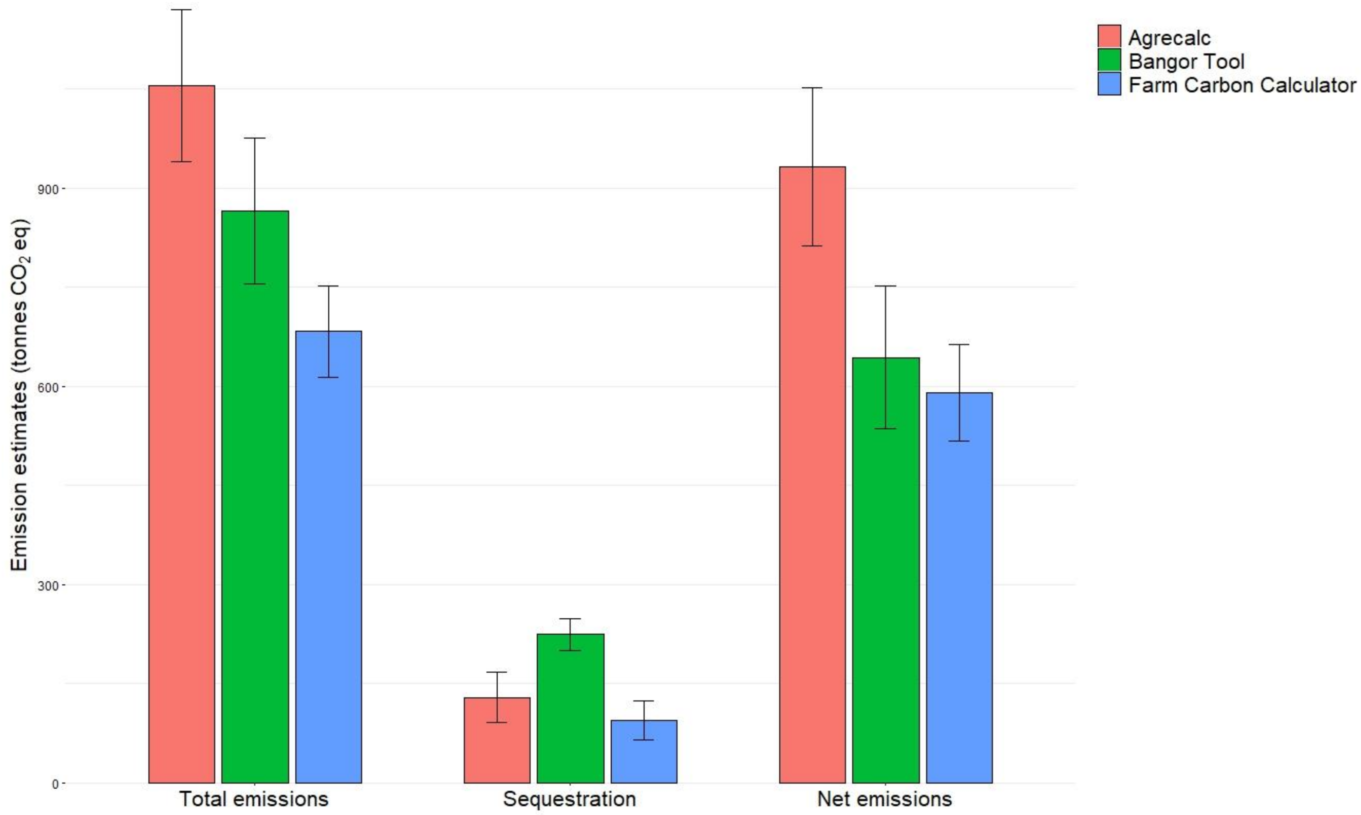


Figure 3.1. Mean emission estimates and standard deviations (*n*=20) for each total emissions, sequestration and net emission estimate from Agrecalc, the Bangor Tool and the Farm Carbon Calculator. Error bars represent standard error.

Table 3.1. Emission and sequestration estimates for each farm from both Agrecalc,the Bangor Tool and the Farm Carbon Calculator.

			Emission and sequestration estimates (kg CO_2e)								
			Total Emissions			Sequestration			Net Emissions		
Farm	Farm type	No. of years data collected	Agrecalc	Bangor Tool	Farm Carbon Calculator	Agrecalc	Bangor Tool	Farm Carbon Calculator	Agrecalc	Bangor Tool	Farm Carbon Calculator
A	Hill	1	952,355	672,099	631,820	762,300	418,979	588,820	190,055	253,120	36,030
B	Hill	3	385,311	232,036	249,785	108,900	163,092	59,381	276,411	68,944	190,404
C	Hill	3	875,494	565,103	557,654	65,340	151,294	45,150	810,154	413,808	512504
D	Hill	1	1,241,440	920,183	824,354	54,450	216,763	85,646	1,186,990	703,420	771,413
E	Hill	3	346,800	242,366	284528	43,560	97,393	30,459	303,240	144,973	246541
F	Hill	3	1,077,862	879,424	730,001	28,314	127,560	20,865	1,049,548	751,864	709,137
G	Hill	3	462,859	535,171	352,801	13,917	82,144	25,539	448,942	453,028	327,262
H	Hill	3	1,183,778	944,328	814,244	109,880	310,048	85,331	1,073,898	682,526	728,913
I	Hill	3	782,675	798,040	545,969	87,120	274,386	30,222	695,555	523,655	515747
J	Hill	2	2,061,080	2,182,558	1,208,026	88,209	211,865	66,338	1,972,871	1,970,693	1,141,688
K	Hill	3	889,212	556,793	605,259	28,423	405,910	31,461	860,789	150,882	573,798
L	Lowland	1	950,314	628,616	565,533	78,953	226,189	48,311	871,361	402,426	517,222
M	Lowland	1	476,358	341,142	317,527	0	97,977	8,472	476,358	243,165	309055
N	Lowland	3	1,411,439	1,354,754	826,590	65,340	133,731	49,869	1,346,099	1,221,023	776,721
O	Upland	3	735,562	590,214	494235	70,785	140,287	106,478	664,777	449,926	387,757
P	Upland	1	2,326,125	1,841,859	1,486,985	16,335	242,350	28,646	2,309,790	1,599,508	1,458,339
Q	Upland	2	802,858	688,856	511,173	146,688	212,974	59,499	656,170	475,882	451,674
R	Upland	2	1,422,551	1,205,748	933,107	229,235	381,210	113,677	1,193,316	824,539	819,430
S	Upland	1	1,325,641	1,009,342	833,624	245,025	364,415	149,520	1,080,616	644,927	684,104
T	Upland	1	1,375,174	1,109,788	888762	206,910	220,571	244,795	1,168,264	889,217	643,967

As the FCC did not provide separate estimates for each GHG, only Agrecalc and the Bangor Tool could be assessed at this level. Carbon Dioxide (CO_2) emissions were similar for both tools with Agrecalc's estimates ranging from 73-538 kt CO2eq (Table 3.2) with an average of 201 kt CO_2eq. The Bangor Tool CO_2 estimates ranged from 79-570kt CO_2eq (Table 3.2) and an average of 248 kt CO2eq (Figure 3.2).

Methane emissions were notably different between tools. Agrecalc produced higher CH_4 estimates ranging from 199-1306 kt CO2eq, averaging at 620 kt CO2eq of CH_4; whilst the Bangor Tool estimated CH_4 from 78-1149 kt CO_2eq with an average of 421 kt CO_2eq (Figure 3.2).

Nitrous Oxide emissions also varied between tools but not as much as CH_4, again with Agrecalc estimating higher with a range of 75-611 kt CO_2eq and an average of 255 kt CO_2eq. The Bangor Tools calculated N_2O from 48-504 kt CO_2eq (Table 3.2) averaging 193 kt CO_2eq between farms (Figure 3.2).

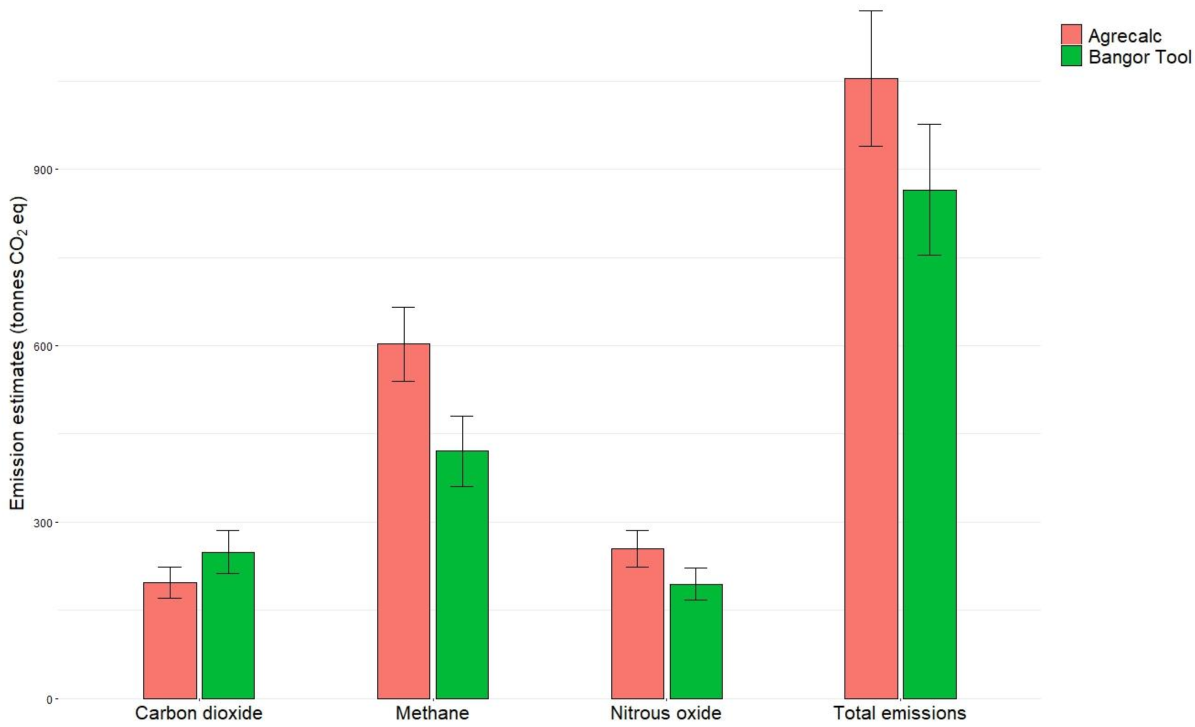


Figure 3.2. Mean livestock emissions estimates and standard deviations (*n*=20) for each greenhouse gas and carbon sequestration estimate from both Agrecalc and the Bangor Tool. Error bars represent standard error.

Table 3.2. Emission estimates for each greenhouse gas and sequestration estimates for all farms from both Agrecalc,the Bangor Tool and the Farm Carbon Calculator.

			Emission and sequestration estimates (kg CO_2e)									
			Carbon dioxide		Methane		Nitrous oxide		Sequestration		Net emissions	
Farm	Farm Type	No. of years data collected	Agrecalc	Bangor Tool	Agrecalc	Bangor Tool	Agrecalc	Bangor Tool	Agrecalc	Bangor Tool	Agrecalc	Bangor Tool
A	Hill	1	171,920	176,117	541,355	294,418	239,080	201,563	762,300	418,979	190,055	253,120
B	Hill	3	81,537	90,069	225,683	93,272	78,090	48,694	108,900	163,092	276,411	68,944
C	Hill	3	111,907	120,471	557,975	271,614	205,612	173,017	65,340	151,294	810,154	413,808
D	Hill	1	129,363	104,878	820,606	569,972	291,471	245,333	54,450	216,763	1,186,990	703,420
E	Hill	3	73,507	93,722	183,728	78,580	89,565	70,064	43,560	97,393	303,240	144,973
F	Hill	3	332,541	339,785	516,320	331,158	229,001	208,480	28,314	127,560	1,049,548	751,864
G	Hill	3	131,876	317,371	228,807	153,379	102,176	64,422	13,917	82,144	448,942	453,028
H	Hill	3	306,666	298,739	621,194	429,452	255,918	216,137	109,880	310,048	1,073,898	682,526
I	Hill	3	171,511	248,962	418,772	409,630	192,392	139,448	87,120	274,386	695,555	523,655
J	Hill	2	393,035	528,329	1,058,454	1,149,655	609,592	504,574	88,209	211,865	1,972,871	1,970,693
K	Hill	3	101,382	80,249	563,935	317,554	223,895	158,989	28,423	405,910	860,789	150,882
L	Lowland	1	191,164	188,345	518,471	247,010	240,679	193,261	78,953	226,189	871,361	402,426
M	Lowland	1	83,738	79,984	270,158	152,105	122,461	109,053	0	97,977	476,358	243,165
N	Lowland	3	219,414	503,850	861,992	779,113	330,032	71,791	65,340	133,731	1,346,099	1,221,023
O	Upland	3	102,268	166,771	458,992	282,613	174,302	140,829	70,785	140,287	664,777	449,926
P	Upland	1	533,844	570,054	1,230,962	768,432	561,319	503,373	16,335	242,350	2,309,790	1,599,508
Q	Upland	2	102,023	106,395	528,312	449,310	172,523	133,152	146,688	212,974	656,170	475,882
R	Upland	2	228,853	260,864	879,802	697,613	313,896	247,271	229,235	381,210	1,193,316	824,539
S	Upland	1	192,379	217,908	799,772	555,551	333,489	235,884	245,025	364,415	1,080,616	644,927
T	Upland	1	289,536	494,358	764,993	391,906	320,645	223,524	206,910	220,571	1,168,264	889,217

The product emission estimates for both beef and lamb were marginally higher for Agrecalc. The total CO_2eq per kg liveweight for beef was 16 kg CO_2eq/kg of LW beef for Agrecalc and 13 kg CO_2eq/kg of LW beef for the Bangor Tool. For lamb, Agrecalc estimated 12kg CO_2eq/kg of LW lamb and the Bangor Tool 11 kg CO_2eq/kg of LW lamb. The FCC had the lowest estimates for both beef and sheep at 11 11 kg CO_2eq/kg of LW beef and 811 kg CO_2eq/kg of LW lamb (Table 3.3).

Table 3.3. Mean product emission estimates and standard deviations (*n*=20) per kg of liveweight of beef and sheep from Agrecalc, the Bangor Tool and the Farm Carbon Calculator.

	Product emissions (kg CO_2eq per kg lwt)	
	Beef	Sheep
Agrecalc	16 ± 6.47	12 +3.96
Bangor Tool	13 ± 6.87	11 ± 4.36
Farm Carbon Calculator	11 ± 4.41	8 ± 3.01

3.4 Discussion

Using data obtained from the 20 beef and sheep enterprises, this study compared the GHG emission estimates of the online Agrecalc and FCC tools and the Bangor University carbon footprinting research tool. This demonstrated some important differences in results notably in CH_4 emissions and sequestration estimates from Agrecalc and the Bangor Tool which were more significant in some farms than other.

3.4.1 Input requirements

A fundamental data-input difference between the two models involved the classification of farm type. The Agrecalc model required a more detailed farming system/enterprise type to the FFC and the Bangor University tool; for example, sheep enterprises were classified as “good hill flock”, “extensive hill flock”, “early lambing” or “late lambing”. As these terms are not well-defined industry standards, interpretation of this category by farmers may have led to misclassification of farms. However, as this section is mainly used for benchmarking purposes, it is unlikely to have significantly impacted the resulting footprint. Overall, the data required for the FCC is less detailed than both the Bangor Tool and Agrecalc making this tool the quickest to complete.

Emission breakdown and categories from Agrecalc are similar to Inventory reporting as they are mainly IPCC sourced. The FCC also shows similar data categories to Agrecalc and therefore Inventory reporting however they do not disaggregate in results. The most important difference in input requirement is in animal categories, particularly in younger animal categories. The Bangor Tool and Agrecalc use different age ranges; Agrecalc uses wider age ranges and differentiates between sexes for cattle which can affect the average liveweight notably and therefore affect the resulting GHG emissions estimates associated with livestock. For sheep, Agrecalc differentiates between types of lamb having separate categories for lambs for slaughter and lambs for replacement whereas the Bangor Tool groups all lambs together, which when comparing livestock emissions e.g. CH_4 and N_2O, can cause a marked effect on the average liveweights and therefore GHG emission estimates. The FCC again has the least detailed categories for livestock. FCC has just 3 categories for sheep: ewes, rams and lambs and much broader categories for cows which are categorised more for their purpose, offering options for beef cows, beef females for slaughter, bulls for breeding, cereal fed bull, heifers for breeding and steers. Potentially more importantly the FCC requires less detailed data about these animals for example no animal weights are required for any of the sheep categories which are important in calculations of both Agrecalc and the Bangor Tool.

Agrecalc requires more details about the categories, for example weight at weaning and weight at 1 year, which is not included in the Bangor Tool or FCC and therefore averages and best estimates where used. Agrecalc has an additional section for “performance” in the input sheet which asks for data such as average daily gain, age at first calving, calving and lambing percentages and also asks for percentage lambs single, twins and triplets. These data are not required for the Bangor Tool (where data was originally collected for) and so national averages were used. Although the Bangor Tool does not include performance data, the FCC does not include any livestock sale data which is present in both the other tools. The sales section is not only important in the allocation of the other tool but also for stock numbers over the sample year in the Bangor Tool.

The final major difference in livestock section is the product emissions, the FCC only requires the total tonnage of product which groups together livestock, crops and any other output. Therefore, the results from the FCC do not give livestock product emissions but instead an emission metric based on a tonne of product. This makes it difficult to compare to any other tool as most use the standard per kg of liveweight for each animal type. The total number of animals is also inputted slightly differently with Agrecalc and FCC, using average number of animals over a 12-month period and the Bangor Tool using animal numbers at year start and year end adjusting with stock entering/leaving farm by month.

crops and forage sections of the FCC also varies in input requirement from the other tools evaluated. For crops the FCC requires the number of hectares and tonnes of product similar to the Bangor Tool but in less detail than Agrecalc which needs yields per hectare and DM for some crops. A more notable difference between the FCC and the other tools is the absence of silage data. Both Agrecalc and the Bangor Tool use hectarage and yield as well as Agrecalc also including DM in their calculations however none of this data seems to be included in the FCC. Averages therefore were taken from "The Farm Management Handbook" (Craig, 2018) to calculate the missing data, so this is another area of uncertainty. Another section not included in the FCC or the Bangor Tool is crop use allocated for livestock requiring a percentage of crop removed and percentage of each grazing/forage between each category. This was calculated roughly by livestock units for each animal. When comparing manure management, Agrecalc also requires percentage of time at grass for in-bye fields and hill which is not included in the questionnaire for the Bangor Tool. Percentage at grass times were split equally between field and hill. This assumption could affect emission estimates slightly as they appear to have different activity factors (Sykes, 2019).

Embedded emissions also varied between tools. Another section which appears to be missing from the FCT is bedding. For some farms this can be a notable source of emissions and both Agrecalc and the Bangor Tool include a range of bedding types requiring a tonnage of each. When straw was the bedding in any of these farms it was included as feed straw in the FCC. This has potential to affect embedded emissions as feed and bedding straw usually have slightly different EFs. Purchased feed was better represented in the FCC. In both other tools, concentrated feed is categorised together for each animal type whereas the FCC gives a list of specific feed type. As this information was not known, it was assumed all concentrate feed was "18% fibre blend". When performing a brief sensitivity, the choice of feed type on the FCC did affect the emission estimate slightly. Fertiliser categories in the FCC also provide more detailed options giving fertiliser manufacturer and specific types as well as an option to provide custom blend in N (AN or Urea) %, phosphate % and potash %. The majority of fertilisers used on the 20 farms did not match with the specific fertilisers listed so custom blends were inputted. Agrecalc and the Bangor Tool use NPK values so these may vary slightly from the phosphate and potash values inputted.

Data input for sequestration calculations also differed between tools. The Bangor Tool and the FCC have more complex sequestration calculations and includes woodland, trees outside woodland, hedgerows and habitats; whereas Agrecalc only includes hectarage of woodland. Agrecalc also uses wider age ranges for trees and only differentiates between broadleaf and conifer whereas the Bangor Tool uses species specific sequestration rates as well as heights. The other tools require a similar level of detail regarding trees such as age, but the Bangor Tool includes tree hight and spacing. The FCC asks for a very specific detail on individual trees on the area under tree canopy in m^2. This data is not known for the trees on any farms therefore it was assumed to be an average of the woodland carbon code. This is another area of potential variation.

Finally, the FCC includes a number of sections which are not relevant to the 20 farms evaluated in this study. The data included in sections such as the inventory, materials and waste are less relevant to beef and sheep farms and are not included so significantly in Agrecalc or the Bangor Tool. Other sections like the distribution and processing seem to be out with the "farm gate" boundary. A report by DEFRA (2024) also found Agrecalc to be more suitable for use on beef and sheep farms than other carbon calculators.

3.4.2 Emissions estimation

Overall, at a farm level, average total emission estimates were lower from the FCC than both Agrecalc and the Bangor Tool. The FCC results do not disaggregate between carbon dioxide, methane or nitrous oxide and just present results in broad categories in tonnes of CO_2eq. Therefore, it is difficult to determine why the FCC underestimates emissions and where the differences in estimations arise. From the EFs alone, differences could be due to the use of IPCC (2019) Tier 2 livestock EFs which are not used in the other tools – Agrecalc uses IPCC (2006) Tier 1 and the Bangor Tool used modified IPCC (2019) Tier 1. The other main source of variation is likely to the lack of detail in data input for livestock categories compared to the other tools. The FCC also uses IPCC (2019) revised guidelines unlike Agrecalc which could be another factor in the notable differences in their estimates.

Agrecalc had the highest emission estimates among the tools evaluated. Agrecalc's emissions estimates were higher than those of the Bangor Tool mainly due to the higher CH_4 emission and lower carbon sequestration estimates. Both direct and indirect CO_2 for both tools were very similar. Both tools use DEFRA EFs for fuel and electricity, Agrecalc uses DEFRA (2011) and the Bangor Tool DEFRA (2007), but these EFs seem to be the same. In addition, the tools use different references for embedded emissions, with Agrecalc using Carbon Trust (2010) for fertiliser and FeedPrint (2012) for feeding and bedding, whereas the Bangor Tool uses fertiliser, bedding, and feeds EFs from averages from Edwards-Jones *et al.* (2009) and Jones *et al.* (2014). However, these EFs are very similar and therefore are unlikely to impact CO_2 estimates significantly.

The biggest source of variation in carbon footprints for all farms was CH_4 (Figure 3.2). The effect was more significant on some farms more than others and was mainly seen in enteric fermentation. This difference could be cause by a number of variables, the first and most obvious being the use of different enteric methane EFs. Agrecalc uses default IPCC (2006) Tier 2 calculations whereas the

Bangor Tool uses consolidated Wales specific EFs (Brown et al., 2017) aligned with full Tier 2 calculations applied in the National Inventory Report. The Bangor Tool also uses separate emission factors for hill, upland and lowland farms for both beef and sheep. The second and potentially most important reason for this difference is the calculation of animal numbers and liveweight. Not only do they require different data to calculate total animal numbers, as mentioned above each tool categories animals differently and as each category uses average liveweight, the total liveweights could differ significantly. For example, in the sheep section from the Bangor Tool, if lambs for replacement and lambs for slaughter are grouped together for input into Agrecalc, the average weight will be affected. GHG emission calculations and emission intensity calculations include average liveweight therefore these differences could influence results. The weights given in the Bangor Tool are also often averages for the breed and are input as the same at the start of the year and the end of the year and therefore make it hard to transfer to a different calculator. Additionally, a brief sensitivity analysisrevealed emission estimates were affected by performance data in Agrecalc e.g. calving percentage and average daily gain. As the Bangor Tool and the original data did not include this performance data, national averages were used for the Agrecalc input, which could have affected the resulting footprint.

When comparing N_2O emissions, a less significant difference is seen in estimates between the two tools (Figure 3.2). Both tools use Tier 2 N_2O EFs, however Agrecalc uses all IPCC (2006) Tier 2 EFs with manure N content values specific to Scotland, so it is unclear if these values are suitable for use on Welsh farms. The Bangor Tool uses IPCC (2019) Tier 2 calculations with consolidated Wales specific EF (Brown et al., 2017) for N_2O emissions per kg N applied which differentiates between hill, upland and lowland farms. Despite this difference, the 2019 revisions of IPCC Tier 2 methods do not affect many of the N_2O EFs significantly and therefore the difference is not seen in this footprint. Taft *et al.* (2018) suggest ideally, N excretion rates are calculated based on intake and national value of feeds on each farm as this would enable further sensitivity to mitigation options involving dietary change.

Soil emissions for each tool were similar, however again Agrecalc uses IPCC (2006) Tier 2 approach and does not include peat soils cultivation and mineralisation from land use change or change of management on existing land. The Bangor Tool uses IPCC (2019) Tier 2 soil EFs and additionally includes peat soil cultivation and mineralisation from land use change.

Carbon sequestration rates also varied significantly between the tools and affected the resulting net emissions markedly (Figure 3.2). Sequestration estimates were highest from the Bangor Tool across all farms for a number of reasons. Firstly, sequestrations calculation in the Bangor Tool are more complex, as mentioned above, they use individual tree species as well as more precise age ranges and heights. Secondly, the Bangor Tool includes more means of sequestration for example it includes hedgerows, individual trees and trees in row systems and field boundaries rather than just areas of pure woodland in Agrecalc. This has proved to be a problem with Agrecalc as one of the farm in this study produced an incorrect sequestration estimate of zero. Despite using the same range of sequestration options as the Bangor Tool and both using the Woodland Carbon Code calculations, the FCC still had notably different estimates. This is likely due to the sequestration from grasslands and soils which is included explicitly in the Bangor Tool and not the FCC.

A report by the Climate Smart Agriculture Wales project assessed currently available GHG calculators for use on Welsh farms. Although the report found no calculator to be fully suited for use across Welsh agriculture, the report made some important recommendations. Firstly, all CH_4 emissions should be based on the highest possible IPCC Tier for UK specific conditions which is employed in the Bangor Tool. Additionally, ideally the Tier 2 calculations would also be linked to feed types and quantities used on farm (Taft *et al.* 2018; DEFRA 2024). Secondly N_2O emissions should also be based on IPCC Tier 2 calculations using Wales-specific N excretion EFs like in the Bangor Tool. The FCC also claims to use IPCC (2019) Tier 2 calculations for livestock however the level of detail required for the tool suggests Tier 2 calculations are not possible. Another recommendation involved the inclusion of sufficient differentiation between feed and fertiliser types to enable the correct EFs to be applied, Agrecalc performs well in this area providing 48 different options for animal feeds. The FCC also provides a large range of feed types however, in many cases, did not fit what was used in the farms in this study- (as many were dairy feed blends). Waste disposal was one area which the report suggested to exclude as it may be out-with of the farm boundary as well as being an additional burden for farmers to supply data. Agrecalc and the FCC includes waste, however, the entry of this data is not essential. Finally, the report recommends an introductory page providing an overview of farm components included in the footprint in an easily understandable visual format as well as the tool itself operating in a logical order with a navigable interface that provides clear information on the input data being used.

It is important to note the tools evaluated in this study were developed (and are therefore fit) for different purposes. Both Agrecalc and the FCC are online tools that are targeted at farmers and advisors whereas the Bangor Tool is an Excel-based tool that was designed for research purposes. Agrecalc and the FCChave a user-friendly interface with clear descriptions and guidance on each page of data entry. As the Bangor Tool is an Excel-based tool, its current form is not easy to navigate and therefore is not as appropriate for farmers to use directly. Additionally, as a research tool, the Bangor Tool aims to provide a higher level of accuracy and therefore requires significantly more detailed input data compared to the other tools. Consequently, not every farmer possesses such detailed data, necessitating more assumptions. However, this also means researchers have greater control over their input data, making it easier to model different scenarios. The Bangor Tool's excel format also enables researchers to trace formulas and easily identify the calculations behind the results. Finally, as these tools were designed for different purposes, their results and outputs are displayed in different formats. Agrecalc and the FCC provide users with a number of simple graphs and tables to display their results whereas the Bangor Tool's results are simply displayed as values over a number of Excel sheet which would not be easy to interpret for most farmers or even advisors. Moreover, Agrecalc generates comparison reports that present farmers and advisors with their carbon footprint results alongside farms with similar enterprise types. These differences in functionality between the tools makes direct comparisons challenging, particularly in the case of the Bangor Tool.

3.4.3 Sensitivity to mitigation options

In order to reduce emissions and reach "Net Zero" targets, it is vital carbon calculators allow the modelling of different mitigation scenarios. Tool sensitivity to mitigation options (MOs) is dependent on their calculation methods including the level of detail and the scope of emissions source and sequestration sinks. All tools have similar potential sensitivities to detect the impact of MOs. Some types of MOs are more easily detected than others, for example a reduction in total fuel use will most likely be detected by both tools. However, if this data is changed using the number of hours or distance driven, these changes may be less obvious. Similar to fuel use, most changes in inputs will be detected by a change in embedded emissions in all calculators. Other types of MOs are unlikely to be detected by either model in their current form; a good example of this is feed supplements which do not have their own EFs yet. Similar MOs such as animal diet may be detected indirectly by increases in productivity and some dietary MOs may be detected if specific feed types are used which have different EFs. Additionally, the models may be sensitive to detect GHG reductions from feed sources, for example if home grown feed replaces imported feed, their embedded emissions will be reduced. Only some changes in fertiliser management are likely to be detected by both models, variables like quantity and type of fertiliser would have visible impact, however the timing of application will only potentially be detected indirectly via increase nutrient use efficiency. Most MOs will only be detected indirectly, especially those relating to animal breeding and husbandry which will be shown through their effects on increased production and decreased time on farm and animal numbers. Taft *et al.* (2018) state Tier 2 approaches may be more likely to detect impacts of MOs indirectly suggesting the FCC and the Bangor Tool may be more accurate for these MOs. Changes in land management are mainly detected indirectly by Tier 2 calculations through animal numbers, time on farm and nutrient intake and possibly fertiliser and possibly fertiliser soils and embedded emissions. Tier 1 also may detect indirectly by the production effects listed above only so the Bangor Tool may be more suited to changes in land management. Manure management MOs are detected similarly to land management, indirectly by Tier 2 calculations by reducing mineral N inputs and increasing productivity.

Taft *et al.* (2018) highlighted key scenarios in which most commercially available tools including Agrecalc and the FCC do not detect the impact of mitigation options. The first being where MOs are related to timing such as the timing of fertiliser or manure application. The second already mentioned above, MOs which do not have their own EF yet, for example feed supplements. Another exception is where MOs are implemented for example how renewable energy produced on farm is used, if it on farm or exported. Finally, the last group of MOs not detected are those relating to land use change and sequestration as the complexities of soil is poorly understood and therefore not included fully. Soil management practices that for example affect soil compaction would unlikely be detected even though it could interact with fertiliser and manure application. In terms of soil sequestration, the Bangor Tool appears to provide a more comprehensive and explicit calculations, therefore it may be better suited to model mitigation scenarios involving changes land use or soil management. Additionally, as the Bangor Tool and the FCC include more means of sequestration, it will also be more effective for offsetting options for example planting hedgerows will be detected by the Bangor Tool and the FCC but not by Agrecalc. Agrecalc omits any uncertain aspects of sequestration estimates and therefore reduced sequestration estimates and decreases potential sensitivity to any sequestration related MOs.

3.5 Conclusions

In conclusion, both tools were able to calculate full carbon footprints for all 20 farms across Wales. The choice of tool is dependent on the specific purpose of the study and level of detail of available data. Despite the two tools resulting in notably different farm and product footprints, their use separately is still valid when benchmarking within (over different years) and between farms. Caution should be exercised when comparing footprints from different tools, as this study has clearly demonstrated the effects of tool choice on the emission estimates generated. Due to the inherent differences between the tool's approaches in their use of different EFs and assumptions, these tools are not directly comparable. Comparison between the FCC and the other tools is additionally difficult due to the lack of detail in the results presented and the lack of disaggregation between GHGs from the FCC.

In summary, the FCC had the least detailed data collection process with the exception of its sequestration section. This means this tool took the least time to complete and therefore might appeal more to some farmers. The FCC is applicable to all farm types however Agrecalc appears to be more suited for use on beef and sheep farms. From the data analysed, Agrecalc seems to require less detailed data in some areas than the Bangor Tool and is therefore likely to be more widely applicable to most farms. Agrecalc also appears to mirror Inventory reporting more accurately which could be an important factor when looking at footprints in relation to government targets. The Bangor Tool however outperforms Agrecalc in other areas such as sequestration, calculating sequestration rates more accurately where the data is available. The Bangor Tool may be more suited for use specifically in Wales due to the EFs used and also includes more detailed EFs depending on the type of farm, e.g. hill, upland and lowland. Finally, the Bangor Tool is updated to the revised IPCC (2019) guidelines as recommended in Taft *et al.* (2018) report whereas currently available version of Agrecalc still uses 2006 guidelines. However, Agrecalc is flexible in its design allowing room for future expansion and will soon be updated to the IPCC (2019) revisions which will be able to be applied automatically to previous farm reports giving an added benefit of avoiding repeated data entry. A "hybrid" version of these two models using Agrecalc's emission estimates and the Bangor Tool's sequestration calculations may be the best option for use on Welsh farms.

3.6 References

Brown, P., Broomfield, M., Cardenas, L., Choudrie, S., Kilroy, E., Jones, L., Passant, N., Thomson, A., Wakeling, D., 2017. UK Greenhouse Gas Inventory, 1990 to 2015: Annual Report for submission under the Framework Convention on Climate Change. Department for Business, Energy & Industrial Strategy.

Blonk, H., van Passen, M., & Broekema, R., 2020. GFLI methodolgy v1 2020. Available at: https://globalfeedlca.org/gfli-database/ (accessed: 10.05.21)

Carbon Trust, 2006. Carbon Footprint Measurement Methodology. Version 1.3. London: The Carbon Trust. Available at: https://semspub.epa.gov/work/09/1142519.pdf (accessed: 10.05.21)

Climate Change Committee, 2020. The Sixth Carbon Budget The UKs path to Net Zero. Available at: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf

Craig, K., 2020. Farm Management Handbook 2020/21. SAC Consulting. FAS.544. https://www.fas.scot/publication/fmh2021/

DEFRA, 2024. Harmonisation of Carbon Accounting Tools for Agriculture - SCF0129 (EVID4 Evidence Project Final Report). RSK ADAS Limited, Department for Environment Food & Rural Affairs. https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=20967%0A

DEFRA, 2012. Greenhouse gas reporting - Conversion factors. GOV.UK. URL https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2011

DEFRA, 2007. Guidelines to Defra Greenhouse Gas (GHG) Conversion Factors for Company Reporting. London, UK: Department for Environment, Food and Rural Affairs.

Edwards-Jones, G., Plassmann, K., Harris, I.M., 2009. Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK. The Journal of Agricultural Science 147, 707–719. https://doi.org/10.1017/S0021859609990165

FAO, 2006. Livestock's long shadow. Environmental Issues and Options., Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2013. Mitigation of greenhouse gas emissions in livestock production: a review of technical options for non-CO2 emissions, FAO animal production and health paper. Food and Agriculture Organization of the United Nations, Rome.

Hyland, J.J., Styles, D., Jones, D.L., Williams, A.P., 2016. Improving livestock production efficiencies presents a major opportunity to reduce sectoral greenhouse gas emissions. Agricultural Systems 147, 123–131. https://doi.org/10.1016/j.agsy.2016.06.006

IPCC (2006). International Panel for Climate Change guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). IGES, Japan.

IPCC (2019). 2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Intergovernmental panel on climate change: Japan.

Janssens, I.A., Freibauer, A., Schlamadinger, B., Ceulemans, R., Ciais, P., Dolman, A.J., Heimann, M., Nabuurs, G.-J., Smith, P., Valentini, R., Schulze, E.-D., 2005. The carbon budget of terrestrial ecosystems at country-scale – a European case study. Biogeosciences 2, 15–26. https://doi.org/10.5194/bg-2-15-2005

Jobling, J., Pearce, M.L., 1977. Free Growth of Oak. Stationery Office Books, London.

Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of lamb: Sources of variation and opportunities for mitigation. Agricultural Systems 123, 97–107. https://doi.org/10.1016/j.agsy.2013.09.006

Kool, A., Marinussen, M., Blonk, H., Consultants, B., 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization 20.

Milne, R., Brown, T.A., 1997. Carbon in the Vegetation and Soils of Great Britain. Journal of Environmental Management 49, 413–433. https://doi.org/10.1006/jema.1995.0118

Read, Freer-Smith, Hanley, West, Snowdon, 2009. Combating climate change: a role for UK forests : an assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change : the synthesis report. Stationery Office, Edinburgh.

Redman, G., 2018. The John Nix Pocketbook for Farm Management: 49th Edition for 2019, 49th edition. ed. Agro Business Consultants Ltd.

Sykes, A., Topp, K., Wilson, R., Reid, G., Rees, B., 2017. A comparison of farm-level greenhouse gas calculators in their application on beef production systems. Journal of Cleaner Production 164. https://doi.org/10.1016/j.jclepro.2017.06.197

Taft, H., Chadwick, D., Styles, D., Kipling, R., Newbold, J., Moorby, J., 2018. A review of greenhouse gas calculators for use in the Welsh agricultural sector, A Climate Smart Agriculture (Wales) Report.

Chapter 4 Net Zero requires ambitious greenhouse gas emission reductions on beef and sheep farms coordinated with afforestation and other land use change measures

L.C. McNicol, N.G. Williams, D. Chadwick, D. Styles, R.M. Rees, R. Ramsey, and A.P. Williams

Abstract

The UK Climate Change Committee has recommended a 64% reduction in greenhouse gas emissions from the agriculture and land-use sector to meet the 2050 Net Zero target in the UK. However, it is unclear how this reduction can be achieved at a farm level.

Using detailed real farm data and novel modelling approaches, we investigated the management interventions and afforestation that would be required to deliver Net Zero within the farm boundary. Baseline carbon footprints were calculated for twenty Welsh beef and sheep farms using the Agrecalc carbon calculator, whilst carbon sequestration was estimated using Bangor University's Carbon Footprinting Tool. Scenarios were created to determine the emissions reductions achievable on each farm through implementation of cost-effective mitigation measures. Mitigation measures and their abatement potentials were sourced from the most recent UK Marginal Abatement Cost Curve, which allow emissions to be reduced mostly through improvements in efficiency thus maintaining the production of the system. Area footprints were calculated for production, with and without offset (afforested) areas needed to achieve Net Zero.

Emission reductions following the implementation of cost-effective mitigation measures averaged 28% across all farms, ranging from 19 to 35%. The woodland needed to offset the remaining emissions to achieve Net Zero ranged from 8 to 85% of the farm area, with an average 38%. This offset area was equivalent to on average 17.4 m^2.yr kg^{-1} deadweight (carcass weight). Apparent area efficiency decreased when the offset area was accounted for, however, the ranking of farms in terms of efficiency was largely unaffected. Mitigation scenarios rely on several assumptions and these need to be refined to accurately inform Net Zero pathways.

Based on the results for these study farms, our modelling indicates that even after implementation of ambitious mitigation across beef and sheep farms, large-scale land use change will be required to achieve Net Zero at an individual farm-level. However, this reform could lead to the unintended consequence of displacing production to less efficient systems and increase overall emissions.

Instead, we advocate a combined approach of carbon and land footprints that could help to identify farms on which either food production or carbon removals should be prioritised to move the industry towards achieving Net Zero at a sectoral, regional or national level.

4.1. Introduction

In 2019, the UK was the first country to introduce legislation to deliver Net Zero greenhouse gas (GHG) emissions by 2050. The Net Zero target is defined by the Intergovernmental Panel on Climate Change (IPCC) as the point at which "anthropogenic emissions are equal to anthropogenic removals" (IPCC, 2018), which will require considerable mitigation efforts from many sectors, including agriculture. Agriculture is responsible for 10% of the UK's total GHG emissions (BEIS, 2022). Livestock make the largest contribution to these emissions, mainly in the form of methane (CH_4) from enteric fermentation within ruminant animals, and nitrous oxide (N_2O) from soils following application of fertiliser (Cardenas *et al.*, 2010) or manure (Thorman *et al.*, 2020) and urine deposition by grazing livestock (Chadwick *et al.*, 2018).

For the UK to reach Net Zero, major innovation and changes to UK farming and land use will be required (Climate Change Committee, 2020a). Reducing GHG emissions from livestock production has natural limits due to the biological processes involved in enteric fermentation. The efficiency of these processes can be improved, and technology exists to reduce these emissions, but they cannot be completely eliminated (FAO, 2013). Therefore, achieving Net Zero on farms will only be possible by offsetting residual emissions through GHG removal mechanisms (such as carbon sequestration).

The biological processes mentioned above not only make some GHG emissions from agriculture hard to reduce but also make them hard to quantify, and result in farm emissions estimates having a high level of uncertainty (Rees *et al.*, 2020). However, accurately quantifying GHG emissions from livestock production systems is an important first step towards reaching current policy targets. Recently, the UK adopted a combination of IPCC Tier 2 and Tier 3 methodologies for CH_4 and N_2O from agriculture, which use country-specific emission factors (EFs) to account for GHGs in the National GHG Inventory and forms a basis for improved mitigation policy (IPCC, 2019). Many GHG accounting tools are available to quantify GHG emissions at the farm level (Sykes *et al.*, 2017; Taft *et al.*, 2018). These tools allow year-on-year comparisons and benchmarking with other farms, which can highlight opportunities for mitigation measures, increased production efficiency, and sharing of good practice.

The UK Climate Change Committee set out a "Further Ambition" scenario for agriculture, land use and peatlands in their 2019 Net Zero report, which specified emissions reductions of 64% by 2050 compared with 2017 (Stark *et al.*, 2019). Although there is not a specific target for livestock sectors, it is presumed this should be in line with the wider agricultural sector. A 64% reduction from 2017 livestock emissions would mean an 37 Mt CO_2e reduction (Climate Change Committee, 2020b). How this is achieved depends on the uptake of GHG mitigation measures. A range of mitigation measures are currently available for the livestock sector, all with varying abatement potentials and cost-effectiveness (Eory *et al.*, 2020, 2015); the uptake for some of which has been incentivised or grant-aided through various schemes e.g. the Farming Investment Fund in England (UK Government, 2021), Small Grants – Efficiency scheme in Wales (Welsh Government, 2022a) and Agri-environment Climate Scheme in Scotland (Scottish Government, 2022).

Mitigation options include measures which address fuel and energy usage, for example, increasing fuel efficiency by actively monitoring fuel use, regular vehicle maintenance and improved driving techniques (Pellerin *et al.*, 2013). Increasing fuel efficiency has a relatively low maximum technical abatement potential (MTP) for UK agriculture, estimated at 75 kt CO_2e yr^{-1} (with interactions) (Eory *et al.*, 2015). More effective mitigation options could include measures relating to animal management such as improving breeding in cattle by directly measuring carcass traits (Bioscience Network Limited, 2012) or improving the health status of animals by targeting specific diseases to reduce morbidity and mortality (Bartley *et al.*, 2016). These measures have the additional benefit of a negative net implementation cost as well as having comparatively high MTP for UK agriculture at 101 kt CO_2e yr^{-1}, 784 kt CO_2e yr^{-1} and 363 kt CO_2e yr^{-1} for cattle breeding, cattle health and sheep health, respectively (Eory *et al.*, 2015). Another measure which could result in net profit is through better animal nutrition e.g. improving the composition of animal diets through forage analysis or improving grazing management (Rooke *et al.*, 2016), which could result in a MTP for UK agriculture of 98 kt CO_2e yr^{-1} in the UK (Eory *et al.*, 2015). Other measures which relate to animal nutrition include feed additives, with one of the most promising being 3-nitrooxypropanol (3NOP), a chemical which inhibits enzymes in the rumen thereby decreasing CH_4 production (Duin *et al.*, 2016). Although not included in the UK's most recent MACC, Eory *et al.* (2020) estimated 3NOP could reduce emissions by 0.855 t CO_2e $head^{-1}$ yr^{-1} in Scotland. Manure management is another area which could be targeted to reduce emissions. For example, using an N planning tool or decreasing the margin of error on application of both synthetic and organic N sources could reduce N_2O emissions. However, there may be a trade-off between abatement potential and cost, manure planning can save money but only has an estimated MTP of 18 kt CO_2e yr^{-1} for UK agriculture whereas low-emission manure spreading is one of the most expensive mitigation measures for beef and sheep farms but it has a high MTP of 163 kt CO_2e yr^{-1} (Eory *et al.*, 2015). Finally, mitigation measures could involve altering land management, e.g. inclusion of legumes such as white (*Trifolium repens*) or red (*T. pratense*) clover in grass mixtures. Legumes fix nitrogen from the atmosphere, reducing the reliance on nitrogen fertiliser (Carswell *et al.*, 2019). This means legumes can be introduced a negative net cost as well as having an abatement potential 170 kt CO_2e yr^{-1} (Eory *et al.*, 2015). Many of these measures represent potential co-benefits, so-called "win-win" scenarios; for example, improved production efficiencies not only reduce GHG emissions from livestock but can also increase animal- or area-based yields. Similarly with increasing clover cover, as well as reducing

CO_2 and N_2O emissions associated with fertiliser production and application, they are also likely to increase digestibility and crude protein of pasture, therefore increasing animal yields (Jensen *et al.*, 2012).

Afforestation will likely play a vital role in removing GHGs from the atmosphere (Stark *et al.*, 2019). Agroforestry, whereby woody biomass is integrated into agricultural systems (in the form of silvopasture, hedgerows, shelterbelts and row systems) could increase on-farm sequestration and deliver other environmental benefits without adversely affecting farm production (Jordon *et al.*, 2020). Another option for GHG removal is increasing soil carbon sequestration. There are numerous management options that can enhance sequestration of carbon in soils, however, the capacity to make significant further gains may be limited in many agricultural soils (Poulton *et al.*, 2018), particularly under permanent grasslands as they are often likely be at a state of carbon equilibrium (Smith, 2014). Moreover, these management practices must be sustained to maintain soil organic matter levels and carbon sequestration.

The aims of this study were to explore the opportunities currently available to both reduce GHG emissions and enhance woodland sequestration on beef and sheep farms. Using real farm data, best available knowledge, and a novel combination of accounting tools, we investigated the management interventions and afforestation that would be required to deliver Net Zero for each farm. Using Wales as a case study, we explored various scenarios to achieve Net Zero without loss of production, for three distinct livestock systems (hill, upland and lowland).

4.2. Methods

4.2.1. Farm data collection

This study focuses on the red meat sector in Wales, which is representative of many temperate farming systems based on grass-fed livestock production (DEFRA, 2021). Red meat accounts for 41% of the value of Welsh agricultural production, almost double the share for the rest of the UK (DEFRA, 2021). Data were collected from twenty farms that were selected to represent a cross-section of Welsh agricultural systems including hill, upland and lowland, and those rearing sheep, cattle or both. Participating farms were categorised into hill (*n*=11), upland (*n*=6) and lowland (*n*=3) farms based on the area where the majority of their land fell. The majority of farms were a mixture of both beef and sheep enterprises, with three being sheep-only. Enterprise types varied between farms for cattle; for example, a mixture of spring and autumn calving suckler herds, breeders, and finishers. Similarly, with sheep systems there was a mixture of early and late lambing flocks, those that purchased or sold store lambs, and finishers.

Data were self-reported by participating farmers using an Excel template in 2020, and, in most cases, follow-up emails and calls were made to participants to verify the information provided. These data were then cross-validated with national data from the Survey of Agriculture and Horticulture (Welsh Government, 2021a) and the British Survey of Fertiliser Practice (DEFRA, 2022) to ensure representativeness of beef and sheep systems in Wales (Table A 4.1). Three years' of data were available for eight farms, two years for three farms, and one year for a further nine farms – datasets from multiple years were averaged for each farm, where possible. In cases where specific data were difficult to obtain or where any data were missing, recently published UK data or standardised estimates were used in their place (Craig, 2020). For example, many participating farms did not have detailed information on their silage production, so total silage yields were assumed to be 38 t ha^{-1} over two cuts at 25% dry matter (Craig, 2020). Additional farm data are summarised in Table A 4.1.

4.2.2. Baseline footprint calculations

4.2.2.1. Emission estimates: Agrecalc

Reported farm activity and land use data were used to calculate baseline carbon footprints using Agrecalc (Agricultural Resource Efficiency Calculator). This was developed by Scotland's Rural College and has been found to be amongst the best-performing carbon accounting tools in terms of transparency, methodology and allocation for use on UK farms (Sykes *et al.*, 2017). Agrecalc methodology is based on GHG reporting guidelines published by the IPCC for National Inventories (IPCC, 2019). The tool uses mainly IPCC (2019) Tier 2 methodologies, and conforms to PAS2050 supply chain standards (2011). IPCC (2019) Tier 2 country-specific calculations were employed for all livestock enteric CH_4 and N_2O emissions from excreta deposited on grazing land. Methane and N_2O emissions from manure management also use IPCC (2019) Tier 2 methods which take into account dietary characteristics and climate. Direct N_2O emissions from soil following fertiliser and manure application follow IPCC Tier 2 guidelines. IPCC (2019) Tier 1 are employed for N_2O emissions from crop residues and indirect N_2O emissions related to volatilisation and leaching. Energy use emission estimates were calculated using EFs from DEFRA (2012). Embedded fertiliser emissions were calculated using values described by Kool *et al.* (2012) and imported feed rations from the Dutch Feedprint database (Vellinga *et al.*, 2013). In cases of co-production (e.g. meat and wool), Agrecalc allocates emissions on an economic basis. A full list of EFs can be found in Table A 4.2.

Standardised emissions estimates were reported in units of carbon dioxide equivalents (CO_2e) using global warming potential over 100 years (GWP). Agrecalc uses GWP values from the fourth assessment report (AR4) which are consistent with National Inventory reporting. For CH_4, the value of GWP_{100} is

25 and for N_2O the value is 298 (IPCC, 2007). Model outputs are expressed as both total emissions per farm and GHG emissions per unit of product i.e., kg CO_2e kg^{-1} of deadweight (dwt) (which equates to carcass weight) post slaughter. Baseline farm data were also expressed as production area footprints, defined as the area of land (in m^2) required to produce 1 kg of dwt per annum, i.e. $m^2.yr\ kg^{-1}$ dwt.

4.2.2.2. Sequestration estimates: the Bangor Tool

The Bangor University Carbon Footprinting Tool (Edwards-Jones *et al.*, 2009; Hyland *et al.*, 2016; Jones *et al.*, 2014) was selected for calculating carbon sequestration, as it includes the most comprehensive set of sequestration calculations (Sykes *et al.*, 2017; Taft *et al.*, 2018), including hedgerows, individual trees, trees in silvicultural systems and field boundaries, as well as areas of pure woodland. Additionally, the Bangor Tool includes potential grassland soil sequestration in its calculations. In terms of woodland, the tool uses yield values from the Woodland Carbon Code (WCC) (Forestry Commission, 2018). All biomass conversion and expansion factors are taken from IPCC (2006). For conifers, it uses mostly IPCC Tier I values, and for broadleaf, conversion factors were taken from Milne and Brown (1997), with above to below ground biomass ratios from Mokany *et al.* (2006). Hedge sequestration is calculated as the area not cut in the sample year (as they are considered to be in equilibrium (Axe, 2018)) and biomass sequestration rates are assumed to be equivalent to short rotation coppice using values from Laureysens *et al.* (2003).

In terms of soil carbon sequestration, all values were taken from Janssens *et al.* (2005), using the IPCC Tier 1 methodology. Under Tier 1 methodology, soil carbon in mineral soil under woodland is assumed to remain unchanged with management, due to incomplete scientific understanding (IPCC, 2006). For organic soils under woodland, only C emissions due to drainage of forest organic soils are considered under Tier 1(IPCC, 2006). For grassland soil sequestration rates, the Bangor Tool uses national net ecosystem C change under UK grasslands taken from Janssens *et al.* (2005). A full list of references for sequestration can be found in Table A 4.3.

4.2.3. Mitigation scenario modelling

Scenarios were created to determine the emission reductions possible when a range of mitigation measures were implemented on each farm and the area of woodland needed to offset the residual emissions from each farm was calculated. Area footprints were calculated for production, with and without the offset (afforested) area needed to achieve Net Zero. Between five and seven mitigation measures were implemented on each farm depending on their applicability to the individual farms.

Mitigation measures and initial abatement potentials with abatement cost of < £224 t CO_2e^{-1} were sourced from the most recent UK Marginal Abatement Cost Curve (MACC) (Eory *et al.*, 2015) (Table 4.1). It was assumed all measures were implemented in full across the study farms, and abatement was calculated in terms of annual emissions reduction at farm (or product) level. Measures were implemented in a sequential approach which aimed to minimise any potential influence of the order of measures. For example, any measure which reduced synthetic (fertiliser) N use, e.g. introducing legume-grass mixtures, were implemented before nitrification inhibitors, and measures which affected livestock emission intensities were implemented before measures such as CH_4 inhibitors or slurry acidification. Although cost was not directly assessed in this study (outside of scope), mitigation measures were chosen from the MACC to ensure that they had previously been deemed as cost-effective and practically feasible (Eory *et al.*, 2015).

Table 4.1. Mitigation measures taken from the UK's most recent Marginal Abatement Cost Curve (MACC) and the abatement potentials used in this study (Eory *et al.*, 2015)

Mitigation measure	Abatement potential
Energy and fuel	
Behavioural change in fuel efficiency	20% reduction in fuel use
Land and Nutrient Management	
Improved synthetic N use	10 kg N ha^{-1} synthetic N use
Legume-grass mixtures	25, 50 or 75% reduction in synthetic N use for hill, upland and lowland farms, respectively
Nitrification inhibitors (dicyandiamide)	66, 46 and 56% reduction in N_2O associated with synthetic N, cattle urine and cattle slurry, respectively
Animal management	
Improved cattle and sheep health	5% reduction in sheep emission intensity 6% reduction in beef emission intensity
Selection for balanced breeding goals in beef cattle	6% reduction in beef emission intensity
Manure management	
Improved organic N use	14.4 kg N ha^{-1} synthetic N use
Slurry acidification	75% reduction in manure CH_4 conversion factor
Nutrition and feed additives	
Improved beef and sheep nutrition	2% increase in digestibility of all feed
3NOP as feed additive	20% reduction in the enteric CH_4 conversion factor

Although Agrecalc accounts for direct effects of some mitigation measures such as reduced fertiliser and fuel use, the remaining mitigation options exhibit indirect effects that may not be directly represented in farm-level emission calculators. For example, mitigation measures relating to animal breeding and husbandry manifest through increased production and are therefore likely to translate to reduced emissions intensities (and possibly reduced national emissions, at a given level of output) but not necessarily to reduced emissions at farm level (because production may increase). In this study, production was held constant and any increases in productivity following the implementation of mitigation measures were assumed to be translated into a reduction in emissions per hectare or emissions intensities. This is a model simplification but enables more consistent comparison across farms and measures, and is an approach used in other studies (ADAS UK Ltd, 2014; Rees *et al.*, 2020). Similarly, feed additives or specific feed types do not have their own EFs and cannot be implemented in Agrecalc. Such mitigation measures effects were estimated through *post-hoc* calculations. Where possible, abatement potentials were estimated using calculations which reflect farm types and individual farm differences. A flow diagram for each mitigation measure was created to ensure all direct and indirect effects were considered (see Figure 4.1 as an example). For robustness, only mitigation measure effects with a high level of certainty in abatement potential were considered i.e., effects for which published scientific literature was in general agreement. Effects with a higher level of uncertainty were excluded from these calculations, for example, any yield effects following improved organic nitrogen (N) use as this is highly dependent on the initial N rate.

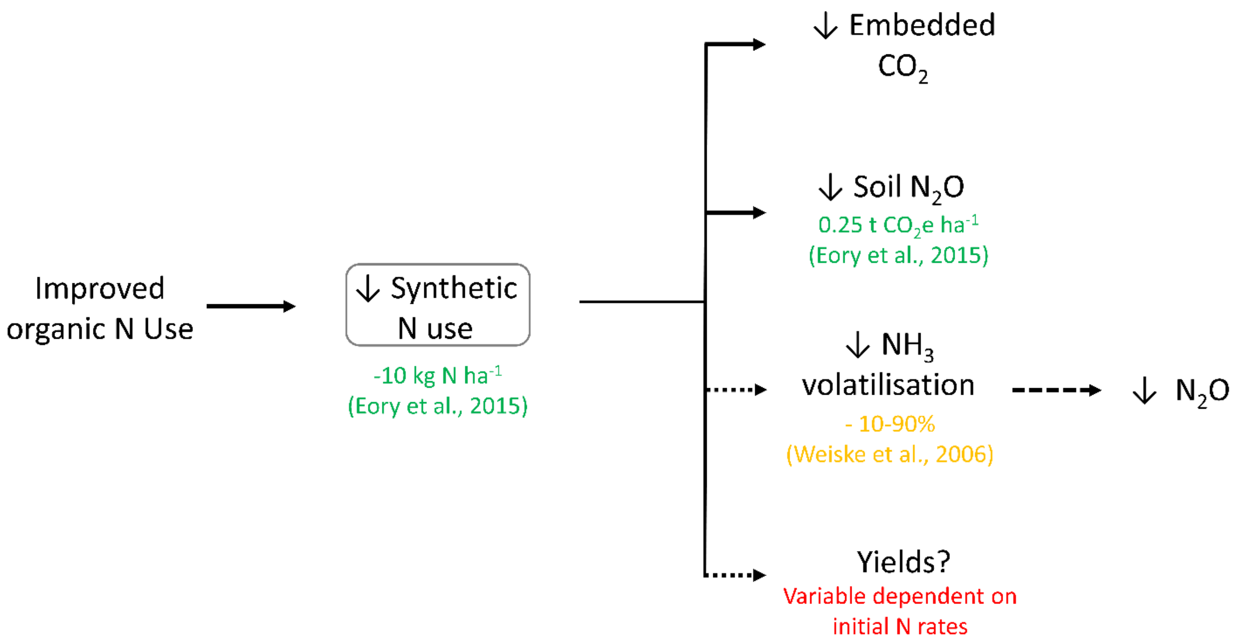


Figure 4.1. An example of a flow diagram created for the mitigation measure improved organic N use, e.g. livestock manure, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials. Circled text represents the input variable.

4.2.3.1. Mitigation measures

The UK MACC (Eory *et al.*, 2015) includes a list of 24 mitigation measures based on their estimated abatement potential, cost, practical feasibility, and risk of negative co-effects (trade-offs). However, many of these mitigation options are not applicable to beef and sheep farms in this study due to the small areas of arable land farmed, the absence of reseeding, and many farms being in "less favourable areas" (typically hill and upland) with grazing animals receiving little to no concentrates. Therefore, there were thirteen remaining mitigation measures applicable to these farms, as follows:

Energy and fuel

Behavioural change in fuel efficiency

This measure involves the uptake of a change in behaviour by farm workers to actively manage fuel use, to carry out regular maintenance of all farm machinery and to improve driving style. It was assumed that a combination of improved energy management and improved engine adjustments resulted in a 20% reduction in fuel use (Pellerin *et al.*, 2013).

Land and nutrient management

Improved synthetic N use

This involves a reduction in N fertiliser use by: using an N-planning tool; reducing the margin for error for N fertiliser application or not applying the fertiliser in waterlogged conditions. Through these measures, it was assumed a reduction of 10 kg N ha^{-1} in synthetic N use could be achieved on average on participating farms (Eory *et al.*, 2015).

Legume-grass mixtures

This measure increases the legume-grass mix area opposed to grass only area, and the proportion of white clover (*T. repens*) in mixed swards. Assuming favourable soil conditions (AHDB, 2022), legumes can fix N from the atmosphere, therefore in *legume-grass mixtures*, the leguminous crops can provide part of the grass's N requirements (as well as meeting their own requirements), reducing the need for N fertilisation. As data on clover cover of these farms was not known, it was assumed that grass swards had little to no legumes in the baseline situation. Before the mitigation effects were considered, the recommended lime application needed for the farms' dominant soil type was calculated using the National Nutrient Management Guide – RB209, assuming a soil pH value of 5.7 (AHDB, 2022). Abatement potentials for legumes were disaggregated for different altitudes so it was assumed that legumes could be introduced to 25%, 50% and 75% of improved grassland for hill, upland and lowland farms, respectively. It was then assumed the introduced level of clover cover could completely satisfy the grass's N requirement, contributing to a 25, 50 and 75% reduction in synthetic N applications for hill, upland and lowland, respectively. This reduction in synthetic N use reduces N_2O accordingly as well as the embedded emissions associated with the avoided N fertiliser manufacturing.

Nitrification inhibitor – Dicyandiamide

Nitrification inhibitors (NIs) like *dicyandiamide* (DCD) reduce N_2O emissions by altering biochemical processes, decreasing the activity of nitrifier bacteria, prolonging the retention of ammonium N in soil and increasing N use efficiency (Singh and Verma, 2007). NIs can be applied to the soil together with liquid fertilisers (Misselbrook *et al.*, 2014), applied as a coating on granular fertilisers (Abalos *et al.*, 2014) or mixed into slurry before application. Additionally, they can be spread onto pastures to reduce emissions from N fertilisers (Cardenas *et al.*, 2019). To calculate NI effects, any ammonium nitrate-based fertilisers were first switched to urea-based fertilisers (which generally have lower N_2O EFs) (Smith *et al.*, 2012) then were applied with DCD as well as spread on grazed pastures. NIs are assumed to reduce N_2O emissions associated with synthetic N by 66% (Cardenas *et al.*, 2019). In this study, DCD also reduced N_2O emissions from cattle urine by 46% (Chadwick *et al.*, 2018) and cattle slurry by 56% (Misselbrook *et al.*, 2014). Due to a lack of well-established literature, reductions in N_2O from sheep urine were not included in these calculations, however, current evidence suggests this would be similar to cattle urine.

Animal management

Improving cattle and sheep health

Improving animal health could lead to significant reductions in emissions intensity (EI) by improving the feed conversion ratio of animals and reducing the number of replacements needed through improved fertility and reduced mortality. In this study, direct measures for ten common cattle diseases in the UK resulted in a 6% reduction in EI (ADAS, 2014). For sheep, prophylactic disease treatment for all common ailments resulted in a 5% reduction in EI compared to only treating for some common ailments (Stott *et al.*, 2010), where it was assumed that all study farms currently treated for some common ailments. A simplified reduction in EI was used, where production levels were held constant to avoid more uncertainty by altering multiple variables.

Selection for balanced breeding goals in beef cattle

This measure relates to the broader uptake of genetic improvement in beef cattle. Although cattle breeding is largely based on the cattle breeding index, carcass traits are often not directly recorded in the UK and selection is based on liveweights, measurements of muscle and fat depth and visual assessments (Beef Improvement Federation, 2018). Selection through directly measuring carcass traits could increase the rate of genetic improvement. In this study, recording feed intake and carcass traits of progeny reduced cattle EI by 6% (Bioscience Network Limited, 2012).

Manure management

Improved organic N use

Improving the application of organic N (manures and slurries) can reduce emissions from spreading manure but can also have a benefit through a reduction in the amount of N fertiliser application. This measure includes the use of N-planning tools and low emission spreading to reduce N losses from ammonia (NH_3) volatilisation and reduce risk of leaching and run-off and increase the N utilised by crops. Here, a simplified approach is used where abatement is measured by the reduction in synthetic N use rather than fully accounting for changes in organic and synthetic N use. The combination of better manure use through improved planning of organic N use and switching to low emission spreading technologies was assumed to reduce synthetic N use by 14.4 kg N ha^{-1} (Pellerin *et al.* 2013). This measure was not implemented in any of the same mitigation scenarios as *improved synthetic N use* to avoid any additive effects of combining these measures.

Slurry acidification

Slurry acidification involves adding strong acids like sulphuric acid or hydrogen chloride to slurry in-house, in storage tanks, or before field application (Fangueiro *et al.*, 2015). This aims to achieve a target slurry pH of 5.5 to 6.0 as a means of reducing NH_3 emissions, but CH_4 emissions from slurry stores are also significantly reduced (Sokolov *et al.*, 2021). In the current study, when slurry was acidified, the manure CH_4 conversion factor was reduced by 75% (Eory *et al.*, 2015). A 70% decrease in the fraction of the manure N which is volatilised as NH_3 was also expected following acidification, however due to inconclusive evidence on the effect of acidification after spreading, the reduction in both direct and indirect N_2O emissions was excluded.

Nutrition and feed additives

Improving beef and sheep nutrition

This measure describes the improvement of ration nutritional values (i.e., digestibility of the ration), in order to improve yield and reduce enteric CH_4 emissions. It involves improving the composition of the diet, complemented with forage analysis and improved grazing management. Specifically, digestibility of animal feed can be increased in a number of ways such as grazing younger grasses, harvesting grass earlier and reseeding grass varieties with a higher digestibility (Bruinenberg *et al.*, 2002). In line with the MACC analysis (Eory *et al.*, 2015), in this study, improved diet formulation and grazing management was assumed to increase the digestibility of roughage and concentrates by 2% of their original values (Eory *et al.*, 2015). However, yields were kept constant to reduce uncertainty in calculations to estimate liveweight gain following mitigation measures (a conservative approach, discussed later in Section 4.4.2).

3NOP as a feed additive

3-Nitrooxypropanol (3NOP) is a chemical that reduces the production of enteric CH_4 by ruminants when added to their rations (or introduced via a bolus). It does so by reducing the rates at which rumen archaea convert hydrogen released from ingested feed into CH_4 (Duin *et al.*, 2016). Although there is little research on the effects of NOP on sheep, and although not commercially available yet, it was assumed 3NOP could be administered to all animals as a bolus (Rooke *et al.*, 2016), which resulted in a 20% reduction in the enteric CH_4 conversion factor (Eory *et al.*, 2015).

4.2.4. Afforestation

Afforestation was the only measure modelled to increase carbon sequestration. Once the reduction in emissions of GHGs due to implementing the mitigation measures was applied to each farm, the area of woodland planting needed to offset the remaining emissions was calculated. Additional planting was assumed to be a mixed broadleaf woodland over 20 years old at 2 m spacing with no clearfell or thinning. Sequestration in trees and soil carbon losses from planting were based on the WCC lookup tables (Forestry Commission, 2018), through the Bangor Tool. This calculation includes CO_2 from land use change, CO_2 from soil carbon losses from tree planting, CO_2 from soil carbon sequestered in forests post-planting, and CO_2 carbon sequestered in growing trees.

4.3. Results

4.3.1. Baseline scenarios

Whole-farm GHG emissions varied considerably between farms in the baseline situation. Baseline emissions at the farm level ranged from 347 - 2326 t $CO_2e\ yr^{-1}$, in part reflecting a wide range of management intensities and farm sizes, from 55 - 540 ha. Farms also varied in efficiencies, with product emissions intensities ranging from 13.8 - 38.5 kg $CO_2e\ kg^{-1}$ dwt (Table 4.2). Although the farms had notably different baseline emissions, all farms showed similar emission profiles, with CH_4 emissions from enteric fermentation accounting for the majority of GHG emissions (mean of 57% across all farms) followed by N_2O from soils (mean of 24%) (Figure 4.2). The relative sinks for carbon (i.e., carbon sequestration) were also similar between farms, with grasslands being the biggest carbon sink, accounting for on average 72% of total sequestration (Figure 4.2).

Table 4.2. Farm characteristics, baseline farm-level emissions, baseline product emissions and baseline emissions per unit area.

Farm	Farm size (ha)	Livestock enterprise	Baseline farm-level emissions ($Mg\ CO_2e\ yr^{-1}$)	Baseline product emissions ($kg\ CO_2e\ kg^{-1}$ dwt)	Baseline emissions per unit area ($kg\ CO_2e\ ha^{-1}\ yr^{-1}$)
A	262	Hill	952	22.1	3635
B	117	Hill	385	29.2	3293
C	157	Hill	875	23.0	5575
D	270	Hill	1241	26.2	4598
E	93	Hill	347	15.5	3729
F	116	Hill	1078	36.1	9292
G	71	Hill	463	26.3	6519
H	258	Hill	1212	23.7	4698
I	288	Hill	783	21.4	2718
J	200	Hill	2061	24.8	10305
K	540	Hill	889	38.4	1647
L	233	Lowland	950	26.4	4076
M	55	Lowland	476	21.7	8661
N	111	Lowland	1411	13.8	12716
O	128	Upland	743	38.0	5802
P	290	Upland	2326	24.3	8021
Q	296	Upland	1423	38.5	4806
R	278	Upland	1326	23.8	4777
S	205	Upland	1375	25.3	6708
T	189	Upland	803	22.0	4248
Average			1056	26.0	5791

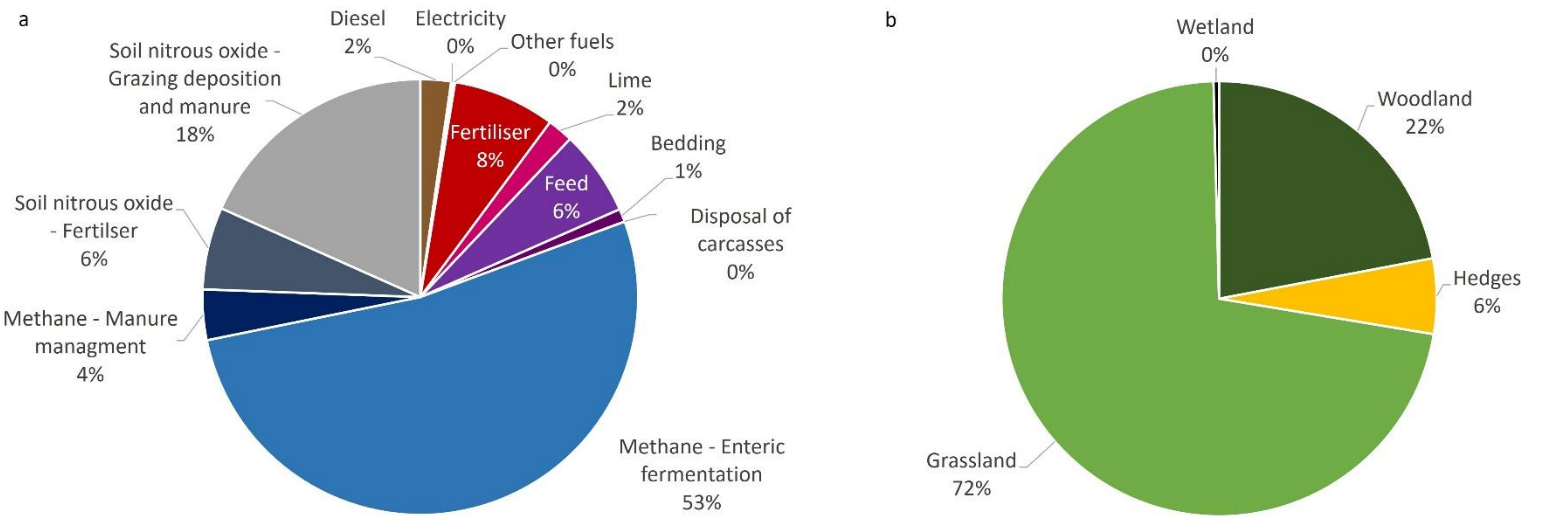


Figure 4.2. Average [a] emission breakdown of greenhouse gases and [b] sequestration breakdown across the twenty farms. Some numbers appear as 0 due to rounding.

4.3.2. Mitigation scenarios

Mitigation measures were implemented in a sequential approach, culminating in a Net Zero GHG scenario for each farm through GHG removals via afforestation; an example farm is shown in Figure 4.3. Mitigation scenarios for each farm can be found in Figures A 4.9 - 27. Implementing the mitigation measures alone was not sufficient to reduce total farm emissions to zero on any farm. Emission reductions following the implementation of five to seven mitigation measures ranged from 19.7 - 35.0%, with an average of 27.9%. Individual mitigation measures resulted in an average 0.8 - 11.9% reduction in overall emissions across farms (Table 4.3) with 3-NOP contributing to the largest reduction. Total emissions following mitigation measures ranged from 264 - 1512 t CO_2e yr^{-1}. Mitigated product emissions ranged from 9.3 - 29.4 kg CO_2e kg^{-1} dwt, with a mean of 18.9 kg CO_2e kg^{-1} dwt (Table 4.4).

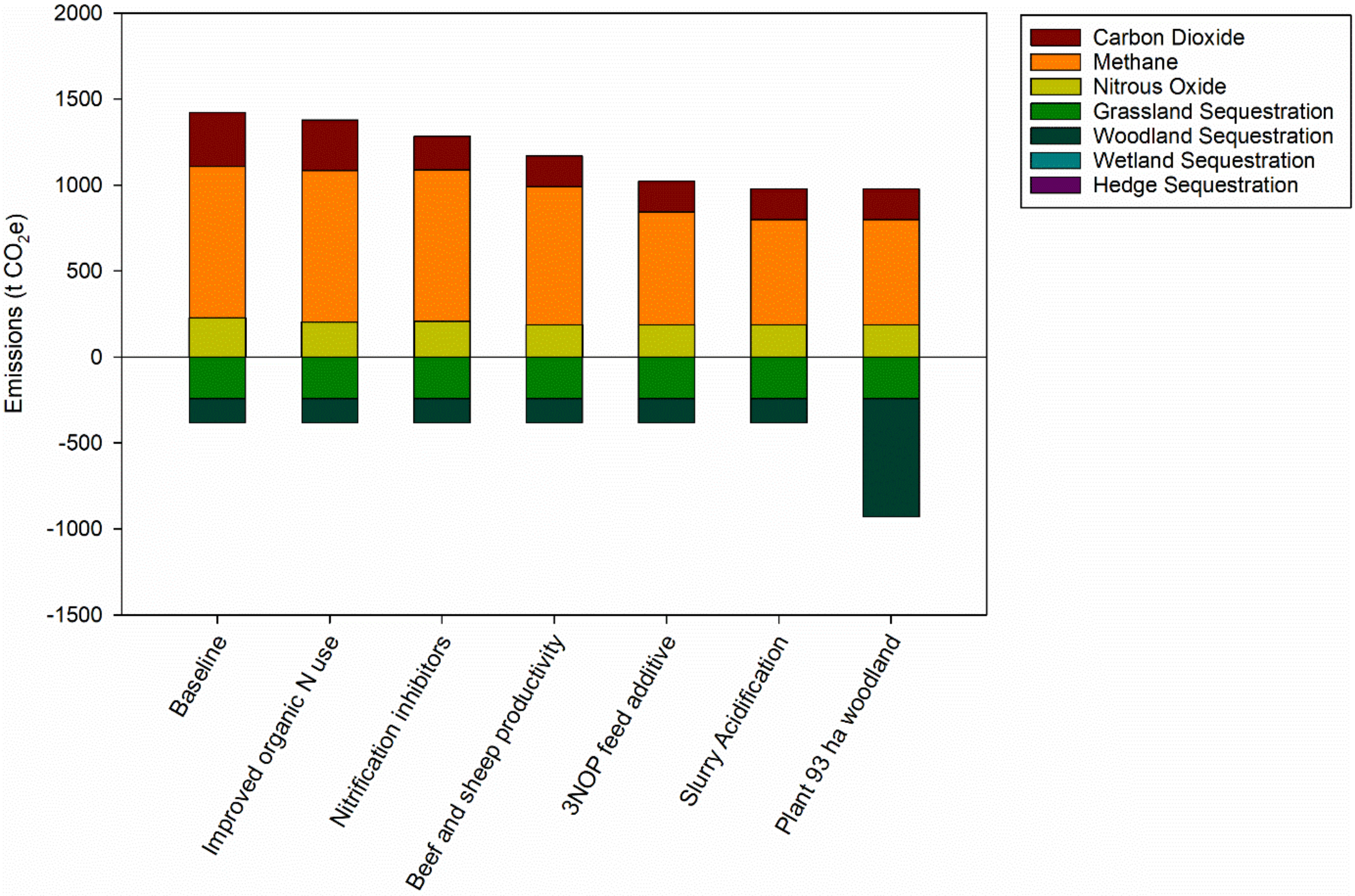


Figure 4.3. An example of one hill farm – Farm Q's (farm characteristics in Table A 4.1) mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (31%). The area of additional woodland needed to offset residual emissions to achieve Net Zero for this farm was calculated at 93 ha. Sensitivity analysis was carried out on a subsample of data and found little effect of the order of mitigation measures.

Table 4.3. Average emissions reductions and standard error of the mean (SEM) for individual mitigation measures across the twenty farms. Measures ordered from largest to smallest emissions reductions.

Mitigation measure	Emission reduction (%)	
	Mean	SEM
3NOP as a feed additive	11.9	0.23
Improved beef and sheep productivity	8.7	0.23
Nitrification inhibitors	6.7	0.58
Legume-grass mixtures	5.0	1.49
Slurry acidification	3.6	0.31
Improved organic N use	2.7	0.26
Improved synthetic N use	2.1	0.31
Behavioural change in fuel efficiency	0.8	0.32

Table 4.4. Emission reductions, mitigated emissions and area of woodland needed to offset residual emissions following mitigation scenarios on each farm. Offset areas are expressed as a percentage of farm's total area as well as specific annual area occupation per unit meat output (in m^2.yr kg^{-1} dwt) to indicate magnitude.

Farm	Emission reduction (%)	Mitigated emissions ($Mg\ CO_2e\ yr^{-1}$)	Mitigated production emissions ($kg\ CO_2e\ kg^{-1}$ dwt)	Woodland needed to reach Net Zero (% total farm) *	Woodland needed to reach Net Zero (m^2.yr kg^{-1} dwt)
A	25.6	708	16.4	17	10.5
B	19.7	309	23.4	15	12.9
C	25.6	649	17.1	49	20.5
D	33.3	827	17.4	26	14.9
E	23.9	264	11.8	28	11.6
F	26.6	792	26.5	66	23.2
G	23.2	355	20.2	60	26.8
H	27.4	875	17.2	25	12.1
I	27.8	562	15.4	16	11.7
J	33.9	1337	16.4	65	15.5
K	23.4	681	29.4	8	17.1
L	28.5	679	18.9	30	19.6
M	25.8	353	16.1	73	35
N	32.4	735	9.3	85	11.8
O	29	527	27	35	22.9
P	35	1512	15.8	51	15.4
Q	31.3	977	28.3	31	26.9
R	28.6	946	17	24	12.1
S	28.2	986	18.2	43	15.7
T	28.5	574	15.8	22	11.5
Average	27.9	732	18.9	38	17.4

* Offset area is equivalent to % of farm's total area, not the area which needs to be afforested on the current farm

4.3.3. Afforestation

The area of woodland needed to offset the remaining emissions to achieve Net Zero on each farm ranged from 8 - 85% of the farm's area, with an average of 38% (Table 4.4); making woodland the primary carbon sequestration (and, indeed, Net Zero) measure for all mitigated scenarios. This offset area was equivalent to 10.5 - 35.0 $m^2.yr\ kg^{-1}$ dwt, with an average of 17.4 $m^2.yr\ kg^{-1}$ dwt. Average area footprints for production plus offset (afforested) area required to reach Net Zero ranged from 25.8 - 231.7 $m^2.yr\ kg^{-1}$ dwt. A scatterplot of production area footprints plotted against production plus offset area footprints which depicts changes in the area efficiency ranking from baseline compared with Net Zero scenarios can be found in Figure A 4.28.

4.4. Discussion

4.4.1. Baseline scenarios

4.4.1.1. Emissions

In order to achieve Net Zero in any sector, it is essential to first gain an understanding of the magnitude of baseline emissions. This not only allows us to consider total emissions but also highlights sources of emissions where there is potential for mitigation. Considerable variation was seen between farms in this study, reflecting large differences in size, land quality, management systems and efficiency. The farm with the highest product emissions – Farm K, at 38.5 kg $CO_2e\ kg^{-1}$ dwt, had product emissions almost three times that of the farm with the lowest product emissions – Farm N, at 13.8 kg $CO_2e\ kg^{-1}$ dwt, indicating the opportunity for efficiency gains (Table 4.2). Hyland *et al.* (2016) demonstrated this potential for emission reductions in the production of Welsh beef and lamb if all enterprises replicated the efficiency levels of the highest-performing producers. Although this modelling was carried out on 20 case study farms in Wales, and therefore the aim was not to generate statistically scalable results, this principle applies at a global as well as local level. For example, Costa *et al.* (2022) found global food systems could reduce emissions by 45% if all food production was shifted to the 30th-percentile of the least emission-intensive systems. However, these efficiency gains must be made sustainably to avoid an unintended increase in total emissions, i.e., by increasing livestock numbers across the sector as a whole.

Despite Farm N having the lowest product emissions, it also had a notably high farm-level GHG emissions – mostly a reflection of the enteric emissions associated with their large livestock numbers (Table 4.2). This shows that the most efficient farms in terms of emissions intensity are not always those with the lowest farm-level emissions due to higher stocking densities. This highlights an important global issue that although food production must be increased to feed a growing population, this must be done sustainably to avoid increasing net GHG emissions (Costa *et al.*, 2022).

This also highlights another key consideration that displacing production from those efficient farms (with a low product footprint) to less efficient farms (which need a greater number of inputs and/or livestock to generate the same amount of product) could lead to an overall increase in emissions across the sector. Conducting a full consequential LCA could account for this potential displaced production.

Farm type had little apparent influence on product emissions, with considerable overlap in values between hill, upland and lowland farms (Table 4.2). In general, lowland farms used more inputs which contributed to a greater weight of products over which those inputs were divided. Hill farms required fewer inputs, however, livestock produced on hill systems were often sold at a lower weight. Moreover, the farms with the highest and lowest total emissions were both the same farm type (hill). There was also no clear association between farm product emissions and farm size or stock numbers across farm types (Table 4.2). This may in part reflect the small sample size in some categories, however, farm size has also been shown in other studies to have no effect of emission intensity (Hyland *et al.*, 2016). These results reiterate the importance of management systems as opposed to geographical factors on product carbon footprints.

Production area footprints appear to be lower on lowland farms at 42.3 $m^2.yr\ kg^{-1}$ dwt than on hill and upland (66.3 $m^2.yr\ kg^{-1}$ dwt and 53.2 $m^2.yr\ kg^{-1}$ dwt, respectively) (Figure A 4.28). However, although study farms were deemed by sectoral stakeholders to be representative of their respective "types", with only three lowland farms in this study, there are not enough data points to be conclusive. Production area footprints did not appear to be associated with total emissions or product emissions, instead this metric addresses a separate issue - competition for land. In order to reach current policy targets, Welsh farms (and indeed farms across the world) will need to reduce both emission intensity and total emissions as well as prioritise land use, especially with the increased demand for land-based CO_2 removal activities (Beauchemin *et al.*, 2020; Rosa and Gabrielli, 2023).

4.4.1.2. Sequestration

On balance, baseline carbon sequestration on these farms was low compared to the level of emissions, offsetting an average 22% of total emissions (Table 4.2). Of this offsetting, the majority was attributed to soil sequestration under grassland, accounting for 67% of total sequestration (Figure 4.2). There is much debate around the potential for soil carbon sequestration in ruminant production systems (Abdalla *et al.*, 2018; Arca *et al.*, 2021; Batalla *et al.*, 2015; Hammer *et al.*, 2016; Soussana *et al.*, 2010). Within the UK, it is widely considered that long term grasslands will have reached an approximate equilibrium in carbon exchange with the atmosphere resulting in a small potential for any additional carbon sequestration (Smith, 2014). Accurately estimating soil carbon sequestration (without field sampling to measure actual change in soil carbon) is difficult, therefore, sequestration estimates must be interpreted with caution.

Existing farm woodland and hedgerow sequestration accounted for relatively little of the total carbon sequestration at only 28% (Figure 4.2), representing an average 7% offset of total farm emissions – however, this was higher than reported in other studies (e.g. Emmett *et al.*, 2017). The contribution of carbon sequestration by woodland differed between farm types, for example on lowland farms, isolated trees (19% of total sequestration) accounted for a considerably greater proportion of sequestration than woodland (7% of total sequestration). This was due to the considerable variation in tree cover on farms (0 - 27%) (Table A 4.1), with some farms reporting they had no trees or hedges. Farmers often had little detailed knowledge of the extent of hedges, individual trees and areas of woodland on their farms, so the estimates of woodland cover have a high level of uncertainty. Upland farms had the highest woodland cover at 8%, with lowland farms having the lowest at 2% (Table A 4.1). Many factors influenced these figures, for example upland farms were more likely to have planted trees as shelter for their more exposed areas. Tree cover was lower on hill farms due to the exposed nature of the land, and lowest on lowland farms despite their soil and climatic conditions favouring tree growth.

Hedgerows are often thought to be an important contributor to sequestration on farms (Blair, 2018), however, their offsetting potential was relatively low in this study. The Bangor Tool assumes no net sequestration in hedges which are cut in the sample year. This means that managed hedges will not count towards any carbon sequestration. Additionally, this management practice could skew carbon sequestration and offset values depending on whether the hedge was flailed in the same year as the footprint was carried out. Allowing hedgerows to grow taller and wider increase the hedge's capacity to sequester carbon in above- and below-ground biomass (Axe, 2018; Axe *et al.*, 2017).

4.4.2. Mitigation scenarios

4.4.2.1. Emission reductions

The implementation of mitigation measures was found to reduce emissions by an average of 28% across all farms. Emission reductions were similar across all farm types, with average emission reductions of 26%, 30% and 29% for hill, upland and lowland, respectively (Table 4.4). Farms with only sheep had lower emission reductions of 24%, most likely reflecting the more limited number of mitigation measures applicable to these farms. Nitrous oxide emissions from sheep only farms were generally lower than those of cattle, so the effectiveness of measures targeting N_2O are limited. Measures relating to manure management are not applicable for sheep farms which are primarily extensive systems with short (or no) periods of animal housing. Sheep farms also have lower levels of inputs including fertiliser and fuel, which limited the potential from mitigation measures in such areas.

The CH_4 inhibitor 3NOP was the measure with the largest mitigation potential (Table 4.3). This finding should be interpreted with caution as 3NOP is still a relatively new product, with most literature arising from experimental studies (Jayanegara *et al.*, 2018; Yu *et al.*, 2021). It was assumed that 3NOP could be administered to all grazing animals as a bolus (Rooke *et al.*, 2016), but little literature exists on its effectiveness in these conditions. The effectiveness of 3NOP to reduce emissions was closely followed by the group of mitigation measures for animal productivity. Improved beef and sheep productivity had the second highest mitigation potential (Table 4.3), however, these emission reductions rely on the assumption that production is held constant. In reality, if farmers were to increase production efficiencies, they may thereafter increase stocking rates, which would in turn affect net emissions as well as the cost of implementing these measures. Measures such as increasing legumes in grass mixtures have been found to have larger mitigation effects in previous studies (Fuchs *et al.*, 2018; Jensen *et al.*, 2012; Klumpp *et al.*, 2011; Li *et al.*, 2011; Schmeer *et al.*, 2014) than in our study; this difference is likely due to the nature of farms in this study, having a small proportion of land suitable for introducing legumes and already using low levels of fertiliser.

The figures obtained for emission reductions in this study are consistent with similar farm-level modelling exercises and previous MACC modelling (MacLeod *et al.*, 2010). Rees *et al.* (2020) modelled a zero-carbon mixed farm in Scotland and similarly found a potential 30% reduction in emissions following the implementation of mitigation measures. Eory *et al.* (2015) suggested a lower emission reduction at the national scale, estimating 15% of agricultural emissions can be abated in the UK. At a national level, a recent report estimated a 23% reduction in GHG emissions could be achieved in the UK across all main livestock types (CIEL, 2022). This report collated multiple modelling exercises for each livestock type, estimating a potential 37% and 34% reduction in greenhouse gas for beef and sheep farms, respectively. Globally, estimated emission reductions for the agriculture sector are marginally higher. For example, Rosa and Gabrielli (2023) estimated agricultural GHG emissions could be reduced by up to 45% if all possible mitigation strategies were implemented. Moreover, Clark *et al.* (2020) predicted that 100% adoption of all mitigation strategies by 2050 could result in negative net emissions from global food systems.

4.4.2.2. Woodland needed to achieve Net Zero

Many countries in the world have ambitious afforestation plans as they aspire to meet Net Zero emissions targets; a scenario that applies to Wales as it strives to increase woodland cover on farms. The most recent available data showed that woodland accounts for 7% (125,323 ha) of the total area on farms (Welsh Government, 2023). In the most recent carbon budget from the Welsh Government, one of the ambition statements for agriculture is that 10% of agricultural land (180,00 ha) will be shared to support tree planting by 2050 (Welsh Government, 2021b).

In this study, the area of woodland needed to achieve Net Zero at a farm level was found to be affected by farm type. Hill and upland farms required on average a lower proportion of woodland to reach Net Zero (Table 4.4). This could be due to the extensive nature of these systems with larger size and generally lower baseline emissions (per hectare) due to fewer inputs and lower livestock numbers. Lowland farms needed on average higher percentages of their total area to be converted to woodland to achieve GHG neutrality. Lowland farms not only had on average higher inputs and total baseline emissions, but they were also smaller in size, making the proportion of land required for woodland planting for Net Zero to appear particularly high. When converted from percentages, the area of woodland needed to achieve Net Zero across farms was on average equivalent to 58 ha, 80 ha and 68 ha for hill, upland and lowland, respectively.

As noted, Farm N - one of the lowland farms - had a notably high farm-level GHG emissions (Table 4.2). Even following mitigation, with this farm having one of the highest levels of emission reductions, it would still require the equivalent of 85% of its total area to be planted to offset the remaining emissions (Table 4.4). Despite this, Farm N was also the most efficient (when ranked by emissions intensity) of the twenty participating farms. If all the study farms were to produce at this level of efficiency, the same level of output could be produced on 28% of the current land area, saving 2984 ha across these 20 farms alone. Although this could result in higher emissions per hectare on the farmed land, such a land 'sparing' approach would make large areas available for carbon sequestration or biodiversity provisioning. As highlighted earlier for Farm N, it is important to interpret farm emissions data with caution and nuance to avoid the potential of displacing production from more efficient farms to less efficient farms, which would likely increase overall emissions (Bateman and Balmford, 2023).

Although expressing the offset area as a percentage of farms is useful for individual farm analysis, Farm N highlights that farm-level metrics can skew these results due to the size and intensity of the different farm types. Based on our results, using the average offset area of 17.4 $m^2.yr\ kg^{-1}$ dwt, Wales would need to plant an additional 154,621 ha of woodland to offset annual beef and lamb production (DEFRA, 2022). This figure is in line with national tree planting target of 180,000 ha by 2050 to meet the 'balanced pathway' set out of the UK Climate Change Commission (Welsh Government, 2021b). Delivering this additional woodland would require land use change equivalent to around 10% of agricultural land in Wales (Welsh Government, 2021b). This land use change would be similar to that of our calculated offset area which equates to 8% of Welsh agricultural land, however, it is yet to be determined where this area of additional woodland would be best situated. It is important to note that the Welsh Government's tree planting target is to offset all emissions in Wales, whereas our woodland area is to solely offset beef and sheep production. In Wales, a notable proportion of land is classified as Severely Disadvantaged Areas (SDA) or Disadvantaged Areas (DA) – 613,000 ha and 164,000 ha, respectively (Welsh Government, 2022b). These areas are potentially less productive and may have higher potential for tree planting. Based on our calculations, around 20% of SDA and DA would need to be planted to offset Welsh beef and lamb production. Although much of Welsh beef and lamb is produced in these areas, a combination of sustainable intensification and new technologies to reduce emissions could enable this afforestation without too significant a loss of production. However, it is important to note due to harsher climates, challenging terrain and prevalence of organic soils, more hilly areas may also be less suitable or productive for trees (Coomes and Allen, 2007).

In this modelling exercise, only mixed broadleaf woodland was considered for sequestration via afforestation, however, many other options are available. Trees can be introduced in silvopasture, hedgerows, shelterbelts and row systems, allowing for sequestration without affecting farm production, or even positively affecting production (Pritchard *et al.*, 2021). Agroforestry has been proven to be an environmentally and economically viable option for land use in many different contexts (Hardaker *et al.*, 2020; Lehmann *et al.*, 2020). However, due to the complexity of sequestration calculations, particularly for soil sequestration, agroforestry systems are challenging to model. Management of existing woodland is also important as there is a limit on duration of carbon sequestration by trees; trees gradually sequester less over time. Harvesting fast-growing trees and using their wood in the bioeconomy can extend the duration of CO_2 removal (Forster *et al.*, 2021). The IPCC now recognise afforestation including timber harvesting, reforestation and agroforestry as a carbon dioxide removal strategy (IPCC, 2022). The sixth assessment report highlights tree planting has a high carbon capture potential of 0.5 - 10 Gt $CO_2e\ yr^{-1}$ at a relatively low cost (0 - 240 USD t CO_2e^{-1}) (IPCC, 2022). Afforestation also has the potential to provide additional benefits in the form of improving biodiversity, flood management and animal welfare (Burgess, 2017). However, afforestation must be carefully planned, implemented and monitored to avoid any unintended negative consequences (Brancalion and Holl, 2020). If poorly planned or managed, trees may not grow (and therefore sequester carbon) efficiently and could result in a reduction in native biodiversity (Veldman *et al.*, 2015). Moreover, inconsiderate afforestation at a large scale could increase competition for land and negatively affect global food security (Doelman *et al.*, 2020; Hasegawa *et al.*, 2018).

4.4.3. Alternative land use mitigation measures

Although not considered in this study, a land 'sharing' approach could be fostered where the needs of both agriculture and GHG mitigation could be met on the same area of land. Land sharing involves farming practices intended to support biodiversity and the delivery of wider ecosystem services on agricultural land simultaneously to producing food (Green *et al.*, 2005). This may mean making more efficient use of applied nutrient inputs (e.g. fertiliser by using an N-planning tool) so that the amount applied can be reduced without compromising soil fertility and crop yields, and/or maintaining trees and hedges (Hardaker *et al.*, 2021). Alternatively, if production efficiencies are increased (assuming stock numbers were not increased), less land will be needed for the same level of production, leaving more land available for carbon offsetting and delivery of wider ecosystem services. Such a land 'sparing' approach requires sustainable intensification on agricultural land with 'spared' areas of land restored for climate change mitigation (as well as nature) (Balmford, 2021; Lamb *et al.*, 2016; Phalan *et al.*, 2011). The land sparing and land sharing debate is still ongoing and an optimised approach to land use has yet to be determined. How to manage land use to deliver this balance of food production and climate change mitigation, as well as how land can deliver many other ecosystem services, is an important issue in the UK and globally.

Another option for GHG removal is increasing soil carbon sequestration. This removal strategy will require areas of land to be identified where soils have been depleted by farming practices and that have potential to be restored by changes in management practices that foster carbon sequestration. However, whilst conversion of arable land to grasslands has been shown to enhance soil carbon sequestration, the capacity for further sequestration may be limited in existing grasslands that are likely to be near or at equilibrium (Chapman *et al.*, 2013; Jones *et al.*, 2017). Alternative carbon removal options are available; however, some of these are not as well researched, especially in the UK. Additional carbon can be stored in soils via the application of biochar (Gupta *et al.*, 2020). Biochar has a high carbon capture potential and has even been found to increase yields when applied to poor soil (El-Naggar *et al.*, 2019). Globally, Costa *et al.* (2022) estimated that 50% of carbon sequestration potential associated with low-emission sequestration options (e.g. soil carbon and agroforestry, biochar) could reduce emissions by a further 24%. However, it is not clear if biochar application is a viable option for use in the UK without any adverse effects (Hilber *et al.*, 2017; Wang *et al.*, 2016). A review by Brtnicky *et al.* (2021) revealed a range of adverse effects following biochar application, for example, the release of various organic contaminants and potentially toxic substances which can negatively impact on soil and non-target organisms.

Bioenergy with carbon capture and storage (BECCS) and direct air capture and carbon storage (DACCS) are other promising new technologies for enhancing carbon removals (Smith *et al.*, 2016); however, they have not yet been deployed at scale in the UK, especially in an economically viable way. One issue with BECCS is it could require large areas of agricultural land to be converted to biomass production, leading to further competition for food production. However, this could be avoided if BECCS utilised existing forestry residues (e.g. low grade wood) or hedgerow biomass (Smith *et al.*, 2016). Compared to other feedstocks, forestry residues generally have a lower environmental impact, however, they are also limited in availability and more difficult to collect (Brack and King, 2021). DACCS has the additional benefit of requiring little or no land requirement and could act as an alternative carbon sink which would minimise the impacts on food production. For farms with degraded peatland, re-wetting and restoration measures could both reduce emissions and be an effective mechanism for increasing long-term sequestration (Bonn *et al.*, 2014; Darusman *et al.*, 2023).

The competition for land use is highlighted in the difference between the baseline area footprints of farms and the area footprint when the offset needed to achieve Net Zero is included. The area footprint notably increases from the baseline average of 58.8 $m^2.yr\ kg^{-1}$ dwt to an average of 76.1 $m^2.yr\ kg^{-1}$ dwt when including offset area. The apparent area efficiency decreased linearly when comparing baseline area footprints with footprints from Net Zero scenarios which include the offset area. However, the ranking of farms was largely unaffected, even following mitigation (Figure A 4.28). Significantly more land will be needed if the same quantity of meat is to be produced in a carbon neutral manner, however, it is unclear where this additional land could come from. Reducing food production on UK farms for sequestration purposes would not be a sensible mitigation strategy if it results in importing food from more GHG-intensive production systems. Moreover, this would have huge social, economic, and environmental implications which were also not considered in this study. The purpose of this paper was to focus on the potential for GHG mitigation at a farm level; many other studies have identified broader changes to global food systems that are needed to achieve Net Zero. These changes often relate to reducing the demand for meat through reducing food waste or dietary change (Costa *et al.*, 2022; Rosa and Gabrielli, 2023). Recently, there have been calls for a complete transformation in our food systems, which traditionally focus on food security alone, to a more integrated approach which ensures security without undermining the environment (Bhunnoo and Poppy, 2020; FAO, 2020; Webb *et al.*, 2020).

This work has demonstrated the need for large and coordinated reductions in both total emissions and emission intensities, as well as changes in land use. The Net Zero policy target will not require the agriculture and land use sector on its own to reach Net Zero since this target is set across all sectors, however, we have highlighted the scale of the challenges the sector will face if it is to achieve Net Zero on account of the vast areas of land which will be required for sequestration.

4.4.4. Limitations

This study has highlighted some assumptions and limitations of modelling farm-scale GHG emissions, carbon sequestration and the impacts of mitigation practices. The mitigation measures and abatement potentials were based on current understanding and best available modelling techniques, however, many factors can affect the results of these types of modelling exercises. For example, emission reductions in this study were cumulative, and therefore the sequence in which measures were implemented could influence results (Eory *et al.*, 2015). The order legumes are introduced is likely to have the biggest impact, when legumes are implemented first the N_2O emissions are lowered significantly before other measures like livestock productivity are modelled using percentage reductions in emission intensities. Although care was taken to avoid the sequence of mitigation measures affecting results, in future work, a sensitivity analysis could be carried out to assess the effect of changing assumptions on the resulting emission reductions. Similarly, it is likely that when implementing multiple mitigation measures, there will be some interaction between these measures. However, these interactions are difficult to account for in these types of modelling exercises, so it is possible there may be an over- and/or under-estimation of abatement potentials. It is also worth noting that the mitigation measures and abatement potentials used in this study were taken from the UK's most recent MACC which accounts for the interactions between measures and conducts sensitivity analyses on the applicability, uptake, abatement and cost of each mitigation measure (Eory *et al.*, 2015).

The main limitation of this mitigation modelling is the exclusion of some of the effects of mitigation measures due to the uncertainty of their abatement potentials. For both reducing synthetic and organic N use, it was assumed there was no effect on yields. This is most likely to be valid where targeted N use allows the N is used more efficiently or there are only small reductions in N application where it is currently over-applied. The yield effects of reducing fertiliser use will depend on baseline N rates and will be different for each farm, but without data/soil analysis it is not possible to predict this for individual farms. However, most mitigation measures under this category, such as better N planning and timing of N application, are unlikely to negatively affect yield. Moreover, in this study we assumed production was held constant. In practice, as mentioned earlier, if production efficiencies were increased, it is possible that farmers would increase livestock numbers, leading to an increase in net GHG emissions. It is also possible that emissions reductions potential we applied from adopting some of the mitigation measures are conservative estimates. This will vary between farms and will depend on the attributes of their current production system. For instance, Fox *et al.* 2018 showed that parasitic worms can increase methane emissions from lambs by 33%. Where such disease burdens exist on farms, resolving such issues could therefore lead to a much greater reduction in emissions than the estimates used in this study (Table 4.1).

Additionally, our modelling focused purely on reducing GHG emissions therefore it is possible that some of these mitigation measures could lead to an unintended increase in other pollutants. For example, NIs reduce N_2O emissions from soils, however, NIs have also been shown to increase NH_3 emissions (Lam *et al.*, 2017). This increase in NH_3 could result in further indirect N_2O emissions, reducing the net effectiveness of NIs as a mitigation measure (Wu *et al.*, 2021). Moreover, we did not consider the variety of socio-economic implications associated with these mitigation scenarios. For example, increasing afforestation on farms could negatively impact water yields (Brancalion and Holl, 2020), as well as lead to a reduction in agricultural income and rural employment (Ryan and O'Donoghue, 2016). In future, a multiple-pollutant MACC could link the abatement potential of GHG mitigation measures to the wider environmental impacts and costs (Eory *et al.*, 2013).

Despite its assumptions and limitations, this study points towards realistic opportunities to fundamentally shift farming systems to both substantially reduce emissions and deliver emissions offsets, as required for Net Zero. It is the first of its kind to use detailed real farm data to present a preliminary assessment of the opportunities for beef and sheep farms to achieve Net Zero, thus provides new insight.

4.5. Conclusions

This paper has used a novel farm-level modelling approach to explore potential pathways towards Net Zero on Welsh beef and sheep farms. The real farm data collected highlights the difference in baseline emissions and mitigation scenarios between ostensibly similar farms, and therefore the different challenges and opportunities the agriculture industry faces if it is to achieve this target.

This assessment has highlighted what needs to be done both in terms of the modelling process and the actions needed on farms to achieve Net Zero. It has shown the realistic opportunities available to reduce emissions and enhance sequestration on Welsh farms and could form a basis for future innovation. Although here we use Wales as a case study, it is likely that many of the same challenges and opportunities will apply to the livestock sector in other countries across the world. Mitigation measures may vary between countries but ultimately all farms will have to reduce emissions and increase sequestration to reach environmental targets while sustainably increasing production to ensure food security.

Our modelling showed that mitigation alone was not enough to achieve farm level carbon neutrality. Application of a wide range of abatement measures reduced emissions by 28% on average. Therefore, measures to increase carbon removals will be essential. Afforestation areas needed to offset farm emissions averaged 38% of farm areas in this study, ranging from 8 - 85%. We have highlighted the complexity of the challenge of generating ruminant products efficiently, whilst trying to meet the Net Zero target, and make a compelling case that not all farms should be required to meet Net Zero, if offsetting can be made elsewhere.

Major innovation and changes to Welsh and UK farming systems are required in order to meet current policy targets. However, policy interventions should consider the displacement effect of shifting production to less efficient systems, be they at home or abroad. Caution is therefore needed to ensure afforestation occurs in a strategic way as Net Zero may not be a logical aspiration at an individual level for all farms.

4.6. References

Abalos, D., Jeffery, S., Sanz-Cobena, A., Guardia, G., Vallejo, A., 2014. Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. Agriculture, Ecosystems & Environment 189, 136–144. https://doi.org/10.1016/j.agee.2014.03.036

Abdalla, M., Hastings, A., Chadwick, D.R., Jones, D.L., Evans, C.D., Jones, M.B., Rees, R.M., Smith, P., 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agriculture, Ecosystems & Environment 253, 62–81. https://doi.org/10.1016/j.agee.2017.10.023

ADAS UK Ltd, 2014. Study to Model the Impact of Controlling Endemic Cattle Diseases and Conditions on National Cattle Productivity, Agricultural Performance and Greenhouse Gas Emissions.

AHDB, 2022. Nutrient Management Guide (RB209). Agriculture and Horticulture Development Board, Kenilworth, UK.

Arca, P., Vagnoni, E., Duce, P., Franca, A., 2021. How does soil carbon sequestration affect greenhouse gas emissions from a sheep farming system? Results of a life cycle assessment case study. Italian Journal of Agronomy 16. https://doi.org/10.4081/ija.2021.1789

Axe, M.S., 2018. Hedgerow agroforestry in England and Wales: increasing width to sequester additional carbon, in: European Agroforestry Conference-Agroforestry as Sustainable Land Use, 4th. EURAF.

Axe, M.S., Grange, I.D., Conway, J.S., 2017. Carbon storage in hedge biomass—A case study of actively managed hedges in England. Agriculture, Ecosystems & Environment 250, 81–88. https://doi.org/10.1016/j.agee.2017.08.008

Balmford, A., 2021. Concentrating vs. spreading our footprint: how to meet humanity's needs at least cost to nature. Journal of Zoology 315, 79–109. https://doi.org/10.1111/jzo.12920

Bartley, D.J., Skuce, P.J., Zadoks, R.N., MacLeod, M., 2016. Endemic sheep and cattle diseases and greenhouse gas emissions. Advances in Animal Biosciences 7, 253–255. https://doi.org/10.1017/S2040470016000327

Batalla, I., Knudsen, M.T., Mogensen, L., Hierro, Ó. del, Pinto, M., Hermansen, J.E., 2015. Carbon footprint of milk from sheep farming systems in Northern Spain including soil carbon sequestration in grasslands. Journal of Cleaner Production 104, 121–129. https://doi.org/10.1016/j.jclepro.2015.05.043

Beauchemin, K.A., Ungerfeld, E.M., Eckard, R.J., Wang, M., 2020. Review: Fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation. animal 14, s2–s16. https://doi.org/10.1017/S1751731119003100

BEIS, 2022. Final UK greenhouse gas emissions national statistics: 1990 to 2020. Department for Business, Energy & Industrial Strategy.

Bhunnoo, R., Poppy, G.M., 2020. A national approach for transformation of the UK food system. Nat Food 1, 6–8. https://doi.org/10.1038/s43016-019-0019-8

Bioscience Network Limited, 2012. Developing options to deliver a substantial environmental and economic sustainability impact through breeding for feed efficiency of feed use in UK beef cattle (DEFRA No. IF0207.).

Blair, J., 2018. Hedgerows as form of agroforestry to sequester and store carbon in agricultural landscapes: a review, in: European Agroforestry Conference-Agroforestry as Sustainable Land Use, 4th. EURAF.

Bonn, A., Reed, M.S., Evans, C.D., Joosten, H., Bain, C., Farmer, J., Emmer, I., Couwenberg, J., Moxey, A., Artz, R., Tanneberger, F., von Unger, M., Smyth, M.-A., Birnie, D., 2014. Investing in nature: Developing ecosystem service markets for peatland restoration. Ecosystem Services 9, 54–65. https://doi.org/10.1016/j.ecoser.2014.06.011

Brack, D., King, R., 2021. Managing Land-based CDR: BECCS, Forests and Carbon Sequestration. Global Policy 12, 45–56. https://doi.org/10.1111/1758-5899.12827

Brancalion, P.H.S., Holl, K.D., 2020. Guidance for successful tree planting initiatives. Journal of Applied Ecology 57, 2349–2361. https://doi.org/10.1111/1365-2664.13725

Brtnicky, M., Datta, R., Holatko, J., Bielska, L., Gusiatin, Z.M., Kucerik, J., Hammerschmiedt, T., Danish, S., Radziemska, M., Mravcova, L., Fahad, S., Kintl, A., Sudoma, M., Ahmed, N., Pecina, V., 2021. A critical review of the possible adverse effects of biochar in the soil environment. Science of The Total Environment 796, 148756. https://doi.org/10.1016/j.scitotenv.2021.148756

Bruinenberg, M.H., Valk, H., Korevaar, H., Struik, P.C., 2002. Factors affecting digestibility of temperate forages from seminatural grasslands: a review. Grass and Forage Science 57, 292–301. https://doi.org/10.1046/j.1365-2494.2002.00327.x

Burgess, P.J., 2017. Agroforestry in the UK. Quarterly Journal of Forestry 111.

Cardenas, L.M., Bhogal, A., Chadwick, D.R., McGeough, K., Misselbrook, T., Rees, R.M., Thorman, R.E., Watson, C.J., Williams, J.R., Smith, K.A., Calvet, S., 2019. Nitrogen use efficiency and nitrous oxide emissions from five UK fertilised grasslands. Science of The Total Environment 661, 696–710. https://doi.org/10.1016/j.scitotenv.2019.01.082

Cardenas, L.M., Thorman, R., Ashlee, N., Butler, M., Chadwick, D., Chambers, B., Cuttle, S., Donovan, N., Kingston, H., Lane, S., Dhanoa, M.S., Scholefield, D., 2010. Quantifying annual N2O emission fluxes from grazed grassland under a range of inorganic fertiliser nitrogen inputs. Agriculture, Ecosystems & Environment, Estimation of nitrous oxide emission from ecosystems and its mitigation technologies 136, 218–226. https://doi.org/10.1016/j.agee.2009.12.006

Carswell, A.M., Gongadze, K., Misselbrook, T.H., Wu, L., 2019. Impact of transition from permanent pasture to new swards on the nitrogen use efficiency, nitrogen and carbon budgets of beef and sheep production. Agriculture, Ecosystems & Environment 283, 106572. https://doi.org/10.1016/j.agee.2019.106572

Chadwick, D.R., Cardenas, L.M., Dhanoa, M.S., Donovan, N., Misselbrook, T., Williams, J.R., Thorman, R.E., McGeough, K.L., Watson, C.J., Bell, M., Anthony, S.G., Rees, R.M., 2018. The contribution of cattle urine and dung to nitrous oxide emissions: Quantification of country specific emission factors and implications for national inventories. Science of The Total Environment 635, 607–617. https://doi.org/10.1016/j.scitotenv.2018.04.152

Chapman, S.J., Bell, J.S., Campbell, C.D., Hudson, G., Lilly, A., Nolan, A.J., Robertson, A.H.J., Potts, J.M., Towers, W., 2013. Comparison of soil carbon stocks in Scottish soils between 1978 and 2009. European Journal of Soil Science 64, 455–465. https://doi.org/10.1111/ejss.12041

CIEL, 2022. Net Zero Carbon & UK Livestock Report: How Farmers Can Reduce Emissions. https://www.cielivestock.co.uk/wp-content/uploads/2022/02/CIEL-LR-220405.pdf

Clark, M.A., Domingo, N.G.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., Azevedo, I.L., Hill, J.D., 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science 370, 705–708. https://doi.org/10.1126/science.aba7357

Climate Change Committee, 2020a. The Sixth Carbon Budget The UKs path to Net Zero. https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf

Climate Change Committee, 2020b. Land use: Policies for a Net Zero UK. https://www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/

Coomes, D.A., Allen, R.B., 2007. Effects of size, competition and altitude on tree growth. Journal of Ecology 95, 1084–1097. https://doi.org/10.1111/j.1365-2745.2007.01280.x

Costa, C., Wollenberg, E., Benitez, M., Newman, R., Gardner, N., Bellone, F., 2022. Roadmap for achieving net-zero emissions in global food systems by 2050. Sci Rep 12, 15064. https://doi.org/10.1038/s41598-022-18601-1

Craig, K., 2020. Farm Management Handbook 2020/21. FAS. https://www.fas.scot/publication/fmh2021/

Darusman, T., Murdiyarso, D., Impron, Anas, I., 2023. Effect of rewetting degraded peatlands on carbon fluxes: a meta-analysis. Mitig Adapt Strateg Glob Change 28, 10. https://doi.org/10.1007/s11027-023-10046-9

DEFRA, 2022. The British survey of fertiliser practice. ISBN 978-0-99297-357-5. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094283/fertiliseruse-annualreport2021-28jul22.pdf

DEFRA, 2021. Agriculture in the United Kingdom 2020. Department for Environment, Food and Rural Affairs Department of Agriculture, Environment and Rural Affairs (Northern Ireland) Welsh Government, Knowledge and Analytical Services The Scottish Government, Rural and Environment Science and Analytical Services.

DEFRA, 2012. Guidelines to Defra Greenhouse Gas (GHG) Conversion Factors for Company Reporting. London, UK: Department for Environment, Food and Rural Affairs.

Doelman, J.C., Stehfest, E., van Vuuren, D.P., Tabeau, A., Hof, A.F., Braakhekke, M.C., Gernaat, D.E.H.J., van den Berg, M., van Zeist, W.-J., Daioglou, V., van Meijl, H., Lucas, P.L., 2020. Afforestation for climate change mitigation: Potentials, risks and trade-offs. Global Change Biology 26, 1576–1591. https://doi.org/10.1111/gcb.14887

Duin, E.C., Wagner, T., Shima, S., Prakash, D., Cronin, B., Yáñez-Ruiz, D.R., Duval, S., Rümbeli, R., Stemmler, R.T., Thauer, R.K., Kindermann, M., 2016. Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol. Proc Natl Acad Sci U S A 113, 6172–6177. https://doi.org/10.1073/pnas.1600298113

Edwards-Jones, G., Plassmann, K., Harris, I.M., 2009. Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK. The Journal of Agricultural Science 147, 707–719. https://doi.org/10.1017/S0021859609990165

El-Naggar, A., El-Naggar, A.H., Shaheen, S.M., Sarkar, B., Chang, S.X., Tsang, D.C.W., Rinklebe, J., Ok, Y.S., 2019. Biochar composition-dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: A review. Journal of Environmental Management 241, 458–467. https://doi.org/10.1016/j.jenvman.2019.02.044

Emmett, B.E., Abdalla, M., Anthony, S., Astbury, S., August, T., Barrett, G., Beckmann, B., Biggs, J., Botham, M., Bradley, D., Brown, M., Burden, A., Carter, H., Chadwick, D., Cigna, F., Collier, R., Cooper, D., Cooper, J., Cosby, B.J., Creer, S., Cross, P., Dadam, D., Edwards, F., Edwards, M., Evans, C., Ewald, N., Fitton, A., Garbutt, A., Giampieri, C., Gooday, R., Grebby, S., Greene, S., Halfpenney, I., Hall, J., Harrison, S., Harrower, C., Henrys, P., Hobson, R., Hughes, P., Hughes, S., Illian, J., Isaac, N., Jackson, B., Jarvis, S., Jones, D.L., Jones, P., Keith, A., Kelly, M., Kneebone, N., Korenko, J., Lallias, D., Leaver, D., Robinson, I., Malcolm, H., Maskell, L., McDonald, J., Moxley, J., Norton, L., O'Hare, M., Oliver, T., Owen, A., Parkhill, K.A., Pereira, M., Peyton, J., Pogson, M., Powney, G., Pritchard, N., Prochorskaite, A., Prosser, M., Pywell, R., Rawlins, B., Reuland, O., Richards, M., Robinson, D.A., Rorke, S., Rowland, C., Roy, D., Scarlett, P., Scholefield, P., Scott, A., Scott, L., Scott, R., Sharps, K., Siriwardena, G., Smart, S., Smith, G., Smith, P., Stopps, J., Swetnam, R., Taft, H., Taylor, R., Tebbs, E., Thomas, A., Todd-Jones, C., Tordoff, G., Turner, G., Van Breda, J., Vincent, H., Wagner, M., Waters, E., Walker-Springett, K., Wallace, H., Watkins, J., Webb, G., White, J., Whitworth, E., Williams, B., Williams, P., Wood, C., Wright, S., 2017. Glastir Monitoring & Evaluation Programme. Final report (Publication - Report). NERC/Centre for Ecology & Hydrology, Bangor, UK.

Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, McVittie, Wall, Borthwick, Watson, Waterhouse, Wiltshire, 2015. Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget period and to 2050. (Final report submitted for the project contract "Provision of services to review and update the UK agriculture MACC and to assess abatement potential for the 5 th carbon budget period and to 2050"). SRUC.

Eory, V., Topp, C.F.E., Moran, D., 2013. Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environmental Science & Policy 27, 55–67. https://doi.org/10.1016/j.envsci.2012.11.003

Eory, V., Topp, K., Rees, B., Leinonen, I., Maire, J., 2020. Marginal abatement cost curve for Scottish agriculture. https://doi.org/10.7488/ERA/755

Fangueiro, D., Hjorth, M., Gioelli, F., 2015. Acidification of animal slurry– a review. Journal of Environmental Management 149, 46–56. https://doi.org/10.1016/j.jenvman.2014.10.001

FAO, 2020. The State of Food Security and Nutrition in the World 2020: Transforming food systems for affordable healthy diets. Food & Agriculture Org.

FAO, 2013. Mitigation of greenhouse gas emissions in livestock production: a review of technical options for non-CO2 emissions, FAO animal production and health paper. Food and Agriculture Organization of the United Nations, Rome.

Forestry Commission, 2021. Woodland Carbon Code: Carbon Lookup Tables.

Forster, E.J., Healey, J.R., Dymond, C., Styles, D., 2021. Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. Nat Commun 12, 3831. https://doi.org/10.1038/s41467-021-24084-x

Fox, N.J., Smith, L.A., Houdijk, J.G.M., Athanasiadou, S., Hutchings, M.R., 2018. Ubiquitous parasites drive a 33% increase in methane yield from livestock. International Journal for Parasitology 48, 1017–1021. https://doi.org/10.1016/j.ijpara.2018.06.001

Fuchs, K., Hörtnagl, L., Buchmann, N., Eugster, W., Snow, V., Merbold, L., 2018. Management matters: testing a mitigation strategy for nitrous oxide emissions using legumes on intensively managed grassland. Biogeosciences 15, 5519–5543. https://doi.org/10.5194/bg-15-5519-2018

Green, R., Cornell, S., Scharlemann, J., Balmford, A., 2005. Farming and the Fate of Wild Nature. Science (New York, N.Y.) 307, 550–5. https://doi.org/10.1126/science.1106049

Gupta, D.K., Gupta, C.K., Dubey, R., Fagodiya, R.K., Sharma, G., A., K., Noor Mohamed, M.B., Dev, R., Shukla, A.K., 2020. Role of Biochar in Carbon Sequestration and Greenhouse Gas Mitigation, in: Singh, J.S., Singh, C. (Eds.), Biochar Applications in Agriculture and Environment Management. Springer International Publishing, Cham, pp. 141–165. https://doi.org/10.1007/978-3-030-40997-5_7

Hammer, T.J., Fierer, N., Hardwick, B., Simojoki, A., Slade, E., Taponen, J., Viljanen, H., Roslin, T., 2016. Treating cattle with antibiotics affects greenhouse gas emissions, and microbiota in dung and dung beetles. Proceedings of the Royal Society B: Biological Sciences 283, 20160150. https://doi.org/10.1098/rspb.2016.0150

Hardaker, A., Pagella, T., Rayment, M., 2021. Ecosystem service and dis-service impacts of increasing tree cover on agricultural land by land-sparing and land-sharing in the Welsh uplands. Ecosystem Services 48, 101253. https://doi.org/10.1016/j.ecoser.2021.101253

Hardaker, A., Pagella, T., Rayment, M., 2020. Integrated assessment, valuation and mapping of ecosystem services and dis-services from upland land use in Wales. Ecosystem Services 43, 101098. https://doi.org/10.1016/j.ecoser.2020.101098

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Pérez Domínguez, I., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., van Zeist, W.-J., Wiebe, K., Witzke, P., 2018. Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Clim Change 8, 699–703. https://doi.org/10.1038/s41558-018-0230-x

Hilber, I., Bastos, A.C., Loureiro, S., Soja, G., Marsz, A., Cornelissen, G., Bucheli, T.D., 2017. The different faces of biochar: contamination risk versus remediation tool. Journal of Environmental Engineering and Landscape Management 25, 86–104. https://doi.org/10.3846/16486897.2016.1254089

Hyland, J.J., Styles, D., Jones, D.L., Williams, A.P., 2016. Improving livestock production efficiencies presents a major opportunity to reduce sectoral greenhouse gas emissions. Agricultural Systems 147, 123–131. https://doi.org/10.1016/j.agsy.2016.06.006

IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009157926

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

IPCC, 2018. Annex I: Glossary, in: Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge University Press, Cambridge, pp. 541–562. https://doi.org/10.1017/9781009157940.008

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use.

IPCC, C.C., 2007. The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 996, 113–119.

Janssens, I.A., Freibauer, A., Schlamadinger, B., Ceulemans, R., Ciais, P., Dolman, A.J., Heimann, M., Nabuurs, G.-J., Smith, P., Valentini, R., Schulze, E.-D., 2005. The carbon budget of terrestrial ecosystems at country-scale – a European case study. Biogeosciences 2, 15–26. https://doi.org/10.5194/bg-2-15-2005

Jayanegara, A., Sarwono, K.A., Kondo, M., Matsui, H., Ridla, M., Laconi, E.B., Nahrowi, 2018. Use of 3-nitrooxypropanol as feed additive for mitigating enteric methane emissions from ruminants: a meta-analysis. Italian Journal of Animal Science 17, 650–656. https://doi.org/10.1080/1828051X.2017.1404945

Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., J.R. Alves, B., Morrison, M.J., 2012. Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. Agron. Sustain. Dev. 32, 329–364. https://doi.org/10.1007/s13593-011-0056-7

Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of lamb: Sources of variation and opportunities for mitigation. Agricultural Systems 123, 97–107. https://doi.org/10.1016/j.agsy.2013.09.006

Jones, S.K., Helfter, C., Anderson, M., Coyle, M., Campbell, C., Famulari, D., Di Marco, C., van Dijk, N., Tang, Y.S., Topp, C.F.E., Kiese, R., Kindler, R., Siemens, J., Schrumpf, M., Kaiser, K., Nemitz, E., Levy, P.E., Rees, R.M., Sutton, M.A., Skiba, U.M., 2017. The nitrogen, carbon and greenhouse gas budget of a grazed, cut and fertilised temperate grassland. Biogeosciences 14, 2069–2088. https://doi.org/10.5194/bg-14-2069-2017

Jordon, M.W., Willis, K.J., Harvey, W.J., Petrokofsky, L., Petrokofsky, G., 2020. Implications of Temperate Agroforestry on Sheep and Cattle Productivity, Environmental Impacts and Enterprise Economics. A Systematic Evidence Map. Forests 11, 1321. https://doi.org/10.3390/f11121321

Klumpp, K., Bloor, J.M.G., Ambus, P., Soussana, J.-F., 2011. Effects of clover density on N2O emissions and plant-soil N transfers in a fertilised upland pasture. Plant Soil 343, 97–107. https://doi.org/10.1007/s11104-010-0526-8

Kool, A., Marinussen, M., Blonk, H., Consultants, B., 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization 20.

Lam, S.K., Suter, H., Mosier, A.R., Chen, D., 2017. Using nitrification inhibitors to mitigate agricultural N2O emission: a double-edged sword? Global Change Biology 23, 485–489. https://doi.org/10.1111/gcb.13338

Lamb, A., Green, R., Bateman, I., Broadmeadow, M., Bruce, T., Burney, J., Carey, P., Chadwick, D., Crane, E., Field, R., Goulding, K., Griffiths, H., Hastings, A., Kasoar, T., Kindred, D., Phalan, B., Pickett, J., Smith, P., Wall, E., zu Ermgassen, E.K.H.J., Balmford, A., 2016. The potential for land sparing to offset greenhouse gas emissions from agriculture. Nature Climate Change 6, 488–492. https://doi.org/10.1038/nclimate2910

Laureysens, I., Deraedt, W., Indeherberge, T., Ceulemans, R., 2003. Population dynamics in a 6-year old coppice culture of poplar. I. Clonal differences in stool mortality, shoot dynamics and shoot diameter distribution in relation to biomass production. Biomass and Bioenergy 24, 81–95. https://doi.org/10.1016/S0961-9534(02)00105-8

Lehmann, L.M., Smith, J., Westaway, S., Pisanelli, A., Russo, G., Borek, R., Sandor, M., Gliga, A., Smith, L., Ghaley, B.B., 2020. Productivity and Economic Evaluation of Agroforestry Systems for Sustainable Production of Food and Non-Food Products. Sustainability 12, 5429. https://doi.org/10.3390/su12135429

Li, D., Lanigan, G., Humphreys, J., 2011. Measured and Simulated Nitrous Oxide Emissions from Ryegrass- and Ryegrass/White Clover-Based Grasslands in a Moist Temperate Climate. PLOS ONE 6, e26176. https://doi.org/10.1371/journal.pone.0026176

MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Smith, P., Moxey, A., 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agricultural Systems 103, 198–209. https://doi.org/10.1016/j.agsy.2010.01.002

Milne, R., Brown, T.A., 1997. Carbon in the Vegetation and Soils of Great Britain. Journal of Environmental Management 49, 413–433. https://doi.org/10.1006/jema.1995.0118

Misselbrook, T.H., Cardenas, L.M., Camp, V., Thorman, R.E., Williams, J.R., Rollett, A.J., Chambers, B.J., 2014. An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. Environ. Res. Lett. 9, 115006. https://doi.org/10.1088/1748-9326/9/11/115006

Mokany, K., Raison, R.J., Prokushkin, A.S., 2006. Critical analysis of root : shoot ratios in terrestrial biomes. Global Change Biology 12, 84–96. https://doi.org/10.1111/j.1365-2486.2005.001043.x

Pellerin, S., Bamière, L., Angers, D., Béline, F., Benoit, M., Butault, J.-P., Chenu, C., Colnenne-David, C., Cara, S. de, Delame, N., Doreau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Hénault, C., Jeuffroy, M.-H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E., Savini, I., Pardon, L., 2013. How can French agriculture contribute to reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures (report). Inra - DEPE.

Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. Science 333, 1289–1291. https://doi.org/10.1126/science.1208742

Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D., 2018. Major limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. Global Change Biology 24, 2563–2584. https://doi.org/10.1111/gcb.14066

Pritchard, C.E., Williams, A.P., Davies, P., Jones, D., Smith, A.R., 2021. Spatial behaviour of sheep during the neonatal period: Preliminary study on the influence of shelter. Animal 15, 100252. https://doi.org/10.1016/j.animal.2021.100252

Rees, R.M., Eory, V., Bell, J., Topp, C.F.E., Sykes, A., Misselbrook, T., Cardenas, L.M., Chadwick, D.R., Sohi, S., Manning, A.C., Smith, P., 2020. How far can greenhouse gas mitigation take us towards net zero emissions in agriculture? 8.

Rooke, J.A., Miller, G.A., Flockhart, J.F., McDowell, M.M., MacLeod, M., 2016. Nutritional strategies to reduce enteric methane emissions.

Rosa, L., Gabrielli, P., 2023. Achieving net-zero emissions in agriculture: a review. Environ. Res. Lett. 18, 063002. https://doi.org/10.1088/1748-9326/acd5e8

Ryan, M., O'Donoghue, C., 2016. Socio-economic drivers of farm afforestation decision-making. Irish Forestry.

Schmeer, M., Loges, R., Dittert, K., Senbayram, M., Horn, R., Taube, F., 2014. Legume-based forage production systems reduce nitrous oxide emissions. Soil and Tillage Research 143, 17–25. https://doi.org/10.1016/j.still.2014.05.001

Scottish Government, 2022. Agri-Environment Climate Scheme [WWW Document]. URL https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/agri-environment-climate-scheme/ (accessed 12.14.22).

Singh, S.N., Verma, A., 2007. ENVIRONMENTAL REVIEW: The Potential of Nitrification Inhibitors to Manage the Pollution Effect of Nitrogen Fertilizers in Agricultural and Other Soils: A Review. Environmental Practice 9, 266–279. https://doi.org/10.1017/S1466046607070482

Smith, K.A., Dobbie, K.E., Thorman, R., Watson, C.J., Chadwick, D.R., Yamulki, S., Ball, B.C., 2012. The effect of N fertilizer forms on nitrous oxide emissions from UK arable land and grassland. Nutr Cycl Agroecosyst 93, 127–149. https://doi.org/10.1007/s10705-012-9505-1

Smith, P., 2014. Do grasslands act as a perpetual sink for carbon? Global Change Biology 20, 2708–2711. https://doi.org/10.1111/gcb.12561

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nature Clim Change 6, 42–50. https://doi.org/10.1038/nclimate2870

Sokolov, V., Habtewold, J., VanderZaag, A., Dunfield, K., Gregorich, E., Wagner-Riddle, C., Venkiteswaran, J.J., Gordon, R., 2021. Response Curves for Ammonia and Methane Emissions From Stored Liquid Manure Receiving Low Rates of Sulfuric Acid. Frontiers in Sustainable Food Systems 5.

Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4, 334–350. https://doi.org/10.1017/S1751731109990784

Stark, C., Thompson, M., Andrew, T., Beasley, G., Bellamy, O., Budden, P., Cole, C., Darke, J., Davies, E., Feliciano, D., 2019. Net Zero: The UK's contribution to stopping global warming.

Stott, A., MacLeod, M., Moran, D., 2010. Reducing greenhouse gas emissions through better animal health Rural Policy Centre, SAC, 8.

Sykes, A., Topp, K., Wilson, R., Reid, G., Rees, B., 2017. A comparison of farm-level greenhouse gas calculators in their application on beef production systems. Journal of Cleaner Production 164. https://doi.org/10.1016/j.jclepro.2017.06.197

Taft, H., Chadwick, D., Styles, D., Kipling, R., Newbold, J., Moorby, J., 2018. A review of greenhouse gas calculators for use in the Welsh agricultural sector, A Climate Smart Agriculture (Wales) Report.

Thorman, R.E., Nicholson, F.A., Topp, C.F.E., Bell, M.J., Cardenas, L.M., Chadwick, D.R., Cloy, J.M., Misselbrook, T.H., Rees, R.M., Watson, C.J., Willimas, J.R., 2020. Towards Country-Specific Nitrous Oxide Emission Factors for Manures Applied to Arable and Grassland Soils in the UK. Frontiers in Sustainable Food Systems 4, 62. https://doi.org/10.3389/fsufs.2020.00062

UK Government, 2021. Farming Investment Fund [WWW Document]. GOV.UK - Rural Payments Agency. URL https://www.gov.uk/guidance/farming-investment-fund (accessed 12.14.22).

Veldman, J.W., Overbeck, G.E., Negreiros, D., Mahy, G., Le Stradic, S., Fernandes, G.W., Durigan, G., Buisson, E., Putz, F.E., Bond, W.J., 2015. Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. BioScience 65, 1011–1018. https://doi.org/10.1093/biosci/biv118

Vellinga, T.V., Blonk, H., Marinussen, M., Zeist, W.J. van, Starmans, D. a. J., 2013. Methodology used in FeedPrint: a tool quantifying greenhouse gas emissions of feed production and utilization (No. 674). Wageningen UR Livestock Research, Lelystad.

Wang, J., Xiong, Z., Kuzyakov, Y., 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8, 512–523. https://doi.org/10.1111/gcbb.12266

Webb, P., Benton, T.G., Beddington, J., Flynn, D., Kelly, N.M., Thomas, S.M., 2020. The urgency of food system transformation is now irrefutable. Nat Food 1, 584–585. https://doi.org/10.1038/s43016-020-00161-0

Welsh Government, 2023. Survey of agriculture and horticulture: June 2023. Welsh Government. https://www.gov.wales/survey-agriculture-and-horticulture-june-2023

Welsh Government, 2022a. Small Grants – Efficiency. Business Wales - Wales Rural Network. URL https://businesswales.gov.wales/walesruralnetwork/rural-programmes/schemes/farm-efficiency-and-diversification/small-grants-efficiency (accessed 12.14.22).

Welsh Government, 2022b. Farming facts and figures: 2022. Welsh Government. https://gov.wales/farming-facts-and-figures-2022

Welsh Government, 2021a. Survey of agriculture and horticulture: June 2021. Welsh Government. https://www.gov.wales/survey-agriculture-and-horticulture-june-2021

Welsh Government, 2021b. Net Zero Wales Carbon Budget 2 (2021 to 2025). Welsh Government. ISBN 978-1-80391-158-8.

Wu, D., Zhang, Y., Dong, G., Du, Z., Wu, W., Chadwick, D., Bol, R., 2021. The importance of ammonia volatilization in estimating the efficacy of nitrification inhibitors to reduce N2O emissions: A global meta-analysis. Environmental Pollution 271, 116365. https://doi.org/10.1016/j.envpol.2020.116365

Yu, G., Beauchemin, K.A., Dong, R., 2021. A Review of 3-Nitrooxypropanol for Enteric Methane Mitigation from Ruminant Livestock. Animals (Basel) 11, 3540. https://doi.org/10.3390/ani11123540

Chapter 5 The nutritional value of meat should be considered when comparing the carbon footprint of lambs produced on different finishing diets

L.C. McNicol, L.S. Perkins, J. Gibbons, N.D. Scollan, A.P. Nugent, E.M. Thomas, E.L. Swancott, C. McRoberts, A. White, S. Chambers, L. Farmer and A.P. Williams

Abstract

Lamb production systems are under increasing pressure to reduce their environmental footprint, particularly emissions of greenhouse gases (GHGs) such as methane. However, the metrics used to express the carbon footprint of lamb seldom consider its nutritional density and contribution to balanced diets in humans. Lamb production systems vary considerably, from low-input pastoral systems to higher-input systems feeding concentrates for the latter 'finishing' period. To date, no studies have explored the effect of finishing diet on the carbon footprint of lamb meat on a nutritional basis.

Data from 444 carcasses were collected from four abattoirs across Wales, United Kingdom. Lambs were derived from 33 farms with one of four distinct finishing diets: forage crops (n = 5), grass (n = 11), concentrates (n = 7), and grass and concentrates (n = 15). Carcass data were analysed using mixed effects models. Significant differences were found in fatty acid composition of two large commercial cuts of meat from different finishing diets. To illustrate the effect of different measures of footprint, mass (kg dwt) and omega-3 polyunsaturated fatty acid content (g omega-3) were selected as functional units. GHG emission estimates were calculated using Agrecalc.

The concentrates diet had the lowest average mass-based product emissions [25.0 kg CO_2e/kg deadweight (dwt)] while the grass systems had the highest (28.1 kg CO_2e/kg dwt; p < 0.001). The semimembranosus muscle cut from the forage crops diet had the lowest average nutrition-based product emissions (19.2 kg CO_2e/g omega-3); whereas the same muscle cut from lambs finished on the grass and concentrates diet had the highest nutrition-based product emissions (29.4 kg CO_2e/g omega-3; p < 0.001). While mass-based functional units can be useful for comparing efficiencies of different farming systems, they do not reflect how farming systems impact the nutritional differences of the final product. This study demonstrates the importance of considering nutrition when expressing and comparing the carbon footprints of nutrient-dense foods such as lamb. This approach could also help inform discussions around the optimal diets for lamb production systems from both a human nutrition and environmental sustainability perspective.

5.1. Introduction

Lamb production systems are under increasing pressure to reduce their environmental footprint, particularly greenhouse gas (GHG) emissions such as methane (Garnett, 2011; Gerber *et al.*, 2013; Jones *et al.*, 2014a). In recent years, carbon footprinting of farms and the resultant produce (e.g. meat) has been increasingly used to estimate resultant environmental impacts (de Vries and de Boer, 2010; Edwards-Jones *et al.*, 2009; Jones *et al.*, 2014b; Röös *et al.*, 2013). Calculating a farm's carbon footprint offers the opportunity to identify sources of high emissions as well as compare emissions from different farming systems. However, such approaches rarely consider the carbon footprint of lamb relative to its nutritional density as a food product, as the standard functional unit for expressing lamb carbon footprint is per unit of product, e.g. kg CO_2e/kg of liveweight (lwt) or kg CO_2e/kg of deadweight (dwt) (Edwards-Jones *et al.*, 2009; Jones *et al.*, 2014b, 2014a; Ripoll-Bosch *et al.*, 2013). While this mass-based functional unit is useful for comparing efficiencies of different farming systems (Hyland *et al.*, 2016; McAuliffe *et al.*, 2018a), it does not reflect the nutritional value of the product to humans. Several different approaches have been taken to address this, including using a nutritional functional unit to model carbon footprint while considering nutrient density (McAuliffe *et al.*, 2023a; McLaren, 2021).

Ensuring an appropriate nutrient to use as a functional unit is paramount, as this can directly affect carbon footprint calculations. Previous research has used protein as a nutritional functional unit (e.g. Poore and Nemecek, 2018; Xu *et al.*, 2018). Protein as a nutritional functional unit is useful due to simplicities in data processing; however, it can be considered a rudimentary approach as it does not reflect the impact of individual amino acids and intricacies associated with digestion and absorption (McLaren, 2021; Sonesson *et al.*, 2017). Consequently, protein quality has been incorporated into nutritional functional units. For example, McAuliffe *et al.* (2023b) used an assessment called the Digestible Indispensable Amino Acid Score (DIAAS), which generates a protein quality "adjusted" functional unit. While this is a useful metric for studies comparing a single nutrient, a product's complete nutritive value is not accurately reflected. Nutrition density scores (NDS) provide a single functional unit in which multiple nutrients can be assessed. The most cited approach for using NDS to express emissions is the Nutrient Rich Food (NRF9.3; Fulgoni *et al.*, 2009) scoring system which accounts for nine nutrients including protein, selected minerals and vitamins, polyunsaturated fatty acids (PUFA) and three nutrients which are to be limited, namely, saturated fatty acids (SFA), sodium and added sugars. Given the complexities and importance of carbon footprinting for environmental targets, policy and consumers, the use of an appropriate functional unit is paramount for accurate determination of a product's nutrient density and carbon footprint (Capper, 2021).

Research has identified that while protein and amino acid profiles of meat remain largely constant across the diets on which livestock are reared, fat content and lipid profiles are heavily influenced by animal nutrition (Scollan *et al.*, 2006). Most notably, grass-based systems have been found to have higher levels of omega-3 PUFA than systems feeding concentrates (Fisher *et al.*, 2000; Warren *et al.*, 2008). Omega-3 PUFA is a functional unit of great importance due to its potential health benefits and nutraceutical properties in humans e.g. reducing the risk of cardiovascular disease and other inflammatory diseases (Swanson *et al.*, 2012). Consequently, omega-3 PUFA as a single nutrient functional unit has been explored to express emissions, particularly when comparing farming systems (McAuliffe *et al.*, 2018b). Lamb production systems also vary across the world, from low-input pastoral systems to higher-input systems feeding concentrates for the latter 'finishing' period. In the UK, many farms are typically grass-based systems, but some will provide supplementary concentrates and/or forage crops (e.g. swede (*Brassica napus*) or stubble turnips (*Brassica rapa*)) during the autumn/winter finishing period as grass availability and quality reduces (Barry, 2013).

To date, no studies have explored the effect of finishing diets on the carbon footprint of lamb expressed on a nutritional basis. Using data gathered on farms adopting one of four distinct finishing diets and data from the produced meat, this study applies a dual approach to evaluate the impacts of diet on the carbon footprint of lamb expressed on both a mass and nutritional basis, using omega-3 PUFA in 1 kg of fresh muscle as a functional unit.

5.2. Methods

5.2.1. Farm data collection

This paper is based on data from a larger 5-year study that included four balanced design trials. The Welsh Lamb Meat Quality Project conducted research trials across the UK, exploring on-farm and processing factors that may influence meat eating and nutritional quality. The on-farm factors were investigated across four trials, and included treatments of breed type, lamb gender, muscle cut, lamb finishing diet, daily liveweight gain, seasonality, lamb sire, and processing factors including length of meat ageing period, carcass hanging and packaging (Hybu Cig Cymru, 2023). Lamb numbers per treatment were balanced within each trial; however, numbers differed across trials due to lamb availability. Trials were conducted with four Protected Geographical Indication (PGI) approved Welsh abattoirs (DEFRA, 2021) that had previous experience of participating in large trials.

The abattoirs identified lamb producers that could supply lambs for the project (based on the specific Trial treatments that were required, e.g. supply lambs of a certain sex, finished on specific diets). A minimum of 24 lambs per farm were needed to reach a target slaughter date. The overall study aim was to research Welsh lamb eating quality across the range of systems that reflect production across the year. As such, the diet of the lambs was representative of those at different seasons / time of year. For example, forage-based crops can only be sown and used for finishing lambs at certain times (Hybu Cig Cymru, 2018).

Farm data were collected from 33 farms feeding one of four distinct finishing diets: *forage crops* (*n*=5), *grass* (*n*=7), *concentrates* (*n*=6), and *grass and concentrates* (*n*=15). The *forage crop* diet consisted of brassicas, fodder beet and forage rape. In the *concentrates* finishing system, lambs were all fed indoors on a diet of concentrates, barley, crimped barley or coarse mix, whereas the *grass* and the *grass and concentrates* diets were all fed outdoors and exclusively on grass and grass and concentrates, respectively. Farm data were self-reported by participating farmers using digital farm information surveys. All farms produced lambs to PGI Welsh lamb standards (DEFRA, 2021). In total, there were 60 lambs fed the *forage crop* diet, 90 lambs fed the *grass* diet, 66 lambs fed the *concentrates* diet, and 228 lambs fed the *grass and concentrates* diet (Table 5.1). Lambs were born between January 2020 and April 2022 and their age was recorded as the number of days between the average lambing date and the date of slaughter. Lambs consisted of several breeds: terminal sire (*n*=382*),* hill (*n*=38) and cross-breeds (*n*=24). Previous studies have found breed could potentially affect meat-eating quality (Arsenos *et al.*, 2002; Fisher *et al.*, 2000), therefore breed was controlled for in the statistical design of the study. Terminal sire breeds included Aberfield, Abermax, Charollais, Lleyn, Primera, Suffolk and Texel. The hill breed type included Beulah Speckled Face, Welsh Mountain and Torddu. Lambs were a mixture of male (entire *n*=288; castrated *n*=72) and females (*n*=84) (Table 5.1). Individual lamb weights were recorded on a fortnightly basis over the 6-week finishing period to calculate their liveweight gain for that period. In cases where specific data were difficult to obtain or where any data were missing, recently published UK data or standardized estimates were used. This was sourced predominantly from SRUC's Farm Management Handbook (Beattie, 2022) and Feedipedia (Heuzé *et al.*, 2015). For example, data were collected for diet type; however, actual feed consumption was not included. Therefore, assumptions were made on forage and concentrate intake based on example finishing systems and values from SRUC's Farm Management Handbook (Beattie, 2022).

Table 5.1. Summary of the mean key performance indicators (± standard error) over the 6-week finishing period and number of farms carbon footprinted for each finishing diet. Different lower-case letters indicate statistically significant differences at the 5% level.

	Diet				
	Forage crops	**Grass**	**Concentrates**	**Grass and concentrates**	**p-value**
No. of farms (No. of lambs)	5 (60)	7 (90)	6 (66)	15 (228)	
Liveweight at start of finishing period (kg)	37.3 ± 0.36[a]	33.0 ± 0.86[b]	35.7 ± 0.27[a]	33.4 ± 0.36[b]	<0.001
Liveweight gain (g/day)	179 ± 8.48 [a]	213 ± 11.40 [a]	189 ± 10.63 [a]	268 ± 8.15 [b]	<0.001
Total weight gain over finishing period (kg)	6.7 ± 0.32[a]	8.6 ± 0.48[b]	7.3 ± 0.31[ab]	10.2 ± 0.17[c]	<0.001
Liveweight at slaughter (kg)	44.0 ± 0.29 [a]	42.0 ± 0.54 [b]	43.0 ± 0.34 [ab]	43.6 ± 0.26 [a]	<0.01
Killing out percentage (%)	46.6 ± 0.38 [a]	45.8 ± 0.56 [a]	46.3 ± 0.32 [a]	46.8 ± 0.20 [a]	>0.05
Carcass weight (kg)	20.5 ± 0.16 [a]	19.1 ± 0.21 [b]	19.9 ± 0.15 [a]	20.3 ± 0.11 [a]	<0.001

5.2.2. Carcass data collection

Lambs were selected at the target carcass weight of 16-22 kg and conformation grade of E, U, R and fat class 2, 3L, 3H (Hybu Cig Cymru, 2012). From the farms selected that provided whole farm data, 444 carcasses were available for analysis. Carcasses were weighed directly after slaughter to calculate the killing out percentage (KO%). Three of the largest lamb muscles used in other lamb sensory scientific studies (Bonny *et al.*, 2018; MSA 2019; Pannier *et al.*, 2018; Pannier *et al.*, 2019) were selected using the Meat Standards Australia cooking protocol, being the *longissimus dorsi* (Loin; *n*= 444), *semimembranosus* (Topside; *n*= 203) and *gluteus medius* (Chump cut; *n*= 96). The *longissimus dorsi* was analysed for all lambs (number of lambs from each diet, breed type and gender can be found in Section 2.1). The *semimembranosus* analysed included 36 lambs fed the *forage crop* diet, 36 lambs fed the *grass* diet, 18 lambs fed the *concentrates* diet, and 113 lambs fed the *grass and concentrates* diet. Lambs from the *semimembranosus* analysed also consisted of several breeds: terminal sire (*n*=173*),* hill (*n*=8) and cross-breeds (*n*=22). All *semimembranosus* samples analysed came from ram lambs (*n*=203). Eight days post slaughter, the muscle pH was recorded for each cut. Muscles were stored at -20 ºC until nutritional analysis.

5.2.3. Nutritional analysis

Fatty acid composition was determined by the method of O'Fallon *et al.* (2007). Lean lamb muscle was hydrolysed with potassium hydroxide in methanol. The potassium hydroxide was neutralised, and the free fatty acids methylated by acid catalysis using sulphuric acid. Fatty acid methyl esters were extracted into hexane and analysed by GC-FID using a CP-SIL 88 column (100 m ×250 µm ×0.2 µm). Intramuscular fat was determined by the method of Folch *et al.* (1956) with the percentage of extracted fat calculated gravimetrically.

For total amino acid analysis, 100 g of fresh muscle was hydrolysed in constant boiling hydrochloric acid. Samples were then dried down, diluted and analysed on a Waters 2695 pump/injector system. The individual amino acids were separated by ion exchange chromatography on a strong cation exchange resin using sodium citrate buffer gradients of increasing pH. The ninhydrin reagent was pumped using a Waters 1515 isocratic pump. The ninhydrin reaction occurs in a heated reaction coil at 125°, and the derivatized amino acids are detected using a Waters 2487 variable wavelength UV/VIS detector.

Mineral analysis was carried out using a two-stage microwave digestion followed by Inductively Coupled Plasma Optical Emission Spectroscopy using wavelengths 238.2 and 213.9 nm for iron and zinc respectively. ERM-BB184 Bovine Muscle from the Joint Research Centre of the European Commission was used as a quality control material. ISO 17034 certified reference standards for zinc and iron were purchased from ROMIL Ltd, Cambridge, UK.

The full nutritional analysis methods are available in Appendix 5

5.2.4. Emission estimates

Baseline carbon footprints were calculated using Agrecalc (Agricultural Resource Efficiency Calculator - https://www.agrecalc.com/). Agrecalc was developed by Scotland's Rural College and has been found to be amongst the best-performing carbon accounting tools in terms of transparency, methodology and allocation for use on UK farms (Sykes *et al.*, 2017). The system boundary for Agrecalc is "cradle-to-grave", i.e. all emissions from agricultural production from the birth of the animal to the farm gate. The tool uses methods from the latest 2019 refinements to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and is certified to PAS2050 standards (2011). Agrecalc follows IPCC (2019) Tier 2 country-specific guidelines for all livestock and manure management CH_4 and N_2O emissions. Direct N_2O emissions from soil following fertilizer and manure application also used IPCC (2019) Tier 2 calculations. IPCC (2019) Tier 1 methodology was used to calculate N_2O emissions from crop residues and indirect N_2O emissions. DEFRA (2012) EFs were employed for calculating emissions relating to energy usage. Emissions for imported feed and embedded fertilizer were based on values from the Dutch Feedprint database (Vellinga *et al.*, 2013) and Kool *et al.* (2012), respectively. Data required to calculate sequestration estimates were not provided, therefore, carbon sequestration was not considered in this study.

For conversion of non-CO_2 gases, Agrecalc uses the global warming potential over a 100-year period (GWP100) published in the fourth assessment report (AR4) which are consistent with National Inventory reporting. Methane has a GWP100 of 25 and the value for N_2O is 298 (IPCC, 2007). It is important to note that these values are different from those in the most recent assessment report (AR6; IPCC, 2023).

Emissions from Agrecalc were expressed as both GHG emissions per unit of product (i.e., kg CO_2e/kg of deadweight (dwt)) and GHG emissions per unit of nutrition. To calculate the latter, the value of mg omega-3 measured in 100 g of fresh muscle, determined as described in Section 2.2, was converted to the equivalent in g omega-3 in 1 kg of fresh muscle. The calculated GHG emissions per kg dwt were then divided by this to give kg CO_2e/g omega-3, giving the GHG emissions per unit of nutrition.

5.2.5. Statistical analyses

For individual variables, models were fitted using mixed effects models in R (R Core Team, 2022). Models were fitted using the lme4 package (Bates *et al.*, 2015) and *p*-values were calculated using Satterthwaite's method from the lmerTest package (Kuzetsova *et al.*, 2017). In all models, Farm was included as a random effect and models included diet, breed type and gender as factors. This approach allowed the analysis of the data that was unbalanced in breed and gender while controlling for any differences in these factors not of direct interest. Gender was not included for the *semimembranosus* models as all the lambs in this group were male. Pairwise differences were calculated using the emmeans package (Length, 2023) using a Tukey correction for multiple comparisons. After fitting diagnostic plots for all models were checked for any evidence of heterogeneity of variance or non-normality of errors. For a few variables a log (or log+1) transformation was applied to correct for heterogeneity of variance. Data were plotted using the ggstats package (Larmarange, 2023).

To assess the effect of diet on finishing system performance, a one-way ANOVA and Tukey pairwise-comparison were performed on individual key performance indicators (KPIs). A one-way ANOVA was conducted to assess the effect of diet on mass-based product emissions and a two-way ANOVA was used to test for an association between diet and muscle cut on nutrition-based product emissions.

Multiple pairwise-comparison between the means of groups were then performed using Tukey multiple pairwise-comparisons. The level of statistical significance was set at 5% for all tests in this study.

5.3. Results

5.3.1. Farm and lamb production data

Lamb growth and weights varied between finishing diets. Lambs from the *forage crops* and *concentrates* diet had significantly higher liveweights at the start of the finishing period compared to lambs on *grass* and *grass and concentrates* diet (Table 5.1). Lamb age varied at the start of the finishing period to reflect the inherent differences in the production and seasonality of the different finishing systems according to industry practice. Lambs from the *grass and concentrates* diet had significantly higher liveweight gain and total weight gain over the finishing period than lambs from all other diets. Lambs on the *forage crops* diet had the highest liveweight at slaughter whereas the *grass* diet had the lowest liveweight at slaughter (Table 5.1). Killing out percentages did not vary significantly between diets. Lambs from the *grass* only diet had significantly lower carcass weights compared to lambs on all other diets (Table 5.1).

Although not directly related to the finishing diet and likely influenced by how lambs were selected, time on farm varied between lambs from different finishing systems. Lambs from the *concentrates* diet were on farm for the longest time (mean 9.2 ± 0.17 months) compared to lambs from: the *forage crops diet* which were on farm for 8.5 ± 0.19 month ($p>0.05$), *grass* diet which were kept for 6.0 ± 0.22 months ($p<0.001$) and *grass and concentrates* diet which were on farm for the least time at 5.2 ± 0.11 months ($p<0.001$).

5.3.2. Nutritional composition of lamb meat

There was no significant difference between the amino acid content of *gluteus medius* across the four diets (Table A 5.1) ($p>0.05$). As expected, there were also no significant differences found in the iron content of both the *longissimus dorsi* and *semimembranosus* across all four diets ($p>0.05$), the iron content of muscle is more associated with age than diet (Pannier *et al.*, 2014). Additionally, there was no significant differences in the zinc content in the *semimembranosus* across all diets, however, diet did have an effect on the zinc content of the *longissimus dorsi* ($p<0.001$).

Fat percentage varied significantly between finishing diets in both the *longissimus dorsi* and *semimembranosus* ($p<0.05$). Differences were noted in the total fatty acid composition and saturated fatty acid in the *longissimus dorsi* across the four diets *(p*<0.05); however, there were no differences found in total fatty acid content of the *semimembranosus* across diets (Table 5.2; discussed in Section 4.1). There were significant differences in the total omega-3 PUFA content in the *longissimus dorsi* across the four finishing diets (*p*<0.001), with the highest and lowest being reported in muscle from the *grass* and *concentrate* diets, respectively. The analysis controlled for the differences in breed type (*longissimus dorsi* and *semimembranosus*) and gender (*longissimus dorsi* only). There was not a consistent pattern among fatty acids, with breed type and gender being significantly different in some but not all of the variables (full results can be found in Table A 5.2). For the variable of interest (omega-3 PUFA), breed type had a significant effect in the *semimembranosus* (*p*<0.05) but not in the *longissimus dorsi* (*p>0.05*). There was also a significant difference in omega-3 PUFA between genders in the *longissimus dorsi* (*p<0.05*).

There were significant differences in levels of palmitic acid (C16:0) and stearic acid (C18:0) across the four diets in the *longissimus dorsi* muscle (*p*<0.05), with no differences detected in the *semimembranosus* (Table 5.2). Linoleic acid (C18:2 n-6) was significantly greater in the *concentrate* diet and lowest in the *grass* diet in the *longissimus dorsi* muscle. There was no difference between C18:2 n-6 levels from lamb finished on the *forage crops* and *grass and concentrate* diet.

Lamb from the *forage crops* diet and *grass* diet had significantly higher alpha-linolenic acid (C18:3 n-3) in both the *longissimus dorsi* and *semimembranosus* with levels being reported as 62 and 61 mg/100 g and 71 and 73 mg/100 g, respectively, compared to the *concentrate* diet where 42 mg/100 g was reported for both muscles. There were differences in levels of eicosapentaenoic acid (C20:5 n-3; *p*<0.001), docosapentaenoic acid (C22:5 n-3; *p*<0.05) and docosahexaenoic acid (C22:6 n-3; *p*<0.001) across diets in the *longissimus dorsi* muscle, however, no differences in any long chain omega-3 PUFA was noted in the *semimembranosus*.

Omega-3 PUFA is known to have a variety of health benefits such as reduced risk of cardiovascular disease and other inflammatory diseases (Swanson *et al.*, 2012). Omega-3 PUFA composition of lamb is also known to vary significantly between animal diets, particularly between grass and concentrate feeding (Fisher *et al.*, 2000; Warren *et al.*, 2008). Our finding are in line with other previous studies. grams of omega-3 in 1 kg of fresh muscle (kg CO_2e/g-omega-3) was selected as a functional unit to express emissions on a nutritional basis.

Table 5.2. Estimated marginal mean (± standard error) fatty acid composition of lamb meat from four finishing diets averaged over breed type and gender for *longissimus dorsi* and breed type for *semimembranosus*. Different lower-case letters indicate statistically significant differences between diets within each muscle at the 5% level.

Fatty acid (mg/100 g)	Longissimus dorsi					Semimembranosus				
	Forage crops	Grass	Concentrates	Grass and concentrates	p-value	Forage crops	Grass	Concentrates	Grass and concentrates	p-value
C12:0	3.9 ± 1.05^{a}	9.8 ± 0.86^{b}	4.7 ± 0.94^{a}	7.3 ± 0.85^{b}	<0.001	4.5 ± 0.58^{a}	4.3 ± 0.69^{a}	4.8 ± 0.64^{a}	5.2 ± 0.51^{a}	0.484
C14:0	61.8 ± 9.72^{a}	104.5 ± 8.18^{b}	58.4 ± 8.12^{a}	78.4 ±7.67^{a}	<0.001	58.4 ± 5.25^{a}	55.3 ± 6.21^{a}	57.1 ± 5.76^{a}	54.9 ± 4.62^{a}	0.927
C16:0	720 ± 44.2^{ab}	648 ± 36.6^{ab}	737 ± 38.2^{b}	622 ± 35.3^{a}	0.008	512 ± 41.4^{a}	521 ± 47.7^{a}	465 ± 41.3^{a}	453 ± 34.5^{a}	0.449
C18:0	537 ± 41.3^{a}	463 ± 33.8^{a}	542 ± 36.7^{a}	466 ± 33.3^{a}	0.030	407 ± 39.1^{a}	445 ± 44.2^{a}	342 ± 36.3^{a}	348 ± 31.1^{a}	0.219
C18:1 t11	109 ± 8.04^{ab}	130 ± 6.69^{b}	111 ± 6.87^{a}	107 ± 6.41^{a}	0.006	71.8 ± 10.09^{a}	95.1 ± 11.69^{a}	79.1 ± 10.25^{a}	79.6 ± 8.51^{a}	0.403
C18:1 n-9 cis	1148 ± 73.1^{ab}	1007 ± 60.3^{a}	1179 ± 63.8^{b}	1016 ± 58.4^{ab}	0.011	824 ± 56.3^{a}	885 ± 65.7^{a}	760 ± 58.6^{a}	740 ± 48.2^{a}	0.190
C18:2 n-6	104.6 ± 10.52^{ab}	89.1 ± 8.70^{a}	138.2 ± 9.54^{c}	121.4 ± 8.83^{bc}	<0.001	104.7 ± 15.5^{a}	92.1 ± 17.0^{a}	139.9 ± 12.9^{a}	130.7 ± 11.5^{a}	0.115
C20:4 n-6	44.9 ± 3.32^{a}	41.3 ± 2.73^{a}	45.3 ± 3.00^{a}	41.1 ± 2.74^{a}	0.221	42.3 ± 2.21^{a}	35.3 ± 2.61^{a}	41.9 ± 2.41^{a}	41.9 ± 1.94^{a}	0.080
C18:3 n-3	62.1 ± 4.45^{b}	60.5 ± 3.66^{b}	44.2 ± 4.03^{a}	52.7 ± 3.69^{ab}	<0.001	70.5 ± 8.43^{a}	73.0 ± 8.93^{a}	44.0 ± 6.38^{a}	50.3 ± 5.86^{a}	0.041
C20:5 n-3	26.5 ± 1.56^{bc}	29.4 ± 1.28^{c}	21.7 ± 1.40^{a}	24.1 ± 1.28^{ab}	<0.001	27.1 ± 1.98^{a}	29.7 ± 2.22^{a}	22.7 ± 1.79^{a}	23.1 ± 1.55^{a}	0.054
C22:5 n-3	35.1 ± 1.59^{ab}	34.7 ± 1.30^{b}	30.8 ± 1.41^{a}	31.1 ± 1.28^{ab}	0.009	34.2 ± 2.42^{a}	35.4 ± 2.62^{a}	29.3 ± 1.97^{a}	29.8 ± 1.77^{a}	0.179
C22:6 n-3	8.3 ± 0.90^{a}	12.1 ± 0.76^{b}	5.6 ± 0.82^{c}	7.6 ± 0.78^{a}	<0.001	4.8 ± 0.89^{a}	5.9 ± 0.97^{a}	5.7 ± 0.74^{a}	6.9 ± 0.66^{a}	0.110
Total SFA	1399 ± 87.0^{ab}	1288 ± 71.9^{ab}	1404 ± 75.5^{b}	1208 ± 69.4^{a}	0.031	1024 ± 83.1^{a}	1061 ± 95.7^{a}	902 ± 82.6^{a}	893 ± 69.2^{a}	0.324
Total MUFA	1236 ± 75.6^{ab}	1089 ± 62.4^{a}	1271 ± 65.7^{b}	1095 ± 60.4^{a}	0.008	890 ± 60.0^{a}	946 ± 70.0^{a}	830 ± 62.5^{a}	805 ± 51.4^{a}	0.244
Total PUFA	297 ± 15.0^{a}	274 ± 12.3^{a}	295 ± 13.5^{a}	284 ± 12.2^{a}	0.202	296 ± 28.9^{a}	286 ± 30.9^{a}	299 ± 22.5^{a}	296 ± 20.5^{a}	0.984
Total n-3	132 ± 6.7^{ab}	137 ± 5.5^{b}	102 ± 6.1^{c}	117 ± 5.5^{bc}	<0.001	138 ± 12.8^{a}	146 ± 13.7^{a}	103 ± 10.0^{a}	111 ± 9.1^{a}	0.067
Total n-6	157 ± 13.7^{ab}	138 ± 11.3^{a}	192 ± 12.4^{b}	170 ± 11.5^{ab}	<0.001	153 ± 17.0^{a}	132 ± 18.9^{a}	192 ± 15.0^{a}	178 ± 13.1^{a}	0.086
n-6/n-3	1.2 ± 0.20^{a}	1.0 ± 0.17^{a}	1.9 ± 0.18^{b}	1.4 ± 0.17^{a}	<0.001	1.2 ± 0.22^{ab}	0.9 ± 0.25^{a}	2.1 ± 0.21^{c}	1.8 ± 0.18^{bc}	0.002
PUFA/SFA	0.23 ± 0.025^{a}	0.23 ± 0.020^{a}	0.22 ± 0.022^{a}	0.24 ± 0.012^{a}	0.687	0.29 ± 0.023^{a}	0.25 ± 0.027^{a}	0.33 ± 0.025^{a}	0.32 ± 0.020^{a}	0.038
Total FA	3080 ± 167^{ab}	2816 ± 138^{ab}	3095 ± 144^{b}	2696 ± 133^{a}	0.016	2291 ± 165^{a}	2398 ± 191^{a}	2117 ± 166^{a}	2083 ± 138^{a}	0.404

5.3.3. Mass-based and nutrition-based product emissions

Mass-based product emissions varied significantly from 21.8 – 36.4 kg CO_2e/kg dwt across finishing diets (p<0.001). There were significant differences in mass-based product emissions between all diets (p<0.05) apart from the *forage crops* and *grass and concentrates* diets (p>0.05). Lambs from the *concentrates* diet had the lowest average mass-based product emissions (25.0 kg CO_2e/kg dwt) whilst those from the *grass* systems had the highest (28.1 kg CO_2e/kg dwt; Figure 5.1) (p<0.001). Variation in mass-based product emissions was also seen within the same diets, for example, *grass and concentrates* diet, highest mass-based product emissions (36.4 kg CO_2e/kg dwt) were more than 1.6 times higher than the lowest (22.2 kg CO_2e/kg dwt).

Further variation was seen when accounting for omega-3 content, with nutrition-based emissions ranging from 12.1 – 73.8 kg CO_2e/g omega-3. Nutrition-based emissions were greater for *longissimus dorsi* than for *semimembranosus* across all diets other than *for grass and concentrates*, although this difference was not statistically significant (p>0.05). Significant differences in nutrition-based product emissions between the two muscle cuts were only found in the *forage crops* diet (p<0.01; data not shown). The *semimembranosus* cut of lambs from the *forage crops* diet had the lowest average nutrition-based product emissions (19.2 kg CO_2e/g omega-3; Figure 5.1), whereas the *semimembranosus* cut of lambs from the *grass and concentrates* diet had the highest nutrition-based product emissions (29.4 kg CO_2e/g omega-3) (p<0.001).

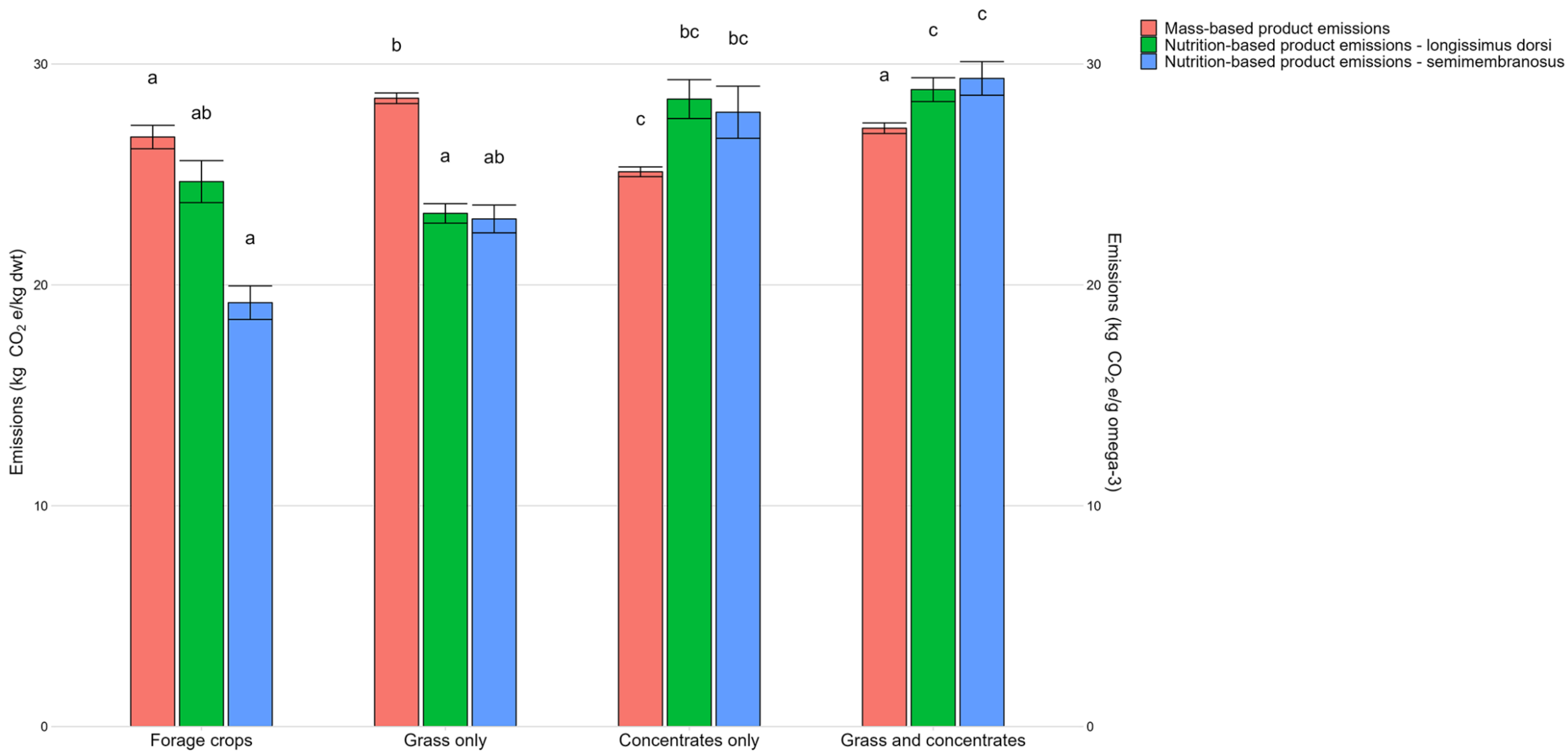


Figure 5.1. Mean emissions estimates (± standard error) for *longissimus dorsi* and *semimembranosus* muscle cuts for each finishing diet expressed as mass-based product emissions and nutrition-based product emissions. Different lower-case letters indicate statistically significant differences in diet within each individual emissions measure at the 5% level.

5.4. Discussion

5.4.1. Omega-3 PUFA composition

Significant differences were found in the total fatty acid composition and saturated fatty acids in the *longissimus dorsi,* but not in the *semimembranosus* across the four finishing diets. This it is likely due to the *longissimus dorsi* having a higher total fat content than the *semimembranosus* (Table A 5.1). Differences were found in the fatty acid composition of the *semimembranosus* across finishing diets, however, these differences were not significant. This may be due to the lower number of *semimembranosus* samples analysed (*n*=203) compared to the *longissimus dorsi* (*n*=444), due to this study being part of a larger research trial looking at multiple variables, one being muscle/cut. Nonetheless, significant differences were found in C18:3 n-3 and the n-6/n-3 ratio in the *semimembranosus* of lambs across finishing diets, which was ultimately a key focus of the study.

The total fat content for lamb meat was highest in the *longissimus dorsi* from the *forage crops* diet and lowest in *semimembranosus* from the *grass and concentrates* diet. Pasture feeding is often associated with lower meat fat content as found by Fisher *et al.* (2000) and Nuernberg *et al.* (2008), who reported 1963 *vs.* 1853 mg/100 g and 2100 *vs.* 1800 mg/100 g muscle in concentrate- and grass-fed lamb, respectively. Conversely, Demirel *et al.* (2006) reported lambs finished on grass hay had higher total fatty acid, compared to concentrate feeding. This is similar to the saturated fatty acid composition in the *longissimus dorsi* in the current study, where again the *grass and concentrates* diet was lowest. However, the saturated fatty acid composition did not differ significantly between the diets in the *semimembranosus*.

Levels of C18:2 n-6 were higher in lambs that had been fed *concentrates* as part of or as a sole dietary component. This is unsurprising as concentrates are rich in linoleic acid, whereas grass and forage crops would have relatively low levels. Lambs from the *grass and concentrates* diet had significantly less C18:2 n-6 compared to the *concentrates* diet. The mixture of grass and concentrates at dietary components will dilute the amount of C18:2 n-6 being deposited into muscle (Scollan *et al.*, 2017). This dominant C18:2 n-6 influence is also reflected in the n-6/n-3 ratio, which is highest for the *concentrate* diet and lowest for the *grass* diet.

The total omega-3 PUFA composition varied across the four diets, with the *forage crops* and *grass* diet having the highest amount and the lowest being reported in the *concentrates* diet for both muscle cuts. Studies in lamb have reported total omega-3 PUFA as 102 and 44 mg/100 g of meat (Fisher *et al.*, 2000), and 78 and 67 mg/100 g of meat (Kitessa *et al.*, 2010) in animals fed on grass and concentrate diets, respectively. This was supported by a study concluding that lambs reared on grass had significantly higher total omega-3 PUFA levels compared to lambs reared on a grass and concentrate and concentrate and hay diet (Boughalmi and Araba, 2016).

Lamb from the *forage crops* diet and *grass* diet had significantly higher C18:3 n-3 in the *longissimus dorsi* compared to the *concentrate* diet. It is well acknowledged that grass is rich in C18:3 n-3. This is because plant chloroplasts can uniquely synthesise (*de novo*) long chain fatty acids (>18 carbons; Harwood, 1999). Levels of C18:3 n-3 in grass and other plants are influenced by season, species, location and environment (e.g. temperature and light exposure; Elgersma *et al.*, 2003; Mir *et al.*, 2006; Tsvetkova and Angelow, 2010; Yalcin *et al.*, 2011; De Brito *et al.*, 2017). This also explains why forage crops and other plant-based materials have high levels of C18:3 n-3. The 'grass effect' is reflected in the data presented, particularly by the titration effect seen between the *grass*, *grass and concentrates* and *concentrate* diets, where any impact is diluted. There were some significant differences reported for the long chain omega-3 PUFAs (C20:5, C22:5 and C22:6 n-3) across the four finishing diets which is contrary to the findings of others (Fisher *et al.*, 2000; Demirel *et al.*, 2006). Higher levels of long chain omega-3 PUFAs including C20:5 n-3 and C22:6 n-3 were found in the *grass and forage crops* in the *longissimus dorsi*. Although lamb diets consisting solely of grass have very little amounts of long chain omega-3 PUFAs (as pasture species are primarily dominant in C18:3 n-3), small increases are not surprising as conversion of C18:3 n-3 to longer chain omega-3 via elongation and desaturation processes can occur in the lamb (Bessa *et al.*, 2015). Nutrition and genetics are the two most influencing factors affecting fatty acid composition in muscle (Dervishi *et al.* 2019; Scollan *et al.* 2014), meaning any variation seen is likely due to lambs being on a grass-based diet more so than the actual species composition in the grazed pastures (Dierking *et al.*, 2010; Scollan *et al.*, 2017).

Due to the differences in omega-3 PUFA composition between the four diets, grams of omega-3 was selected as a functional unit to express emissions on a nutritional basis. While the n-6/n-3 ratio was also considered for use as a nutritional functional unit, we focus on omega-3 PUFA because it accounts for absolute amounts, rather proportions of fatty acids present (EFSA, 2010).Omega-3 PUFA is known to vary between grass and concentrate based diets (Fisher *et al.*, 2000; Warren *et al.*, 2008), and has been previously used as a functional unit to express emissions whilst comparing farming systems (McAuliffe *et al.*, 2018b). Additionally, omega-3 PUFA is important in human nutrition with documented health benefits such as reducing the risk of cardiovascular disease and other inflammatory diseases (EFSA, 2010; Swanson *et al.*, 2012).

5.4.2. Mass-based product emissions

Mass-based product emissions varied significantly across finishing systems, which largely reflects the variation in efficiencies between the different diets. The *concentrates* diet had the lowest average mass-based product emissions whilst the *grass* systems had the highest. Although lambs from the *concentrates* diet were on farm for longer and the bought-in feed would lead to greater embedded GHG emissions, concentrates have a lower fibre content which can result in lower CH_4 production (van Wyngaard *et al.*, 2018; Yan *et al.*, 2010). Lambs on the *concentrates* diet also had higher carcass weights and KO% compared to the lambs form the *grass* diet, resulting in lower emissions per kg of product. Considerable variation was also seen in mass-based product emissions of finishing systems within the same diets. This highlights the difference in efficiencies of finishing systems within the same diet. This could be explained by animal health issues (e.g. lameness or gastrointestinal worm challenge), the quality of the diet offered, and genetic variation.

5.4.3. Nutrition-based product emissions

The significantly higher omega-3 PUFA content of the *forage crops* diet resulted in the *semimembranosus* cuts from this diet having the lowest nutrition-based product emissions. Similarly, *grass* systems had the lowest nutrition-based product emissions for the *longissimus dorsi* due to lambs from the *grass* diets having the highest omega-3 PUFA content of the *longissimus dorsi*. The *grass and concentrates* diet had the highest nutrition-based product emissions for both the *longissimus dorsi* and *semimembranosus*. This is likely a result of their initially higher mass-based product emissions and relatively lower omega-3 PUFA content compared to that of the *forage crops* and *grass* diets. The *concentrates* diet had lowest omega-3 PUFA content for both the *longissimus dorsi* and *semimembranosus* resulting in higher nutrition-based product emissions. However, as the concentrates diet had the lowest mass-based emissions to begin with, this effect is somewhat masked.

Across all diets except the *forage crops* diet, there was no significant difference in nutrition-based product emissions between the *longissimus dorsi* and *semimembranosus*. This is due to the similar average omega-3 PUFA content between *longissimus dorsi* and *semimembranosus*. For all systems, except for the *grass and concentrate* diet, nutrition-based product emissions were higher in the *longissimus dorsi* than in the *semimembranosus*. This could be explained by the *forage crops* and *grass* diets having higher omega-3 PUFA contents in their *semimembranosus* cuts than in their *longissimus dorsi.* This is likely due to *longissimus dorsi* having a higher SFA and lower PUFA content than the *semimembranosus*. Fowler *et al.* (2019) also found the *longissimus dorsi* of lambs in extensive systems had lower omega-3 PUFA content than the *semimembranosus*. However, the *forage crops* diet showed significant differences in nutrition-based product emissions between *longissimus dorsi* and *semimembranosus.* This result should be treated with caution due to the small number of farms in this study on the *forage crops* diet as well as the variation of feeds and therefore fatty acid composition of lambs within the *forage crops* diet. For example, the *forage crops* diet consisted of finishing systems feeding brassica, fodder beet and forage rape, which may all affect the nutritional composition of lambs differently. Even within diets that were finished on solely grass, grass quality will vary between farms and therefore this will likely impact the nutritional composition of lambs, particularly omega-3 PUFA content (Howes *et al.*, 2010).

This study found marginally lower nutrition-based emissions for lamb production systems than previous studies. McAuliffe *et al.* (2018) noted lambs on upland and lowland systems had nutrition-based emissions of 30.0 kg CO_2e/g omega-3 and 28.7 kg CO_2e/g omega-3, respectively. These values are higher than both cuts from the *forage crops*, *grass* and *concentrates* diets found in the present study. However, these differences must be interpreted with caution as different carbon footprinting tools have been used to calculate emissions estimates in this study. Additionally, our study found higher omega-3 PUFA content in lambs across some diets e.g. 146 mg/100 g from the *semimembranosus* from the *grass* diet compared to published values, which reported levels of 103 mg/100 g of meat (Whittington *et al.*, 2006).

The present study highlights the importance of nutritional functional unit when considering health and wellbeing implications of products, especially given the diversity in nutritional fatty acid composition in ruminant products. Using omega-3 PUFA as a nutritional functional unit demonstrated its value and warrants further consideration given the numerous reported benefits optimal consumption has on human health and well-being (Jacobson *et al.*, 2012; Givens, 2015; Singh *et al.*, 2016). Although the lamb in this study will unlikely have a nutraceutical effect at a normal portion size, the aim of this study was to explore the effect of finishing diet on the carbon footprint of lamb expressed on a nutritional basis rather than making recommendations on lamb portion sizes.

This study has uniquely used real farm data to highlight the importance of shifting from mass-based functional units to nutrient-based functional units. While mass-based functional units such as per kg dwt still have a valuable place in comparing production efficiencies of farms, they do not reflect the degree of nutrition provided by consumption of the meat produced from each system.

5.4.4. Limitations

Some appropriate assumptions had to be made to calculate carbon footprints for each finishing system where some farm data were unavailable. For example, although data were collected for diet type, actual feed consumption was not recorded. Although such assumptions and default values regularly have to be applied in farm carbon footprint studies (McAuliffe *et al.*, 2018a; Ripoll-Bosch *et al.*, 2013; Edward-Jones *et al.*, 2009), there may be an over- and/or under-estimations of emission estimates as a result. Ensuring a larger sample size with an equal number of finishing systems from each diet would reduce unequal variances between diets and improve the statistical power of results. Nonetheless, although breed type and gender were unbalanced between treatments, farms were selected for this study to represent a cross-section of lamb finishing systems, and therefore these differences in production and seasonality are reflected in the results. For example, hill breeds will more likely be associated with grass-based finishing systems as opposed to concentrates. However, for the variables such as breed type (e.g. hill and cross- breeds) which have lower numbers in each group, there will inevitably be a greater level of uncertainty in the results.

Using a single nutrient functional unit does not reflect the products' complete nutritive value. Focusing on a single nutrient functional unit could lead to an under or over-supply of other key nutrients. In this study, we have focused purely on omega-3 PUFA, however, there would likely be variation in a number of other fatty acids between finishing diets, for example, conjugated linoleic acid (CLA) which have a high nutraceutical value. Future studies should therefore consider CLA and indeed the full fatty acid profile. Moreover, lamb can provide a considerable range of nutritional benefits that were not considered in this study. Although many parameters (52 fatty acid parameters, 19 amino acid parameters, and two mineral parameters) were collected for this study, measurement of other key nutrients (e.g. vitamins and certain minerals) would generate a fuller nutrient density score (Fulgoni *et al.*, 2009). Moreover, nutrient density scores often consider the daily recommended intake of each nutrient. Nutrients collected in this study were from 100 g of fresh muscle, so future work would need to consider cooking losses of meat if a nutrient density score was to be created. However, nutrient density scores are not without their limitations. The outcomes of nLCAs which employ a nutrient density score are highly dependent on the nutrients which are included in the metric. This means some metrics are more suitable for some foods than others, and other important aspects of nutrition (such as the bioavailability of nutrients and interaction between nutrients) are not captured (Bianchi et al, 2020). Moreover, foods are rarely consumed in isolation and therefore future nLCA studies should consider nutrition at a diet-level (McAuliffe *et al.*, 2018b). Recently, some studies have taken a novel approach which involves a diet-level assessment that accounts for the foods' effect on human health. For example, Stylianou *et al.* (2016) developed the Combined Nutritional and Environmental Life Cycle

Assessment (CONE-LCA). The CONE-LCA uses a traditional LCA approach and predicts health outcomes following changes in diet, using epidemiological data based on the nutritional quality of food. However, these outcomes will obviously depend on the initial diet and its nutritional status of the individuals making the dietary change.

As with all LCA studies, the results of nLCA depend upon the type of LCA (attributional vs. consequential), where system boundaries are drawn, and the allocation method they employ (Silva, 2021). Clearly, nLCAs also require an extra layer of data relating to the nutritional value of food, introducing additional sources of variation. Studies often rely on a range of external databases for this nutritional information. Although not an issue in this study, data availability and quality are major limitations of nLCA. This includes both primary data from agricultural production and secondary data from agricultural databases. When utilising primary data, there can be concerns of the representativeness of data, particularly if data comes from a single, specific year (Notarnicola *et al.*, 2017). With secondary data, databases exhibit significant variability in terms of detail and completeness and are often biased towards conventional production in high-income countries (Carvalho *et al.*, 2023; Teixeira, 2015). Moreover, some nLCA studies may require additional information such as nutritional intake recommendation, interactions with other foods, and food processing and preparation (Mclaren *et al.*, 2021). Again, while this was not a limitation in the current study, the lack of available high-quality data will likely limit the wider use and application of nLCA.

Despite the assumptions and limitations of this study, a novel functional unit has been successfully used to compare four finishing diets of lambs and has highlighted the importance of considering nutrition when expressing GHG emissions.

5.5. Conclusions

This preliminary assessment is the first of its kind to use real farm and carcass data to assess the effect of finishing diet on lamb carbon footprints expressed on a nutritional basis. Despite recognised limitations, this study has demonstrated the need to consider nutrition when expressing carbon footprints. When a mass-based functional unit was employed, *grass* diets had on average the highest carbon footprint, however, when omega-3 PUFA content was accounted for, the *grass* diet had the lowest carbon footprint for the *longissimus dorsi*. While mass-based functional units can be useful for comparing efficiencies of different farming systems, they do not reflect the function of the final product, human nutrition. Therefore, future work should consider both mass-based and nutrition-based functional units when comparing different farming systems. Future studies should also collect a comprehensive set of carcass and nutritional parameters for emissions to be expressed through a full nutrient density score. This would allow us to accurately determine the role nutrient density of a product plays in environmental sustainability of livestock farming.

5.6. References

Arsenos, G., Banos, G., Fortomaris, P., Katsaounis, N., Stamataris, C., Tsaras, L., Zygoyiannis, D., 2002. Eating quality of lamb meat: effects of breed, sex, degree of maturity and nutritional management. Meat Science 60, 379–387. https://doi.org/10.1016/S0309-1740(01)00147-4

Barry, T.N., 2013. The feeding value of forage brassica plants for grazing ruminant livestock. Animal Feed Science and Technology 181, 15–25. https://doi.org/10.1016/j.anifeedsci.2013.01.012

Bates, D, Maechler, M, Bolker, B, Walker, S, 2015. Fitting Linear Mixed-Effects Models. Using lme4. Journal of Statistical Software, 67(1), 1-48. Doi:10.18637/jss.v067.i01.

Beattie, A., 2022. Farm Management Handbook 2022/23. SAC Consulting, Farm Advisory Service (FAS). https://www.fas.scot/publication/farm-management-handbook-2022-23/

Bessa, R. J. B., Alves, S. P. & Santos-Silva, J. 2015. Constraints and potentials for the nutritional modulation of the fatty acid composition of ruminant meat. European Journal of Lipid Science and Technology, 117, 1325-1344. https://doi.org/10.1002/ejlt.201400468

Bianchi, M., Strid, A., Winkvist, A., Lindroos, A.-K., Sonesson, U., Hallström, E., 2020. Systematic Evaluation of Nutrition Indicators for Use within Food LCA Studies. Sustainability 12, 8992. https://doi.org/10.3390/su12218992

Bonny, S.P.F., O'Reilly, R.A., Pethick, D.W., Gardner, G.E., Hocquette, J.-F., Pannier, L., 2018. Update of Meat Standards Australia and the cuts based grading scheme for beef and sheepmeat. Journal of Integrative Agriculture 17, 1641–1654. https://doi.org/10.1016/S2095-3119(18)61924-0

Boughalmi, A., Araba, A., 2016. Effect of feeding management from grass to concentrate feed on growth, carcass characteristics, meat quality and fatty acid profile of Timahdite lamb breed. Small Ruminant Research 144, 158–163. https://doi.org/10.1016/j.smallrumres.2016.09.013

Capper, J.L., 2021. Current issues and controversies in assessing the environmental impacts of livestock production. CABI Reviews 2021. https://doi.org/10.1079/PAVSNNR202116044

Carvalho, C., Correia, D., Costa, S.A., Lopes, C., Torres, D., 2023. Assessing the environmental impact of diet – Influence of using different databases of foods' environmental footprints. Journal of Cleaner Production 416, 137973. https://doi.org/10.1016/j.jclepro.2023.137973

De Brito, G. F., Ponnampalam, E. N. & Hopkins, D. L. 2017. The effect of extensive feeding systems on growth rate, carcass traits, and meat quality of finishing lambs. Comprehensive Reviews in Food Science and Food Safety, 16, 23-38. https://doi.org/10.1111/1541-4337.12230

Dervishi, E., González-Calvo, L., Blanco, M., Joy, M., Sarto, P., Martin-Hernandez, R., Ordovás, J.M., Serrano, M., Calvo, J.H., 2019. Gene Expression and Fatty Acid Profiling in Longissimus thoracis Muscle, Subcutaneous Fat, and Liver of Light Lambs in Response to Concentrate or Alfalfa Grazing. Frontiers in Genetics 10. https://doi.org/10.3389/fgene.2019.01070

de Vries, M., de Boer, I.J.M., 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. Livest. Sci. 128, 1–11. https://doi.org/10.1016/j.livsci.2009.11.007

DEFRA. Product Specification: Welsh Lamb (PGI). 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/786674/pfn-welsh-lamb-spec.pdf

Demirel, G., Ozpinar, H., Nazli, B. & Keser, Ö. 2006. Fatty acids of lamb meat from two breeds fed different forage: Concentrate ratio. Meat science, 72, 229-235. https://doi.org/10.1016/j.meatsci.2005.07.006

Dierking, R.M., Kallenbach, R.L., Roberts, C.A., 2010. Fatty Acid Profiles of Orchardgrass, Tall Fescue, Perennial Ryegrass, and Alfalfa. Crop Science 50, 391–402. https://doi.org/10.2135/cropsci2008.12.0741

Edwards-Jones, G., Plassmann, K. and Harris, I.M., 2009. Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK. The Journal of Agricultural Science, 147(6), pp.707-719. https://doi.org/10.1017/S0021859609990165

EFSA Panel on Dietetic Products, Nutrition, and Allergies (NDA), 2010. Scientific Opinion on Dietary Reference Values for fats, including saturated fatty acids, polyunsaturated fatty acids, monounsaturated fatty acids, trans fatty acids, and cholesterol. EFSA Journal 8, 1461. https://doi.org/10.2903/j.efsa.2010.1461

Elgersma, A., Ellen, G., Van Der Horst, H., Muuse, B. G., Boer, H. & Tamminga, S. 2003. Influence of cultivar and cutting date on the fatty acid composition of perennial ryegrass (Lolium perenne L.). Grass and Forage Science, 58, 323-331. https://doi.org/10.1046/j.1365-2494.2003.00384.x

Fisher, A.V., Enser, M., Richardson, R.I., Wood, J.D., Nute, G.R., Kurt, E., Sinclair, L.A. and Wilkinson, R.G., 2000. Fatty acid composition and eating quality of lamb types derived from four diverse breed× production systems. Meat science, 55(2), pp.141-147. https://doi.org/10.1016/S0309-1740(99)00136-9

Folch, J., Lees, M. and Sloane-Stanely, G.H., 1956. A simple method for isolation and purification of total lipids from animal tissue. *Journal of Biological Chemistry*. 226, 497-509.

Fowler, S.M., Morris, S. and Hopkins, D.L., 2019. Nutritional composition of lamb retail cuts from the carcases of extensively finished lambs. Meat science, 154, pp.126-132.https://doi.org/10.1016/j.meatsci.2019.04.016

Fulgoni III, V.L., Keast, D.R. and Drewnowski, A., 2009. Development and validation of the nutrient-rich foods index: a tool to measure nutritional quality of foods. The Journal of nutrition, 139(8), pp.1549-1554. https://doi.org/10.3945/jn.108.101360

Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy, The challenge of global food sustainability 36, S23–S32. https://doi.org/10.1016/j.foodpol.2010.10.010

Gerber, P.J., Hristov, A.N., Henderson, B., Makkar, H., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J. and Rotz, A., 2013. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. Animal, 7(s2), pp.220-234. https://doi.org/10.1017/S1751731113000876

Givens, D. I. 2015. Manipulation of lipids in animal-derived foods: Can it contribute to public health nutrition? European Journal of Lipid Science and Technology, 117, 1306-1316. https://doi.org/10.1002/ejlt.201400427

Harwood, J.L. 1999. Plant Fatty Acid Synthesis. Available: https://lipidlibrary.aocs.org/chemistry/physics/plant-lipid/plant-fatty-acid-synthesis. Accessed 10th September 2023.

Heuzé, V., Tran, G., Delagarde, R., Bastianelli, D., Lebas, F., 2015. Feedipedia-Animal Feed Resources Information System. Rome Italy FAO.

Howes, N.L., Bekhit, A.E.-D.A., Burritt, D.J., Campbell, A.W., 2015. Opportunities and Implications of Pasture-Based Lamb Fattening to Enhance the Long-Chain Fatty Acid Composition in Meat. Comprehensive Reviews in Food Science and Food Safety 14, 22–36. https://doi.org/10.1111/1541-4337.12118

Hybu Cig Cymru – Meat Promotion Wales, 2012. Know what you're looking at A guide to stock judging. https://meatpromotion.wales/images/resources/HCC_Llyfryn_YFC_cropped.pdf

Hybu Cig Cymru – Meat Promotion Wales. 2018. Lamb finishing systems. https://meatpromotion.wales/images/resources/LAMB_FINSIHING_ENGLISH_VERSION.pdf

Hybu Cig Cymru – Meat Promotion Wales. 2023. Welsh Lamb Meat Quality Project – Final Project Report. https://meatpromotion.wales/en/industry-projects/red-meat-development-programme/cynllun-safon-bwyta-cig-oen/results

Hyland, J.J., Styles, D., Jones, D.L. and Williams, A.P., 2016. Improving livestock production efficiencies presents a major opportunity to reduce sectoral greenhouse gas emissions. Agricultural Systems, 147, pp.123-131. https://doi.org/10.1016/j.agsy.2016.06.006

IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC. 2019.Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

Jacobson, T. A., Glickstein, S. B., Rowe, J. D. & Soni, P. N. 2012. Effects of eicosapentaenoic acid and docosahexaenoic acid on low-density lipoprotein cholesterol and other lipids: a review. Journal of Clinical Lipidology, 6, 5-18. https://doi.org/10.1016/j.jacl.2011.10.018

Jones, A.K., Jones, D.L., Cross, P., 2014a. The carbon footprint of lamb: Sources of variation and opportunities for mitigation. Agric. Syst. 123, 97–107. https://doi.org/10.1016/j.agsy.2013.09.006

Jones, A.K., Jones, D.L., Cross, P., 2014b. The carbon footprint of UK sheep production: current knowledge and opportunities for reduction in temperate zones. J. Agric. Sci. 152, 288–308. https://doi.org/10.1017/S0021859613000245

Kitessa, S., Liu, S., Briegel, J., Pethick, D., Gardner, G., Ferguson, M., Allingham, P., Nattrass, G., McDonagh, M., Ponnampalam, E., Hopkins, D., 2010. Effects of intensive or pasture finishing in spring and linseed supplementation in autumn on the omega-3 content of lamb meat and its carcass distribution. Anim. Prod. Sci. 50, 130–137. https://doi.org/10.1071/AN09095

Kool, A., Marinussen, M., Blonk, H., Consultants, B., 2012. LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization 20.

Kuznetsova A, Brockhoff PB, Christensen RHB, 2017. lmerTest Package: Tests in Linear Mixed Effects Models. Journal of Statistical Software, 82(13), 1-26. doi:10.18637/jss.v082.i13

Larmarange J, 2023. ggstats: Extension to 'ggplot2' for Plotting Stats. R package version 0.3.0, https://CRAN.R-project.org/package=ggstats.

Lenth R, 2023. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.8.5, https://CRAN.R-project.org/package=emmeans.

McAuliffe, G.A., Takahashi, T., Beal, T., Huppertz, T., Leroy, F., Buttriss, J., Collins, A.L., Drewnowski, A., McLaren, S.J., Ortenzi, F. and van der Pols, J.C., 2023a. Protein quality as a complementary functional unit in life cycle assessment (LCA). The International Journal of Life Cycle Assessment, 28(2), pp.146-155. https://doi.org/10.1007/s11367-022-02123-z

McAuliffe, G.A., Takahashi, T., Lee, M.R.F., 2018b. Framework for life cycle assessment of livestock production systems to account for the nutritional quality of final products. Food and Energy Security 7, e00143. https://doi.org/10.1002/fes3.143

McAuliffe, G.A., Takahashi, T., Lee, M.R.F., Jebari, A., Cardenas, L., Kumar, A., Pereyra-Goday, F., Scalabrino, H., Collins, A.L., 2023b. A commentary on key methodological developments related to nutritional life cycle assessment (nLCA) generated throughout a 6-year strategic scientific programme. Food Energy Security. 12, e480. https://doi.org/10.1002/fes3.480

McAuliffe, G.A., Takahashi, T., Orr, R.J., Harris, P., Lee, M.R.F., 2018a. Distributions of emissions intensity for individual beef cattle reared on pasture-based production systems. Journal of Cleaner Production 171, 1672–1680. https://doi.org/10.1016/j.jclepro.2017.10.113

McLaren, S., 2021. Integration of environment and nutrition in life cycle assessment of food items: opportunities and challenges. FAO, Rome, Italy. https://doi.org/10.4060/cb8054en

Mir, P., Bittman, S., Hunt, D., Entz, T. & Yip, B. 2006. Lipid content and fatty acid composition of grasses sampled on different dates through the early part of the growing season. Canadian Journal of Animal Science, 86, 279-290.

MSA, 2019. Meat Standards Australia sheepmeat information kit. Meat and Livestock Australia. https://www.mla.com.au/globalassets/mla-corporate/marketing-beef-and-lamb/documents/meat-standards-australia/msa-sheep-tt-july-2019-lr.pdf

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. Journal of Cleaner Production, Towards eco-efficient agriculture and food systems: selected papers addressing the global challenges for food systems, including those presented at the Conference “LCA for Feeding the planet and energy for life” (6-8 October 2015, Stresa & Milan Expo, Italy) 140, 399–409. https://doi.org/10.1016/j.jclepro.2016.06.071

Nuernberg, K., Fischer, A., Nuernberg, G., Ender, K. & Dannenberger, D. 2008. Meat quality and fatty acid composition of lipids in muscle and fatty tissue of Skudde lambs fed grass versus concentrate. Small Ruminant Research, 74, 279- 283. https://doi.org/10.1016/j.smallrumres.2007.07.009

O'Fallon,J.V., Busboom, J.R., Nelson, M.L and Gaskins,C.T. 2007. A direct method for fatty acid methyl ester synthesis: Application to wet meat tissues, oils and feedstuffs. Journal of Animal Science, 85, 1511-1521. https://doi.org/10.2527/jas.2006-491

Pannier, L., Pethick, D.W., Boyce, M.D., Ball, A.J., Jacob, R.H., Gardner, G.E., 2014. Associations of genetic and non-genetic factors with concentrations of iron and zinc in the longissimus muscle of lamb. Meat Science, Australian Sheep CRC Meat: Meat Science Special Issue 96, 1111–1119. https://doi.org/10.1016/j.meatsci.2013.08.013

Pannier, L., Gardner, G.E., O'Reilly, R.A., Pethick, D.W., 2018. Factors affecting lamb eating quality and the potential for their integration into an MSA sheepmeat grading model. Meat Science, Quality and Integrity for Global Consumers. The 64th International Congress of Meat Science and Technology, Melbourne, Australia 144, 43–52. https://doi.org/10.1016/j.meatsci.2018.06.035

Pannier, L., Corlett, M., Payne, C., Pethick, D., 2019. Meat and Livestock Australia Limited - Cuts based MSA lamb development – lamb turn off and packaging effects. Meat and Livestock Australia Limited. https://www.mla.com.au/contentassets/3d4209c303ae44558f170a92e248f1d2/l.eqt.1810_final_report_.pdf

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216

R Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Ripoll-Bosch, R., De Boer, I.J.M., Bernués, A. and Vellinga, T.V., 2013. Accounting for multi-functionality of sheep farming in the carbon footprint of lamb: A comparison of three contrasting Mediterranean systems. Agricultural Systems, 116, pp.60-68. https://doi.org/10.1016/j.agsy.2012.11.002

Röös, E., Sundberg, C., Tidåker, P., Strid, I. and Hansson, P.A., 2013. Can carbon footprint serve as an indicator of the environmental impact of meat production?. Ecological indicators, 24, pp.573-581. https://doi.org/10.1016/j.ecolind.2012.08.004

Scollan, N., Hocquette, J.-F., Nuernberg, K., Dannenberger, D., Richardson, I., Moloney, A., 2006. Innovations in beef production systems that enhance the nutritional and health value of beef lipids and their relationship with meat quality. Meat Sci., 52nd International Congress of Meat Science and Technology (52nd ICoMST) 13-18 August 2006 Dublin, Ireland 74, 17–33. https://doi.org/10.1016/j.meatsci.2006.05.002

Scollan, N.D., Dannenberger, D., Nuernberg, K., Richardson, I., MacKintosh, S., Hocquette, J.-F., Moloney, A.P., 2014. Enhancing the nutritional and health value of beef lipids and their relationship with meat quality. Meat Science, Advancing Beef Safety through Research and Innovation: Prosafebeef 97, 384–394. https://doi.org/10.1016/j.meatsci.2014.02.015

Scollan, N.D., Price, E.M., Morgan, S.A., Huws, S.A., Shingfield, K.J., 2017. Can we improve the nutritional quality of meat? Proceedings of the Nutrition Society 76, 603–618. https://doi.org/10.1017/S0029665117001112

Silva, D.A.L., 2021. Life Cycle Assessment (LCA)—Definition of Goals and Scope, in: de Oliveira, J.A., Lopes Silva, D.A., Puglieri, F.N., Saavedra, Y.M.B. (Eds.), Life Cycle Engineering and Management of Products: Theory and Practice. Springer International Publishing, Cham, pp. 45–69. https://doi.org/10.1007/978-3-030-78044-9_3

Singh, S., Arora, R. R., Singh, M. & Khosla, S. 2016. Eicosapentaenoic acid versus docosahexaenoic acid as options for vascular risk prevention: a fish story. American Journal of Therapeutics, 23, e905-910. https://doi.org/10.1097/MJT.0000000000000165

Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., Witthöft, C., 2017. Protein quality as functional unit – A methodological framework for inclusion in life cycle assessment of food. J. Clean. Prod., Towards eco-efficient agriculture and food systems: selected papers addressing the global challenges for food systems, including those presented at the Conference "LCA for Feeding the planet and energy for life" (6-8 October 2015, Stresa & Milan Expo, Italy) 140, 470–478. https://doi.org/10.1016/j.jclepro.2016.06.115

Stylianou, K.S., Heller, M.C., Fulgoni, V.L., Ernstoff, A.S., Keoleian, G.A., Jolliet, O., 2016. A life cycle assessment framework combining nutritional and environmental health impacts of diet: a case study on milk. Int J Life Cycle Assess 21, 734–746. https://doi.org/10.1007/s11367-015-0961-0

Swanson, D., Block, R., Mousa, S.A., 2012. Omega-3 Fatty Acids EPA and DHA: Health Benefits Throughout Life. Adv. Nutr. 3, 1–7. https://doi.org/10.3945/an.111.000893

Sykes, A.J., Topp, C.F., Wilson, R.M., Reid, G. and Rees, R.M., 2017. A comparison of farm-level greenhouse gas calculators in their application on beef production systems. Journal of Cleaner Production, 164, pp.398-409. https://doi.org/10.1016/j.jclepro.2017.06.197

Teixeira, R.F.M., 2015. Critical Appraisal of Life Cycle Impact Assessment Databases for Agri-food Materials. Journal of Industrial Ecology 19, 38–50. https://doi.org/10.1111/jiec.12148

Tsvetkova, V. & Angelow, L. 2010. Influence of the season on the total lipids and fatty acid composition of grasses at the different altitudes in the region of the middle rhodopes. Bulgarian Journal of Agricultural Science, 16, 748-753.

van Wyngaard, J.D.V., Meeske, R., Erasmus, L.J., 2018. Effect of concentrate feeding level on methane emissions, production performance and rumen fermentation of Jersey cows grazing ryegrass pasture during spring. Animal Feed Science and Technology 241, 121–132. https://doi.org/10.1016/j.anifeedsci.2018.04.025

Vellinga, T.V., Blonk, H., Marinussen, M., Zeist, W.J. van, Starmans, D. a. J., 2013. Methodology used in FeedPrint: a tool quantifying greenhouse gas emissions of feed production and utilization (No. 674). Wageningen UR Livestock Research, Lelystad.

Warren, H.E., Scollan, N.D., Nute, G.R., Hughes, S.I., Wood, J.D. and Richardson, R.I., 2008. Effects of breed and a concentrate or grass silage diet on beef quality in cattle of 3 ages. II: Meat stability and flavour. Meat science, 78(3), pp.270-278. https://doi.org/10.1016/j.meatsci.2007.06.007

Whittington, F., Dunn, R., Nute, G., Richardson, R., Wood, J., 2006. Effect of pasture type on lamb product quality. New Developments in Sheepmeat Quality 9th Annual Langford Food Industry Conference 24-25 May 27–31.

Xu, Z., Xu, W., Peng, Z., Yang, Q. and Zhang, Z., 2018. Effects of different functional units on carbon footprint values of different carbohydrate-rich foods in China. Journal of Cleaner Production, 198, pp.907-916. https://doi.org/10.1016/j.jclepro.2018.07.091

Yalcin, H., Zt¸Rk, I., Tulukáu, E. & Sagdic, O. 2011. Influence of the harvesting year and fertilizer on the fatty acid composition and some physicochemical properties of linseed (*Linum usitatissimum* L.). Journal of Consumer Protection and Food Safety, 6, 197-202. https://doi.org/10.1007/s00003-010-0631-x

Yan, T., Mayne, C.S., Gordon, F.G., Porter, M.G., Agnew, R.E., Patterson, D.C., Ferris, C.P., Kilpatrick, D.J., 2010. Mitigation of enteric methane emissions through improving efficiency of energy utilization and productivity in lactating dairy cows. Journal of Dairy Science 93, 2630–2638. https://doi.org/10.3168/jds.2009-2929

Chapter 6 Barriers and opportunities to achieving Net Zero on UK beef and sheep farms

L.C. McNicol, S. Wynne-Jones, D. Chadwick, D. Styles, R.M. Rees and A.P. Williams

Abstract

Achieving the Net Zero target will require significant changes to agriculture and land use in the UK. Despite the range of different mitigation and sequestration options available for the livestock systems, uptake remains low in the beef and sheep sector. To reach Net Zero, various barriers must be overcome to increase the uptake of these measures.

To gain a deeper insight into farmers' perspectives on the Net Zero target and their attitudes towards different mitigation and sequestration options, an online survey was conducted among 111 beef and sheep farmers from across the UK.

Few factors affected farmers' decision-making in relation to Net Zero, with "hill farms" being the only variable which had a significant effect. Our survey highlighted many socio-economic barriers to achieving Net Zero on beef and sheep farms. For example, the majority of farmers were not aware of any additional benefits of the GHG mitigation measures listed even though the majority of the measures listed represented "win-win" scenarios whereby they not only reduce emissions but also increase production efficiencies. Moreover, the level of adoption reported in the survey would notably reduce the maximum technical abatement potential of many mitigation measures calculated in the previous modelling work.

Financial incentives were ranked as the most important mechanism to improve uptake of mitigation measures. However, farmers also ranked themselves first as to who should be most responsible for improving uptake of mitigation measures. Improving uptake of GHG mitigation measures will likely require a combination of economic incentives, targeted regulation, and information provision based on individual measures to overcome these barriers.

6.1. Introduction

In June 2019, the UK government amended the Climate Change Act 2008 to set a target of Net Zero greenhouse gas (GHG) emissions by 2050. This is in line with the 2015 Paris Agreement, a legally binding international treaty to hold the increase in global temperature to well below 2°C (BEIS, 2022). Following an in-depth analysis, the Committee on Climate Change (CCC) has advised a 64% reduction in gross GHG emissions from the agriculture and land-use sector in the UK to meet the Net Zero target. Whilst there is not a specific target for livestock, it is thought that a similar target to the wider sector is appropriate.

Achieving the Net Zero target will require significant changes to agriculture and land use in the UK. Although farming practices can be optimised to reduce agricultural emissions, much of these emissions are the result of biological processes so can never be removed completely (FAO, 2013). Therefore, offsetting residual emissions will be essential if the industry is to reach Net Zero. There are a range GHG mitigation measures available for the livestock sector which all vary in their abatement potentials, cost and co-benefits/trade-offs (Smith *et al.*, 2007). Mitigation options range from measures that address nitrogen fertiliser use, improve production efficiencies, reduce direct methane emissions, manure management and altering land management. However, although these measures reduce emissions per unit of product, it is important to note they may also encourage farmers to increase their stock number, which would lead to an increase in total emissions.

Marginal abatement cost curves (MACCs) for agriculture have been developed in the UK to calculate the cost of avoiding or sequestering an additional unit of CO_2 equivalent for a series of GHG mitigation measures (Eory *et al.*, 2020; Jones *et al.*, 2015; Moran *et al.*, 2011). Many of these measures can be implemented at a low cost and many actually result in a net profit. These so-called “win-win” options have co-benefits and are often originally implemented to increase productivity. For example, improving animal health not only reduces GHG emissions from livestock but also improves production efficiencies.

Although MACCs are useful for assessing the technical abatement potential of GHG mitigation measures, they do not consider the socio-economic implications and actual uptake of these measures. Despite many GHG mitigation measures for farms making economic sense, uptake in the beef and sheep sector remains low compared to other sectors such as dairy. For instance, recent work in England showed that only 28% of famers with holdings on Less Favoured Area (LFA) said they were currently taking action to reduce GHG emissions on their farm, compared to 76% of dairy farmers

(DEFRA, 2023a). To improve the uptake of mitigation measures, it is fundamental to understand why mitigation measures are not being adopted.

Many economic, social and psychological factors influence farmers' decision-making (Blackstock *et al.*, 2010; Dessart *et al.*, 2019; Hayden *et al.*, 2021; Hyland *et al.*, 2018a). Recently, the importance of psychological factors has been stressed, particularly relating to farmers' attitudes and effects of social pressure (Blackstock *et al.*, 2010; Daxini *et al.*, 2018). This can be linked to the Theory of Planned Behaviour, a concept in which behaviour can be explained through the intention to behave in a certain way (Ajzen, 1991). These intentions are driven by an individual's attitudes and beliefs. However, even when intentions are strong, they do not always translate into behaviour (Kollmuss and Agyeman, 2002; Liu *et al.*, 2020; Niles *et al.*, 2016; Sheeran, 2002). Many studies examine the actual level of adoption of mitigation measures (Jørgensen and Termansen, 2016; Kreft *et al.*, 2020) whereas others look at farmers' intention to adopt mitigation measures (Moerkerken *et al.*, 2020; Niles *et al.*, 2016). Despite farmer's intentions, actual uptake of mitigation measures is affected by various socio-economic barriers to the implementation (Dandy, 2012; Feliciano *et al.*, 2014; Hallam *et al.*, 2012; Smith *et al.*, 2007). Kipling *et al.* (2019) identified four key themes relating to challenges to implementing GHG mitigation measures on Welsh farms: practical limitations, knowledge limitations, cognitive limitations and interest. Many of the same barriers are shared across different mitigation measures, for example, initial cost is one of the most cited barriers across all measures and many farmers will not adopt these measures unless they are incentivised (Smith and Olesen, 2010). Selected barriers are only applicable to specific farms, for example, some farms may have physical-environmental constraints such as farm size or farm environment (Dandy, 2012). Personal interest and values can be a key barrier to adopting mitigation measures for some farmers, farmers' attitudes will impact on their behaviour and therefore their willingness to implement certain practices (Hallam *et al.*, 2012; Hyland *et al.*, 2018b). Similarly, community and society can impact farmers attitudes towards certain mitigation measures and consequently their decision-making (Feliciano *et al.*, 2014; Kipling *et al.*, 2019a). Lack of knowledge and skills can also limit the uptake of mitigation options, many farmers are not aware of the measures available and other may not have the skills to implement these practices (Bustamante *et al.*, 2014; Hyland *et al.*, 2018b; Kipling *et al.*, 2019a)

Regulatory pressure can also influence the uptake of GHG mitigation measures on farms (Dicks *et al.*, 2019; Kipling *et al.*, 2019b; Smith *et al.*, 2007). The transitions from the Basic Payment Scheme (BPS) to the new Sustainable Farming Incentive (SFI) in England and Sustainable Farming Scheme (SFS) in Wales has the potential to accelerate the uptake of GHG mitigation measures (DEFRA, 2023b; Welsh

Government, 2022a). These new schemes support payment for ecosystem services and public goods and incentivise certain GHG mitigation measures. For example, in England, farmers who take part in the SFI will be paid £102/ha for legumes on improved grassland (DEFRA, 2023b). In Wales, the level of payment has yet to be announced, however, the outline proposal shows participating farmers will have to implement practices such as soil testing and "actively manage at least 10% of their land to maintain or enhance semi-natural habitats" to receive payment (Welsh Government, 2022a). However, this does not necessarily translate into change.

If Net Zero target is to be met, the uptake of GHG mitigation measures on farms must be increased, and to achieve this, implementation barriers must be overcome. The aims of this study were therefore to:

i) Identify what factors affect farmers' decision-making in relation to Net Zero.
ii) Assess which GHG mitigation and sequestration options are preferred by farmers and calculate the actual abatement potential (based on level of adoption) versus the maximum technical abatement potential of each measure from previous modelling work.
iii) Highlight the barriers influencing farmers' uptake of GHG mitigation and sequestration options and assess how the uptake of these measures can be improved.

6.2. Materials and methods

6.2.1. Survey/data collection

To better understand farmers' views on the Net Zero target and their attitudes towards various mitigation and sequestration options, 111 beef and sheep farmers from across the UK were surveyed. The survey was administered using Jisc Online Surveys (Jisc, 2023) and was widely publicised through various UK farming organisations, press and social media in January 2023. The survey was designed to collect primarily quantitative data on:

- Respondent demographics
- Farm characteristics and management
- Respondent's views on the Net Zero target
- GHG mitigation and sequestration options which had already been implemented or would be considered
- Improving uptake of GHG mitigation and sequestration options

The profile of survey respondents can be found in Table 6.1. Most questions were simple multiple response or ranking questions. Some open-ended questions were included to provide qualitative data on any additional benefits of GHG mitigation and sequestration measures respondents were aware of, as well as perceived barriers of increased afforestation (an important pathway for offsetting residual GHG emissions) on farm. Questions were devised to capture respondents' view on the Net Zero target (i.e. if they though the target was achievable and if it had affected their decision-making), their attitudes towards various mitigation and sequestration options, additional benefits and barriers to these measures and how the uptake of these measures can be improved. The full survey can be found in Appendix 6.

6.2.2. Analyses

Descriptive statistics were used to explore data from multiple response and ranking questions as well as test for collinearity between predictors prior to modelling. All statistical analysis of survey data was carried out using R 4.2.1 (R Core Team, 2023). A generalised linear mixed (GLM) model was used to determine if respondents' awareness of what they need to do to move towards Net Zero and various other factors predicted if the target had affected their decision-making. Models were fitted using the lme4 package (Bates *et al.*, 2015). The response variable was a binary indicator of whether the Net Zero target had influenced respondents' decision-making or not. Respondent age, gender, farm total area, farm type, enterprise type, farm tenure and respondents' previous or existing involvement of an agri-environment scheme were all included in the model as fixed effects.

Respondents were also asked to rate their willingness to consider a series of GHG mitigation and sequestration measures using a Likert scale from "already implemented" to "would not consider". The proportion of each measure already implemented was then cross-referenced to the most recent Farm Practices Survey (DEFRA, 2023a). The "actual" abatement potential was then calculated by multiplying the percentage of respondents who had already implemented, were currently considering or would consider in the future each individual measure, by the maximum technical abatement potential calculated in the farm modelling in Chapter 4. For measures that were grouped e.g. improving animal nutrition, improving animal health and selection for balanced breeding goals in cattle, the average number of respondents who would consider each measure was used. Model and Likert data were plotted using the sjPlot package (Lüdecke, 2023).

An inductive thematic analysis was used to carry out qualitative data analysis on open-ended questions (Braun and Clarke, 2013). The inductive approach identified themes from the data collected without any preconceived themes or categories but were guided by the research questions. Text was then coded by breaking down respondents' answers into smaller distinct responses and labelled. The coded text was then organised into initial themes which were then merged to form the core themes reported in the results (Braun and Clarke, 2013). To avoid researcher bias in the thematic analysis, a second researcher examined the coding to ensure all assumptions were valid.

Table 6.1. Profile of survey respondents and their farm characteristics. Note: not all variables will equal 100% due to rounding.

Variable	Level	Percentage of total respondents (n = 111)
Age	<25	36
	25-55	32
	>55	32
Gender	Male	71
	Female	25
	Prefer not to say	4
Position in farming business	Sole trader	19
	In partnership (non-family business)	66
	In partnership (family business)	2
	Farm manager/employee	12
	Part of a co-operative	1
Employment status	Full-time farming	58
	Part-time farming and part time work off farm	28
	Full-time farming and farming in spare time	14
Tenure	Wholly owned	39
	Wholly tenanted/rented	7
	Mostly owned with some rented land	34
	Mostly tenanted/rented	10
	Manage/employed on a farm	10
Region of farm	England	18
	Northern Ireland	2
	Scotland	6
	Wales	75
Farm total area	< 50ha	21
	50-99ha	25
	> 100ha	60
Farm type *	Hill	15
	Upland	42
	Lowland	42
Enterprise type	Mixed (cattle and sheep)	67
	Beef only	16
	Sheep only	8
	Other	9
Organic	Organic	14
	Not organic	86
Diversification	Run diversification activities	33
	Do not run diversification	67
Agri-environment scheme	Previously involved in or currently part of an agri-environment scheme	52
	Not previously involved in or currently part of an agri-environment scheme	48

* Farm type was based on the land where the majority of the holding fell

6.3. Results

6.3.1. The Net Zero target

Respondents' attitudes towards Net Zero varied; the majority thought the target was achievable at a sector level, however, a notable proportion of respondents were unsure (Figure 6.1). Similarly, over half of respondents thought Net Zero was achievable on their farm and only small percentage thought the target was not achievable on their farm (Figure 6.1). For those who did not think Net Zero was achievable on their farm, "There are only a few measures that I can apply on my farm" and "Livestock emissions are hard to reduce" were cited as the most common reasons why they thought the target was not achievable (Table 6.2).

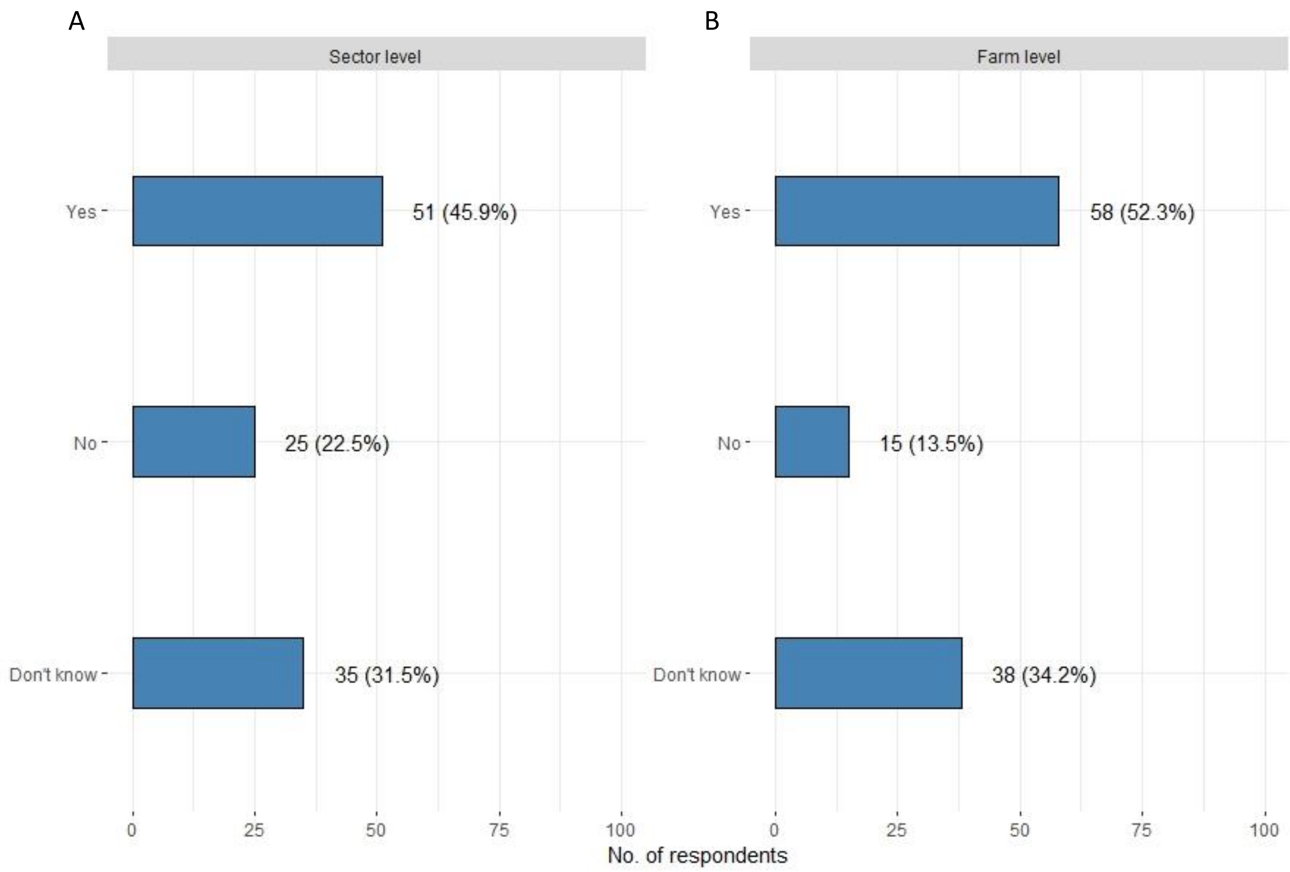


Figure 6.1. Respondents' answers to "Do you think Net Zero is achievable [A] at a sector level and [B] on their farm?".

Table 6.2. Respondents' reasoning for why they thought Net Zero was not achievable on their farm in descending order. Respondents were free to select all answers that applied from a presented list. Note: this question was only answered by respondents who answered "No" to "Do you think Net Zero is achievable on your farm?"

Why do you think the Net Zero target is not achievable on your farm?	No. of respondents	%
There are only a few measures that I can apply on my farm	6	40
Livestock emissions are hard to reduce	6	40
Not enough land for sequestration	5	33
Other	4	27
Already highly efficient so hard to achieve efficiency gains	3	20
Lack of knowledge on mitigation/sequestration options	3	20
Current emissions are too high	2	13
Too expensive	2	13
Restricted by management control e.g. tenanted farm	1	7

The majority of farmers said they were aware to some extent of what they needed to do to move towards Net Zero (Figure 6.2). However, almost two thirds of respondents still noted that the Net Zero target had not affected their decision-making in the last 5 years. To evaluate if "awareness" could predict if the Net Zero target had affected respondents' decision-making, a binomial regression was fitted (Figure 6.2). Extremely high standard error on the "not aware" variable indicated complete separation i.e., all respondents who were not aware of what they needed to do to reach Net Zero said the target had not affected their decision-making. The only variable which had a significant effect on farmers' decision-making in relation to Net Zero was farm type, specifically hill farms ($p<0.05$) (Figure 6.2). Other variables which had a notable (but not significant) positive effect on decision-making in relation to the target were respondents who were aware of what they needed to do to reach Net Zero ($p>0.05$) and respondents who mostly owned their farm with some rented land ($p>0.05$). Although none were statistically significant ($p>0.05$), sheep only farms, farms with other enterprises, and wholly tenanted/rented farms had a negative impact on decision-making in relation to Net Zero (Figure 6.2).

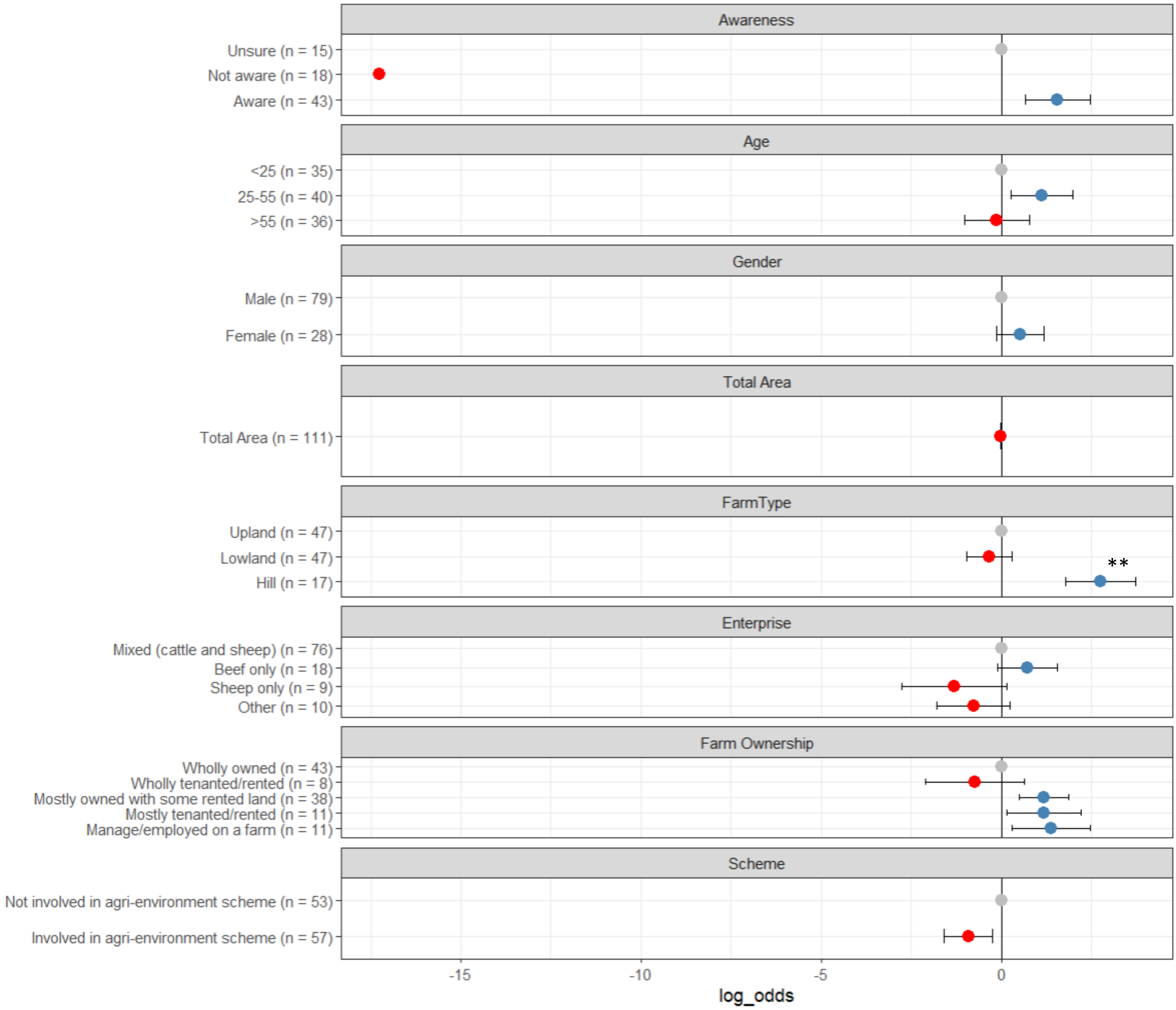


Figure 6.2. Regression coefficients with standard errors from a general linear mixed model of whether the Net Zero target had influenced respondents' decision-making. Awareness relates to if respondents knew what they needed to do on their farm to move toward Net Zero. Factors which negatively affected respondents' decision-making are represented in red and factors which positively affect respondent's decision-making are represented in blue. Significance, ***p <0.001, **p <0.01, and *p <0.05. Error bars are not presented on the "Not aware" variable due to high standard error.

6.3.2. Greenhouse gas mitigation and sequestration measures

Over half of farmers had already implemented measures to improve animal health, introduce legumes, improve grazing management and improve synthetic N use (Figure 6.3). Improved animal nutrition, selection for balanced breeding goals in cattle and methane inhibitors were amongst the measures that the highest number of respondents would consider currently or in the future. Afforestation and reducing stock numbers were the measures that the highest percentage of respondents would not consider (Figure 6.3). Measures relating to slurry e.g. low emission spreading of slurry and slurry acidification were reported to be not applicable on the highest percentage of farms, presumably because their system did not generate slurry.

The above data was then incorporated into the previous chapter's farm-level modelling (by multiplying the percentage of respondents who would consider each measure by its maximum technical abatement potential), resulting in a notable reduction in the abatement potentials of each measure. Nitrification inhibitors and slurry acidification had the biggest reductions from their maximum technical abatement potential to their actual abatement potential (Table 6.3). The majority of farmers had already implemented or would consider introducing legumes; therefore, the actual abatement potential of introducing legumes was similar to its maximum technical abatement (Table 6.3).

Table 6.3. Maximum technical abatement potential of greenhouse gas mitigation measures from farm-level modelling in Chapter 4 and the actual abatement potential (percentage of respondents who would consider each measure multiplied by its maximum technical abatement potential).

Mitigation measure	Maximum technical abatement potential (%)	Actual abatement potential (%)	Percentage reduction (%)
3NOP as a feed additive	11.9	5.8	51.3
Improved beef and sheep productivity	8.7	6.7	23.0
Nitrification inhibitors	6.7	2.9	56.7
Legume-grass mixtures	5.0	4.3	14.0
Slurry acidification	3.6	1.2	66.7
Improved organic N use	2.7	1.6	40.7
Improved synthetic N use	2.1	1.6	23.8
Behavioural change in fuel efficiency	0.8	0.5	37.5

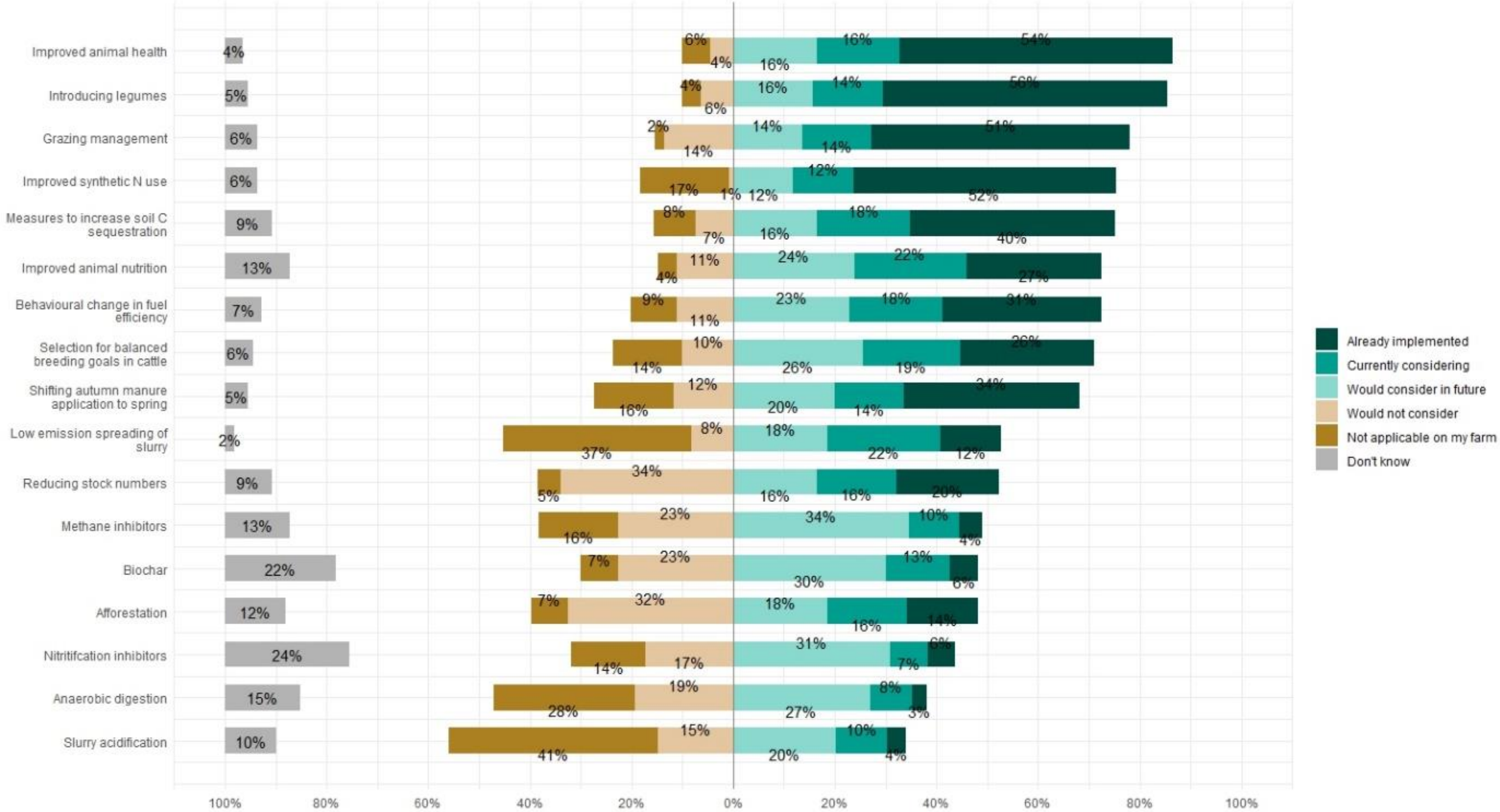


Figure 6.3. Respondents' willingness to consider a series of greenhouse gas mitigation and sequestration measures. Measures are in descending order, starting with the measure that was considered by the most respondents.

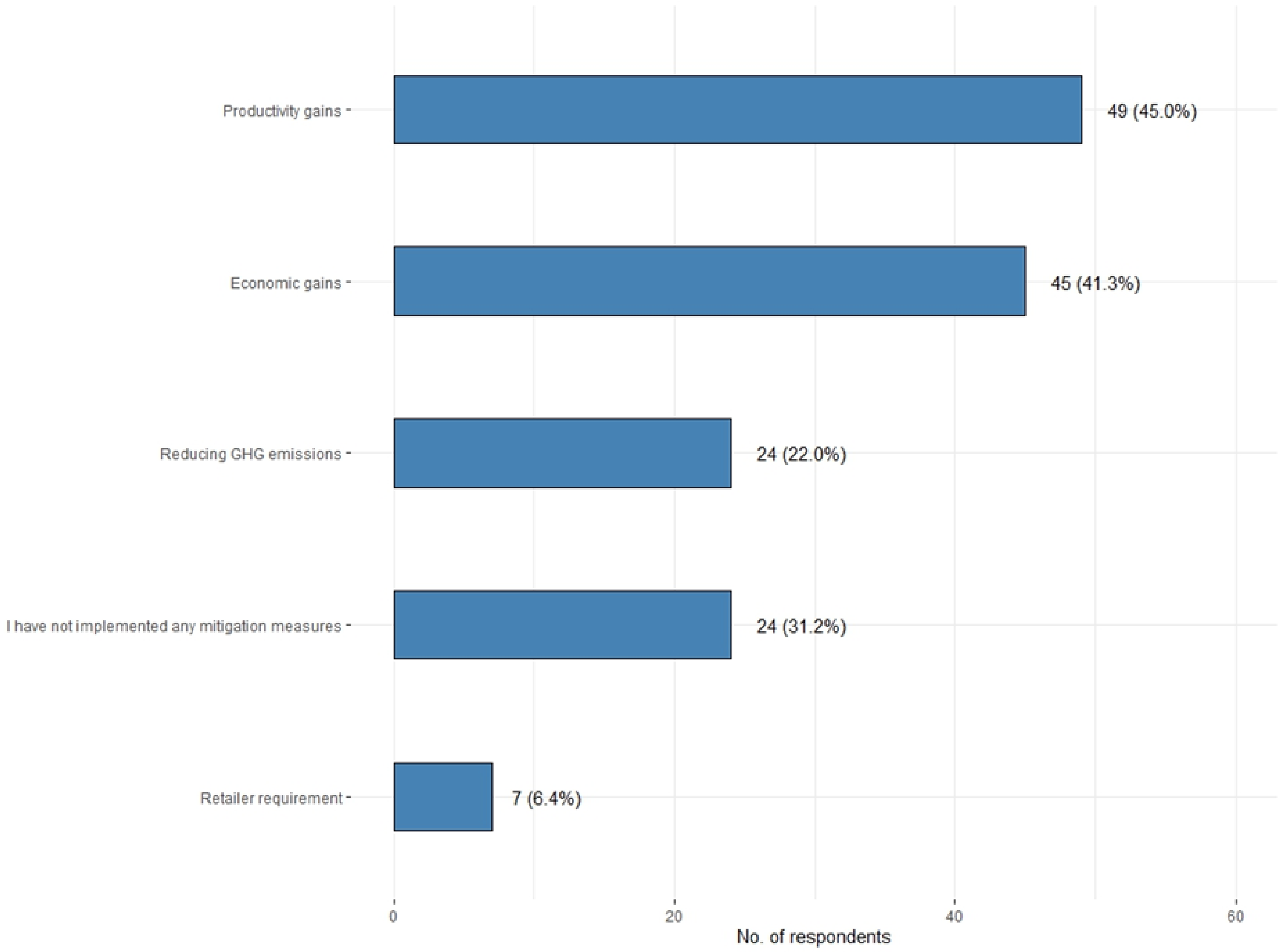


Figure 6.4. Respondents' main motivations for implementing GHG mitigation measures. Respondents were free to select all answers that applied from a presented list.

Respondents who had already implemented GHG mitigation or sequestration measures cited productivity and economic gains as their main motivations for doing so, whereas retailer requirement was selected by fewer respondents (Figure 6.4). Respondents were then asked to rank factors they considered when implementing GHG mitigation measures; cost and knowledge of the change needed were seen as the most important factors, whereas abatement potential and management control were the least important (Figure 6.5).

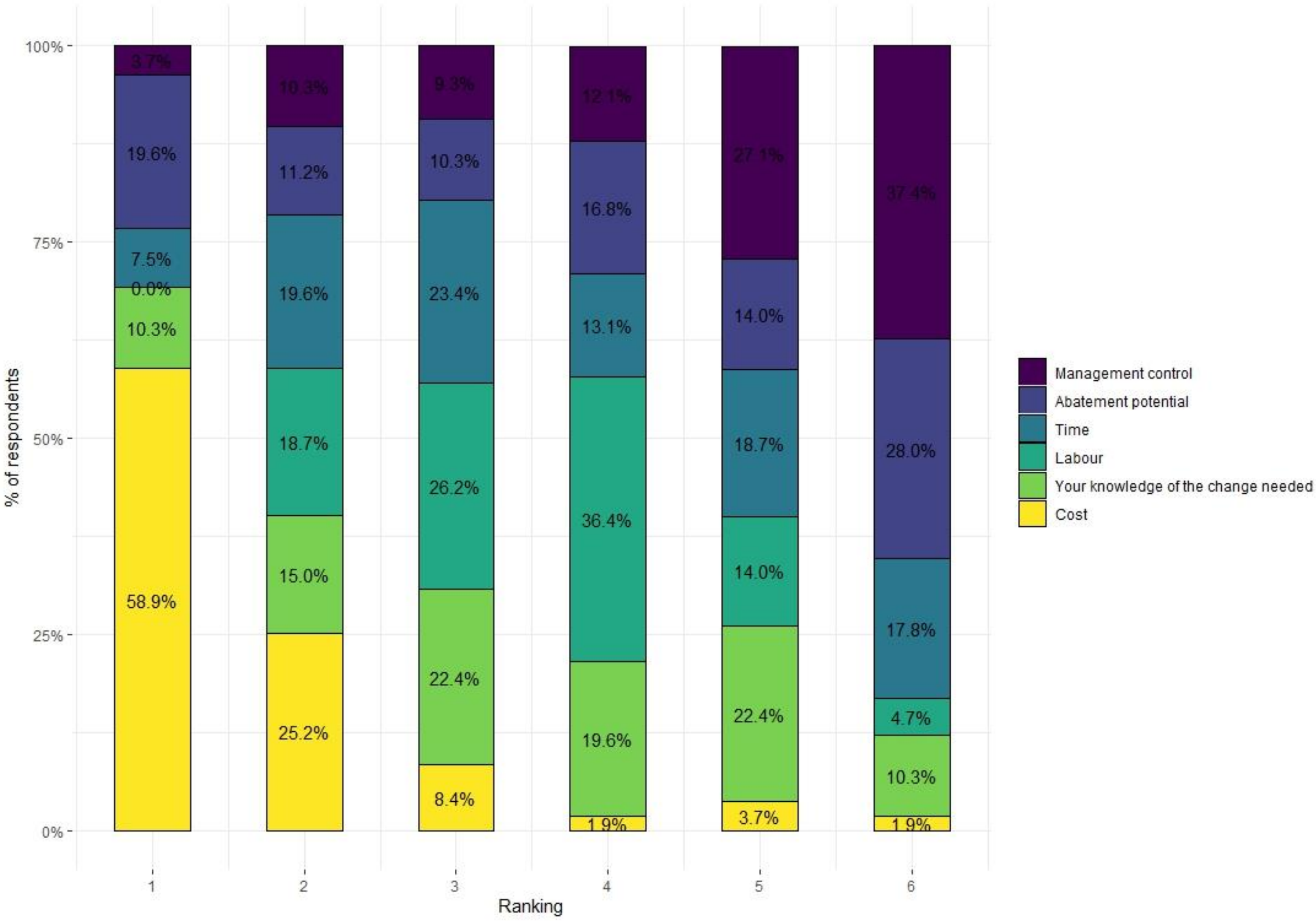


Figure 6.5. Respondents' mean scores of important factors when considering mitigation measures. Options ranked 1 – 6 (1 being the most important, 6 being the least important).

6.3.3. Additional benefits of mitigation measures and barriers to implementation (Qualitative)

The majority of respondents (62%) were not aware of any additional benefits of the GHG mitigation measures listed. Similarly, 71% of respondents were not aware of any additional benefits of sequestration measures. Only 38% and 29% of respondents were aware of any additional benefits of GHG mitigation measures and sequestration measures, respectively. Respondents were then given the opportunity to list these benefits in open-ended questions. Three main themes were identified when analysing the data from both questions: "economic", "animal welfare and productivity" and "other environmental benefits". The "economic" theme had a number of sub-themes such as farm resilience, profitability and better use of inputs for both mitigation and sequestration measures. Animal health and productivity were both cited for additional benefits of GHG mitigation measures, whereas for additional benefits of sequestration measures, only shelter and animal welfare were referenced under the "Animal welfare/productivity" theme. "Other environmental benefits" consisted of namely soil health and biodiversity, as well as water benefits for sequestration measures. A full list of quotes for each theme can be found in the Appendix.

Farmers were also asked to select what they considered to be the main barriers to increased afforestation on farms from a presented list. Cost and lack of perceived benefit were selected by the greatest number of respondents (Figure 6.6). This was followed by the "Other" category, which was selected by 27% of respondents. Main themes for other barriers to increased afforestation on farms included: "loss of productive land", "personal interest and values" and "policy". A full list of quotes for each theme can be found in the Appendix.

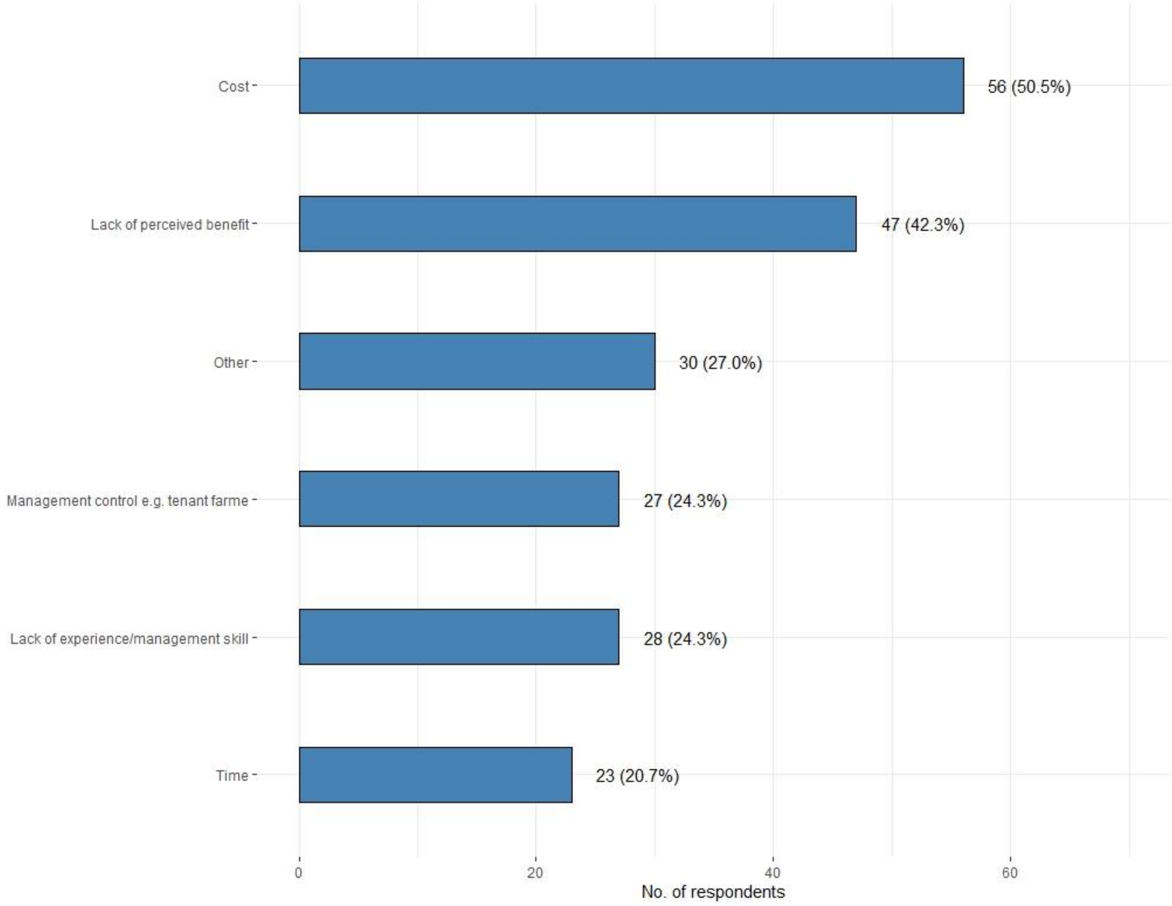


Figure 6.6. Main barriers respondents felt there were to increased afforestation on farms. Respondents were free to select all answers that applied from a presented list.

6.3.4. Improving uptake of mitigation measures

To improve the uptake of GHG mitigation measures, farmers ranked financial incentives and knowledge exchange events as the top interventions that would be needed to amend their farming practices (Figure 6.7). When asked who should be responsible for improving the uptake of GHG mitigation measures, respondents ranked farmers and the government as the most responsible, and retailers and processors as the least (Figure 6.8).

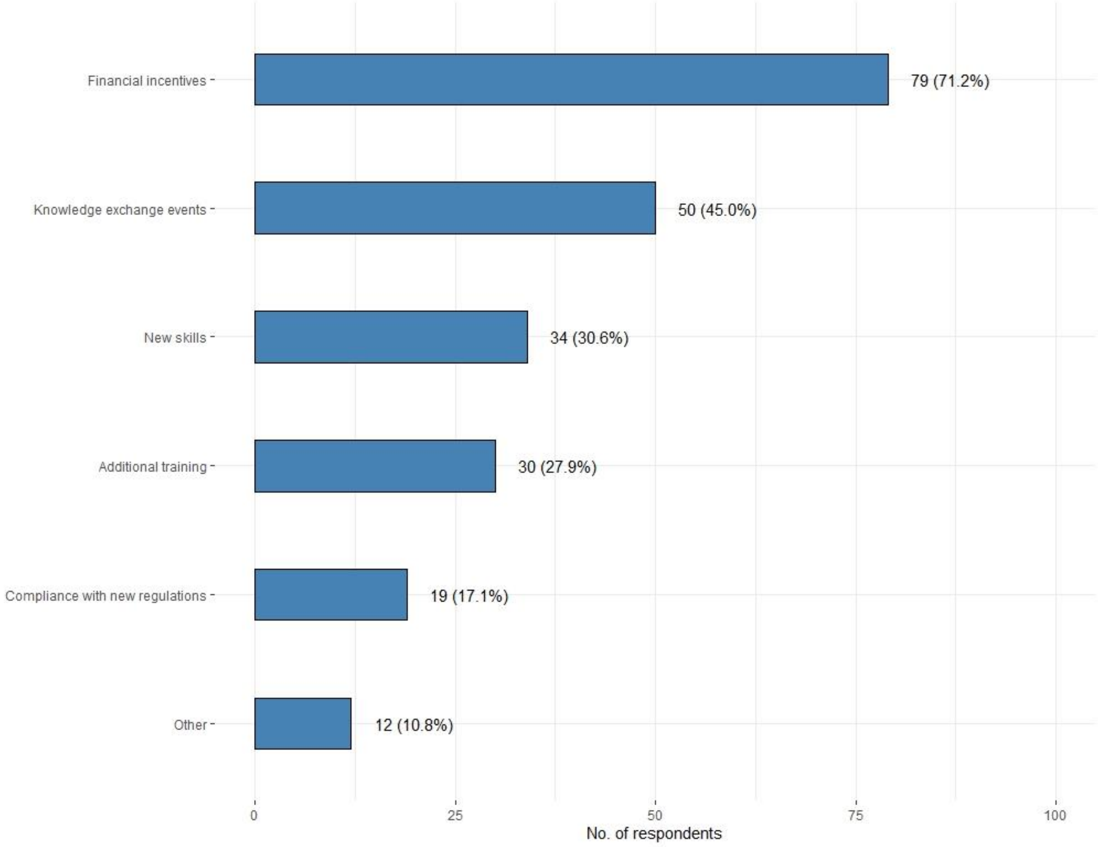


Figure 6.7. Mechanisms reported by respondents as necessary to reduce GHG emissions from farming practices. Respondents were free to select all answers that applied from a presented list.

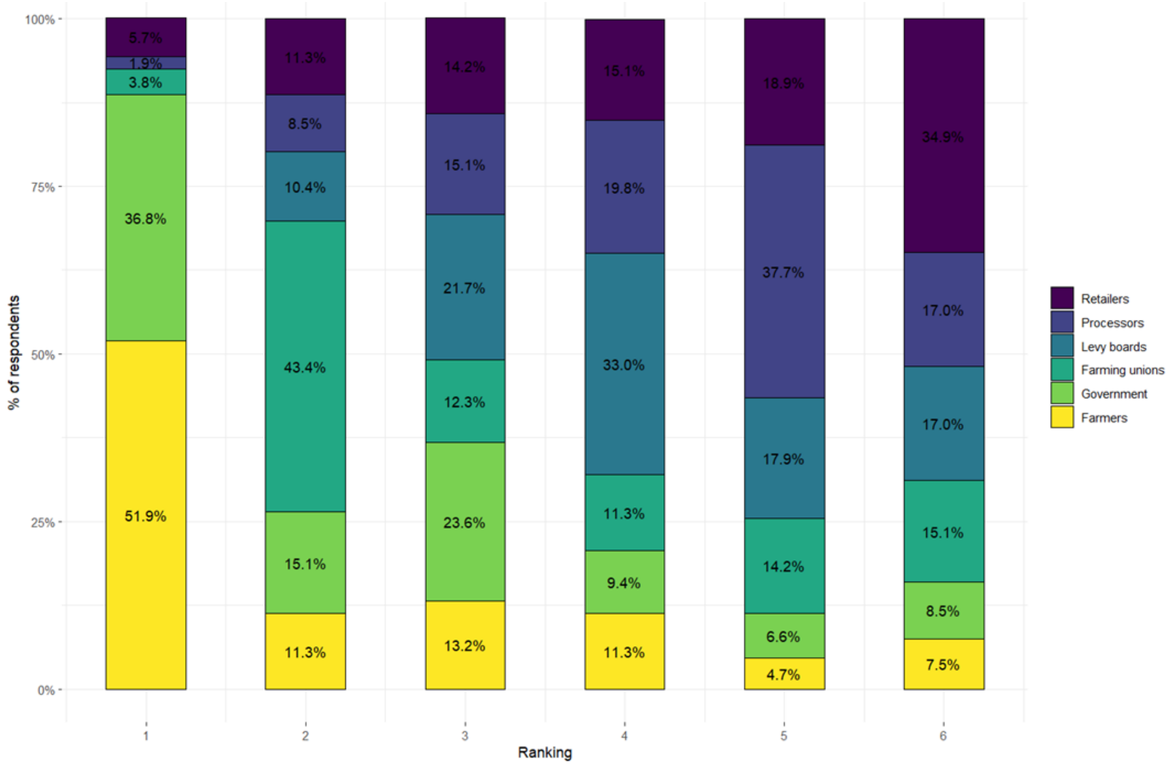


Figure 6.8. Respondents' mean scores of who should be responsible for improving the uptake of GHG mitigation measures. Options ranked 1 – 6 (1 being the most important, 6 being the least important).

6.4. Discussion

6.4.1. Net Zero target

Just under half of respondents thought the Net Zero target was achievable at a sector level, with a large percentage unsure (Figure 6.1). However, it is unclear how many of these farmers fully understand Net Zero, both in terms of its technical definition and the implications of reaching the target. Although there have not been studies specifically on farmers, the UK Government (2021) found that only 39% of 6,947 members of the UK public said they had at least "a fair enough" of knowledge on Net Zero. Moreover, 18% of the public said they knew "hardly anything" about Net Zero and another 13% had never heard of it (UK Government, 2021). Therefore, it is important to highlight that this question refers to what farmers think is possible at a sector level, which could be hugely affected by their prior knowledge.

Within the farming population who thought Net Zero was achievable, those who did not and those who were unsure, it is likely there will be a split of farmers who have genuine environmental concerns and farmers who dismiss environmental targets and may even reject the idea that agriculture emits GHG emissions. Hyland *et al.* (2016) demonstrated this concept by grouping farmer into typologies based their identity (productivism and environmental responsibility) and their behavioural capacity to adopt mitigation measures (awareness and perceived risk). This resulted in four farmer typologies: “The Productivist”, “The Countryside Steward”, “The Environmentalist” and “The Dejected”. “The Productivist” unsurprisingly displayed a penchant for productivism but lower levels of environmental sustainability and awareness of climate change. Similarly, “The Countryside Steward” demonstrated lower awareness of climate change but had a higher sense of environmental responsibility. “The Environmentalist” had the highest levels of awareness of climate change and environmental responsibility but the lowest sense of perceived risk. Finally, the “The Dejected” scored high in terms of awareness but show had a high sense of perceived risk. The group within which respondents fall will likely affect their attitudes towards Net Zero. The 2023 Farm Practices Survey in England found 51% of LFA grazing and 54% of lowland grazing livestock farmers ranked GHG emissions as at least “fairly important” when making decisions about their land, crops and livestock which suggests the majority of farmers are already showing some environmental responsibility (DEFRA, 2023a). However, the same question revealed that 9% of grazing livestock farmers believed their farm did not produce GHG emissions (higher than any other farm type) demonstrating there is still a number of farmers who dismiss environmental targets (Hyland *et al.*, 2016). However, it is important to note the climate debate has significantly evolved since 2016, particularly within agriculture. Moreover, while data from the Farm Practices Survey is based on farms in England, the repondents in this survey were predominantly from Wales (75%).

Marginally more respondents thought Net Zero was achievable on their farm (Figure 6.1). The views of these respondents are consistent with the fact that Net Zero will not be achievable on every farm (McNicol *et al.*, 2024). For those who did not think Net Zero was achievable on their farm, “few measures being applicable on their farm” was one of the reasons selected by the most respondents (Table 6.2). This barrier has been well cited in the literature, e.g. Gillespie *et al.* (2007) found “non-applicability” to be one of the most important barriers for the non-adoption of best practices on cattle farms. However, respondents’ beliefs that there were few measures that were applicable on their farm could be explained by other barriers such as cognitive limitations i.e. understanding their own interests and recognising knowledge limitations (Kipling *et al.*, 2019a). For example, more measures could be applicable on these farms, but farmers may require more education on the benefits of these measures and how to implement them (Hallam *et al.*, 2012; Smith and Olesen, 2010). The feeling that “Livestock emissions (were) hard to reduce” was another one of the main reasons selected by respondents as to why they thought Net Zero was not achievable on their farm (Table 6.2). This barrier is not one which has been reported in literature, however, it demonstrates that these farmers have some knowledge of biological emissions and the natural limits of mitigating them (FAO, 2013).

Again, it is important to note these questions were based on what farmers thought was possible at a farm and sector level which may well be very different from what could and should be done to reach environmental targets at a national level. The agriculture sector alone will unlikely reach Net Zero due the biological emissions mentioned above, however, the Agriculture, Forestry and Other Land Use (AFOLU) sector will need to be achieve net negative emissions to achieve the overall national Net Zero target.

The GLM indicated complete separation on the "Not aware" variable i.e., all respondents who were not aware of what they needed to do to reach Net Zero, said the target had not influenced their decision-making (Figure 6.2). Lack of knowledge/information is a common barrier to the uptake of new practices (Feliciano *et al.*, 2014; Kipling *et al.*, 2019a; Smith and Olesen, 2010). The only factor which had a significant effect on farmers' decision-making in relation to Net Zero was farm type. Farm type has been reported to influence farmers' decision-making in relation to the environment (Dandy, 2012; Hallam *et al.*, 2012). However, in this study, it was hill farmers who said the target had influenced their decision-making more than upland or lowland farmers. This was surprising as hill farms are often associated with lower rates of deployment of measures applicable on their farms (Eory *et al.*, 2015; Jones *et al.*, 2015). This result in the present study may reflect the lower number of hill farmers surveyed compared to the upland and lowland farmers; however, the Net Zero target may have affected hill farmers' decision-making for a number of reasons, for example, productivity gains are often harder to achieve on hill farms and therefore more measures have already been implemented. Although not significant, tenure influenced farmer decision-making in relation to Net Zero. Farmers who wholly tenanted/rented their farm said the target had influenced their decision-making less than farmers who wholly owned their farms. Farm tenancy constraints are a well-researched barrier to implementing new practices on farms (Crabtree *et al.*, 2001; Dandy, 2012; Feliciano *et al.*, 2022). Tenancy agreements can be complex, and often farmers cannot make changes to the land or management as the rights are retained by the landowner. At least a third of farmland in England and Wales is still managed by tenant farmers (DEFRA, 2024) therefore this is a barrier that must be addressed in policy to improve the uptake of mitigation measures amongst these farmers.

Surprisingly, involvement in agri-environmental schemes appeared to have negative effect on farmers' decision-making in relation to Net Zero. This could be due to a barrier observed in other studies which relates to interference with other regulations (Dandy, 2012; Feliciano *et al.*, 2014; Smith and Olesen, 2010). Dandy (2012) highlighted the complexity of different rules and regulations that dictate which incentives can be received alongside others as they can potentially be in competition or conflict. For example, in the UK, Cross Compliance sets the standards that all farmers must meet in order to receive Basic Payment Scheme (BPS) payments and certain agri-environment scheme payments under the

Common Agricultural Policy (CAP) such as Glastir (UK Government, 2023a; Welsh Government, 2022b). However, the UK is currently making changes to its agri-environment schemes, shifting its focus away from the BPS and the Cross Compliance regulations associated with it. The new SFI in England and SFS in Wales have the potential to accelerate the uptake of GHG mitigation measures (DEFRA, 2023b; Welsh Government, 2022a). However, there is currently much uncertainty around the incentives available under these future schemes. No variables except farm type (namely hill farms) had a significant effect on farmers' decision-making in relation to Net Zero. However, this could be due to the lower numbers in some groups (e.g. hill farms), leading to a higher level in uncertainty in their results. Moreover, it is important to note that 75% of respondents in this survey were from Wales and having more farmers from England, Scotland and Northern Ireland could provide a more representative overview of farmers' views in the UK.

6.4.2. Greenhouse gas mitigation and sequestration measures

Over half of respondents had implemented measures to improve animal health, introduce legumes, improve grazing management and improve synthetic N use on their farm (Figure 6.3). This was comparable to adoption levels in England from the Farm Practices Survey which found 61% of farmers had a farm health plan, 54% of farmers had sown at least 20% of their temporary grassland with legumes and 56% of farmers had a nutrient management plan (DEFRA, 2023a). Improved animal nutrition and selection for balanced breeding goals in cattle were the measures that were considered by the most respondents. These results are unsurprising as all these measures represent "win-win" scenarios that will likely increase efficiencies and profitability as well as reduce GHG emissions (Eory *et al.*, 2015; Verspecht *et al.*, 2012). Afforestation and reducing stock numbers were measures that the greatest number of farmers would not consider (Figure 6.3; discussed further in Section 6.4.3). This reluctance to reduce stock number is particularly significant as if production efficiencies were increased, stock numbers are also likely to increase (despite lower emissions per kg of product), leading to an increase in net GHG emissions. This is known as the "Jevons Paradox" whereby increases in efficiency generate an increase (rather than a decrease) in resource consumption (Giampietro and Mayumi, 2018). This is an important issue that needs to be considered in future policy, as farmers are not only expected to sequester their own emissions but also offset emissions from other sectors to move towards Net Zero (UK Government, 2023b). To meet the Climate Change Committee's Net Zero pathway, 21% of agricultural land will be need to be released for offsetting (Climate Change Committee, 2020).

The uptake of GHG mitigation and sequestration measures can be explained by the Diffusion of Innovation (Rogers *et al.*, 2014). The theory describes how innovations are adopted over time based on what the innovation is, how it is spread and its social context. It states that adoption of innovation is not simultaneous, and Rogers *et al.* (2014) splits the population into five adopter categories: innovators, early adopters, early majority, late majority and laggards. This is seen in the results of this study, with few farmers (*n*=14 (13%)) implementing more than nine mitigation measures (innovators) and most farmers (*n*=44 (40%)) implementing between two and seven measures (early and late majority). However, a large proportion of respondents (*n*=37 (33%)) said they had implemented two or less mitigation measures, suggesting many farmers surveyed fall into the 'laggards' category – the last category in the adoption curve (Rogers *et al.*, 2014).

Many studies have evaluated the difference between intended and actual behaviour (e.g. Hennessy *et al.*, 2016; Niles *et al.*, 2016; Slavec *et al.*, 2023). Niles *et al.* (2016) found farmers beliefs and attitudes were only associated with intended, not actual adoption of climate change practices. They found there were different drivers for intended and actual adoption of mitigation measures, so even though a farmer may be willing to change their behaviour, they do not act due to other barriers (Niles *et al.*, 2016). This "intention-behaviour gap" is a well-cited concept in psychological research particularly in relation to environmental behaviour (Grimmer and Miles, 2017; Kollmuss and Agyeman, 2002; Sheeran, 2002). Numerous studies have illustrated that the actual abatement potential of mitigation measures is a lot lower than the maximum technical abatement potential due to various barriers to implementation (Kesicki and Ekins, 2012; Moran *et al.*, 2011; Vermont and De Cara, 2010). Therefore, to calculate the actual abatement potential of the GHG mitigation measures listed in the survey, the proportion of respondents who had already implemented, would currently consider and would consider in the future was multiplied by the measure's maximum technical abatement potential calculated in the previous Chapter. The majority of farmers had already implemented or would consider introducing legumes, therefore, its actual abatement potential was similar to its maximum technical abatement (Table 6.3). As many respondents did not know if they would implement NIs and many claimed slurry acidification was not applicable on their farm, these measures had the biggest reduction from their maximum *technical* to their *actual* abatement potential. This highlights more education on the benefits and implementation of NIs could be needed before farmers consider this measure on their farms (Hallam *et al.*, 2012; Kipling *et al.*, 2019b). Reductions in the maximum technical abatement potential of mitigation measures of up to 66.7% emphasises the importance of improving the uptake of GHG mitigation measures if Net Zero targets are to be met.

It is important to note that results from the survey regarding intended implementation of GHG measures should be interpreted with caution. For example, 6% of farmers claimed they were already using biochar, however, biochar is currently classed as a by-product of bioenergy production, so its use is limited under the EU Waste Framework Directive (2006). Similarly, 16% of farmers said they were already using CH_4 inhibitors, however, there are only a small number of CH_4 inhibitors approved and on the market in the UK. Therefore, the current level of adoption of both of these measures is unlikely as high as reported in our survey. Lefebvre *et al.* (2014) outlined multiple reasons why intentions reported in surveys do not result in actual behavioural change. These included timing bias (results are affected by when the survey was carried out), negligence bias (if respondents are unsure but feel like they have to answer anyway), manipulation bias (a respondent tries to influence the outcome of the survey) and sampling bias (where only certain types of farms are surveyed e.g. only more efficient or larger farms) (Lefebvre *et al.*, 2014).

The majority of respondents who had already implemented GHG mitigation measures on their farm said they had implemented measures for productivity (45.0%) and economic gains (41.3%). Similar motivations were cited in the Farm Practices Survey, with 50% of respondents saying they implemented GHG mitigation measures to improve profitability and 83% because they considered it to be good business practice (DEFRA, 2023a). Moreover, 73% of farmers surveyed in England reported they implemented GHG mitigation measures out of concern for the environment (DEFRA, 2023a). Previous research has stressed farmers' motivations go far beyond profit maximisation and farmer decision-making is the result of many complex physical and psychological factors (Kipling *et al.*, 2019a; Morris *et al.*, 2017; Wynne-Jones, 2013).

It is also possible the adoption of GHG mitigation measures could lead to a "rebound effect" whereby reducing emissions in one area of the farm increases emissions in another area (Hertel, 2012). For example, if production efficiencies were increased, prices would fall leading to greater demand for produce (Dreijerink *et al.*, 2023). This is the result of a number of economic and social-psychological adaptation mechanisms which occur when efficiencies are increased and which lead to an increase in consumption (Paul *et al*., 2019). However, previous studies have found that the rebound effect is often not large enough to result in a net increase in resource use (Gillingham *et al*., 2013; Gillingham *et al*., 2016).

Motivations for implementing GHG mitigation measures were consistent with the factors farmers said were important when considering measures. For example, cost and knowledge of the change needed were rated the most important factors when considering GHG mitigation measures (Figure 6.5). Implementation costs have been well cited as a barrier to adopting mitigation measures, and measures which do not generate profit will not likely be implemented without financial incentives (Feliciano *et al.*, 2014; Smith and Olesen, 2010). Management control was on average the least important factor when considering mitigation measures; however, this is likely due to the majority of respondents surveyed wholly owning or mostly owning their farm (Table 6.1).

6.4.3. Additional benefits of mitigation measures and barriers to implementation

The majority of respondents said they were not aware of any additional benefits of GHG mitigation measures or sequestration options. This demonstrates a huge barrier as most of the measures listed in the survey could increase productivity and economic gains (Bustamante *et al.*, 2014; Eory *et al.*, 2015; Moran *et al.*, 2013). Similarly, the Farm Practices Survey found only 29% of LFA grazing livestock farmers believed reducing GHG emissions from their farm would increase overall profitability (DEFRA, 2023a). These finding indicate there could be an issue with the messaging around these measures i.e., because some farmers have strong negative attitudes towards environmental targets, they immediately dismiss GHG mitigation measures despite their potential economic benefits. It is important to note that this is assuming production is held constant and profitability is defined in terms of the cost of production per unit of product. Moreover, if production efficiencies were increased, farmers could sustain the same level of output on a smaller area of land, freeing up more land available for future schemes and their associated income. The co-benefits of these GHG mitigation measures must therefore be promoted to address this issue (Hallam *et al.*, 2012; Kipling *et al.*, 2019b; Smith *et al.*, 2007), or perhaps policy mechanisms need to frame implementing these measures as options to increase efficiency.

The small proportion of farmers who were aware of any additional benefits of GHG mitigation measures and sequestration measures gave an extensive list of co-benefits. These includes economic benefits, which farmers related to increased farm resilience, profitability and better use of inputs. Improved animal welfare and productivity were also listed by many farmers as co-benefits for mitigation measures. A few farmers also cited shelter and animal welfare as co-benefits of sequestration options. Finally, many farmers cited other environmental benefits, including soil health, biodiversity and water management. Many measures have economic gain through increased yields or reduced inputs (Freibauer *et al.*, 2004; MacLeod *et al.*, 2010; Verspecht *et al.*, 2012) e.g. health, nutrition and breeding, all increase animal productivity and therefore profit as well as reduce methane (Smith *et al.*, 2007). Many of these measures can affect more than one of these themes. For example, improving synthetic N use has economic benefits by reducing fertiliser inputs but also other environmental benefits like improving water quality, biodiversity and soil quality by reducing acidification and nitrate leaching (Verspecht *et al.*, 2012).

Despite these benefits, some farmers still do not adopt these practices. MacLeod *et al.* (2010) suggests although many GHG mitigation measures appear to be "win-win" options, farmers argue that not all cost are fully taken into account, for example, the time and administration costs to implement these measures are not considered. However, it is possible farmers were also aware of trade-offs that exist for the GHG mitigation measures listed. For example, although NIs reduce emissions from soils, they can also increase NH_3 emissions (Lam *et al.*, 2017). It is therefore important farmers and policymakers do not to focus solely on one pollutant to avoid "pollution swapping". Dawson and Smith (2010) recommended measures should be integrated or at least grouped by pollutants with similar physical phases and pathways. Moreover, mitigation measures will rarely be implemented in isolation therefore interactions must also be considered (Del Prado *et al.*, 2010; Eory *et al.*, 2015; MacLeod *et al.*, 2010). In summary, all interactions, co-benefits and trade-offs must be considered by farmers and policymakers before implementing GHG mitigation measures (Bustamante *et al.*, 2014). However, not all co-benefits and trade-offs are fully understood, and economic and environmental benefits do not always line up (Verspecht *et al.*, 2012).

Cost and lack of perceived benefit were selected as the biggest barriers to increased afforestation. The topic of planting trees on farms appears to be a highly emotive subject, with many respondents selecting the "Other" answer option (27%) providing quite antagonistic quotes which can be found in the Appendix. Loss of productive land was by far the most cited theme. A few farmers referenced "loss of productive/grazing land to cover fixed costs" with another referring to tree planting on farms as having "short-sighted gains". Some respondents said their farm was "too small" or "too productive" to plant trees, which could be a genuine physical barrier (Dandy, 2012; Hallam *et al.*, 2012). However, it is also possible farmers only think this due their personal interests and beliefs – the second theme in this question. Many farmers reported they simply "don't want to plant trees". A couple of farmers believed well-managed grazed pasture was better for carbon sequestration than woodland. One farmer actually responded to this question expressing they felt the survey was "bias in favour of tree planting" and another said there was "No evidence about the benefits of afforestation against current practise. I don't like the assumption in the questionnaire", despite the survey only having two questions on afforestation. Although not mentioned by as many farmers, policy was the final theme identified as a barrier to increased afforestation on farms, with one farmer stating they felt there was a "mistrust of regulatory regime", and another felt there was a "hostile policy environment and lack of joined up approach from government departments".

Similarly, Duesberg *et al.* (2014) found prioritising food production and family tradition to be the most important barriers to tree planting on farms, with farm size and lack of information also significant. Wynne-Jones (2013) identified similar barriers for farmer delivering ecosystem services, such as a farmers' sense of identity and family values. Wynne-Jones (2013) also found farmers were critical of the government's current approach to food and environmental policy. Although not mentioned in this study, a survey by the Nature Friendly Farming Network found 80% of their public and farmer members were concerned that Net Zero targets could drive woodland creation that threatens natural habitats and biodiversity if not implemented by a "right tree, right place" approach; suggesting farmers may also have other environmental concerns regarding afforestation. Despite loss of productive land cited as a barrier to increased farm afforestation in this study and others, Ryan and O'Donoghue (2016) found one third of farms in Ireland did not change their stocking density following tree planting, and a quarter of farms actually increased stocking density; illustrating not all farms would have to decrease production to increase afforestation. Kaine *et al.* (2023) highlighted caution must be exercised when referring to these issues as "barriers" to increased afforestation as the term suggests there was originally an intention to plant trees. However, this lack of intention could also be considered a barrier.

6.4.4. Improving uptake of mitigation measures

Financial incentives were the overwhelming first choice of interventions farmers felt they needed to amend their farming practices. These findings are in line with the mechanisms to improve uptake identified in literature (Feliciano *et al.*, 2014; Kipling *et al.*, 2019b; Moerkerken *et al.*, 2020; Smith *et al.*, 2007; Wynne-Jones, 2013). These mechanisms can broadly be categorised into: economic incentives, regulations and education/information provision (Feliciano *et al.*, 2014; Glenk *et al.*, 2014). Economic incentives, as reported in this study, have been identified as one of the most important strategies to improve the uptake of GHG mitigation measures (Dandy, 2012; Smith *et al.*, 2007; Wynne-Jones, 2013). Bustamante *et al.* (2014) discussed various socio-economic barriers and opportunities to mitigating GHG emissions from the agriculture and highlighted "design and coverage of the financing mechanisms" as key to reaching full mitigation potential. There has been debate over which costs financial mechanisms should cover, however, transaction and monitoring cost must be covered or measures are not likely to be implemented (Bustamante *et al.*, 2014). Moreover, these costs vary significantly between measures. For example, transaction and monitoring costs could be much lower for some more simple mandates compared to seemingly more palatable but often more administratively complex payment for ecosystem services approaches. Some studies have argued financial incentives should also cover opportunity costs as otherwise mitigation measures could be less appealing than alternative land use option (Böttcher *et al.*, 2009). However for certain measures, financial incentives won't be enough for many farmers, for example, Ryan and O'Donoghue (2016) found 84% of farmers would not consider afforestation, regardless of the financial incentives offered. Westaway *et al.* (2023) found that the effectiveness of financial incentives to increase afforestation were highly dependent on farmers pre-existing interests and values. It is important to note, this question focused on the mechanisms which farmers felt were the most important to improve uptake of GHG mitigation measures. If posed to individuals outside the farming community, other solutions such as regulations or pollution tax could be preferred.

Regulations are another mechanism that have the potential to increase the uptake of GHG mitigation measures on farms. Regulations can range from taxes on emissions or inputs, to withdrawal of subsidies (Jakobsson *et al.*, 2002). For example, Nitrate Vulnerable Zones (NVZ) in the UK are areas which have been identified as high risk from nitrate pollution and so farmers must meet all NVZ requirements regarding N fertiliser use and storage of organic manure to receive full payment under the BPS; prosecution by the regulatory body is also possible if they do not comply (DEFRA, 2021). As previously mentioned, the UK is in the process of moving away from the BSP and Cross Compliance rules whereby a minimum standard had to be met to receive payment and penalties applied if rules were broken. From the 1$^{st\ of}$ January 2024, the BPS will be replaced by the Rural Payments Agency (RPA) and delinked payments in England (DEFRA, 2023c); which, as the name suggests, will remove the link between direct payments and land. Compliance will still be monitored; however, there will be no link between these rules and the delinked payments. The UK Government claim these regulations will take a more “preventative” and “advice-led approach”. In Wales, BPS payments are set to continue in 2024, reducing by 20% per year from 2025-2029 (Welsh Government, 2023a) and although the exact trajectory of future regulations is currently not known as the scheme is under its final consultation (Welsh Government, 2023a), The Agriculture (Wales) Act 2023 was recently introduced. The Agriculture (Wales) Act 2023 provides a policy and legislative framework for future agricultural support and regulation in Wales. The Act establishes four Sustainable Land Management (SLM) objectives, one being “to mitigate and adapt to climate change” (Welsh Government, 2023b). The Bill will also protect tenant farmers and ensure they are not unfairly restricted from accessing financial aids, which will help to overcome one barrier highlighted in this study. The Act also establishes a monitoring and reporting framework consisting of a multi-annual support plans, annual reports, SLM and impact reports every five years.

Dessart *et al.* (2019) recommended a mixture of voluntary and mandatory adoption approaches based on “dispositional” factors influencing farmers’ decision-making. For example, voluntary approaches should be used to target farmers who are more open to change and are concerned about the environment, whereas mandatory schemes should be introduced for farmers who are more reluctant. Alternatively, Dessart *et al.* (2019) suggests policy could be segmented on physical/demographic data such as age, sex and country; e.g. young farmers tend to have more environmental concerns and are more prone to taking risks so voluntary mechanisms could be introduced to target younger farmers.

However, Wynne-Jones (2013) highlighted targeting specific farmers could deepen the division between these farmer groups and a broader approach to increasing sustainable production should also be adopted to avoid this. To a degree, the CAP already bases direct payments and rural development programmes based on age. However, age did not have a significant effect on farmers' decision-making in relation to Net Zero in this study so it is unclear if basing payments on demographic data would be effective in helping farmers move towards Net Zero. Moreover, in practice basing payments on specific farmer types would be difficult to execute without being discriminatory.

Basing policy on specific measures could be a better approach to improve the uptake of GHG mitigation options. Bustamante *et al.* (2014) highlighted the importance of considering each GHG mitigation measure on a case-by-case basis because each measure has its own set of barriers and opportunities (which will also be context-specific). The GHG mitigation measures available to farmers in the UK vary significantly in complexity, applicability, and cost. Tailoring policy to account for these differences could help to limit the perceived barrier to implementing these measures. Moreover, Kipling *et al.* (2019b) demonstrated the need for "specifically prescribed solutions" which should be driven by detailed performance data and data about stakeholders themselves. Farming systems in the UK vary significantly so collecting information about farms and practices can enable more effective policy with fewer unintended consequences (Kipling *et al.*, 2019b). In another survey, when asked what support farmers needed to reach Net Zero, responses included "Alongside targets, they need to provide multiple options as there is not a one size fits all solution for this" (Nature Friendly Farming Network, 2021). Many studies have called for policy to account for the heterogeneity in the farming sector (Dandy, 2012; Dessart *et al.*, 2019; Kipling *et al.*, 2019b). One study suggested country- or region-specific policy as environmental concerns and risk perceptions can differ between areas (Dessart *et al.*, 2019) as well as co-benefits and trade-off varying between regions due to different soil types and climatic conditions (Verspecht *et al.*, 2012). More specifically, Westaway *et al.* (2023) highlighted the importance of flexibility when designing policy to increase tree planting as it would enable farmers to plant trees where it best suits their local conditions.

The new SFI in England and SFS in Wales offer / propose to offer target payments based on specific GHG mitigation measures on different types of eligible land. For example, in England eligible farmers could be paid £589 per year to assess their nutrient management and produce a review report on arable or permanent grassland, in a bid to reduce (or at least improve) the use of fertilisers (DEFRA, 2023b). In Wales, although the exact level of payment has yet to be announced, the outline proposal revealed there will be different layers of payment in the scheme (Welsh Government, 2023). The layers of the scheme are split into Universal, Optional and Collaborative actions. Farmers who join the SFS will be expected to carry out all the applicable Universal actions (such as carry out soil testing, submit nutrient accounts and complete a carbon assessment) to receive baseline and capital payments. Optional actions build on these base level actions but could be more complex to deliver and need to be tailored to each farm (such as growing crops to feed livestock and establishing/maintaining a mixed sward of grasses, legumes and herbs). Collaborative actions in the SFS are targeted at more specific priorities which need more flexibility and a combination of actions to maximise their benefits. Collaborative actions include providing support for farmers to work together in a catchment to improve water quality and providing support for projects to restore and manage peatland shared by multiple farmers. Farmers who implement these Optional or Collaborative actions will receive additional revenue and/or capital payments.

Despite financial incentives being ranked as the most important mechanisms to improve uptake of mitigation measures, on average farmers ranked themselves first as to who should be most responsible for improving uptake of mitigation measures (Figure 6.8). This shows that financial incentives alongside education could allow respondents to take a farmer led approach and take on more responsibility. Knowledge exchange events were the second most important intervention needed for farmers to amend their farming practice (Figure 6.7). Therefore, providing farmers with information on the benefits and implementation of GHG mitigation measures could be fundamental to increasing adoption of GHG mitigation measures (Hallam *et al.*, 2012; Kipling *et al.*, 2019; Westaway *et al.*, 2023). Hyland *et al.* (2018b) highlighted that no single model was sufficient to achieve effective knowledge exchange, illustrating the importance of acknowledging the heterogeneity between farms. Hyland *et al.* (2018b) also observed differences in the attitudes between high and low adopters and therefore advocated for tailored knowledge dissemination to improve uptake, a point made by other studies (Knowler and Bradshaw, 2007; Liu *et al.*, 2020).

On average, farmers ranked the Government second for who should be responsible for improving the uptake of GHG mitigation measures. Kipling *et al.* (2019b) also highlighted the importance of the role of the Government for driving uptake, particularly in their so-called “controlled” approach to change. Kipling *et al.* (2019b) identified three themes in approaches to change: accommodating, which involved minimal interventions and relies on others to drive change; control, which included all forms of payments, regulations and incentives; and empowerment, which was a data-driven approach for farmers. The Government clearly have control over who receive payments, however, if recipients can decide how these payments are spent, there is a shift from control to empowerment (Kipling *et al.*, 2019b). For example, payments which aim to overcome a barrier such as a farmer’s negative interest take a more controlling approach, but if payments support farmers’ interest and helps them overcome a practical barrier, they are empowered, which can often be received more positively by farmers. Wynne-Jones (2013) advocated a multifunctional agro-ecological approach which “takes a more considered negotiation of the compatibility between food provisioning and other ecosystem services", as most of the farmers surveyed would prioritise food production, regardless of any potential short-term financial gain. The Government was closely followed by farming unions for who should be responsible for improving the uptake of GHG mitigation measures. Farming unions in the UK have made their own commitments, for example, the National Farmers Union (NFU) have committed to reaching Net Zero by 2040 (NFU, 2019a). The NFU have published various reports providing farmers with information on the Net Zero target and promoting how farmers are currently working towards Net Zero (NFU, 2021, 2019b).

A combination of economic incentives, regulations and information provision will likely be required to overcome the implementation barriers highlighted in Sections 6.4.1 – 6.4.3. If farmers are provided with this support, it could enable them to make these changes themselves and drive the uptake of GHG mitigation and sequestration measures. Moreover, different GHG mitigation measures should be targeted independently to ensure effective adoption.

6.5. Conclusions

Many farmers thought that Net Zero was achievable at both a sector and farm level, however, a large proportion of farmers were unsure. However, it is unclear if all farmers actually understand Net Zero, both in terms of its technical definition and its real implications. Few factors affected farmers' decision-making in relation to Net Zero, with "hill farms" being the only variable which had a significant effect. Many farmers had already implemented a number of GHG mitigation measures on their farm and many more would consider additional measures. The level of adoption still had a notable effect on the maximum technical abatement potential of some measures e.g. nitrification inhibitors and slurry acidification. Despite many farmers reporting they would consider various GHG mitigation measures, this does not necessarily translate into behavioural change. Many socio-economic barriers must be overcome in order for farmers to move towards Net Zero. For example, most farmers were not aware of any co-benefits of GHG mitigation or sequestration measures, despite the majority of measures listed representing "win-win" scenarios. Therefore, more education is needed on the economic benefits of GHG mitigation measures and perhaps policy mechanisms should promote these options as measures that could also increase efficiency and profitability rather than solely reduce GHG emissions.

Unsurprisingly, financial incentives were identified as the key mechanism for farmers to amend their practices. However, policy that includes the provision of financial incentives must carefully consider the mitigation and sequestration options on a case-by-case basis, account for the heterogeneity in the farming sector, and support farmers in implementing these measures whilst maintaining food production. Even with these incentives, it is likely that certain measures will not be considered by some farmers, due to their own personal interest and beliefs that are not based just on profit maximisation. For example, this survey has reiterated that afforestation of farmland is an emotive subject and consequently significant effort will be required before many farmers consider its adoption. Despite farmers reporting they felt financial incentives were the most important intervention to support them to amend their farming practices, it was clearly important that the actual change was led by the farmers themselves. This could suggest education and information provision could be key to increasing the adoption of GHG mitigation and sequestration measures. However, these findings could also suggest, given the current low uptake of GHG mitigation and sequestration options, a more stringent regulatory framework from the government could be needed to achieve Net Zero.

6.6. References

Ajzen, I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process., Theories of Cognitive Self-Regulation 50, 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Blackstock, K.L., Ingram, J., Burton, R., Brown, K.M., Slee, B., 2010. Understanding and influencing behaviour change by farmers to improve water quality. Sci. Total Environ., Special Section: Integrating Water and Agricultural Management Under Climate Change 408, 5631–5638. https://doi.org/10.1016/j.scitotenv.2009.04.029

Böttcher, H., Eisbrenner, K., Fritz, S., Kindermann, G., Kraxner, F., McCallum, I., Obersteiner, M., 2009. An assessment of monitoring requirements and costs of "Reduced Emissions from Deforestation and Degradation." Carbon Balance Manag. 4, 7. https://doi.org/10.1186/1750-0680-4-7

Braun, V., Clarke, V., 2013. Successful Qualitative Research: A Practical Guide for Beginners.

Bustamante, M., Robledo-Abad, C., Harper, R., Mbow, C., Ravindranat, N.H., Sperling, F., Haberl, H., de Siqueira Pinto, A., Smith, P., 2014. Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. Glob. Change Biol. 20, 3270–3290. https://doi.org/10.1111/gcb.12591

Climate Change Committee, 2020. The Sixth Carbon Budget The UKs path to Net Zero.

Crabtree, B., Chalmers, N., Eiser, D., 2001. Voluntary incentive schemes for farm forestry: uptake, policy effectiveness and employment impacts. For. Int. J. For. Res. 74, 455–465. https://doi.org/10.1093/forestry/74.5.455

Dandy, N., 2012. Understanding Private Land-manager Decision-making. For. Res. https://cdn.forestresearch.gov.uk/2022/02/understanding_land-manager_decision-making_dandy2012.pdf

Dawson, J.J., Smith, P., 2010. Integrative management to mitigate diffuse pollution in multi-functional landscapes. Curr. Opin. Environ. Sustain. 2, 375–382. https://doi.org/10.1016/j.cosust.2010.09.005

Daxini, A., O'Donoghue, C., Ryan, M., Buckley, C., Barnes, A.P., Daly, K., 2018. Which factors influence farmers' intentions to adopt nutrient management planning? J. Environ. Manage. 224, 350–360. https://doi.org/10.1016/j.jenvman.2018.07.059

DEFRA, 2023a. Farm practices survey. GOV.UK. https://www.gov.uk/government/collections/farm-practices-survey

DEFRA, 2023. Sustainable Farming Incentive guidance. GOV.UK. https://www.gov.uk/government/collections/sustainable-farming-incentive-guidance

DEFRA, 2021. Nitrate vulnerable zones. GOV.UK. https://www.gov.uk/government/collections/nitrate-vulnerable-zones

Del Prado, A., Chadwick, D.R., Cardenas, L.M., Misselbrook, T.H., Scholefield, D., Merino, P., 2010. Exploring systems responses to mitigation of GHG in UK dairy farms. Agric. Ecosyst. Environ. 136, 318–332. https://doi.org/10.1016/j.agee.2009.09.015

Department for Business, Energy & Industrial Strategy, 2022. Final UK greenhouse gas emissions national statistics: 1990 to 2020.

Dessart, F.J., Barreiro-Hurlé, J., van Bavel, R., 2019. Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. Eur. Rev. Agric. Econ. 46, 417–471. https://doi.org/10.1093/erae/jbz019

Dicks, L.V., Rose, D.C., Ang, F., Aston, S., Birch, A.N.E., Boatman, N., Bowles, E.L., Chadwick, D., Dinsdale, A., Durham, S., Elliott, J., Firbank, L., Humphreys, S., Jarvis, P., Jones, D., Kindred, D., Knight, S.M., Lee, M.R.F., Leifert, C., Lobley, M., Matthews, K., Midmer, A., Moore, M., Morris, C., Mortimer, S., Murray, T.C., Norman, K., Ramsden, S., Roberts, D., Smith, L.G., Soffe, R., Stoate, C., Taylor, B., Tinker, D., Topliff, M., Wallace, J., Williams, P., Wilson, P., Winter, M., Sutherland, W.J., 2019. What agricultural practices are most likely to deliver "sustainable intensification" in the UK? Food Energy Secur. 8, e00148. https://doi.org/10.1002/fes3.148

Duesberg, S., Dhubháin, Á.N., O'Connor, D., 2014. Assessing policy tools for encouraging farm afforestation in Ireland. Land Use Policy 38, 194–203. https://doi.org/10.1016/j.landusepol.2013.11.001

Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, McVittie, Wall, Borthwick, Watson, Waterhouse, Wiltshire, 2015. Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget period and to 2050. (Final report submitted for the project contract "Provision of services to review and update the UK agriculture MACC and to assess abatement potential for the 5 th carbon budget period and to 2050"). SRUC.

Eory, V., Topp, K., Rees, B., Leinonen, I., Maire, J., 2020. Marginal abatement cost curve for Scottish agriculture. https://doi.org/10.7488/ERA/755

European Climate Change Programme, 2003. Working Group 7—Agriculture. Mitigation Potential of Greenhouse Gases in the Agricultural Sector. Final Report. COMM(2000)88. European Commission, Brussels.

FAO, 2013. Mitigation of greenhouse gas emissions in livestock production: a review of technical options for non-CO2 emissions, FAO animal production and health paper. Food and Agriculture Organization of the United Nations, Rome.

Feliciano, D., Hunter, C., Slee, B., Smith, P., 2014. Climate change mitigation options in the rural land use sector: Stakeholders' perspectives on barriers, enablers and the role of policy in North East Scotland. Environ. Sci. Policy 44, 26–38. https://doi.org/10.1016/j.envsci.2014.07.010

Feliciano, D., Recha, J., Ambaw, G., MacSween, K., Solomon, D., Wollenberg, E., 2022. Assessment of agricultural emissions, climate change mitigation and adaptation practices in Ethiopia. Clim. Policy 22, 427–444. https://doi.org/10.1080/14693062.2022.2028597

Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122, 1–23. https://doi.org/10.1016/j.geoderma.2004.01.021

Gillespie, J., Kim, S.-A., Paudel, K., 2007. Why don't producers adopt best management practices? An analysis of the beef cattle industry. Agric. Econ. 36, 89–102. https://doi.org/10.1111/j.1574-0862.2007.00179.x

Gillingham, K., Rapson, D., Wagner, G., 2016. The Rebound Effect and Energy Efficiency Policy. Review of Environmental Economics and Policy 10, 68–88. https://doi.org/10.1093/reep/rev017

Gillingham, K., Kotchen, M.J., Rapson, D.S., Wagner, G., 2013. The rebound effect is overplayed. Nature 493, 475–476. https://doi.org/10.1038/493475a

Glenk, K., Eory, V., Colombo, S., Barnes, A., 2014. Adoption of greenhouse gas mitigation in agriculture: An analysis of dairy farmers' perceptions and adoption behaviour. Ecol. Econ. 108, 49–58. https://doi.org/10.1016/j.ecolecon.2014.09.027

Grimmer, M., Miles, M.P., 2017. With the best of intentions: a large sample test of the intention-behaviour gap in pro-environmental consumer behaviour. Int. J. Consum. Stud. 41, 2–10. https://doi.org/10.1111/ijcs.12290

Hallam, A., Bowden, A., Kasprzyk, K., 2012. Agriculture and climate change: evidence on influencing farmer behaviours. Scottish Government, Social Research.

Hayden, M.T., Mattimoe, R., Jack, L., 2021. Sensemaking and the influencing factors on farmer decision-making. J. Rural Stud. 84, 31–44. https://doi.org/10.1016/j.jrurstud.2021.03.007

Hennessy, T., Kinsella, A., Thorne, F. (Eds.), 2016. Planned intentions versus actual behaviour: assessing the reliability of intention surveys in predicting farmers' production levels post decoupling. Int. J. Agric. Manag. https://doi.org/10.22004/ag.econ.287259

Hertel, T.W., 2012. Implications of agricultural productivity for global cropland use and GHG emissions: Borlaug vs. Jevons. AgEcon Search. 69. http://dx.doi.org/10.22004/ag.econ.283487

Hyland, J.J., Heanue, K., McKillop, J., Micha, E., 2018a. Factors influencing dairy farmers' adoption of best management grazing practices. Land Use Policy 78, 562–571. https://doi.org/10.1016/j.landusepol.2018.07.006

Hyland, J.J., Heanue, K., McKillop, J., Micha, E., 2018b. Factors underlying farmers' intentions to adopt best practices: The case of paddock based grazing systems. Agric. Syst. 162, 97–106. https://doi.org/10.1016/j.agsy.2018.01.023

Hyland, J.J., Jones, D.L., Parkhill, K.A., Barnes, A.P., Williams, A.P., 2016. Farmers' perceptions of climate change: identifying types. Agric. Hum. Values 33, 323–339. https://doi.org/10.1007/s10460-015-9608-9

Jakobsson, C., Sommer, E.B., De Clercq, P., Bonazzi, G., Schröder, J., 2002. The policy implementation of nutrient management legislation and effects in some European Countries, in: The Final Workshop of the EU Concerted Action Nutrient Management Legislation in European Countries NUMALEC.

Jisc, 2023. Jisc online surveys. https://www.onlinesurveys.ac.uk/

Jones, A.K., Jones, D.L., Cross, P., 2015. Developing farm-specific marginal abatement cost curves: Cost-effective greenhouse gas mitigation opportunities in sheep farming systems. Land Use Policy 49, 394–403. https://doi.org/10.1016/j.landusepol.2015.08.006

Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of lamb: Sources of variation and opportunities for mitigation. Agric. Syst. 123, 97–107. https://doi.org/10.1016/j.agsy.2013.09.006

Jørgensen, S.L., Termansen, M., 2016. Linking climate change perceptions to adaptation and mitigation action. Clim. Change 138, 283–296. https://doi.org/10.1007/s10584-016-1718-x

Kaine, G., Edwards, P., Polyakov, M., Stahlmann-Brown, P., 2023. Who knew afforestation was such a challenge? Motivations and impediments to afforestation policy in New Zealand. For. Policy Econ. 154, 103031. https://doi.org/10.1016/j.forpol.2023.103031

Kesicki, F., Ekins, P., 2012. Marginal abatement cost curves: a call for caution. Clim. Policy 12, 219–236. https://doi.org/10.1080/14693062.2011.582347

Kipling, R.P., Taft, H.E., Chadwick, D.R., Styles, D., Moorby, J., 2019a. Challenges to implementing greenhouse gas mitigation measures in livestock agriculture: A conceptual framework for policymakers. Environ. Sci. Policy 92, 107–115. https://doi.org/10.1016/j.envsci.2018.11.013

Kipling, R.P., Taft, H.E., Chadwick, D.R., Styles, D., Moorby, J., 2019b. Implementation solutions for greenhouse gas mitigation measures in livestock agriculture: A framework for coherent strategy. Environ. Sci. Policy 101, 232–244. https://doi.org/10.1016/j.envsci.2019.08.015

Knowler, D., Bradshaw, B., 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. Food Policy 32, 25–48. https://doi.org/10.1016/j.foodpol.2006.01.003

Kollmuss, A., Agyeman, J., 2002. Mind the Gap: Why do people act environmentally and what are the barriers to pro-environmental behavior? Environ. Educ. Res. 8, 239–260. https://doi.org/10.1080/13504620220145401

Kreft, C.S., Huber, R., Wüpper, D.J., Finger, R., 2020. Data on farmers' adoption of climate change mitigation measures, individual characteristics, risk attitudes and social influences in a region of Switzerland. Data Brief 30, 105410. https://doi.org/10.1016/j.dib.2020.105410

Lam, S.K., Suter, H., Mosier, A.R., Chen, D., 2017. Using nitrification inhibitors to mitigate agricultural N2O emission: a double-edged sword? Glob. Change Biol. 23, 485–489. https://doi.org/10.1111/gcb.13338

Lefebvre, M., Raggi, M., Gomez Y Paloma, S., Viaggi, D., 2014. An analysis of the intention-realisation discrepancy in EU farmers' land investment decisions. Rev. D'Études En Agric. Environ. 95, 51–75.

Liu, P., Teng, M., Han, C., 2020. How does environmental knowledge translate into pro-environmental behaviors?: The mediating role of environmental attitudes and behavioral intentions. Sci. Total Environ. 728, 138126. https://doi.org/10.1016/j.scitotenv.2020.138126

MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Smith, P., Moxey, A., 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agric. Syst. 103, 198–209. https://doi.org/10.1016/j.agsy.2010.01.002

McNicol, L.C., Williams, N.G., Chadwick, D.R., Styles, D., Rees, R.M., Ramsey, R., Williams, A.P., 2023. Net Zero Requires Ambitious Greenhouse Gas Emission Reductions on Beef and Sheep Farms Coordinated with Afforestation and Other Land Use Change Measures. https://doi.org/10.2139/ssrn.4421415

Moerkerken, A., Blasch, J., van Beukering, P., van Well, E., 2020. A new approach to explain farmers' adoption of climate change mitigation measures. Clim. Change 159, 141–161. https://doi.org/10.1007/s10584-019-02595-3

Moran, D., Lucas, A., Barnes, A., 2013. Mitigation win–win. Nat. Clim. Change 3, 611–613. https://doi.org/10.1038/nclimate1922

Moran, D., Macleod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, R., Topp, C.F.E., Moxey, A., 2011. Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions. J. Agric. Econ. 62, 93–118. https://doi.org/10.1111/j.1477-9552.2010.00268.x

Morris, W., Henley, A., Dowell, D., 2017. Farm diversification, entrepreneurship and technology adoption: Analysis of upland farmers in Wales. J. Rural Stud. 53, 132–143. https://doi.org/10.1016/j.jrurstud.2017.05.014

Nature Friendly Farming Network, 2021. Rethink Farming: A Practical Guide for Farming, Nature & Climate. https://www.nffn.org.uk/wp-content/uploads/2021/12/NFFN-Rethink-Farming-Report_Digital-Final-Release-1221.pdf

NFU, 2021. Our Journey to Net Zero: Farming's 2040 Goal. National Farmers' Union. https://www.nfuonline.com/media/rwzkb3fc/our-journey-to-net-zero-2021.pdf

NFU, 2019a. Achieving Net Zero: Farming's 2040 goal. National Farmers' Union. https://www.nfuonline.com/media/jq1b2nx5/achieving-net-zero-farming-s-2040-goal.pdf

NFU, 2019b. Doing Our Bit For Net Zero. https://www.nfuonline.com/media/zzklvrkk/doing-our-bit-for-net-zero.pdf

Niles, M.T., Brown, M., Dynes, R., 2016. Farmer's intended and actual adoption of climate change mitigation and adaptation strategies. Clim. Change 135, 277–295. https://doi.org/10.1007/s10584-015-1558-0

Paul, C., Techen, A.-K., Robinson, J.S., Helming, K., 2019. Rebound effects in agricultural land and soil management: Review and analytical framework. Journal of Cleaner Production 227, 1054–1067. https://doi.org/10.1016/j.jclepro.2019.04.115

R Core Team (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rogers, E.M., Singhal, A., Quinlan, M.M., 2014. Diffusion of innovations, in: An Integrated Approach to Communication Theory and Research. Routledge, pp. 432–448.

Ryan, M. and O'Donoghue, C., 2016. Socio-economic drivers of farm afforestation decision-making. Irish Forestry, 73, 96-121.

Sheeran, P., 2002. Intention—Behavior Relations: A Conceptual and Empirical Review. Eur. Rev. Soc. Psychol. 12, 1–36. https://doi.org/10.1080/14792772143000003

Slavec, A., Hoeben, A.D., Moreno-Torres, M., Primožič, L., Stern, T., 2023. When intentions do not matter: Climate change mitigation and adaptation innovations in the Forest-based sector. For. Policy Econ. 157, 103074. https://doi.org/10.1016/j.forpol.2023.103074

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., 2007. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agric. Ecosyst. Environ. 118, 6–28. https://doi.org/10.1016/j.agee.2006.06.006

Smith, P., Olesen, J.E., 2010. Synergies between the mitigation of, and adaptation to, climate change in agriculture. J. Agric. Sci. 148, 543–552. https://doi.org/10.1017/S0021859610000341

UK Government, 2023a. Guide to cross compliance in England 2023. GOV.UK. https://www.gov.uk/government/publications/cross-compliance-2023

UK Government, 2023b. Powering up Britain. GOV.UK. https://www.gov.uk/government/publications/powering-up-britain

UK Government, 2021. Climate change and net zero: public awareness and perceptions (No. 2021/034). GOV.UK. https://www.gov.uk/government/publications/climate-change-and-net-zero-public-awareness-and-perceptions

Vermont, B., De Cara, S., 2010. How costly is mitigation of non-CO2 greenhouse gas emissions from agriculture?: A meta-analysis. Ecol. Econ., Special Section: Ecosystem Services Valuation in China 69, 1373–1386. https://doi.org/10.1016/j.ecolecon.2010.02.020

Verspecht, A., Vandermeulen, V., Ter Avest, E., Van Huylenbroeck, G., 2012. Review of trade-offs and co-benefits from greenhouse gas mitigation measures in agricultural production. J. Integr. Environ. Sci. 9, 147–157. https://doi.org/10.1080/1943815X.2012.698989

Welsh Government, 2022a. Sustainable Farming Scheme: Outline Proposals for 2025 71. https://www.gov.wales/sustainable-farming-scheme-outline-proposals-2025

Welsh Government, 2022b. Common Agriculture Policy; Cross Compliance Farmers Factsheets. GOV.WALES. https://www.gov.wales/sites/default/files/publications/2021-12/cross-compliance-verifiable-standards-2022.pdf

Wynne-Jones, S., 2013. Ecosystem Service Delivery in Wales: Evaluating Farmers' Engagement and Willingness to Participate. J. Environ. Policy Plan. 15, 493–511. https://doi.org/10.1080/1523908X.2013.788443

Chapter 7 Discussion: synthesis and conclusions

7.1. Summary of key findings

As stated in Chapter 1, the overarching aim of this thesis was to explore the opportunities available to Welsh beef and sheep farmers to move towards Net Zero. The key findings of this research are presented below in relation to the thesis objectives stated in Chapter 1.

Chapter 2: Greenhouse gas emissions and the pathway to Net Zero on Welsh beef and sheep farms: a literature review

The key objective of this chapter was to evaluate the existing literature surrounding GHG emissions and Net Zero in beef and sheep production systems. Through the extensive review of the literature in Chapter 2, it was clear that agriculture produces a large quantity of GHG emissions, particularly livestock production systems. Although ambitious environmental targets have been set, there has been little guidance on how these targets will be met at a farm level. Chapter 2 gives an overview of the different methodologies, metrics and functional units used to quantify emissions and the significant effect they can have on emissions estimates. This chapter highlights the impacts of new metrics such as GWP*, which better represents the warming potential of CH_4. This chapter also highlights the recent shift in policy post-Brexit, from susbsidies to support farmers income to payment for payment for public good and reducing their GHG emissions. Chapter 2also summarised the range of mitigation measures and sequestration options available for beef and sheep farms to reduce their GHG emissions. From "win-win" GHG mitigation measures such as targeting nitrogen fertilser use and increasing livestock production efficiencies through improving nutrition, breeding and health, to more novel measures such as precision livestock farming technologies and methane-inhibiting feed additives such as 3NOP. Despite the various mitigation measures available, some level of GHG emissions will always exsist from livestock systems due to the biological processes involved in enteric fermentation. Therefore, achieving Net Zero will require residual emissions to be offset through GHG sequestration. Afforestation will likely be the most important GHG removal option in the UK, however, many other sequestration options are available such as biochar, BECCS and DACCS.

Chapter 3: Greenhouse gas emissions and the pathway to Net Zero on Welsh beef and sheep farms: a literature review

To achieve Net Zero, it is essential to first calculate accurate baseline carbon footprints. There are many carbon calculators available for use on Welsh beef and sheep farms which are known to produce notably different emission estimates for the same farms (Sykes *et al.*, 2017; Taft *et al.*, 2018). The aim of this chapter was to assess the variation in GHG emission and sequestration estimates of three widely used carbon calculators for application on Welsh beef and sheep farms. The last peer-reviewed study which compared carbon calculator for use on UK farms was published in 2017, and the calculators evaluated in that study have developed considerably since then (Sykes *et al.*, 2017). In Chapter 3, we evaluated two widely used commercially available carbon calculators: Agrecalc and Farm Carbon Calculator (FCC) as well as Bangor University's own Carbon Footprinting Tool for application on Welsh beef and sheep farms. In summary, Agrecalc produced the highest emissions estimates, whereas the FCC produced the lowest. Sequestration estimates were the highest in the Bangor Tool and the lowest in the FCC. These differences were likely due to the variation in the level of detail required for the input of the different tools. Moreover, the methodology of the FCC was less transparent than the other tools. Agrecalc closely mirrors inventory reporting which could be important in the future when considering carbon footprints in relation to government targets. In the future, carbon calculators should be transparent in their methodology as well as being updated regularly to utilise the latest emission factors. The main conclusion of this chapter was that results from these different carbon calculators are not directly comparable, however, their use separately is still valid when benchmarking within and between farms.

Chapter 4: Greenhouse gas emissions and the pathway to Net Zero on Welsh beef and sheep farms: a literature review

Although both the UK and Welsh governments have set a Net Zero by 2050 target, it is unclear what change will need to be implemented at farm level to achieve this target. The aim of this chapter was therefore to explore the opportunities currently available to reduce GHG emissions and enhance sequestration on Welsh beef and sheep farms. Chapter 4 investigated the combination of mitigation measures and afforestation that would be required to achieve Net Zero on twenty real beef and sheep farms in Wales. Our modelling showed that mitigation alone was not enough to reach carbon neutrality at a farm level and therefore measures to increase carbon sequestration were required. Implementation of a wide variety of GHG mitigation measures across farms resulted in an average abatement potential of 28%. Afforestation needed to offset remaining emissions equated to roughly

38% of farm's total area on average, however, this ranged from 8% - 85%. The farm with the highest area of woodland needed to offset its remaining emissions was the most efficient farm (in terms of GHG emissions per unit of product) of the twenty in this study. This highlighted an important issue that Net Zero may not be a logical aspiration for all farms if it leads to displacing production to less efficient systems. Overall, Chapter 4 demonstrated that major changes are needed on Welsh farms to meet current environmental targets; however, measures to reduce emissions and enhance sequestration will need to consider potential negative and impacts on the overall sustainability of food production systems.

Chapter 5: The nutritional value of meat should be considered when comparing the carbon footprint of lambs produced on different finishing diets

The functional unit (FU) used to express emissions can significantly influence the resultant carbon footprint, particularly when comparing foods or farming systems. Recently, standard approaches to the carbon footprinting of foods have been criticised, as they do not reflect the function of the final product, human nutrition. The objective of this chapter was therefore to evaluatie the impact of using nutrition-based functional units on the carbon footprint of lambs on different production systems, namely finishing diet. Chapter 6 compared four lamb finishing diets using both a mass-based and nutrient-based functional unit. It found that while employing a mass-based functional unit, lambs finished on a diet of concentrates had the lowest carbon footprint and the grass-only diet had the highest, whereas when employing a nutrient-based functional unit, the forage crop diet had the lowest and the grass and concentrate diet had the highest. This chapter highlighted that although traditional mass-based functional units can be useful for comparing the efficiency of different farming systems, they do not reflect the nutitional value of the product. These findings highlight the importance of selecting an appropriate functional unit to express emissions and the impact this choice can have on the final footprint results.

Chapter 6: Barriers and opportunities to achieving Net Zero on UK beef and sheep farms

There are a range of mitigation measures and sequestration options available for beef and sheep farms to move towards Net Zero. Many of these measures represent "win-win" scenarios as they reduce emissions as well as increase productivity and therefore profit. Despite many of these measures making economic sense, uptake remains low on beef and sheep farms. The aim of this chapter was therefore to investigate the barriers to achieving Net Zero and how to improve the uptake of GHG mitigation and sequestration measures on farms. Chapter 5 explored the various socio-economic barriers to uptake of mitigation and sequestration measures. Many farmers reported they had already implemented a number of mitigation measures on their farm and even more would consider additional measures. The anticipated level of adoption still notably reduced the abatement potential of a few measures such as nitrification inhibitors and slurry acidification. This chapter identified many barriers that must be overcome to increase the uptake of mitigation measures, for example, the majority of farmers were not aware of any co-benefits of the mitigation measures listed. Financial incentives were identified as the most important mechanism for farmers to amend their farming practices, yet farmers ranked themselves as first to who should be responsible for improving the uptake of mitigation measures. These findings suggest improved knowledge exchange and communication could be key to enable farmers to lead this change, however, the reluctance shown by some farmers may also require more stringent regulatory framework.

7.2. Limitations

Several limitations to the work have already been highlighted within chapters, but a broader consideration is made here.

The carbon footprinting process and carbon calculators are rapidly evolving. For example, in Chapter 3, two widely used commercially available carbon calculators and Bangor University's own Carbon Footprinting Tool were chosen to be evaluated. However, since this chapter was written, a new carbon calculator has been released that has seemingly gained popularity in the UK (Trinity Agtech, 2023). Moreover, carbon calculators are continuously being developed; therefore, it is difficult for studies to stay current. For example, Agrecalc has recently been updated from using values from AR4 to use values from AR5, which could potentially affect the results from Chapters 3, 4 and 6 (although Chapter 6 does not necessarily focus on absolute emissions but instead comparing finishing diets and functional units). Similarly, Agrecalc have also introduced a soil carbon module since completion of Chapter 3, meaning the sequestration estimates will inevitably differ from those reported in this chapter.

This thesis has focused exclusively on GHG emissions originating from beef and sheep production; however, livestock systems give rise to several other environmental impacts that have not been addressed in this study. For example, livestock are responsible for a large proportion of the UK's total ammonia emissions, which can have a detrimental effect on biodiversity (Guthrie et al., 2018). Livestock production can also cause water pollution through nitrate leaching and phosphorus runoff, which can result in eutrophication (Smolders *et al.*, 2010; Withers *et al.*, 2014). However, livestock farming has many environmental benefits. When grazed at a suitable level (i.e. the correct number and type of livestock at the appropriate time of the year), livestock can help maintain a range of habitats for birds, insects and mammals (Natural England, 2012). Livestock manure also fertilises soil, reducing the need for synthetic fertilisers (Petersen *et al.*, 2007). Reducing or removing grazing animals altogether could even lead to negative environmental impacts such as scrub encroachment and the spread aggressive species (Laborde and Thompson, 2015).

One of the major limitations of Chapters 3 and 4 relate to the scalability of results. This modelling was carried out on twenty beef and sheep farms in Wales, so although these results are not statistically scalable, these farms were chosen to represent a cross-section of Welsh agriculture. Similarly, in Chapter 5, a larger sample size could drastically improve the statistical power of the findings relating to farmers' attitudes towards Net Zero. Additionally, 75% of the farmers surveyed in this chapter were Welsh, so having more farmers from England, Scotland and Northern Ireland could provide a more representative overview of farmers in the UK.

The main limitation of Chapter 6 lies with the unbalanced dataset. This chapter utilised data from a larger research project, which included four balanced design trials. However, only farms that provided whole farm data were included in this chapter, which resulted in an unbalanced number of lambs in each diet, breed and gender. However, these farms were chosen to represent a cross-section of lamb finishing systems and therefore these differences in production and seasonality would lead to some variation in the dataset.

7.3. Future research

A key recommendation for future research that has become evident throughout this thesis is for baseline carbon footprints and mitigation scenarios to be modelled on more farms. Several chapters in this thesis were based on findings from twenty farms, so modelling more farms in Wales could markedly increase the scalability of this work. Moreover, in Chapter 4, only mitigation measures from the UK's most recent marginal abatement cost curve (MACC) were implemented in Net Zero scenarios to ensure a high level of certainty in the abatement potentials. However, many new innovations and technologies have been developed in recent years that have the potential to reduce GHG emissions significantly. For these new mitigation measures to be modelled in mitigation scenarios, more experimental studies would be required to ensure a high-level certainty in their abatement potentials.

Moreover, afforestation was the only measure considered in this study to increase carbon sequestration. In future, other carbon removal options such as biochar could help farms offset their emissions and move towards Net Zero. The potential for additional sequestration in grassland soils also needs greater exploration, particularly as the land area of deep-rooting multi-species leys increases and their potential for sequestration at lower depths is recognised (Leake *et al.*, 2006). Such work is of considerable importance and significance to ruminant production systems, where soils act as a considerable store of carbon, and options to grow this store could have notable implications for the overall balance of emissions and offsetting of carbon (and other GHGs).

Future studies should also consider more than purely GHG emissions. Implementing certain GHG mitigation measures could lead to unintended consequences such as "pollution swapping". For example, NIs reduce soil N_2O emissions, however, they could also increase NH_3 emissions (Lam *et al.*, 2017). Moreover, this study did not conduct any economic analysis on implementing mitigation measures. A full multiple-pollutant MACC could account for all GHG emissions, wider environmental impacts and costs of mitigation measures (Eory *et al.*, 2013). Future work should consider not only economic sustainability but also social sustainability. For example, Smith *et al.* (2022) found that agroforestry not only had the potential to contribute positively to environmental sustainability but also social sustainability through increased land-use efficiency, employment and engagement with local communities. The Well-being of Future Generations (Wales) Act was introduced in 2015 and defines sustainable development in Wales broadly as "improving economic, social, environmental and cultural well-being". Welsh agriculture contributes to all of these and has many positive effects on society (Hill and Bradley, 2019). In 2021, the food and drinks supply chain employed 233,500 people in Wales, accounting for 17.5% of Wales' total workforce and a turnover of £22.3 billion (Welsh Government, 2022). Moreover, it is estimated family farms procure over 80% of goods and services from within a 25-mile radius of the holding (Amaeth Cymru, 2017). Future mitigation scenarios should therefore consider the effects of reducing production (caused by increases in offset areas) and the potential loss of family farms on rural communities.

In this thesis, the Net Zero target was explored at a farm level; however, Net Zero is arguably not a feasible farm-level target, but a national-level target. Although the findings from the farm-level mitigation scenarios in Chapter 4 were extrapolated to a national scale, future work should carry out detailed national-level modelling to assess the future land use that could deliver Net Zero. Duffy *et al.* (2022) generated randomized scenarios that could achieve carbon neutrality in the AFOLU sector in Ireland. A similar approach could be utilised in Wales, whereby the combination of animal numbers and their productivity are balanced with the area of land available (including land for afforestation). However, the food production system in Wales (and in any country) does not operate independently and therefore upstream and downstream emissions as well as land use change must be accurately accounted for.

7.4. Wider implications

The findings of this thesis bear particular significance during a period in which significant policy changes are taking place in Wales, and indeed throughout the UK. Moreover, discussions around land use policies to achieve Net Zero are widespread throughout the world, including Australia (Australian Government, 2023), China (Government of China, 2021), New Zealand (New Zealand Government, 2019) and the United States (U.S. Department of State, 2021). However, what makes this study particularly timely and pertinent in a UK context is the development of post-Brexit agricultural and environmental policies. As touched on in previous chapters, the UK is currently transitioning from the Basic Payment Scheme (BPS) to, for instance, the new Sustainable Farming Incentive (SFI) in England (DEFRA, 2023) and Sustainable Farming Scheme (SFS) in Wales (Welsh Government, 2023). The new schemes will shift policy from land-based payments to payments for ecosystem services and public goods. Both schemes incentivise the uptake of certain GHG mitigation measures. The specific level of funding from the SFS is yet to be announced, however, the Welsh Government have stated that there will be various tiers of payment within the scheme (Welsh Government, 2023). To receive the baseline level of payment, farmers will be required to carry out all applicable "Universal Actions" outlined in the scheme – measures that are based on ensuring a minimum level of good practise from a business and environmental perspective. For farmers who want to build on these actions and receive further payments, Optional or Collaborative Actions that involve more bespoke and targeted measures can be implemented. For example, Universal Actions include soil health planning, actively managing peatland and establishing an animal health plan. One Universal Action in the SFS that has been particularly controversial is the need for participating farmers to have "at least 10% tree cover as woodland or individual trees" on their farm. Many farmers argue they simply do not have the additional land to spare as well as the National Farmers Union (NFU) Cymru citing various concerns including regulatory, environmental, economic and agronomic issues (NFU Cymru, 2024). The key issue surrounding this target is that every farm is different and will vary in its capacity to reach 10% tree cover threshold. Consequently, the scheme's requirement is considered to be unfair as some farms may already meet the 10% threshold, while smaller farms could find it more difficult, leading to a more pronounced impact on their production capacity. Farm sizes are typically small in Wales, meaning this issue will resonate with many. This emphasises an important point highlighted in Chapter 6, that policy must account for the heterogeneity in the farming sector (Dandy, 2012; Dessart *et al.*, 2019; Kipling *et al.*, 2019).

Carbon calculators will likely become increasingly important as policy shifts to payments for ecosystem services and public goods. Under the SFS, Welsh farmers will be required to complete a carbon audit within the first year of joining the scheme as one of the aforementioned Universal Actions. The

Farming Connect programme offers support for farmers to perform a carbon audit, with up to 80% funding for eligible businesses and full funding for groups of farmers working together. Similarly, in Scotland, under the Preparing for Sustainable Farming Incentive, farmers can claim a standard cost payment to have a carbon audit carried out on their farm if they have not already done one in the last three years. However, the tool in which is used in these carbon audits is often decided by the chosen consultant. The only requirement for the Scottish Government support is the tool conforms to PAS2050 supply chain standards. Moreover, there is rapidly increasing consumer (and therefore retailer) demand for lower carbon food. Morrisons have already committed to being the first supermarket to supply beef and lamb from Net Zero farms (Morrisons, 2021). Morrisons have committed to providing their farmers with free advice on sustainability, subsided carbon audits and soil testing as well as paying these farmers a payment premium of 10p/kg for their meat for “rearing one type of cattle under 18 months old to a sustainable diet” (Morrisons, 2022). With an increasing number of farmers calculating their carbon footprint, it is more important than ever for the sector to understand the differences between carbon calculators.

Many companies and organisations in the UK already use sustainability as a marketing tool. For example, in their recent publication – “The Welsh Way”, Hybu Cig Cymru (HCC) claim Welsh beef and lamb are “some of the most sustainable production systems globally” (HCC, 2020). Although the results of their carbon footprinting work implies this to be true, it is important to caveat that the studies these findings were compared to will have used different tools and methodologies, which could significantly affect the results. Given the range of values that are found in the carbon intensity of the same products from different farms, extrapolation from a small group of farms to represent national averages should also always be treated with caution. It is also important that the industry, and indeed all involved in such discussions avoid making bold environmental claims and using terms such as “sustainable” based purely on carbon footprints, as although some farms may have lower GHG emissions, it does not necessarily mean they are the best performing in other aspects of sustainability such as biodiversity or water quality. Although reducing net GHG emissions from agriculture is of critical importance, caution is needed to ensure that policy-makers, the industry, researchers, and environmental organisations take a more holistic view of all aspects of sustainability.

The findings of this research could aid farmers’ decision-making around the Net Zero target. A similar modelling framework could be applied on many farms to help inform farmers which measures could be implemented on their farm effectively and following emission reductions, the scale of afforestation that could be required to offset their remaining emissions. As previously mentioned in Chapter 4, this modelling framework could also help identify which farms should be prioritised for food production or afforestation in order to avoid production being displaced to less efficient systems and increasing emissions overall. This is particularly important with the global population expected to rise to over 9.7 billion by 2050 (United Nations, 2022), which will require a substantial increase in food production without increasing net GHG emissions. Although this thesis has used Wales as a case study, the same issues face farmers around the world. Many developing countries are trying to increase their agricultural production; however, they are already experiencing first-hand the effects of climate change through prolonged periods of drought, floods, and more extreme weather events. Mitigation measures may vary between countries, but ultimately all farms will need to reduce their GHG emissions. Many of the findings from this thesis apply to other livestock production systems globally as well as local level - from the opportunity for efficiency gains on farms, the need for increased carbon removals, the barriers that farmers face in implementing GHG mitigation measures, to the way in which emissions are expressed. Particularly in terms of the barriers to implementing GHG mitigation measures in the UK, the same barriers to adoption such as cost and personal interest have been cited around the world (Bustamante *et al.*, 2014; Smith *et al.*, 2007).

As more farmers change their management practices to reduce GHG emissions, Chapter 6 had demonstrated the importance of considering the nutritional quality of meat when expressing emissions. Although in this study, lamb finishing diets were compared using omega-3 PUFA as a functional unit, this work highlights that standard carbon footprints do not necessarily account for the effect of management practices on meat quality. Therefore, in the future, using a nutrient-based functional unit (such as a nutrient density score) could help inform the implementation of different management practices to both reduce GHG emissions and ensure the nutritional quality of meat is not compromised.

Finally, it is important to note that the results presented in this thesis are based on LCA and farm-level emissions calculations. In contrast, the UK and Devolved Governments set, and track policy targets (including Net Zero) based on National GHG Inventories. There are many potential differences between these two approaches, for example, the scope and boundaries of their calculations. National GHG Inventories account for emissions within a country's borders at a sectoral level, whereas LCA includes emissions for the entire life cycle of a product, which may include embedded emissions from inputs sourced from other countries. Another important difference between the approaches lies in the methods and data they utilise. LCA relies on detailed farm-level data for modelling, while National GHG Inventories use more standardised national data and follow international IPCC guidelines, which may not capture specific local or product variations. Understanding these potential conflicts is crucial for aligning farm-level GHG emissions calculations with national and international policy targets such as Net Zero.

7.5. References

Abbott, D.W., Aasen, I.M., Beauchemin, K.A., Grondahl, F., Gruninger, R., Hayes, M., Huws, S., Kenny, D.A., Krizsan, S.J., Kirwan, S.F., Lind, V., Meyer, U., Ramin, M., Theodoridou, K., von Soosten, D., Walsh, P.J., Waters, S., Xing, X., 2020. Seaweed and Seaweed Bioactives for Mitigation of Enteric Methane: Challenges and Opportunities. Animals 10, 2432. https://doi.org/10.3390/ani10122432

Abdalla, M., Hastings, A., Chadwick, D.R., Jones, D.L., Evans, C.D., Jones, M.B., Rees, R.M., Smith, P., 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agric. Ecosyst. Environ. 253, 62–81. https://doi.org/10.1016/j.agee.2017.10.023

Aboagye, I.A., Beauchemin, K.A., 2019. Potential of Molecular Weight and Structure of Tannins to Reduce Methane Emissions from Ruminants: A Review. Animals 9, 856. https://doi.org/10.3390/ani9110856

ADAS UK Ltd, 2014. Study to Model the Impact of Controlling Endemic Cattle Diseases and Conditions on National Cattle Productivity, Agricultural Performance and Greenhouse Gas Emissions.

Ahvanooei, M.R.R., Norouzian, M.A., Piray, A.H., Vahmani, P., Ghaffari, M.H., 2023. Effects of monensin supplementation on rumen fermentation, methane emissions, nitrogen balance, and metabolic responses of dairy cows: a systematic review and dose–response meta-analysis. J. Dairy Sci. https://doi.org/10.3168/jds.2023-23441

Alhamada, M., Debus, N., Lurette, A., Bocquier, F., 2017. Automatic oestrus detection system enables monitoring of sexual behaviour in sheep. Small Rumin. Res. 149, 105–111. https://doi.org/10.1016/j.smallrumres.2017.02.003

Allen, M.R., Shine, K.P., Fuglestvedt, J.S., Millar, R.J., Cain, M., Frame, D.J., Macey, A.H., 2018. A solution to the misrepresentations of CO 2 -equivalent emissions of short-lived climate pollutants under ambitious mitigation. Npj Clim. Atmospheric Sci. 1, 1–8. https://doi.org/10.1038/s41612-018-0026-8

Amaeth Cymru, 2017. The future of agriculture in Wales: the way forward [WWW Document]. URL https://www.gov.wales/sites/default/files/publications/2018-02/amaeth-cymru-the-future-of-agriculture-in-wales.pdf (accessed 1.11.24).

Arcidiacono, C., Porto, S.M.C., Mancino, M., Cascone, G., 2018. A software tool for the automatic and real-time analysis of cow velocity data in free-stall barns: The case study of oestrus detection from Ultra-Wide-Band data. Biosyst. Eng., Advances in the Engineering of Sensor-based Monitoring and Management Systems for Precision Livestock Farming 173, 157–165. https://doi.org/10.1016/j.biosystemseng.2017.10.007

Armstrong, E., 2016. The Farming Sector in Wales. Research Briefing, National Assembly. https://research.senedd.wales/media/aixbb5t4/16-053-web-english2.pdf

Australian Government, 2023. Australia's path to Net Zero (GOV.AU). Department of Climate Change, Energy, the Environment and Water. Australian Government.

Bailey, D.W., Mosley, J.C., Estell, R.E., Cibils, A.F., Horney, M., Hendrickson, J.R., Walker, J.W., Launchbaugh, K.L., Burritt, E.A., 2019. Synthesis Paper: Targeted Livestock Grazing: Prescription for Healthy Rangelands. Rangel. Ecol. Manag. 72, 865–877. https://doi.org/10.1016/j.rama.2019.06.003

Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., Wal, T.V. der, Soto, I., Gómez-Barbero, M., Barnes, A., Eory, V., 2017. Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics. Sustainability 9, 1339. https://doi.org/10.3390/su9081339

Balmford, A., 2021. Concentrating vs. spreading our footprint: how to meet humanity's needs at least cost to nature. J. Zool. 315, 79–109. https://doi.org/10.1111/jzo.12920

Bartley, D.J., Skuce, P.J., Zadoks, R.N., MacLeod, M., 2016. Endemic sheep and cattle diseases and greenhouse gas emissions. Adv. Anim. Biosci. 7, 253–255. https://doi.org/10.1017/S2040470016000327

Barzan, F.R., Bellis, L.M., Dardanelli, S., 2021. Livestock grazing constrains bird abundance and species richness: A global meta-analysis. Basic Appl. Ecol. 56, 289–298. https://doi.org/10.1016/j.baae.2021.08.007

Bateman, I., Balmford, A., 2023. Current conservation policies risk accelerating biodiversity loss. Nature 618, 671–674. https://doi.org/10.1038/d41586-023-01979-x

Beauchemin, K.A., Ungerfeld, E.M., Eckard, R.J., Wang, M., 2020. Review: Fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation. animal 14, s2–s16. https://doi.org/10.1017/S1751731119003100

BEIS, 2021. 2021 UK Greenhouse Gas Emissions, Final Figures. Department for Buisness, Energy & Industrial Strategy, National Statistics. Department for Business, Energy & Industrial Strategy.

BEIS, 2022. Final UK greenhouse gas emissions national statistics: 1990 to 2020. Department for Business, Energy & Industrial Strategy. https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2020

Bell, M.J., Wall, E., Simm, G., Russell, G., 2011. Effects of genetic line and feeding system on methane emissions from dairy systems. Anim. Feed Sci. Technol. 166, 699–707. https://doi.org/10.1016/j.anifeedsci.2011.04.049

Benchaar, C., Hassanat, F., Yang, W.Z., 2024. Effects of active dried yeast (Saccharomyces cerevisiae), a non-ionic surfactant, or their combination on gas production, rumen microbial fermentation and methane production in vitro. Anim. Feed Sci. Technol. 307, 115844. https://doi.org/10.1016/j.anifeedsci.2023.115844

Bengtsson, J., Bullock, J.M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P.J., Smith, H.G., Lindborg, R., 2019. Grasslands—more important for ecosystem services than you might think. Ecosphere 10, e02582. https://doi.org/10.1002/ecs2.2582

Berg, W., Brunsch, R., Pazsiczki, I., 2006. Greenhouse gas emissions from covered slurry compared with uncovered during storage. Agric. Ecosyst. Environ., Mitigation of Greenhouse Gas Emissions from Livestock Production 112, 129–134. https://doi.org/10.1016/j.agee.2005.08.031

Bernués, A., Rodríguez-Ortega, T., Olaizola, A., Ripoll-Bosch, R., 2017. Evaluating ecosystem services and disservices of livestock agroecosystems for targeted policy design and management.

Bhatta, R., Enishi, O., 2007. Measurement of Methane Production from Ruminants. Asian-Australas. J. Anim. Sci. 20, 1305–1318. https://doi.org/2007.20.8.1305

Blanco, J., Dendoncker, N., Barnaud, C., Sirami, C., 2019. Ecosystem disservices matter: Towards their systematic integration within ecosystem service research and policy. Ecosyst. Serv. 36, 100913. https://doi.org/10.1016/j.ecoser.2019.100913

Borrell, B., Hubbard, L., 2000. Global economic effects of the EU Common Agricultural Policy. Econ. Aff. 20, 18–26. https://doi.org/10.1111/1468-0270.00218

Brack, D., King, R., 2021. Managing Land-based CDR: BECCS, Forests and Carbon Sequestration. Glob. Policy 12, 45–56. https://doi.org/10.1111/1758-5899.12827

Bracken, C.J., Lanigan, G.J., Richards, K.G., Müller, C., Tracy, S.R., Murphy, P.N.C., 2022. Seasonal effects reveal potential mitigation strategies to reduce N2O emission and N leaching from grassland swards of differing composition (grass monoculture, grass/clover and multispecies). Agric. Ecosyst. Environ. 340, 108187. https://doi.org/10.1016/j.agee.2022.108187

Breidenich, C., Magraw, D., Rowley, A., Rubin, J.W., 1998. The Kyoto protocol to the United Nations framework convention on climate change. Am. J. Int. Law 92, 315–331.

Broucek, J., 2018. Nitrous oxide production in ruminants: A review. Anim. Sci. Pap. Rep. 36, 5–19.

Brown, P., Cardenas, L.M., Choudrie, S., Jones, L., Karagianni, E., MacCarthy, J., Passant, N., Richmond, B., Smith, H., Thistlewaite, G., Thomson, A., Turtle, L., Wakeling, D., Bradley, S., Broomfield, M., Buys, G., Cliverd, H., Gibbs, M., Gilhespy, S., Glendining, M., Gluckman, R., Henshall, P., Hobson, M., Lambert, N., Malcolm, H., Manning, A., Matthews, R., May, K., Milne, A., Misra, A., Misselbrook, T., 2019. UK Greenhouse Gas Inventory, 1990 to 2018: Annual Report for Submission under the Framework Convention on Climate Change. Department for Business, Energy & Industrial Strategy.

Browne, N.A., Eckard, R.J., Behrendt, R., Kingwell, R.S., 2011. A comparative analysis of on-farm greenhouse gas emissions from agricultural enterprises in south eastern Australia. Anim. Feed Sci. Technol., Special Issue: Greenhouse Gases in Animal Agriculture - Finding a Balance between Food and Emissions 166–167, 641–652. https://doi.org/10.1016/j.anifeedsci.2011.04.045

Burgess, P.J., 2017. Agroforestry in the UK. Q. J. For. 111.

Bustamante, M., Robledo-Abad, C., Harper, R., Mbow, C., Ravindranat, N.H., Sperling, F., Haberl, H., de Siqueira Pinto, A., Smith, P., 2014. Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. Global Change Biology 20, 3270–3290. https://doi.org/10.1111/gcb.12591

Cain, M., Lynch, J., Allen, M.R., Fuglestvedt, J.S., Frame, D.J., Macey, A.H., 2019. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. Npj Clim. Atmospheric Sci. 2, 1–7. https://doi.org/10.1038/s41612-019-0086-4

Cameron, L., Chagunda, M.G.G., Roberts, D.J., Lee, M.A., 2018. A comparison of milk yields and methane production from three contrasting high-yielding dairy cattle feeding regimes: Cut-and-carry, partial grazing and total mixed ration. Grass Forage Sci. 73, 789–797. https://doi.org/10.1111/gfs.12353

Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S.I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A., Shindell, D., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecol. Soc. 22. https://doi.org/10.2307/26798991

Cardenas, L.M., Thorman, R., Ashlee, N., Butler, M., Chadwick, D., Chambers, B., Cuttle, S., Donovan, N., Kingston, H., Lane, S., Dhanoa, M.S., Scholefield, D., 2010. Quantifying annual N2O emission fluxes from grazed grassland under a range of inorganic fertiliser nitrogen inputs. Agriculture, Ecosystems & Environment, Estimation of nitrous oxide emission from ecosystems and its mitigation technologies 136, 218–226. https://doi.org/10.1016/j.agee.2009.12.006

Castanheira, É.G., Freire, F., 2013. Greenhouse gas assessment of soybean production: implications of land use change and different cultivation systems. Journal of Cleaner Production 54, 49–60. https://doi.org/10.1016/j.jclepro.2013.05.026

Chadwick, D.R., Cardenas, L.M., Dhanoa, M.S., Donovan, N., Misselbrook, T., Williams, J.R., Thorman, R.E., McGeough, K.L., Watson, C.J., Bell, M., Anthony, S.G., Rees, R.M., 2018b. The contribution of cattle urine and dung to nitrous oxide emissions: Quantification of country specific emission factors and implications for national inventories. Sci. Total Environ. 635, 607–617. https://doi.org/10.1016/j.scitotenv.2018.04.152

CIEL, 2020. Net Zero Carbon UK Livestock: How Farmers Can Reduce Emissions. https://www.cielivestock.co.uk/wp-content/uploads/2022/02/CIEL-LR-220405.pdf

Climate Change Committee, 2019. Net Zero - The UK's contribution to stopping global warming. https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

Climate Change Committee, 2020a. The Sixth Carbon Budget The UKs path to Net Zero. https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf

Climate Change Committee, 2020b. Advice Report: The path to a Net Zero Wales. https://www.theccc.org.uk/wp-content/uploads/2020/12/Advice-Report-The-path-to-a-Net-Zero-Wales.pdf

Climate Change Committee, 2020c. Land use: Policies for a Net Zero UK. https://www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/

Colby, L., 2015. World Sheep Meat Market To 2025. AHDB Beef & Lamb and the International Meat Secretariat. https://www.scribd.com/document/420137768/World-sheep-meat-market-to-2025-pdf

Conant, R.T., Cerri, C.E.P., Osborne, B.B., Paustian, K., 2017. Grassland management impacts on soil carbon stocks: a new synthesis. Ecol. Appl. 27, 662–668. https://doi.org/10.1002/eap.1473

Crutzen, P.J., 2006. The "Anthropocene," in: Ehlers, E., Krafft, T. (Eds.), Earth System Science in the Anthropocene. Springer, Berlin, Heidelberg, pp. 13–18. https://doi.org/10.1007/3-540-26590-2_3

Cummins, S., Finn, J.A., Richards, K.G., Lanigan, G.J., Grange, G., Brophy, C., Cardenas, L.M., Misselbrook, T.H., Reynolds, C.K., Krol, D.J., 2021. Beneficial effects of multi-species mixtures on N2O emissions from intensively managed grassland swards. Sci. Total Environ. 792, 148163. https://doi.org/10.1016/j.scitotenv.2021.148163

Cutress, D., Williams, C., 2021. Can clover cut carbon - Legumes and nitrogen use on farms. Farming Connect.

Dandy, N., 2012. Understanding Private Land-manager Decision-making. Forest Research. https://cdn.forestresearch.gov.uk/2022/02/understanding_land-manager_decision-making_dandy2012.pdf

Darabighane, B., Salem, A.Z.M., Mirzaei Aghjehgheshlagh, F., Mahdavi, A., Zarei, A., Elghandour, M.M.M.Y., López, S., 2019. Environmental efficiency of Saccharomyces cerevisiae on methane production in dairy and beef cattle via a meta-analysis. Environ. Sci. Pollut. Res. 26, 3651–3658. https://doi.org/10.1007/s11356-018-3878-x

Dawson, J.J.C., Smith, P., 2007. Carbon losses from soil and its consequences for land-use management. Sci. Total Environ. 382, 165–190. https://doi.org/10.1016/j.scitotenv.2007.03.023

de Haas, Y., Windig, J.J., Calus, M.P.L., Dijkstra, J., de Haan, M., Bannink, A., Veerkamp, R.F., 2011. Genetic parameters for predicted methane production and potential for reducing enteric emissions through genomic selection. J. Dairy Sci. 94, 6122–6134. https://doi.org/10.3168/jds.2011-4439

DEFRA, 2019. Clean Air Strategy 2019. GOV.UK. 109. https://www.gov.uk/government/publications/clean-air-strategy-2019

DEFRA, 2021. Agriculture in the United Kingdom 2020. Department for Environment, Food and Rural Affairs Department of Agriculture, Environment and Rural Affairs (Northern Ireland) Welsh Government, Knowledge and Analytical Services The Scottish Government, Rural and Environment Science and Analytical Services.

DEFRA, 2022. Agri-climate report. Department for Environment, Food and Rural Affairs. https://www.gov.uk/government/statistics/agri-climate-report-2022/agri-climate-report-2022

DEFRA, 2023a. Sustainable Farming Incentive guidance. GOV.UK. https://www.gov.uk/government/collections/sustainable-farming-incentive-guidance

DEFRA, 2023b. Total income from farming in the UK in 2022. GOV.UK. https://www.gov.uk/government/statistics/total-income-from-farming-in-the-uk/total-income-from-farming-in-the-uk-in-2022

DEFRA, 2023c. Latest cattle, sheep and pig slaughter statistics. GOV.UK. https://www.gov.uk/government/statistics/cattle-sheep-and-pig-slaughter

DEFRA, 2023d. Emissions of air pollutants in the UK – Ammonia (NH3). GOV.UK. URL https://www.gov.uk/government/statistics/emissions-of-air-pollutants/emissions-of-air-pollutants-in-the-uk-ammonia-nh3

Dessart, F.J., Barreiro-Hurlé, J., van Bavel, R., 2019. Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. European Review of Agricultural Economics 46, 417–471. https://doi.org/10.1093/erae/jbz019

Detheridge, A., Scullion, J., Griffith, G., Gwynn-Jones, D., 2014. Soil organic carbon in Wales. What is it and why is it important? Welsh Government. https://www.flexis.wales/grc-engineering/wp-content/uploads/sites/4/2019/03/Soil_Organic_Carbon_in_Wales.pdf

Dominguez Aldama, D., Grassauer, F., Zhu, Y., Ardestani-Jaafari, A., Pelletier, N., 2023. Allocation methods in life cycle assessments (LCAs) of agri-food co-products and food waste valorization systems: Systematic review and recommendations. J. Clean. Prod. 421, 138488. https://doi.org/10.1016/j.jclepro.2023.138488

Dominiak, K., Kristensen, A.R., 2017. Prioritizing alarms from sensor-based detection models in livestock production - A review on model performance and alarm reducing methods. Comput. Electron. Agric. 133, 46–67. https://doi.org/10.1016/j.compag.2016.12.008

Duffy, C., Prudhomme, R., Duffy, B., Gibbons, J., Iannetta, P.P.M., O'Donoghue, C., Ryan, M., Styles, D., 2022. Randomized national land management strategies for net-zero emissions. Nat Sustain 1–8. https://doi.org/10.1038/s41893-022-00946-0

Duin, E.C., Wagner, T., Shima, S., Prakash, D., Cronin, B., Yáñez-Ruiz, D.R., Duval, S., Rümbeli, R., Stemmler, R.T., Thauer, R.K., Kindermann, M., 2016. Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol. Proc. Natl. Acad. Sci. U. S. A. 113, 6172–6177. https://doi.org/10.1073/pnas.1600298113

Durand, P., Breuer, L., Johnes, P.J., Billen, G., Butturini, A., Pinay, G., van Grinsven, H., Garnier, J., Rivett, M., Reay, D.S., Curtis, C., Siemens, J., Maberly, S., Kaste, O., Humborg, C., Loeb, R., de Klein, J., Hejzlar, J., Skoulikidis, N., Kortelainen, P., Lepisto, A., Wright, R., 2011. Nitrogen processes in aquatic ecosystems, in: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., Grizzetti, B. (Eds.), . Cambridge University Press, Cambridge, pp. 126–146.

Edwards-Jones, G., Plassmann, K., Harris, I.M., 2009. Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK. J. Agric. Sci. 147, 707–719. https://doi.org/10.1017/S0021859609990165

Eory, V., Topp, C.F.E., Moran, D., 2013. Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environmental Science & Policy 27, 55–67. https://doi.org/10.1016/j.envsci.2012.11.003

Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, McVittie, Wall, Borthwick, Watson, Waterhouse, Wiltshire, 2015. Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget period and to 2050. (Final report submitted for the project contract "Provision of services to review and update the UK agriculture MACC and to assess abatement potential for the 5 th carbon budget period and to 2050"). SRUC.

Eory, V., Topp, K., Rees, B., Leinonen, I., Maire, J., 2020. Marginal abatement cost curve for Scottish agriculture. https://doi.org/10.7488/ERA/755

FAO, 2013. Mitigation of greenhouse gas emissions in livestock production: a review of technical options for non-CO2 emissions, FAO animal production and health paper. Food and Agriculture Organization of the United Nations, Rome.

FAO, 2018. The future of food and agriculture: alternative pathways to 2050. Food and Agriculture Organization of the United Nations Rome. https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1175393/

Forster, E.J., Healey, J.R., Dymond, C., Styles, D., 2021. Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. Nat. Commun. 12, 3831. https://doi.org/10.1038/s41467-021-24084-x

Fouts, J.Q., Honan, M.C., Roque, B.M., Tricarico, J.M., Kebreab, E., 2022. Enteric methane mitigation interventions. Transl. Anim. Sci. 6, txac041. https://doi.org/10.1093/tas/txac041

Fraser, D., Duncan, I.J.H., Edwards, S.A., Grandin, T., Gregory, N.G., Guyonnet, V., Hemsworth, P.H., Huertas, S.M., Huzzey, J.M., Mellor, D.J., Mench, J.A., Špinka, M., Whay, H.R., 2013. General Principles for the welfare of animals in production systems: The underlying science and its application. Vet. J. 198, 19–27. https://doi.org/10.1016/j.tvjl.2013.06.028

Gardiner, C., Clough, T., Cameron, K., Di, H., Edwards, G., de Klein, C., 2016. Potential for forage diet manipulation in New Zealand pasture ecosystems to mitigate ruminant urine derived N2O emissions: a review. N. Z. J. Agric. Res. 59, 301–317. https://doi.org/10.1080/00288233.2016.1190386

Gerber, P.J., Hristov, A.N., Henderson, B., Makkar, H., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A.T., Yang, W.Z., Tricarico, J.M., Kebreab, E., Waghorn, G., Dijkstra, J., Oosting, S., 2013. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. Anim. Int. J. Anim. Biosci. 7 Suppl 2, 220–234. https://doi.org/10.1017/S1751731113000876

Gerten, D., Rockström, J., Heinke, J., Steffen, W., Richardson, K., Cornell, S., 2015. Response to Comment on "Planetary boundaries: Guiding human development on a changing planet." Science 348, 1217–1217. https://doi.org/10.1126/science.aab0031

Giampietro, M., Mayumi, K., 2018. Unraveling the Complexity of the Jevons Paradox: The Link Between Innovation, Efficiency, and Sustainability. Front. Energy Res. 6.

Glasson, C.R.K., Kinley, R.D., de Nys, R., King, N., Adams, S.L., Packer, M.A., Svenson, J., Eason, C.T., Magnusson, M., 2022. Benefits and risks of including the bromoform containing seaweed Asparagopsis in feed for the reduction of methane production from ruminants. Algal Res. 64, 102673. https://doi.org/10.1016/j.algal.2022.102673

Goel, G., Makkar, H.P.S., 2012. Methane mitigation from ruminants using tannins and saponins. Trop. Anim. Health Prod. 44, 729–739. https://doi.org/10.1007/s11250-011-9966-2

González, L.A., Kyriazakis, I., Tedeschi, L.O., 2018. Review: Precision nutrition of ruminants: approaches, challenges and potential gains. animal 12, s246–s261. https://doi.org/10.1017/S1751731118002288

Government of China, 2021. China's Mid-Century Long-Term Low Greenhouse Gas Emission Development Strategy. Government of China, Beijing, China.

Gren, I.-M., Aklilu, A.Z., 2016. Policy design for forest carbon sequestration: A review of the literature. For. Policy Econ. 70, 128–136. https://doi.org/10.1016/j.forpol.2016.06.008

Grêt-Regamey, A., Sirén, E., Brunner, S.H., Weibel, B., 2017. Review of decision support tools to operationalize the ecosystem services concept. Ecosyst. Serv., Putting ES into practice 26, 306–315. https://doi.org/10.1016/j.ecoser.2016.10.012

Groenestein, C.M., Smits, M.C.J., Huijsmans, J.F.M., Oenema, O., 2011. Measures to reduce ammonia emissions from livestock manures: now, soon and later (No. 488). Wageningen UR Livestock Research, Lelystad.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life Cycle Assessment: Past, Present, and Future. Environ. Sci. Technol. 45, 90–96. https://doi.org/10.1021/es101316v

Guthrie, S., Dunkerley, F., Tabaqchali, H., Harshfield, A., Ioppolo, B., Manville, C., 2018. Impact of ammonia emissions from agriculture on biodiversity: An evidence synthesis. https://doi.org/10.7249/RR2695

Hallam, A., Bowden, A., Kasprzyk, K., 2012. Agriculture and climate change: evidence on influencing farmer behaviours. Scottish Government, Social Research.

Hardaker, A., 2018. Is forestry really more profitable than upland farming? A historic and present day farm level economic comparison of upland sheep farming and forestry in the UK. Land Use Policy 71, 98–120. https://doi.org/10.1016/j.landusepol.2017.11.032

Hardaker, A., Styles, D., Williams, P., Chadwick, D., Dandy, N., 2022. A framework for integrating ecosystem services as endpoint impacts in life cycle assessment. Journal of Cleaner Production 370, 133450. https://doi.org/10.1016/j.jclepro.2022.133450

HCC, 2020. The Welsh Way: Towards Global Leadership in Sustainable Lamb and Beef Production. Hybu Cig Cymru - Meat Promotions Wales. https://meatpromotion.wales/images/resources/Welsh_Way_Final_Eng.pdf

HCC, 2022. Little Book of Meat Facts: Compendium of Welsh Red Meat and Livestock Industry Statistics 2022. Hybu Cig Cymru - Meat Promotions Wales.

Hegarty, R.S., McEwan, J.C., 2010. Genetic opportunities to reduce enteric methane emissions from ruminant livestock, in: Proceedings of the 9th World Congress on Genetics Applied to Livestock Production, Leipzig, Germany. pp. 1–6.

Hietala, S., Heusala, H., Katajajuuri, J.-M., Järvenranta, K., Virkajärvi, P., Huuskonen, A., Nousiainen, J., 2021. Environmental life cycle assessment of Finnish beef – cradle-to-farm gate analysis of dairy and beef breed beef production. Agric. Syst. 194, 103250. https://doi.org/10.1016/j.agsy.2021.103250

Hill, B., Bradley, D., 2019. Will Brexit Impact on the Social Contributions Made by Agriculture? EuroChoices 18, 17–22. https://doi.org/10.1111/1746-692X.12235

Honan, M., Feng, X., Tricarico, J.M., Kebreab, E., 2021. Feed additives as a strategic approach to reduce enteric methane production in cattle: modes of action, effectiveness and safety. Anim. Prod. Sci. 62, 1303–1317. https://doi.org/10.1071/AN20295

Houlbrooke, D.J., Laurenson, S., 2013. Effect of sheep and cattle treading damage on soil microporosity and soil water holding capacity. Agric. Water Manag. 121, 81–84. https://doi.org/10.1016/j.agwat.2013.01.010

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B., Tricarico, J.M., 2013. SPECIAL TOPICS — Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options1. J. Anim. Sci. 91, 5045–5069. https://doi.org/10.2527/jas.2013-6583

Humer, E., Aschenbach, J.R., Neubauer, V., Kröger, I., Khiaosa-ard, R., Baumgartner, W., Zebeli, Q., 2018. Signals for identifying cows at risk of subacute ruminal acidosis in dairy veterinary practice. J. Anim. Physiol. Anim. Nutr. 102, 380–392. https://doi.org/10.1111/jpn.12850

Hyland, J.J., Styles, D., Jones, D.L., Williams, A.P., 2016. Improving livestock production efficiencies presents a major opportunity to reduce sectoral greenhouse gas emissions. Agric. Syst. 147, 123–131. https://doi.org/10.1016/j.agsy.2016.06.006

IDF, 2015. A common carbon footprint approach for the dairy sector: The IDF guide to standard life cycle assessment methodology. *International Dairy Federation.*

Igos, E., Benetto, E., Meyer, R., Baustert, P., Othoniel, B., 2019. How to treat uncertainties in life cycle assessment studies? Int. J. Life Cycle Assess. 24, 794–807. https://doi.org/10.1007/s11367-018-1477-1

International Organization for Standardization, 2006. Environmental management: life cycle assessment; requirements and guidelines. ISO Geneva, Switzerland.

IPCC, 2000. Land Use, Land-Use Change and Forestry. Cambridge University Press, UK.

IPCC, 2018. Annex I: Glossary, in: Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge University Press, Cambridge, pp. 541–562. https://doi.org/10.1017/9781009157940.008

IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

IPCC, 2021. Chapter 11: weather and climate extreme events in a changing climate. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC, 2021. Climate change 2021: The physical science basis. Contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change.

Jayanegara, A., Leiber, F., Kreuzer, M., 2012. Meta-analysis of the relationship between dietary tannin level and methane formation in ruminants from in vivo and in vitro experiments. J. Anim. Physiol. Anim. Nutr. 96, 365–375. https://doi.org/10.1111/j.1439-0396.2011.01172.x

Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., J.R. Alves, B., Morrison, M.J., 2012. Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. Agron. Sustain. Dev. 32, 329–364. https://doi.org/10.1007/s13593-011-0056-7

Jerrentrup, J.S., Komainda, M., Seither, M., Cuchillo-Hilario, M., Wrage-Mönnig, N., Isselstein, J., 2020. Diverse Swards and Mixed-Grazing of Cattle and Sheep for Improved Productivity. Front. Sustain. Food Syst. 3.

Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of lamb: Sources of variation and opportunities for mitigation. Agric. Syst. 123, 97–107. https://doi.org/10.1016/j.agsy.2013.09.006

Jones, A.K., Jones, D.L., Cross, P., 2015. Developing farm-specific marginal abatement cost curves: Cost-effective greenhouse gas mitigation opportunities in sheep farming systems. Land Use Policy 49, 394–403. https://doi.org/10.1016/j.landusepol.2015.08.006

Kavanagh, I., Burchill, W., Healy, M.G., Fenton, O., Krol, D.J., Lanigan, G.J., 2019. Mitigation of ammonia and greenhouse gas emissions from stored cattle slurry using acidifiers and chemical amendments. J. Clean. Prod. 237, 117822. https://doi.org/10.1016/j.jclepro.2019.117822

Kenyon, F., Dick, J.M., Smith, R.I., Coulter, D.G., McBean, D., Skuce, P.J., 2013. Reduction in Greenhouse Gas Emissions Associated with Worm Control in Lambs. Agriculture 3, 271–284. https://doi.org/10.3390/agriculture3020271

Khatoon, H., Solanki, P., Narayan, M., Tewari, L., Rai, J., 2017. Role of microbes in organic carbon decomposition and maintenance of soil ecosystem 5, 1648–1656.

King, M.T.M., LeBlanc, S.J., Pajor, E.A., Wright, T.C., DeVries, T.J., 2018. Behavior and productivity of cows milked in automated systems before diagnosis of health disorders in early lactation. J. Dairy Sci. 101, 4343–4356. https://doi.org/10.3168/jds.2017-13686

Kinley, R.D., Martinez-Fernandez, G., Matthews, M.K., de Nys, R., Magnusson, M., Tomkins, N.W., 2020. Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. J. Clean. Prod. 259, 120836. https://doi.org/10.1016/j.jclepro.2020.120836

Kipling, R.P., Taft, H.E., Chadwick, D.R., Styles, D., Moorby, J., 2019. Implementation solutions for greenhouse gas mitigation measures in livestock agriculture: A framework for coherent strategy. Environmental Science & Policy 101, 232–244. https://doi.org/10.1016/j.envsci.2019.08.015

Koenig, K.M., Beauchemin, K.A., 2013. Nitrogen metabolism and route of excretion in beef feedlot cattle fed barley-based backgrounding diets varying in protein concentration and rumen degradability1,2. J. Anim. Sci. 91, 2295–2309. https://doi.org/10.2527/jas.2012-5652

Króliczewska, B., Pecka-Kiełb, E., Bujok, J., 2023. Strategies Used to Reduce Methane Emissions from Ruminants: Controversies and Issues. Agriculture 13, 602. https://doi.org/10.3390/agriculture13030602

Kumari, S., Fagodiya, R.K., Hiloidhari, M., Dahiya, R.P., Kumar, A., 2020. Methane production and estimation from livestock husbandry: A mechanistic understanding and emerging mitigation options. Sci. Total Environ. 709, 136135. https://doi.org/10.1016/j.scitotenv.2019.136135

Laborde, J., Thompson, K., 2015. Scrub encroachment into species-rich limestone grassland: recruitment, herbivory and the threat from incipient scrub. Plant Ecology & Diversity 8, 101–112. https://doi.org/10.1080/17550874.2013.851295

Laborde, J., Thompson, K., 2015. Scrub encroachment into species-rich limestone grassland: recruitment, herbivory and the threat from incipient scrub. Plant Ecol. Divers. 8, 101–112. https://doi.org/10.1080/17550874.2013.851295

Lal, R., 2016. Soil health and carbon management. Food Energy Secur. 5, 212–222. https://doi.org/10.1002/fes3.96

Lam, S.K., Suter, H., Mosier, A.R., Chen, D., 2017. Using nitrification inhibitors to mitigate agricultural N2O emission: a double-edged sword? Global Change Biology 23, 485–489. https://doi.org/10.1111/gcb.13338

Lamb, A., Green, R., Bateman, I., Broadmeadow, M., Bruce, T., Burney, J., Carey, P., Chadwick, D., Crane, E., Field, R., Goulding, K., Griffiths, H., Hastings, A., Kasoar, T., Kindred, D., Phalan, B., Pickett, J., Smith, P., Wall, E., zu Ermgassen, E.K.H.J., Balmford, A., 2016. The potential for land sparing to offset greenhouse gas emissions from agriculture. Nat. Clim. Change 6, 488–492. https://doi.org/10.1038/nclimate2910

Langley, J., 2022. The Impact of Slurry Acidification on Soil and Crop Quality: A UK Case Study. Bangor University (United Kingdom).

Lanzoni, L., Waxenberg, K., Ramsey, R., Rees, R.M., Bell, J., Vignola, G., Atzori, A.S., 2023. The potential of improved animal welfare as an environmental impact mitigation strategy in dairy sheep farming. Anim. - Sci. Proc., Proceedings of the British Society of Animal Science (BSAS 2023) 14, 370. https://doi.org/10.1016/j.anscip.2023.01.492

Leake, J., Ostle, N., Rangel, I., Johnson, D., 2006. Carbon fluxes from plants through soil organisms determined by field 13CO2 pulse-labelling in an upland grassland. Applied Soil Ecology 33, 152–175. https://doi.org/10.1016/j.apsoil.2006.03.001

Lehmann, J., Hansel, C.M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Nunan, N., Reichstein, M., Schimel, J.P., Torn, M.S., Wieder, W.R., Kögel-Knabner, I., 2020. Persistence of soil organic carbon caused by functional complexity. Nat. Geosci. 13, 529–534. https://doi.org/10.1038/s41561-020-0612-3

Llonch, P., Haskell, M.J., Dewhurst, R.J., Turner, S.P., 2017. Current available strategies to mitigate greenhouse gas emissions in livestock systems: an animal welfare perspective. animal 11, 274–284. https://doi.org/10.1017/S1751731116001440

Loide, V., Saue, T., Võsa, T., Tamm, K., 2020. The effect of acidified slurry on crop uptake and leaching of nutrients from a loamy topsoil. Acta Agric. Scand. Sect. B — Soil Plant Sci. 70, 31–38. https://doi.org/10.1080/09064710.2019.1665705

Lynch, J., Cain, M., Pierrehumbert, R., Allen, M., 2020. Demonstrating GWP\ast: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. Environ. Res. Lett. 15, 044023. https://doi.org/10.1088/1748-9326/ab6d7e

Ma, Y., Hou, Y., Dong, P., Velthof, G.L., Long, W., Ma, L., Ma, W., Jiang, R., Oenema, O., 2022. Cooperation between specialized livestock and crop farms can reduce environmental footprints and increase net profits in livestock production. J. Environ. Manage. 302, 113960. https://doi.org/10.1016/j.jenvman.2021.113960

Machado, L., Magnusson, M., Paul, N.A., Kinley, R., de Nys, R., Tomkins, N., 2016. Identification of bioactives from the red seaweed Asparagopsis taxiformis that promote antimethanogenic activity in vitro. J. Appl. Phycol. 28, 3117–3126. https://doi.org/10.1007/s10811-016-0830-7

MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Matthews, R., Smith, P., Moxey, A., 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. Agric. Syst. 103, 198–209. https://doi.org/10.1016/j.agsy.2010.01.002

Marino, R., Atzori, A.S., D'Andrea, M., Iovane, G., Trabalza-Marinucci, M., Rinaldi, L., 2016. Climate change: Production performance, health issues, greenhouse gas emissions and mitigation strategies in sheep and goat farming. Small Rumin. Res., Special Issue: Advances in Sheep and Goats Research: A Holistic Approach. Selected papers from SIPAOC 2014 Meeting, Italy 135, 50–59. https://doi.org/10.1016/j.smallrumres.2015.12.012

Mazzetto, A.M., Feigl, B.J., Schils, R.L.M., Cerri, C.E.P., Cerri, C.C., 2015. Improved pasture and herd management to reduce greenhouse gas emissions from a Brazilian beef production system. Livest. Sci. 175, 101–112. https://doi.org/10.1016/j.livsci.2015.02.014

McAuliffe, G.A., Lynch, J., Cain, M., Buckingham, S., Rees, R.M., Collins, A.L., Allen, M., Pierrehumbert, R., Lee, M.R.F., Takahashi, T., 2023. Are single global warming potential impact assessments adequate for carbon footprints of agri-food systems? Environ. Res. Lett. 18, 084014. https://doi.org/10.1088/1748-9326/ace204

McAuliffe, G.A., Takahashi, T., Lee, M.R.F., 2020. Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. Int. J. Life Cycle Assess. 25, 208–221. https://doi.org/10.1007/s11367-019-01679-7

McAuliffe, G.A., Takahashi, T., Lee, M.R.F., Jebari, A., Cardenas, L., Kumar, A., Pereyra-Goday, F., Scalabrino, H., Collins, A.L., 2023. A commentary on key methodological developments related to nutritional life cycle assessment (nLCA) generated throughout a 6-year strategic scientific programme. Food and Energy Security 12, e480. https://doi.org/10.1002/fes3.480

McLaren, S., 2021. Integration of environment and nutrition in life cycle assessment of food items: opportunities and challenges. FAO, Rome, Italy. https://doi.org/10.4060/cb8054en

Milligan, G., Rose, R.J., Marrs, R.H., 2016. Winners and losers in a long-term study of vegetation change at Moor House NNR: effects of sheep-grazing and its removal on British upland vegetation. Ecol. Indic. 68, 89–101. https://doi.org/10.1016/j.ecolind.2015.10.053

Misselbrook, T., Hunt, J., Perazzolo, F., Provolo, G., 2016. Greenhouse Gas and Ammonia Emissions from Slurry Storage: Impacts of Temperature and Potential Mitigation through Covering (Pig Slurry) or Acidification (Cattle Slurry). J. Environ. Qual. 45, 1520–1530. https://doi.org/10.2134/jeq2015.12.0618

Misselbrook, T.H., Cardenas, L.M., Camp, V., Thorman, R.E., Williams, J.R., Rollett, A.J., Chambers, B.J., 2014. An assessment of nitrification inhibitors to reduce nitrous oxide emissions from UK agriculture. Environ. Res. Lett. 9, 115006. https://doi.org/10.1088/1748-9326/9/11/115006

Misselbrook, T.H., Gilhespy, S.L., Carswell, A.M., Cardenas, L.M., 2023. Inventory of Ammonia Emissions from UK Agriculture 2021.

Moloney, T., Sheridan, H., Grant, J., O'Riordan, E.G., O'Kiely, P., 2021. Yield of binary- and multi-species swards relative to single-species swards in intensive silage systems. Ir. J. Agric. Food Res. 59. https://doi.org/10.2478/ijafr-2020-0002

Moran, D., Macleod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, R., Topp, C.F.E., Moxey, A., 2011. Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions. J. Agric. Econ. 62, 93–118. https://doi.org/10.1111/j.1477-9552.2010.00268.x

Morrisons, 2021. Morrisons commits to Net Zero Carbon Emissions from its own operations by 2035 [WWW Document]. Morrisons. URL https://www.morrisons-corporate.com/media-centre/corporate-news/morrisons-commits-to-net-zero-carbon-emissions-from-its-own-operations-by-2035/ (accessed 1.13.24).

Morrisons, 2022. The Morrisons Sustainable Beef and Lamb Scheme [WWW Document]. Morrisons. URL https://my.morrisons.com/blog/community/sustainable-beef-and-lamb-scheme/ (accessed 1.13.24).

Nagpal, R., Shrivastava, B., Kumar, N., Dhewa, T., Sahay, H., 2015. Microbial Feed Additives, in: Puniya, A.K., Singh, R., Kamra, D.N. (Eds.), Rumen Microbiology: From Evolution to Revolution. Springer India, New Delhi, pp. 161–175. https://doi.org/10.1007/978-81-322-2401-3_12

Nair, P.K.R., Kumar, B.M., Nair, V.D., 2021. Definition and Concepts of Agroforestry, in: Nair, P.K.R., Kumar, B.M., Nair, V.D. (Eds.), An Introduction to Agroforestry: Four Decades of Scientific Developments. Springer International Publishing, Cham, pp. 21–28. https://doi.org/10.1007/978-3-030-75358-0_2

Natural England, 2012. The importance of livestock grazing for wildlife conservation - IN170 [WWW Document]. Natural England - Access to Evidence. URL https://publications.naturalengland.org.uk/publication/68026 (accessed 1.11.24).

New Zealand Government, 2019. Climate Change Response (Zero Carbon) Amendment Bill: Summary. New Zealand Government, Wellington: Ministry for the Environment.

Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., De Palma, A., Ferrier, S., Hill, S.L.L., Hoskins, A.J., Lysenko, I., Phillips, H.R.P., Burton, V.J., Chng, C.W.T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B.I., Whitmee, S., Zhang, H., Scharlemann, J.P.W., Purvis, A., 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353, 288–291. https://doi.org/10.1126/science.aaf2201

NFU Cymru, 2024. NFU Cymru officeholder team question farmers' participation in new support scheme based on current proposals [WWW Document]. URL https://www.nfu-cymru.org.uk/news-and-information/nfu-cymru-officeholder-team-question-farmers-participation-in-new-support-scheme-based-on-current-proposals/ (accessed 1.23.24).

Nguyen, T.L.T., Hermansen, J.E., Mogensen, L., 2010. Environmental consequences of different beef production systems in the EU. J. Clean. Prod. 18, 756–766. https://doi.org/10.1016/j.jclepro.2009.12.023

Nugent, D.T., Baker-Gabb, D.J., Leonard, S.W.J., Morgan, J.W., 2022. Livestock grazing to maintain habitat of a critically endangered grassland bird: Is grazer species important? Ecol. Appl. 32, e2587. https://doi.org/10.1002/eap.2587

Ostle, N.J., Levy, P.E., Evans, C.D., Smith, P., 2009. UK land use and soil carbon sequestration. Land Use Policy, Land Use Futures 26, S274–S283. https://doi.org/10.1016/j.landusepol.2009.08.006

Palangi, V., Taghizadeh, A., Abachi, S., Lackner, M., 2022. Strategies to Mitigate Enteric Methane Emissions in Ruminants: A Review. Sustainability 14, 13229. https://doi.org/10.3390/su142013229

Patra, A.K., 2013. The effect of dietary fats on methane emissions, and its other effects on digestibility, rumen fermentation and lactation performance in cattle: A meta-analysis. Livest. Sci. 155, 244–254. https://doi.org/10.1016/j.livsci.2013.05.023

Pe'er, G., Bonn, A., Bruelheide, H., Dieker, P., Eisenhauer, N., Feindt, P.H., Hagedorn, G., Hansjürgens, B., Herzon, I., Lomba, Â., Marquard, E., Moreira, F., Nitsch, H., Oppermann, R., Perino, A., Röder, N., Schleyer, C., Schindler, S., Wolf, C., Zinngrebe, Y., Lakner, S., 2020. Action needed for the EU Common Agricultural Policy to address sustainability challenges. People Nat. 2, 305–316. https://doi.org/10.1002/pan3.10080

Pe'er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., Bontzorlos, V., Clough, D., Bezák, P., Bonn, A., Hansjürgens, B., Lomba, A., Möckel, S., Passoni, G., Schleyer, C., Schmidt, J., Lakner, S., 2019. A greener path for the EU Common Agricultural Policy. Science 365, 449–451. https://doi.org/10.1126/science.aax3146

Pericherla, S., Karnena, M.K., Vara, S., 2020. A review on impacts of agricultural runoff on freshwater resources. Int J Emerg Technol 11, 829–833.

Petersen, S.O., Andersen, A.J., Eriksen, J., 2012. Effects of Cattle Slurry Acidification on Ammonia and Methane Evolution during Storage. J. Environ. Qual. 41, 88–94. https://doi.org/10.2134/jeq2011.0184

Petersen, S.O., Sommer, S.G., Béline, F., Burton, C., Dach, J., Dourmad, J.Y., Leip, A., Misselbrook, T., Nicholson, F., Poulsen, H.D., Provolo, G., Sørensen, P., Vinnerås, B., Weiske, A., Bernal, M.-P., Böhm, R., Juhász, C., Mihelic, R., 2007. Recycling of livestock manure in a whole-farm perspective. Livestock Science, Recycling of Livestock Manure in a Whole-Farm Perspective 112, 180–191. https://doi.org/10.1016/j.livsci.2007.09.001

Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. Science 333, 1289–1291. https://doi.org/10.1126/science.1208742

Pinares-Patiño, C.S., Hickey, S.M., Young, E.A., Dodds, K.G., MacLean, S., Molano, G., Sandoval, E., Kjestrup, H., Harland, R., Hunt, C., Pickering, N.K., McEwan, J.C., 2013. Heritability estimates of methane emissions from sheep. animal 7, 316–321. https://doi.org/10.1017/S1751731113000864

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992. https://doi.org/10.1126/science.aaq0216

Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D., 2018. Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. Glob. Change Biol. 24, 2563–2584. https://doi.org/10.1111/gcb.14066

Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T., Whitmore, A.P., 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. Agric. Ecosyst. Environ. 146, 23–33. https://doi.org/10.1016/j.agee.2011.10.004

Radočaj, D., Jurišić, M., Gašparović, M., 2022. The Role of Remote Sensing Data and Methods in a Modern Approach to Fertilization in Precision Agriculture. Remote Sens. 14, 778. https://doi.org/10.3390/rs14030778

Ramos-Morales, E., de la Fuente, G., Duval, S., Wehrli, C., Bouillon, M., Lahmann, M., Preskett, D., Braganca, R., Newbold, C.J., 2017. Antiprotozoal Effect of Saponins in the Rumen Can Be Enhanced by Chemical Modifications in Their Structure. Front. Microbiol. 8.

Reed, M.S., Moxey, A., Prager, K., Hanley, N., Skates, J., Bonn, A., Evans, C.D., Glenk, K., Thomson, K., 2014. Improving the link between payments and the provision of ecosystem services in agri-environment schemes. Ecosyst. Serv. 9, 44–53. https://doi.org/10.1016/j.ecoser.2014.06.008

Rees, R.M., Eory, V., Bell, J., Topp, C.F.E., Sykes, A., Misselbrook, T., Cardenas, L.M., Chadwick, D.R., Sohi, S., Manning, A.C., Smith, P., 2020. How far can greenhouse gas mitigation take us towards net zero emissions in agriculture? 8.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9, eadh2458. https://doi.org/10.1126/sciadv.adh2458

Ridoutt, B., Huang, J., 2019. When Climate Metrics and Climate Stabilization Goals Do Not Align. Environ. Sci. Technol. 53, 14093–14094. https://doi.org/10.1021/acs.est.9b06593

Ripoll-Bosch, R., de Boer, I.J.M., Bernués, A., Vellinga, T.V., 2013. Accounting for multi-functionality of sheep farming in the carbon footprint of lamb: A comparison of three contrasting Mediterranean systems. Agric. Syst. 116, 60–68. https://doi.org/10.1016/j.agsy.2012.11.002

Rockström, J., Steffen, W.L., Noone, K., Persson, Å., Iii, F.S.C., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecol. Soc. 35.

Roehe, R., Dewhurst, R.J., Duthie, C.-A., Rooke, J.A., McKain, N., Ross, D.W., Hyslop, J.J., Waterhouse, A., Freeman, T.C., Watson, M., Wallace, R.J., 2016. Bovine Host Genetic Variation Influences Rumen Microbial Methane Production with Best Selection Criterion for Low Methane Emitting and Efficiently Feed Converting Hosts Based on Metagenomic Gene Abundance. PLOS Genet. 12, e1005846. https://doi.org/10.1371/journal.pgen.1005846

Rogelj, J., Schleussner, C.-F., 2019. Unintentional unfairness when applying new greenhouse gas emissions metrics at country level. Environ. Res. Lett. 14, 114039. https://doi.org/10.1088/1748-9326/ab4928

Rooke, J.A., Miller, G.A., Flockhart, J.F., McDowell, M.M., MacLeod, M., 2016. Nutritional strategies to reduce enteric methane emissions.

Rotz, C.A., Soder, K.J., Skinner, R.H., Dell, C.J., Kleinman, P.J., Schmidt, J.P., Bryant, R.B., 2009. Grazing Can Reduce the Environmental Impact of Dairy Production Systems. Forage Grazinglands 7, 1–9. https://doi.org/10.1094/FG-2009-0916-01-RS

Rutledge, S., Mudge, P.L., Wallace, D.F., Campbell, D.I., Woodward, S.L., Wall, A.M., Schipper, L.A., 2014. CO2 emissions following cultivation of a temperate permanent pasture. Agric. Ecosyst. Environ. 184, 21–33. https://doi.org/10.1016/j.agee.2013.11.005

Ryan, M., O'Donoghue, C., 2016. Socio-economic drivers of farm afforestation decision-making. Ir. For. 73. 96-121.

Saarinen, M., Fogelholm, M., Tahvonen, R., Kurppa, S., 2017. Taking nutrition into account within the life cycle assessment of food products. J. Clean. Prod. 149, 828–844. https://doi.org/10.1016/j.jclepro.2017.02.062

Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., Benetto, E., 2021. Attributional & Consequential Life Cycle Assessment: Definitions, Conceptual Characteristics and Modelling Restrictions. Sustainability 13, 7386. https://doi.org/10.3390/su13137386

Schils, R.L.M., Olesen, J.E., del Prado, A., Soussana, J.F., 2007. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livest. Sci., Recycling of Livestock Manure in a Whole-Farm Perspective 112, 240–251. https://doi.org/10.1016/j.livsci.2007.09.005

Selbie, D.R., Buckthought, L.E., Shepherd, M.A., 2015. Chapter Four - The Challenge of the Urine Patch for Managing Nitrogen in Grazed Pasture Systems, in: Sparks, D.L. (Ed.), Advances in Agronomy. Academic Press, pp. 229–292. https://doi.org/10.1016/bs.agron.2014.09.004

Sharpe, N., Osborn, E., Samuel, J., Smith, R., 2001. Anglia Woodnet woodland assessment project: stage II. Summary report. Angl. Woodnet.

Shields, S., Orme-Evans, G., 2015. The Impacts of Climate Change Mitigation Strategies on Animal Welfare. Animals 5, 361–394. https://doi.org/10.3390/ani5020361

Silva, D.A.L., 2021. Life Cycle Assessment (LCA)—Definition of Goals and Scope, in: de Oliveira, J.A., Lopes Silva, D.A., Puglieri, F.N., Saavedra, Y.M.B. (Eds.), Life Cycle Engineering and Management of Products: Theory and Practice. Springer International Publishing, Cham, pp. 45–69. https://doi.org/10.1007/978-3-030-78044-9_3

Simon, P.L., de Klein, C.A.M., Worth, W., Rutherford, A.J., Dieckow, J., 2019. The efficacy of Plantago lanceolata for mitigating nitrous oxide emissions from cattle urine patches. Sci. Total Environ. 691, 430–441. https://doi.org/10.1016/j.scitotenv.2019.07.141

Skuce, P., Bartley, D., Zadoks, R., MacLeod, M., 2016. Livestock Health & Greenhouse Gas Emissions.

Smith, L.G., Westaway, S., Mullender, S., Ghaley, B.B., Xu, Y., Lehmann, L.M., Pisanelli, A., Russo, G., Borek, R., Wawer, R., Borzęcka, M., Sandor, M., Gliga, A., Smith, J., 2022. Assessing the multidimensional elements of sustainability in European agroforestry systems. Agricultural Systems 197, 103357. https://doi.org/10.1016/j.agsy.2021.103357

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., 2007. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture, Ecosystems & Environment 118, 6–28. https://doi.org/10.1016/j.agee.2006.06.006

Smith, P., Olesen, J.E., 2010. Synergies between the mitigation of, and adaptation to, climate change in agriculture. The Journal of Agricultural Science 148, 543–552. https://doi.org/10.1017/S0021859610000341

Smith, P., 2014. Do grasslands act as a perpetual sink for carbon? Glob. Change Biol. 20, 2708–2711. https://doi.org/10.1111/gcb.12561

Smith, P., House, J.I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., West, P., Clark, J., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M.F., Elliott, J.A., McDowell, R., Griffiths, R.I., Asakawa, S., Bondeau, A., Jain, A.K., Meersmans, J., Pugh, T.A.M., 2015. Global Change Pressures on Soils from Land Use and Management. Glob Change Biol. https://doi.org/10.1111/gcb.13068

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nat. Clim. Change 6, 42–50. https://doi.org/10.1038/nclimate2870

Smolders, A.J.P., Lucassen, E.C.H.E.T., Bobbink, R., Roelofs, J.G.M., Lamers, L.P.M., 2010. How nitrate leaching from agricultural lands provokes phosphate eutrophication in groundwater fed wetlands: the sulphur bridge. Biogeochemistry 98, 1–7. https://doi.org/10.1007/s10533-009-9387-8

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ., Reactive nitrogen in agroecosystems: Integration with greenhouse gas interactions 133, 247–266. https://doi.org/10.1016/j.agee.2009.04.021

Soussana, J.F., Allard, V., Pilegaard, K., Ambus, P., Amman, C., Campbell, C., Ceschia, E., Clifton-Brown, J., Czobel, S., Domingues, R., Flechard, C., Fuhrer, J., Hensen, A., Horvath, L., Jones, M., Kasper, G., Martin, C., Nagy, Z., Neftel, A., Raschi, A., Baronti, S., Rees, R.M., Skiba, U., Stefani, P., Manca, G., Sutton, M., Tuba, Z., Valentini, R., 2007. Full accounting of the greenhouse gas (CO2, N2O, CH4) budget of nine European grassland sites. Agric. Ecosyst. Environ., The Greenhouse Gas Balance of Grasslands in Europe 121, 121–134. https://doi.org/10.1016/j.agee.2006.12.022

Stark, C., Thompson, M., Andrew, T., Beasley, G., Bellamy, O., Budden, P., Cole, C., Darke, J., Davies, E., Feliciano, D., 2019. Net Zero: The UK's contribution to stopping global warming.

Stylianou, K.S., Heller, M.C., Fulgoni, V.L., Ernstoff, A.S., Keoleian, G.A., Jolliet, O., 2016. A life cycle assessment framework combining nutritional and environmental health impacts of diet: a case study on milk. Int. J. Life Cycle Assess. 21, 734–746. https://doi.org/10.1007/s11367-015-0961-0

Sykes, A., Topp, K., Wilson, R., Reid, G., Rees, B., 2017. A comparison of farm-level greenhouse gas calculators in their application on beef production systems. Journal of Cleaner Production 164. https://doi.org/10.1016/j.jclepro.2017.06.197

Taft, H., Chadwick, D., Styles, D., Kipling, R., Newbold, J., Moorby, J., 2018. A review of greenhouse gas calculators for use in the Welsh agricultural sector, A Climate Smart Agriculture (Wales) Report.

Teague, R., Kreuter, U., 2020. Managing Grazing to Restore Soil Health, Ecosystem Function, and Ecosystem Services. Front. Sustain. Food Syst. 4.

Thompson, L.R., Rowntree, J.E., 2020. Invited Review: Methane sources, quantification, and mitigation in grazing beef systems. Appl. Anim. Sci. 36, 556–573. https://doi.org/10.15232/aas.2019-01951

Thorman, R.E., Nicholson, F.A., Topp, C.F.E., Bell, M.J., Cardenas, L.M., Chadwick, D.R., Cloy, J.M., Misselbrook, T.H., Rees, R.M., Watson, C.J., Willimas, J.R., 2020. Towards Country-Specific Nitrous Oxide Emission Factors for Manures Applied to Arable and Grassland Soils in the UK. Front. Sustain. Food Syst. 4, 62. https://doi.org/10.3389/fsufs.2020.00062

Trinity Agtech, 2023. Sandy: farming's new generation natural capital navigator [WWW Document]. URL https://www.trinityagtech.com/what-is-sandy-agtech-software

Troy, S.M., Duthie, C.-A., Hyslop, J.J., Roehe, R., Ross, D.W., Wallace, R.J., Waterhouse, A., Rooke, J.A., 2015. Effectiveness of nitrate addition and increased oil content as methane mitigation strategies for beef cattle fed two contrasting basal diets. J. Anim. Sci. 93, 1815–1823. https://doi.org/10.2527/jas.2014-8688

Tullo, E., Finzi, A., Guarino, M., 2019. Review: Environmental impact of livestock farming and Precision Livestock Farming as a mitigation strategy. Sci. Total Environ. 650, 2751–2760. https://doi.org/10.1016/j.scitotenv.2018.10.018

U.S. Department of State, 2021. The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. United States Department of State and the United States Executive Office of the President, Washington DC.

United Nations, 2022. World population prospects 2022: Summary of results. UN Department for Economics and Social Affairs.

van der Werf, H., Knudsen, M., Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nature Sustainability 3, 419–425. https://doi.org/10.1038/s41893-020-0489-6

van Gastelen, S., Dijkstra, J., Bannink, A., 2019. Are dietary strategies to mitigate enteric methane emission equally effective across dairy cattle, beef cattle, and sheep? J. Dairy Sci. 102, 6109–6130. https://doi.org/10.3168/jds.2018-15785

Van Hertem, T., Rooijakkers, L., Berckmans, D., Peña Fernández, A., Norton, T., Vranken, E., 2017. Appropriate data visualisation is key to Precision Livestock Farming acceptance. Comput. Electron. Agric. 138, 1–10. https://doi.org/10.1016/j.compag.2017.04.003

Verspecht, A., Vandermeulen, V., Ter Avest, E., Van Huylenbroeck, G., 2012. Review of trade-offs and co-benefits from greenhouse gas mitigation measures in agricultural production. J. Integr. Environ. Sci. 9, 147–157. https://doi.org/10.1080/1943815X.2012.698989

Waghorn, G.C., Hegarty, R.S., 2011. Lowering ruminant methane emissions through improved feed conversion efficiency. Anim. Feed Sci. Technol., Special Issue: Greenhouse Gases in Animal Agriculture - Finding a Balance between Food and Emissions 166–167, 291–301. https://doi.org/10.1016/j.anifeedsci.2011.04.019

Wang, S., Kreuzer, M., Braun, U., Schwarm, A., 2017. Effect of unconventional oilseeds (safflower, poppy, hemp, camelina) on in vitro ruminal methane production and fermentation. J. Sci. Food Agric. 97, 3864–3870. https://doi.org/10.1002/jsfa.8260

Wang, C., Tang, Y., 2019. A global meta-analyses of the response of multi-taxa diversity to grazing intensity in grasslands. Environ. Res. Lett. 14, 114003. https://doi.org/10.1088/1748-9326/ab4932

Wang, Z.-H., Li, S.-X., 2019. Chapter Three - Nitrate N loss by leaching and surface runoff in agricultural land: A global issue (a review), in: Sparks, D.L. (Ed.), Advances in Agronomy. Academic Press, pp. 159–217. https://doi.org/10.1016/bs.agron.2019.01.007

Weigel, K.A., Lin, S.W., 2000. Use of Computerized Mate Selection Programs to Control Inbreeding of Holstein and Jersey Cattle in the Next Generation. J. Dairy Sci. 83, 822–828. https://doi.org/10.3168/jds.S0022-0302(00)74945-9

Welsh Government, 2021. Net Zero Wales Carbon Budget 2 (2021 to 2025). Welsh Government. ISBN 978-1-80391-158-8.

Welsh Government, 2022a. Sustainable Farming Scheme: Outline Proposals from 2025. GOV.WALES. 71. https://www.gov.wales/sustainable-farming-scheme-outline-proposals-2025

Welsh Government, 2022b. Welsh Food and Drink Economic Appraisal. https://businesswales.gov.wales/foodanddrink/sites/foodanddrink/files/Economic%20Appraisal%202022.pdf

Welsh Government, 2023a. Aggregate agricultural output and income: 2022. https://www.gov.wales/aggregate-agricultural-output-and-income-2022

Welsh Government, 2023b. Sustainable Farming Scheme: Keeping farmers farming. https://www.gov.wales/sustainable-farming-scheme-consultation

Welsh Government, 2023c. Aggregate agricultural output and income: 2022. https://www.gov.wales/aggregate-agricultural-output-and-income-2022

Welsh Government, 2023d. Woodland Carbon: A guide for farmers, landowners and managers. https://www.gov.wales/woodland-carbon-guide-farmers-landowners-and-managers-html

Winders, T.M., Jolly-Breithaupt, M.L., Wilson, H.C., MacDonald, J.C., Erickson, G.E., Watson, A.K., 2019. Evaluation of the effects of biochar on diet digestibility and methane production from growing and finishing steers. Translational Animal Science 3, 775–783. https://doi.org/10.1093/tas/txz027

Withers, P.J.A., Neal, C., Jarvie, H.P., Doody, D.G., 2014. Agriculture and Eutrophication: Where Do We Go from Here? Sustainability 6, 5853–5875. https://doi.org/10.3390/su6095853

WRAP, 2023. Retailer Net Zero Collaboration Action Programme [WWW Document]. Waste Resour. Action Programme. URL https://wrap.org.uk/taking-action/food-drink/initiatives/courtauld-commitment/scope-3-GHG-Emissions/retailer-net-zero-collaboration-action-programme (accessed 1.22.24).

Wyer, K.E., Kelleghan, D.B., Blanes-Vidal, V., Schauberger, G., Curran, T.P., 2022. Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health. J. Environ. Manage. 323, 116285. https://doi.org/10.1016/j.jenvman.2022.116285

Wynne-Jones, S., 2013. Carbon blinkers and policy blindness: The difficulties of 'Growing Our Woodland in Wales.' Land Use Policy 32, 250–260. https://doi.org/10.1016/j.landusepol.2012.10.012

Xu, Z., Xu, W., Peng, Z., Yang, Q., Zhang, Z., 2018. Effects of different functional units on carbon footprint values of different carbohydrate-rich foods in China. Journal of Cleaner Production 198. https://doi.org/10.1016/j.jclepro.2018.07.091

Yang, K., Qing, Y., Yu, Q., Tang, X., Chen, G., Fang, R., Liu, H., 2021. By-Product Feeds: Current Understanding and Future Perspectives. Agriculture 11, 207. https://doi.org/10.3390/agriculture11030207

Yanza, Y.R., Szumacher-Strabel, M., Jayanegara, A., Kasenta, A.M., Gao, M., Huang, H., Patra, A.K., Warzych, E., Cieślak, A., 2021. The effects of dietary medium-chain fatty acids on ruminal methanogenesis and fermentation in vitro and in vivo: A meta-analysis. J. Anim. Physiol. Anim. Nutr. 105, 874–889. https://doi.org/10.1111/jpn.13367

Yu, L., Tang, J., Zhang, R., Wu, Q., Gong, M., 2013. Effects of biochar application on soil methane emission at different soil moisture levels. Biol Fertil Soils 49, 119–128. https://doi.org/10.1007/s00374-012-0703-4

Yu, G., Beauchemin, K.A., Dong, R., 2021. A Review of 3-Nitrooxypropanol for Enteric Methane Mitigation from Ruminant Livestock. Anim. Open Access J. MDPI 11, 3540. https://doi.org/10.3390/ani11123540

Zhang, L., Lu, J., Nogami, H., Okada, H., Itoh, T., Arai, S., 2018. Solid-state pH sensor prototype for real-time monitoring of the rumen pH value of Japanese cows. Microsyst. Technol. 24, 457–463. https://doi.org/10.1007/s00542-017-3346-4

Zhao, K., Bewley, J.M., He, D., Jin, X., 2018. Automatic lameness detection in dairy cattle based on leg swing analysis with an image processing technique. Comput. Electron. Agric. 148, 226–236. https://doi.org/10.1016/j.compag.2018.03.014

Zhao, Y., Liu, Z., Wu, J., 2020. Grassland ecosystem services: a systematic review of research advances and future directions. Landscape Ecol 35, 793–814. https://doi.org/10.1007/s10980-020-00980-3

Appendices

Appendix 4 – Supplementary material to Chapter 4 Methods

Table A 4.1. Summary of farm characteristics including farm size, types, number of breeding ewes, number of suckler cows and woodland cover for all study farms.

Farm	Farm size (ha)	Farm type	Livestock enterprise	No. of breeding ewes	No. of suckler cows	No. of store cattle	Fertiliser use (Mg N ha^{-1})	Woodland cover (% of total farm area)
A	262	Hill	Mixed	950	35	-	57	27
B	117	Hill	Sheep	690	-	-	0	9
C	157	Hill	Mixed	800	37	-	36	4
D	270	Hill	Mixed	690	100	-	31	2
E	93	Hill	Sheep	560	-	-	50	4
F	116	Hill	Mixed	489	77	-	99	2
G	71	Hill	Mixed	387	-	31	55	2
H	258	Hill	Mixed	959	54	-	42	4
I	288	Hill	Mixed	838	-	128	32	3
J	200	Hill	Mixed	574	-	307	190	4
K	540	Hill	Mixed	930	32	-	7	1
L	233	Lowland	Sheep	1400	-	-	44	3
M	55	Lowland	Mixed	430	19	-	104	0
N	111	Lowland	Mixed	240	-	229	36	5
O	128	Upland	Mixed	376	33	-	45	5
P	290	Upland	Mixed	825	140	-	101	0
Q	296	Upland	Mixed	985	95	-	29	7
R	278	Upland	Mixed	995	79	-	38	11
S	205	Upland	Mixed	600	100	-	60	9
T	189	Upland	Mixed	702	52	-	0	7
National average				673[1]	23[1]		51[2]	7[1]

1. Welsh Government, 2022. Survey of agriculture and horticulture: June 2022
URL https://www.gov.wales/survey-agriculture-andhorticulture-june-2022

2. Department for Environment, Food & Rural Affairs, 2022. The British survey of fertiliser practice
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094283/fertiliseruse-annualreport2021-28jul22.pdf

Table A 4.2. Summary of emission factors from AgRECalc and the data used in the calculation of each emission estimate.

GHG Source	Data used for calculation	Reference
Methane		
Enteric fermentation (sheep)	Monthly stock numbers, Activity levels, Growth rates, Life stages, Gender, Climate	IPCC (2019) Tier II
Enteric fermentation (cattle)	Monthly stock numbers, Activity levels, Growth rates, Life stages, Gender, Climate	IPCC (2019) Tier II
Excreta and managed manure (sheep)	Monthly stock numbers, Activity levels, Growth rates, Life stages, Gender, Climate	IPCC (2019) Tier II
Excreta and managed manure (cattle)	Monthly stock numbers, Activity levels, Growth rates, Life stages, Gender, Climate	IPCC (2019) Tier II
Nitrous Oxide (Direct)		
N additions to soil:		
Organic and inorganic fertiliser	N applied in fertiliser	IPCC (2019) Tier II
Manure	Monthly stock numbers housed and liveweights, N excretion rate, Fraction of N lost in manure management	IPCC (2019) Tier II
Crop residues	Crop yields and fraction of residues removed, N content of above and below ground residues	IPCC (2019) Tier I
Excreta deposited on pasture	Monthly stock numbers grazing and liveweights, N excretion rates, activity levels, growth rates, life stages, gender, dietary characteristics, and climate	IPCC (2019) Tier II
Managed manure	Monthly stock numbers housed and liveweights, N excretion rates, Climate	IPCC (2019) Tier II
Nitrous Oxide (Indirect)		
N volatilised from soil and redeposited	N applied to fertiliser, manure and excreta, Fraction of applied synthetic and organic N volatilised	IPCC (2019) Tier I
N leaching and runoff from managed soil	N applied to fertiliser, manure, excreta and crop residues, Fraction of applied N lost through leaching and runoff	IPCC (2019) Tier I
Managed manure	Monthly stock numbers housed and liveweight, N content of livestock diet, N excretion rate, Fraction of N volatilised in manure management	IPCC (2019) Tier II
Embedded Resource		
Energy use (UK)	Energy usage	DEFRA (2012)
Fertiliser	Fertiliser applied	Kool *et al.*, (2012)
Imported feed rations	Purchased feed	Dutch Feedprint database (2013)

Table A 4.3. Summary of the sequestration references in the Bangor Tool.

Sequestration reference values	Reference
Net annual increment (yield class)	Forestry Commission, 2018. Woodland Carbon Code: Carbon Lookup Tables.
BCEF1 (biomass conversion and expansion factors)	IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use. P51
R (ratio below to above ground biomass)	Mokany *et al.*, 2006. Critical analysis of root: shoot ratios in terrestrial biomes. Global Change Biology 12, 84–96. https://doi.org/10.1111/j.1365-2486.2005.001043.x
CF (C frac dry matter) conifers	IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use.
CF (C frac dry matter) broadleaf	Matthews, G., 1993. The carbon content of trees. Forestry Commision, Technical Paper 4.
D (wood density) conifers	IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use. P71
D (wood density) broadleaves	IPCC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use. P71
CF (ratio total wood to standing volume conifers)	Milne and Brown, 1997. Carbon in the Vegetation and Soils of Great Britain. Journal of Environmental Management 49, 413–433. https://doi.org/10.1006/jema.1995.0118
Litter input from wood, foliage, seeds, understory and litter	Matthews and Broadmeadow, 2003. Forests, Carbon and Climate Change the UK Contribution. Forestry Commission.
Single tree harvestable wood volume oak	Jobling and Pearce, 1977. Free Growth of Oak. Stationery Office Books, London.
Soil C net ecosystem change under UK forestry	Janssens *et al.*, 2005. The carbon budget of terrestrial ecosystems at country-scale – a European case study. Biogeosciences 2, 15–26. https://doi.org/10.5194/bg-2-15-2005
Soil C net ecosystem loss through erosion under UK forestry and clearfelling	Janssens *et al.*, 2005. The carbon budget of terrestrial ecosystems at country-scale – a European case study. Biogeosciences 2, 15–26. https://doi.org/10.5194/bg-2-15-2005
Net ecosystem C change under UK grasslands, forestry, cropland and peatlands	Janssens *et al.*, 2005. The carbon budget of terrestrial ecosystems at country-scale – a European case study. Biogeosciences 2, 15–26. https://doi.org/10.5194/bg-2-15-2005
Biomass production of SRC poplar clones	Laureysens *et al.*, 2003. Population dynamics in a 6-year-old coppice culture of poplar. I. Clonal differences in stool mortality, shoot dynamics and shoot diameter distribution in relation to biomass production. Biomass and Bioenergy 24, 81–95. https://doi.org/10.1016/S0961-9534(02)00105-8
C sequestration in unmanaged peatlands	Watson *et al.*, 2000. Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change. Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change.
Single tree (oak) mean annual increment	Jobling and Pearce, 1977. Free Growth of Oak. Stationery Office Books, London.

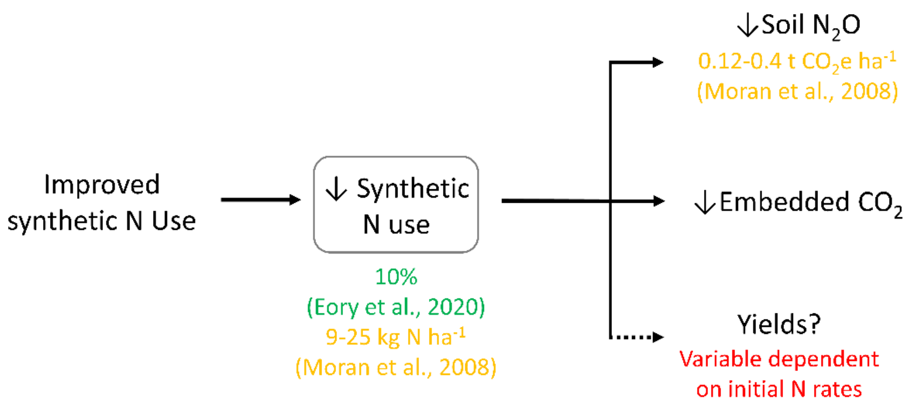


Figure A 4. 1. An example of a flow diagram created for the mitigation measure improved synthetic N use, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials. Circled text represents the input variable.

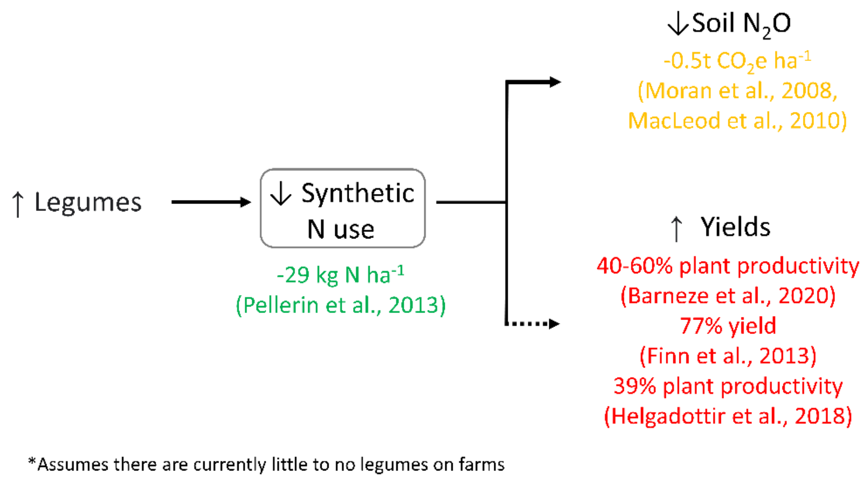


Figure A 4. 2. An example of a flow diagram created for the mitigation measure legume-grass mixtures, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials. Circled text represents the input variable.

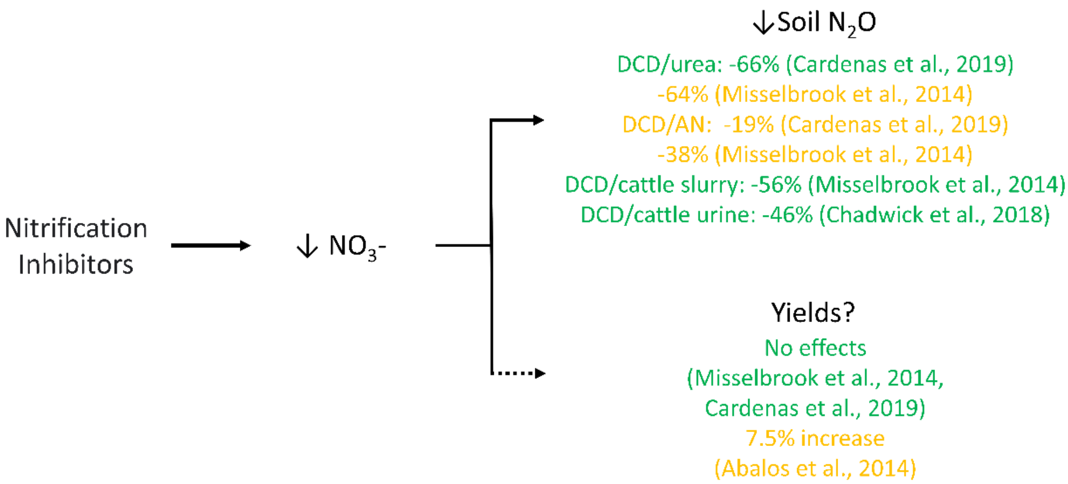


Figure A 4. 3. An example of a flow diagram created for the mitigation measure nitrification inhibitors, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials.

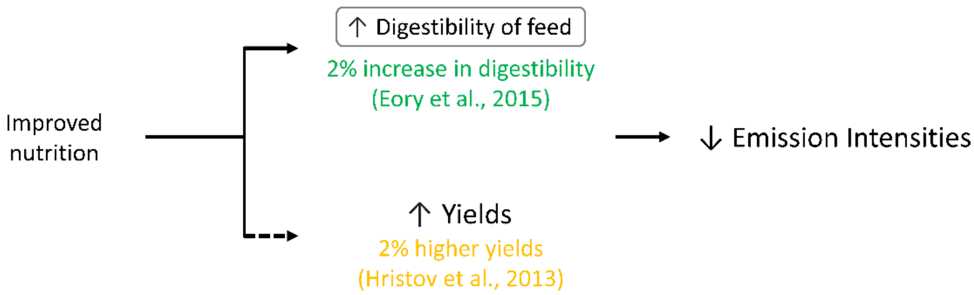


Figure A 4. 4. An example of a flow diagram created for the mitigation measure improving beef and sheep nutrition, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials. Circled text represents the input variable.

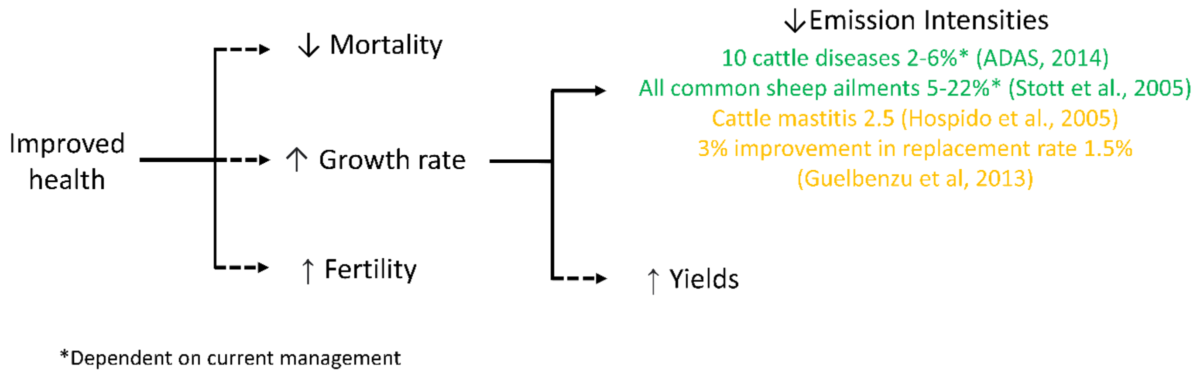


Figure A 4. 5. An example of a flow diagram created for the mitigation measure improving beef and sheep health, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials.

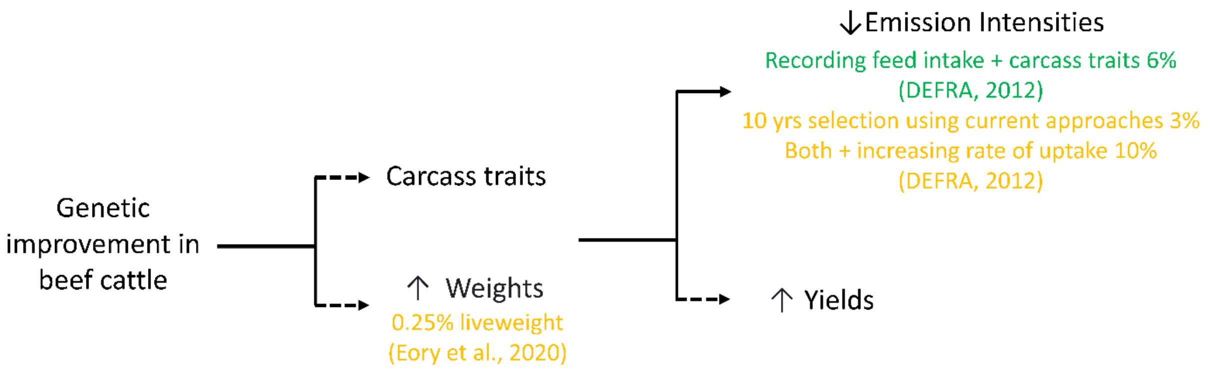
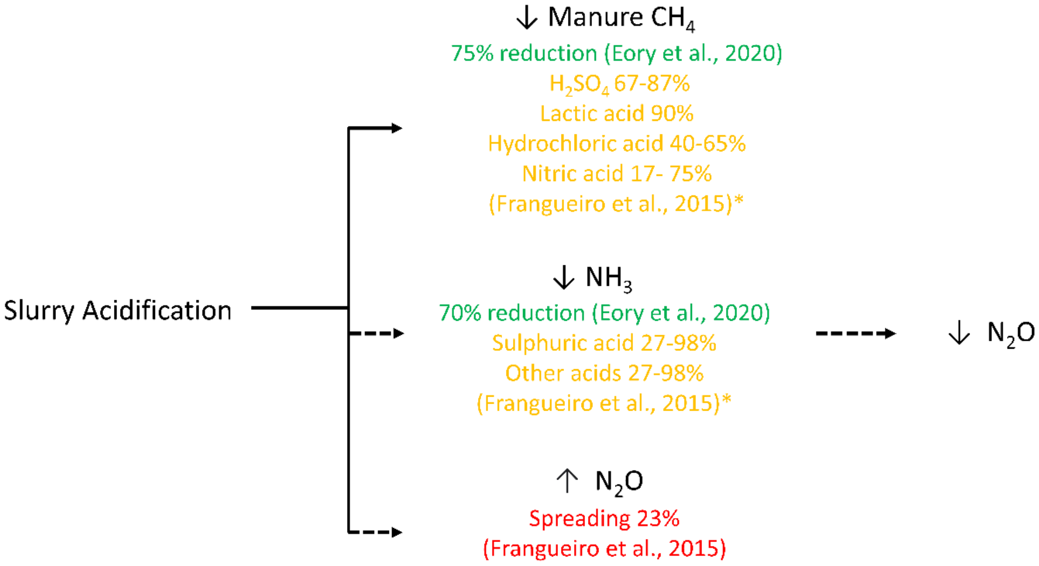
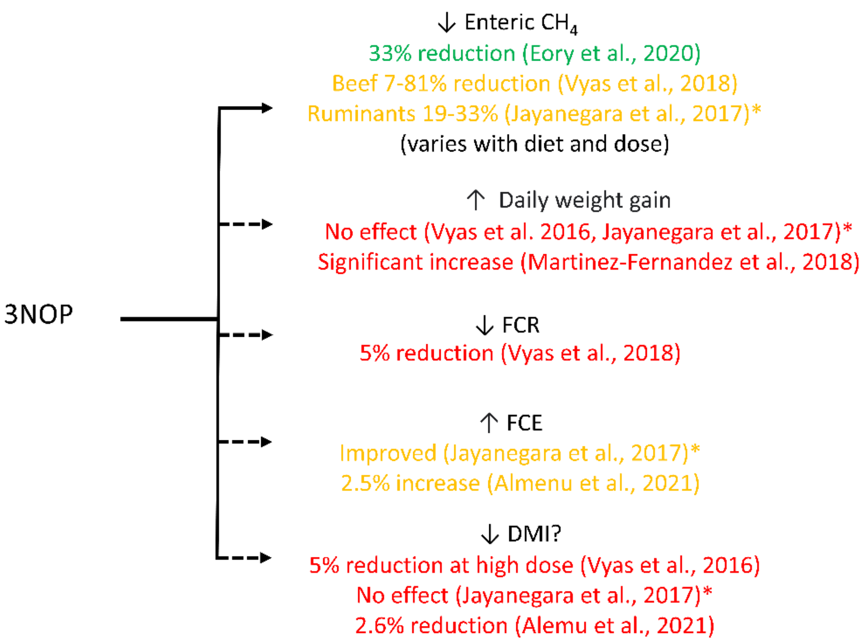


Figure A 4. 6. An example of a flow diagram created for the mitigation measure selection for balanced breeding goals in beef cattle, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials.



*Review article

Figure A 4. 7. An example of a flow diagram created for the mitigation measure slurry acidification, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials.



*Meta-analysis

Figure A 4. 8. An example of a flow diagram created for the mitigation measure 3NOP, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials.

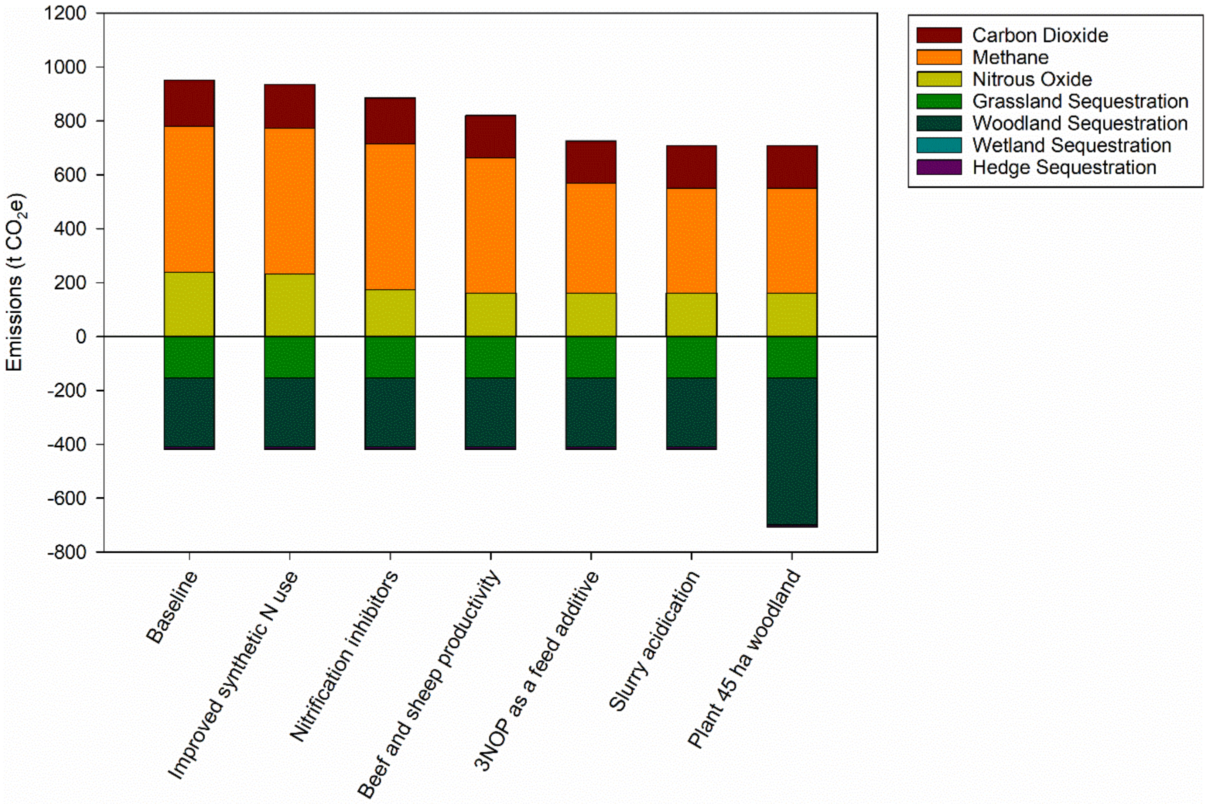


Figure A 4. 9. Farm A's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (34%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 45 ha.

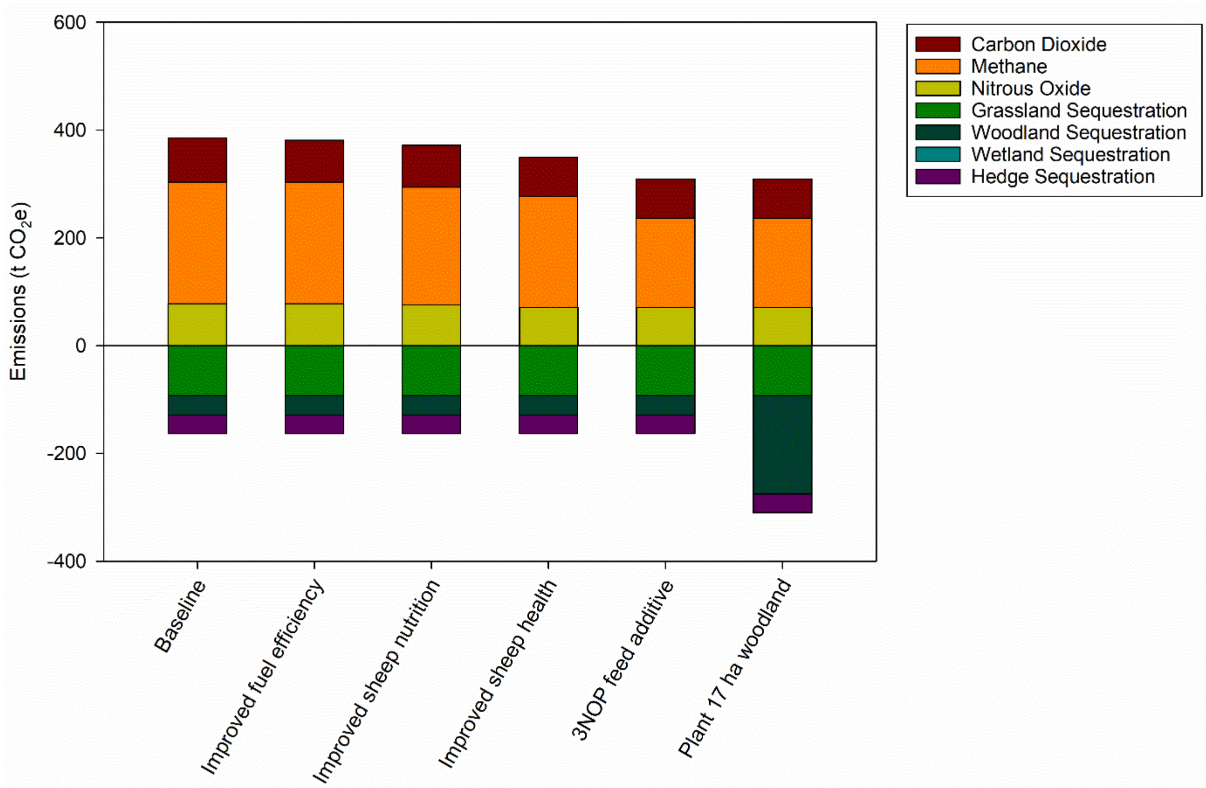


Figure A 4. 10. Farm B's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (20%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 17 ha.

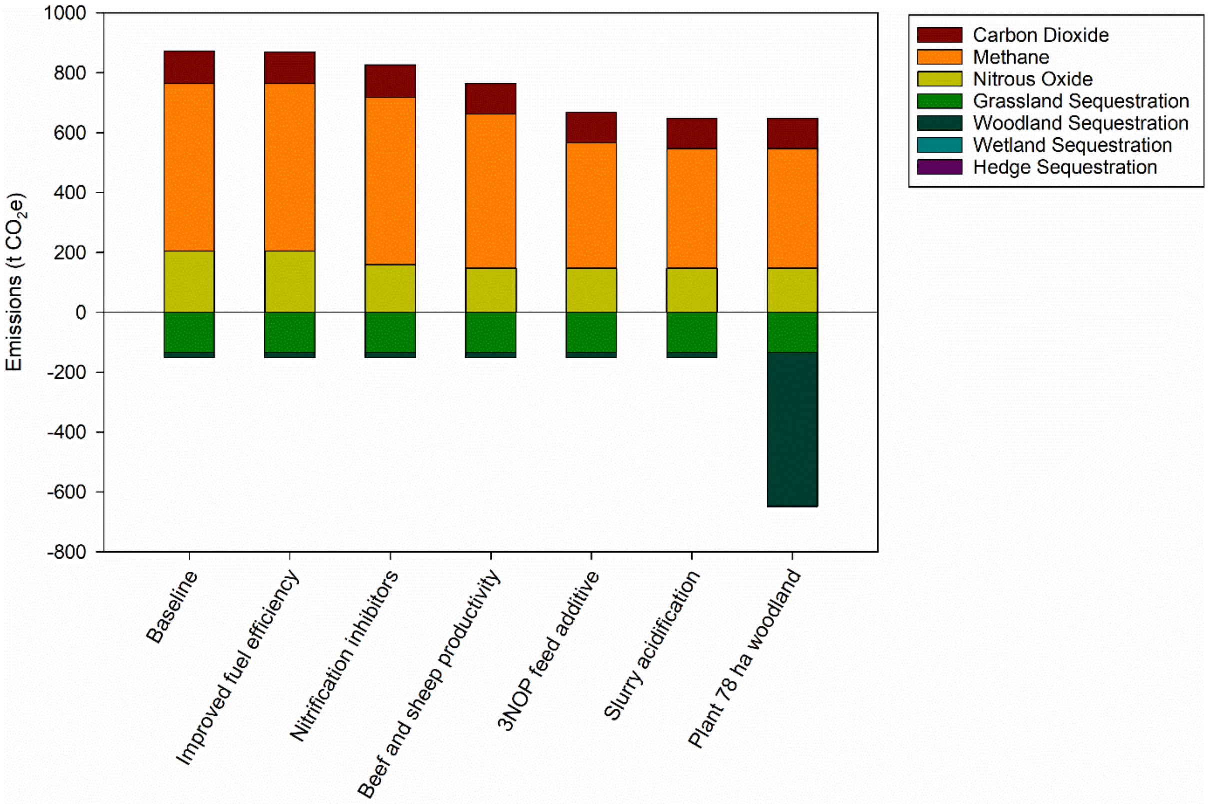


Figure A 4. 11. Farm C's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (26%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 78 ha.

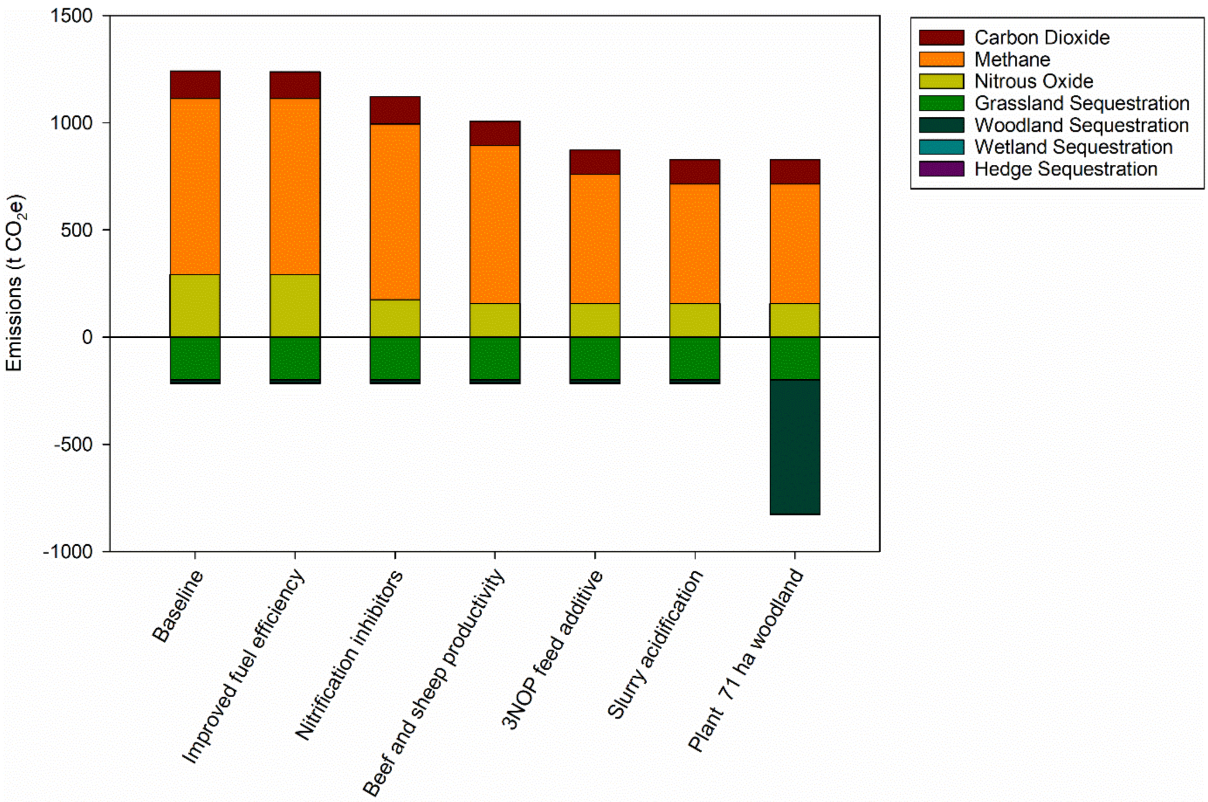


Figure A 4. 12. Farm D's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (33%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 71 ha.

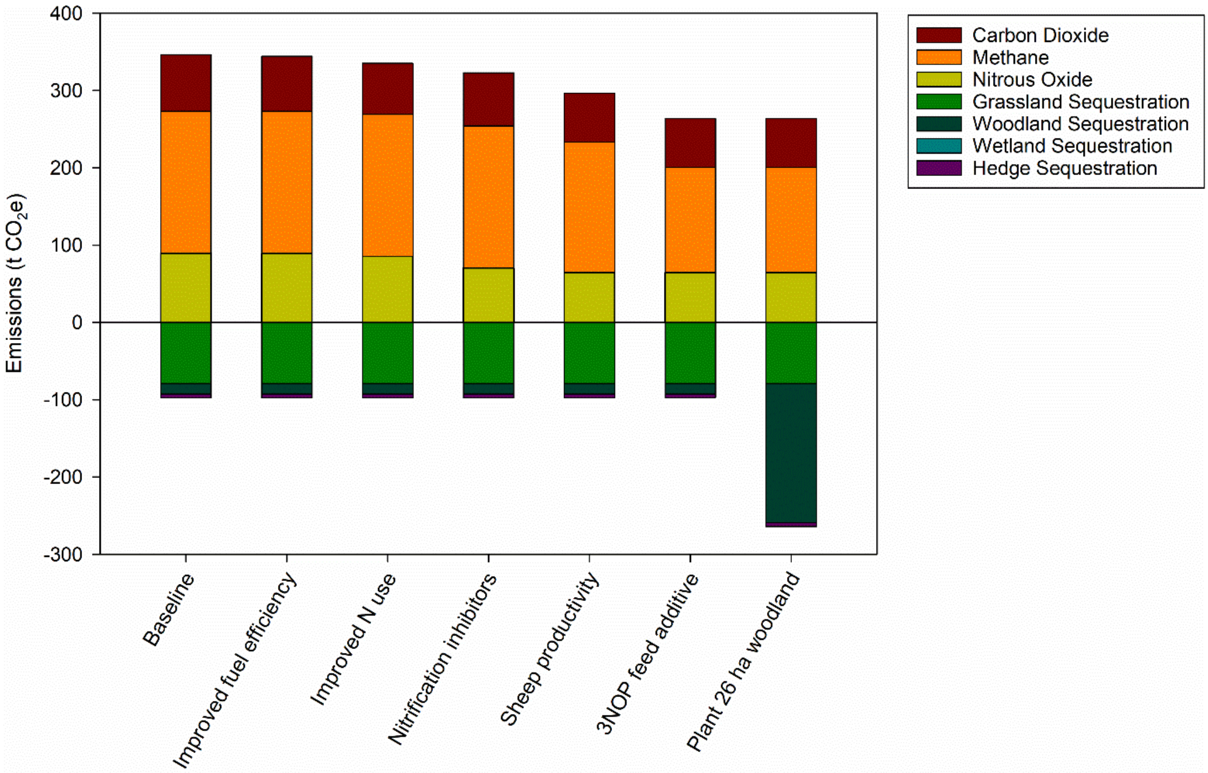


Figure A 4. 13. Farm E's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (24%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 26 ha.

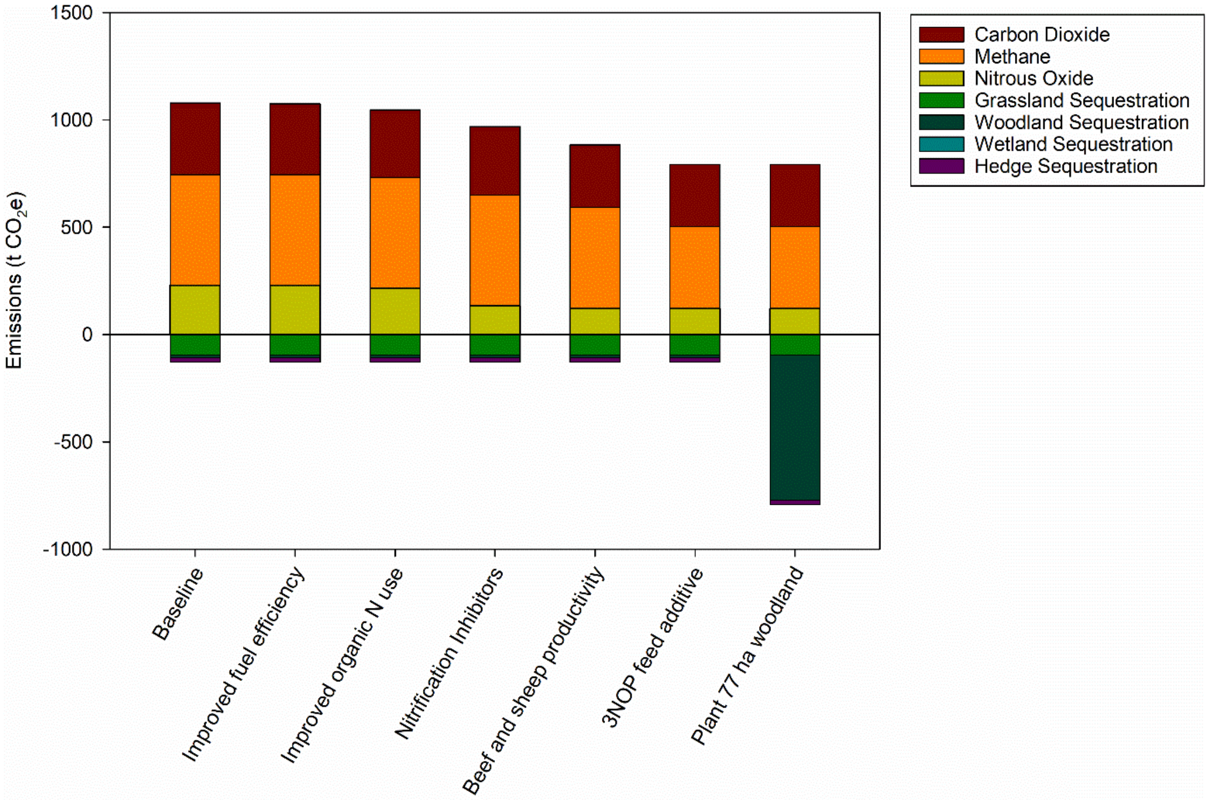


Figure A 4. 14. Farm F's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (27%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 77 ha.

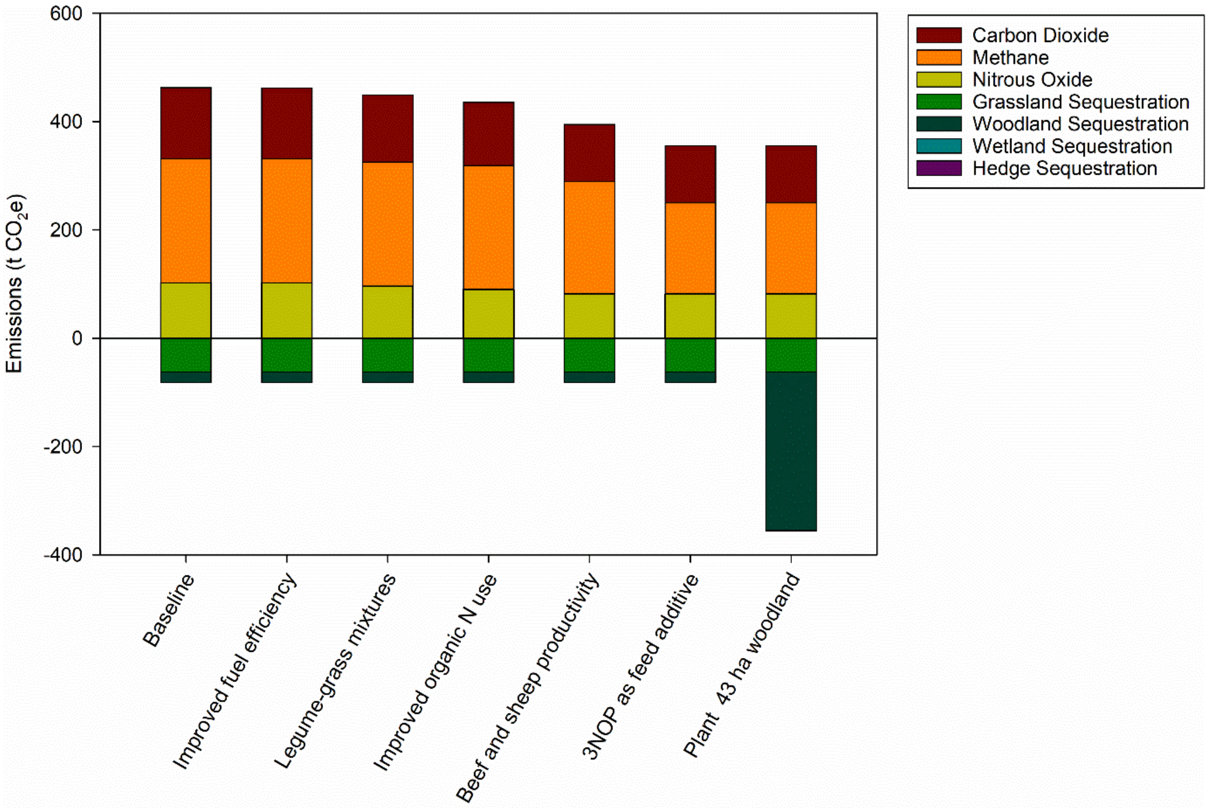


Figure A 4. 15. Farm G's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (23%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 43 ha.

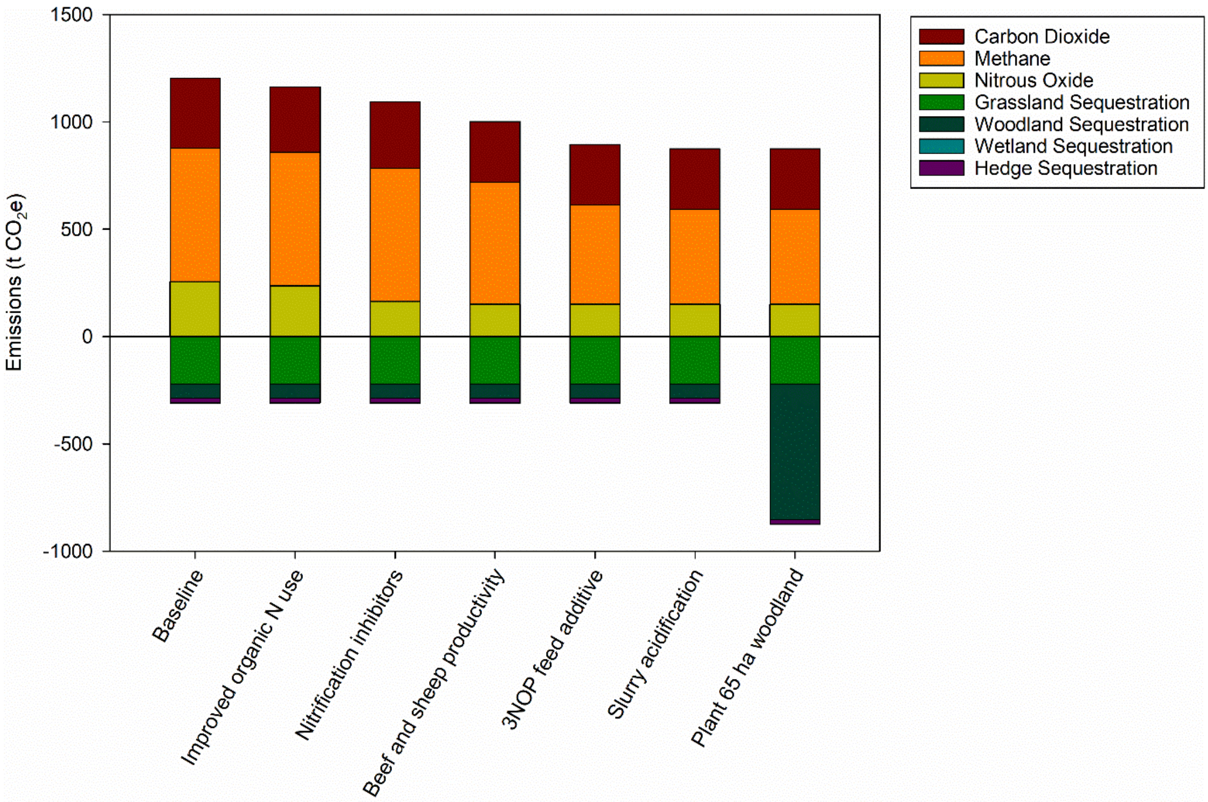


Figure A 4. 16. Farm H's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (27%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 65 ha.

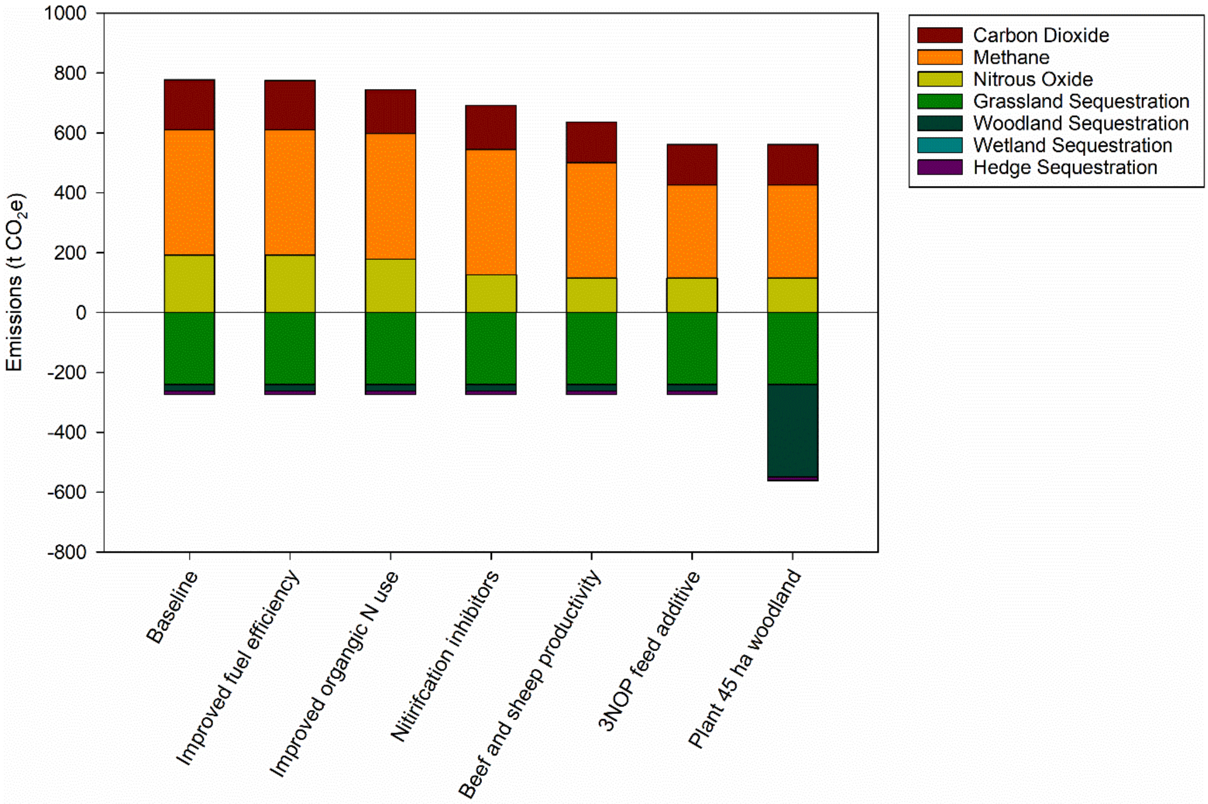


Figure A 4. 17. Farm I's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (28%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 45 ha.

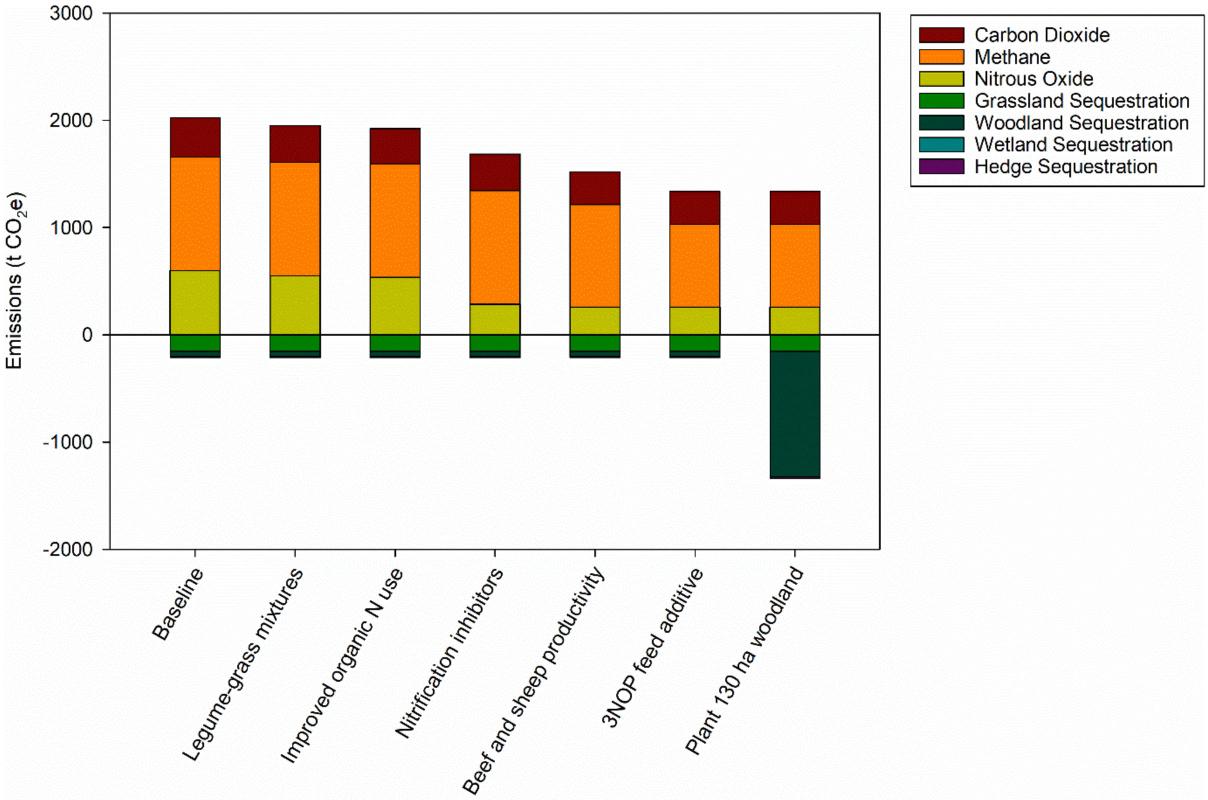


Figure A 4. 18. Farm J's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (34%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 130 ha.

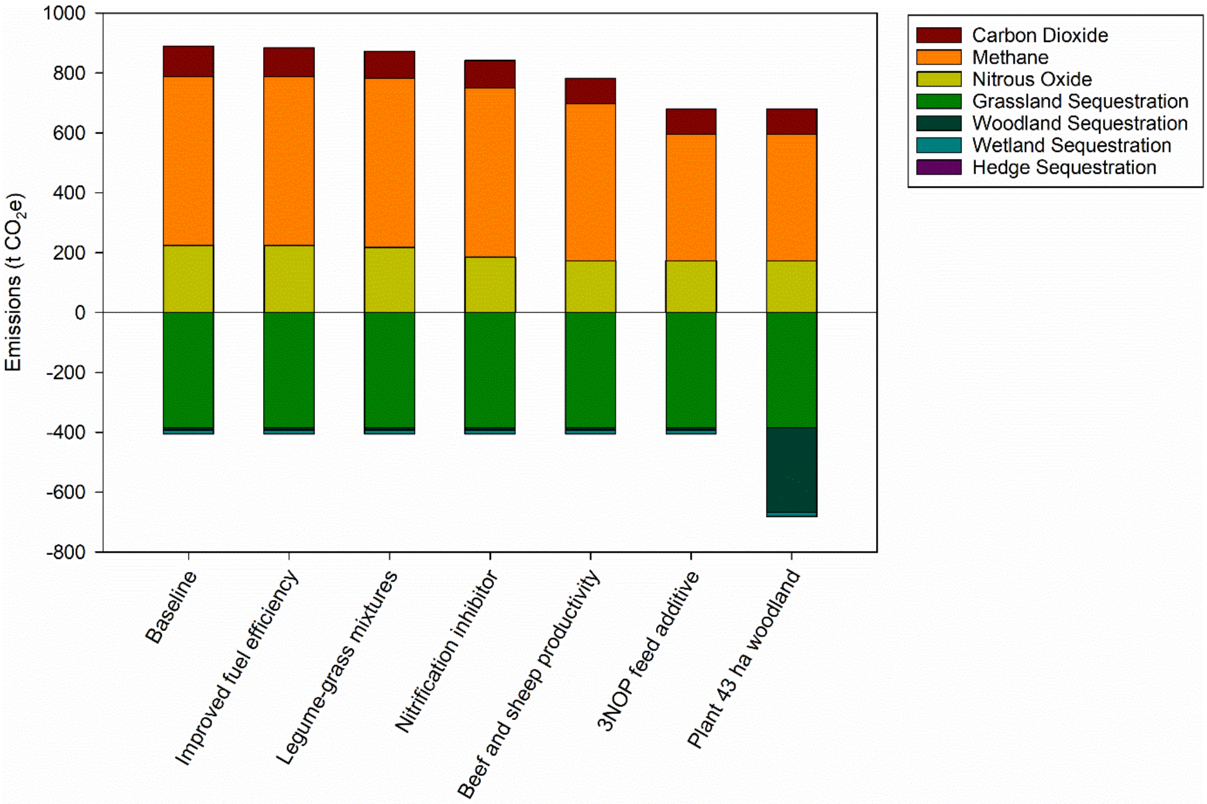


Figure A 4. 19. Farm K's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (23%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 43 ha.

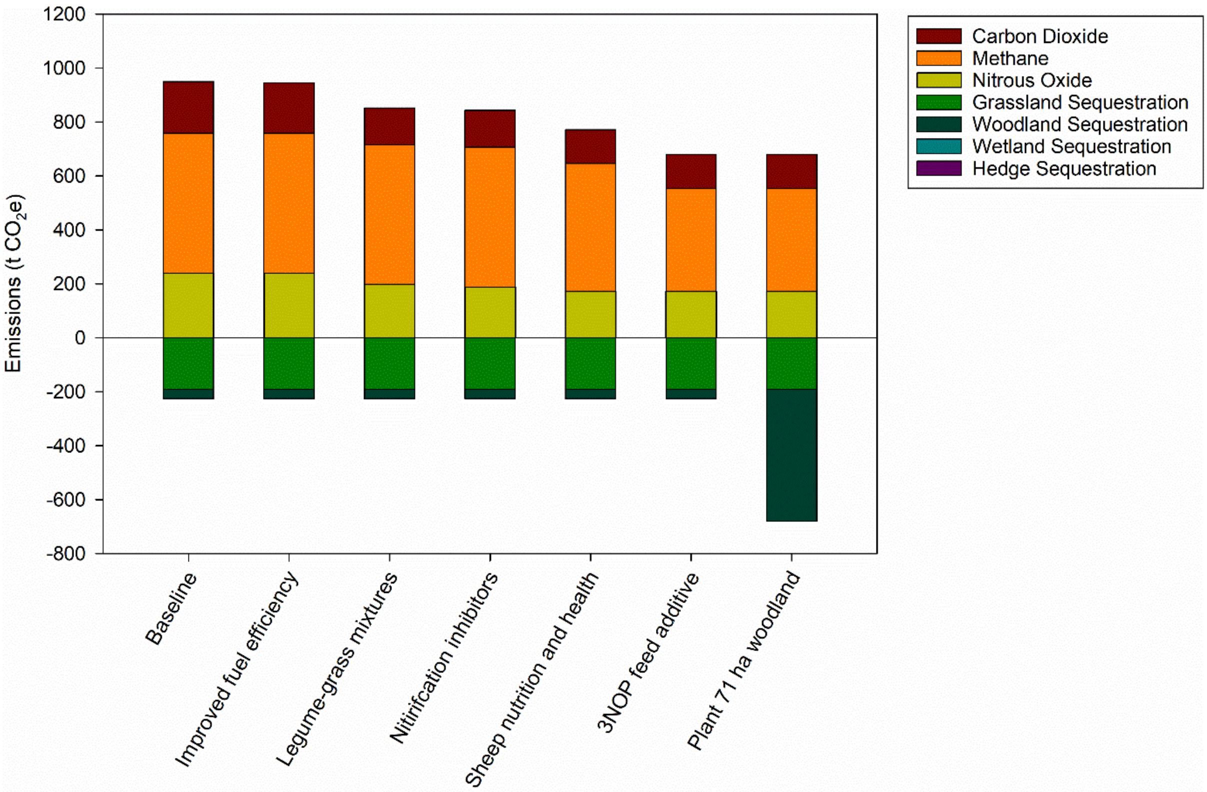


Figure A 4. 20. Farm L's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (28%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 71 ha.

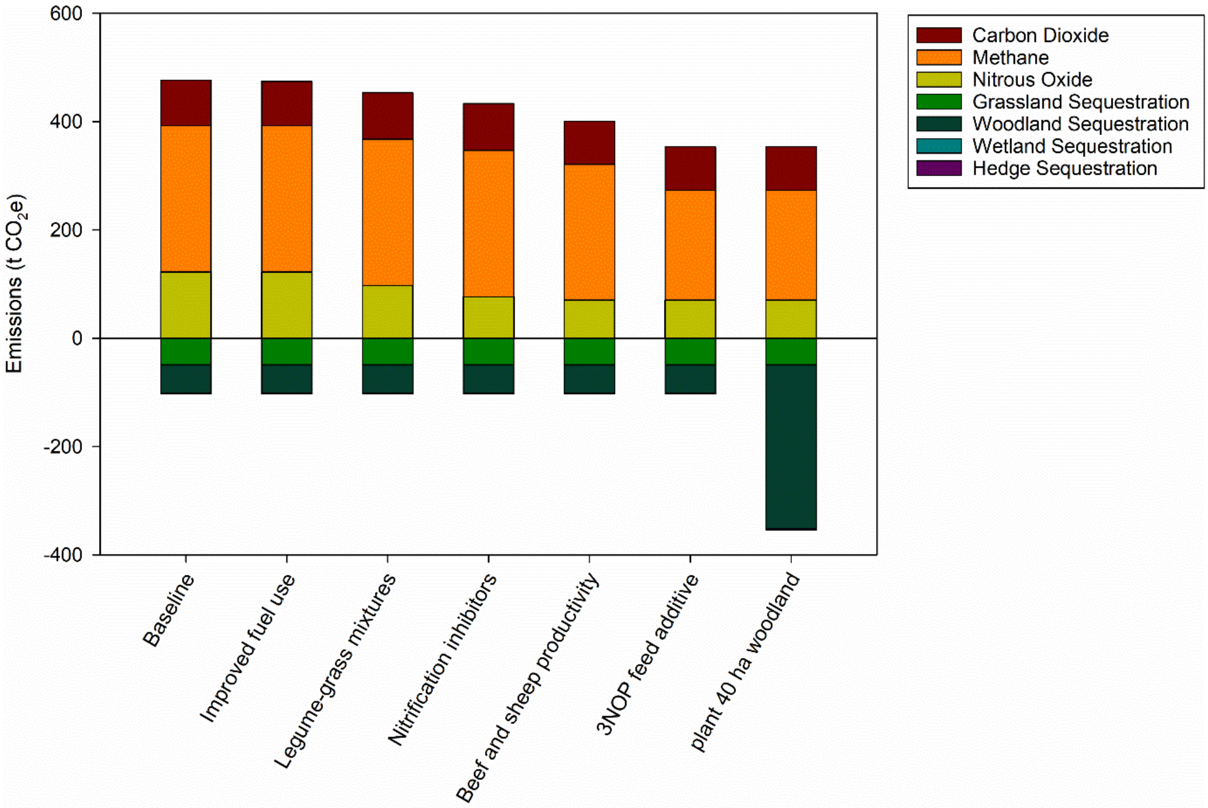


Figure A 4. 21. Farm M's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (26%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 40 ha.

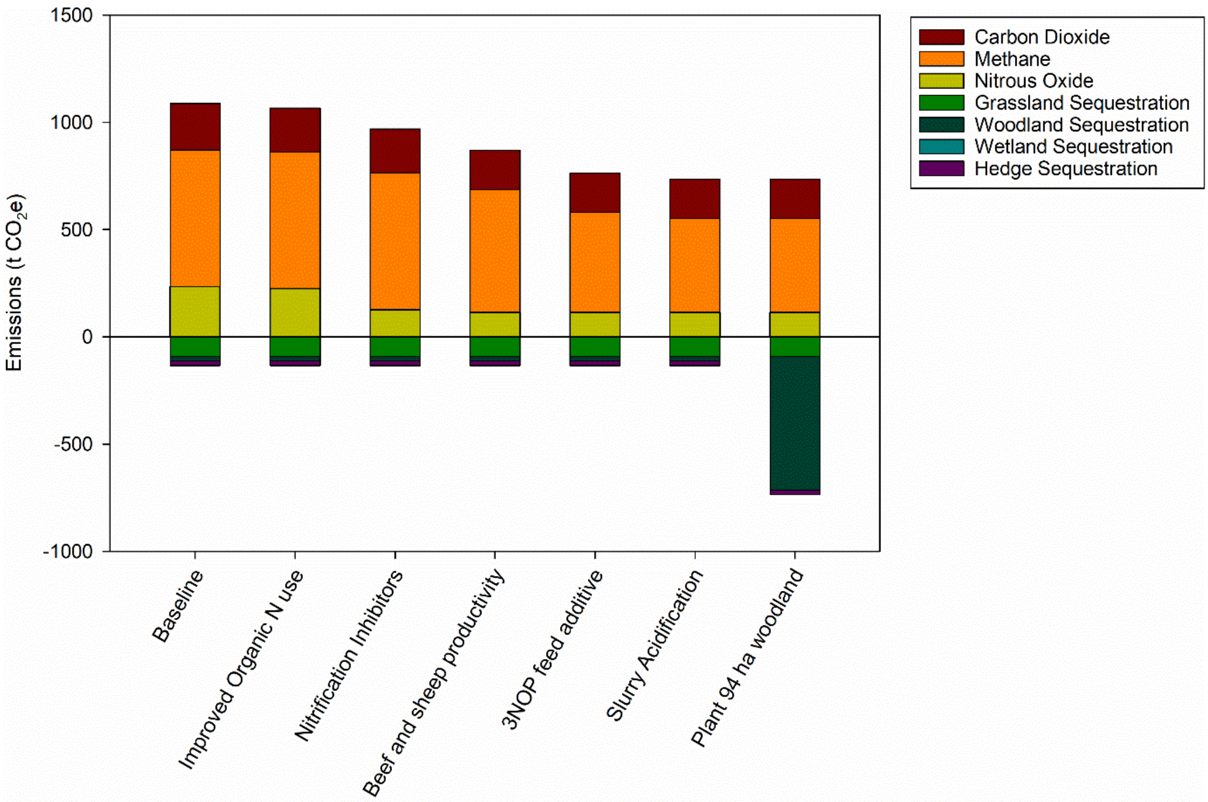


Figure A 4. 22. Farm N's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (32%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 94 ha.

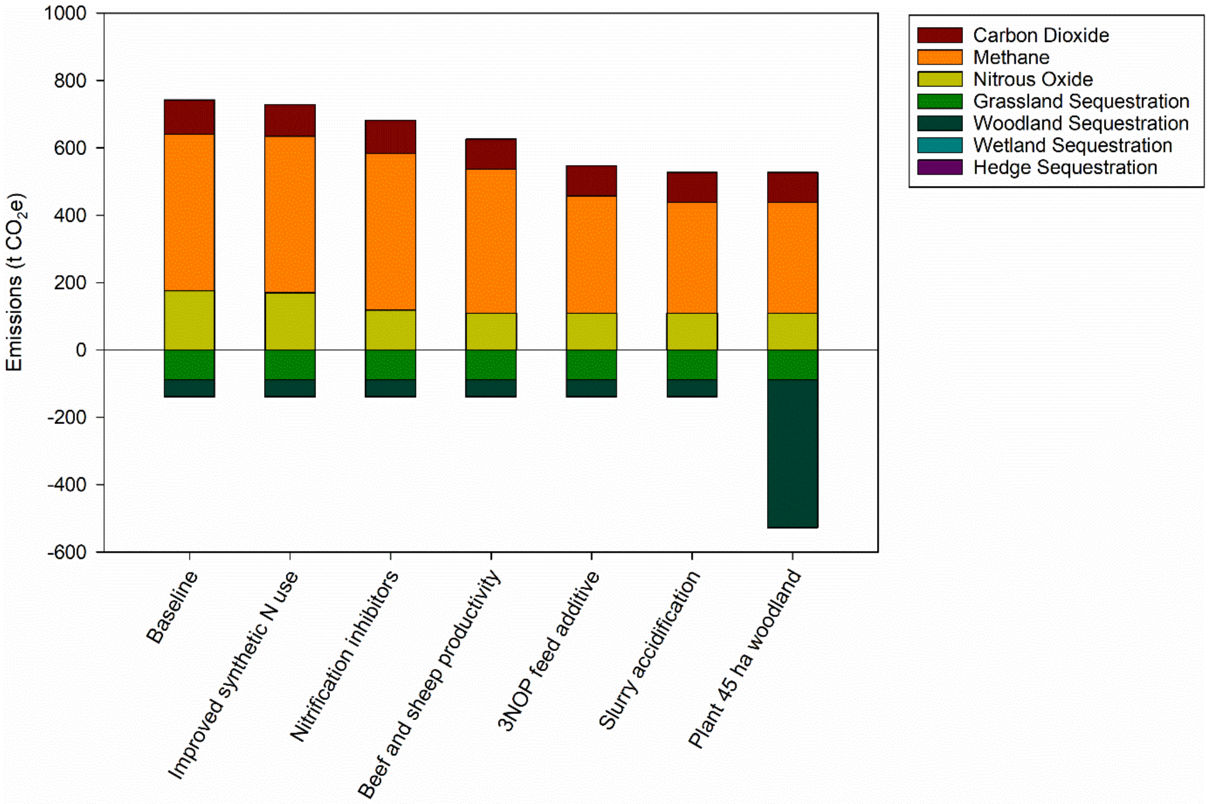


Figure A 4. 23. Farm O's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (29%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 45 ha.

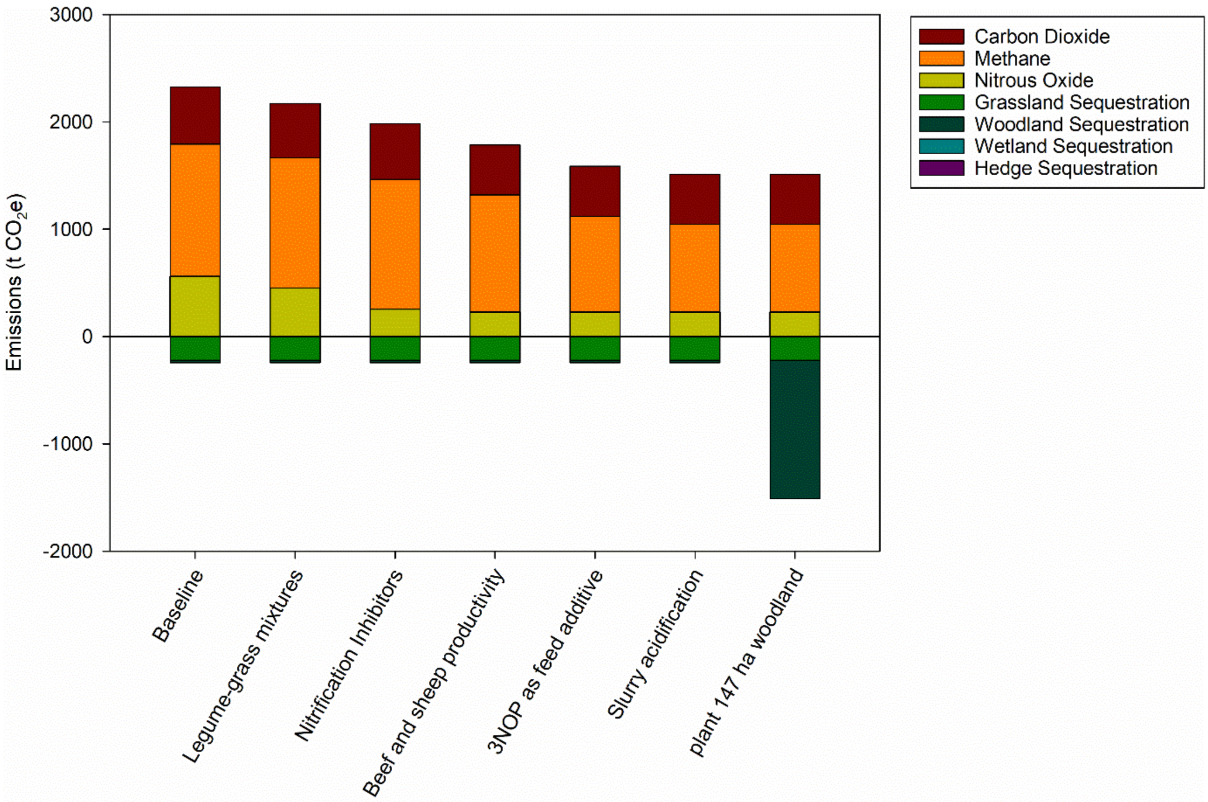


Figure A 4. 24. Farm P's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (35%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 147 ha.

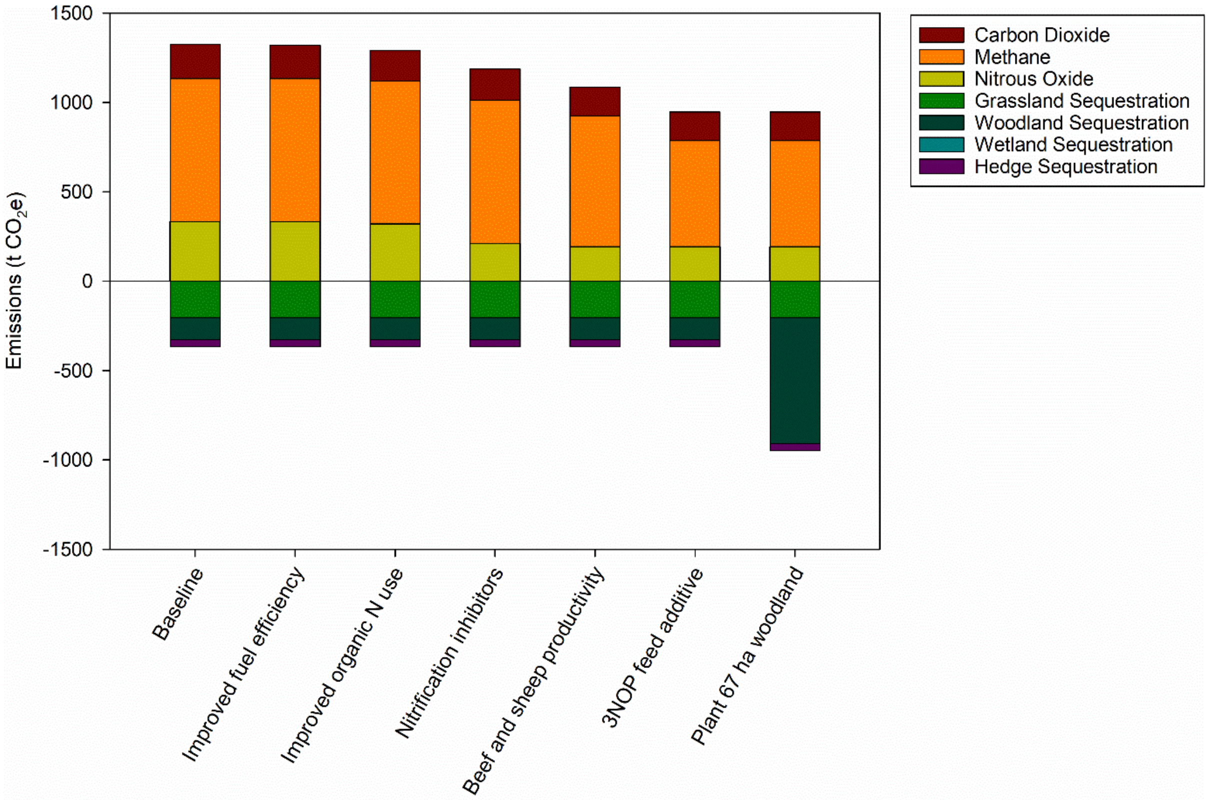


Figure A 4. 25. Farm R's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (29%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 67 ha.

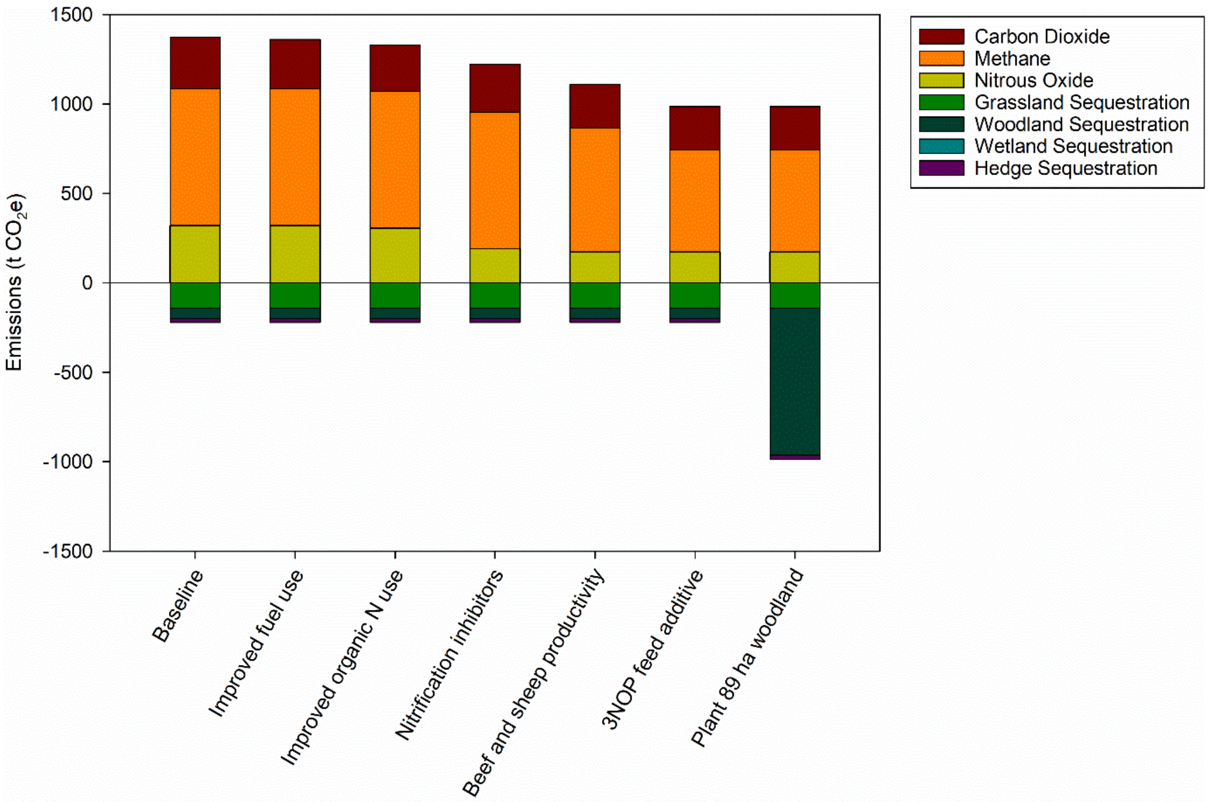


Figure A 4. 26. Farm S's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (28%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 89 ha.

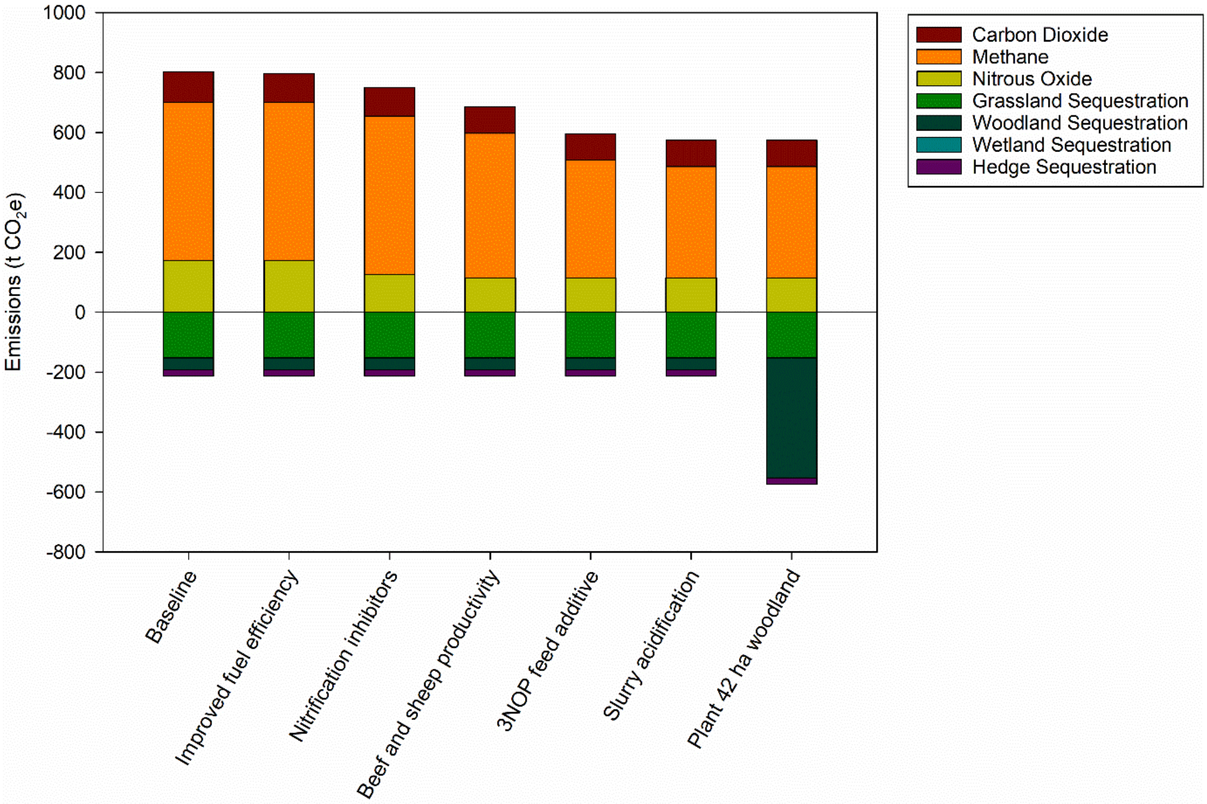


Figure A 4. 27. Farm T's mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (28%) before the area of additional woodland needed to offset residual emissions to achieve Net Zero was calculated at 42 ha.

Table A 4.4. Baseline production area footprints, alongside production area footprints plus offset (afforested) areas required to reach Net Zero, all expressed per unit of output.

Farm	Area production footprint ($m^2.yr\ kg^{-1}$ dwt)	Area production footprint + offset area ($m^2.yr\ kg^{-1}$ dwt)
A	60.7	71.2
B	88.6	101.5
C	41.4	61.9
D	56.9	71.8
E	41.6	53.2
F	38.8	64.5
G	40.4	64.5
H	47.7	59.8
I	75.0	86.6
J	23.8	39.2
K	214.6	231.7
L	64.7	84.3
M	48.3	83.3
N	14.0	25.8
O	65.4	88.3
P	30.3	45.7
Q	85.6	112.6
R	49.8	61.8
S	36.2	51.9
T	51.9	63.3
Average	58.8	76.1

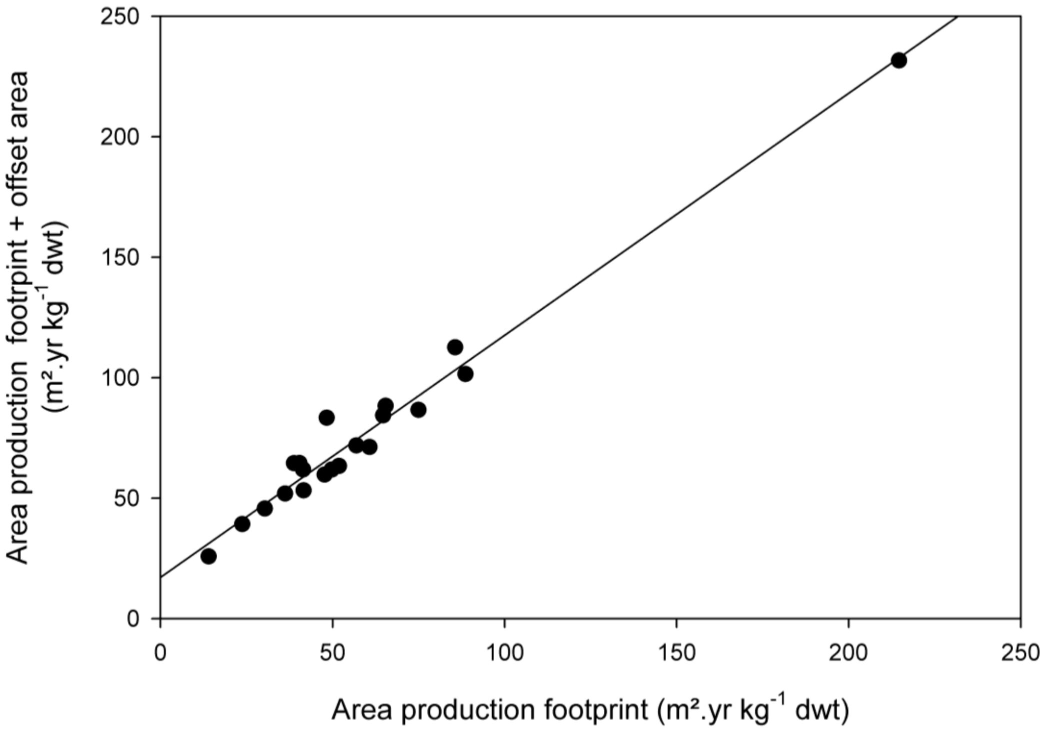


Figure A 4. 28. Scatterplot of the production area footprint against production + offset area footprint across all farms, depicting changes in the area efficiency ranking from baseline compared with Net Zero scenarios.

Appendix 5 – Supplementary material to Chapter 5

A 5.1. Supplementary Methods

The lamb muscle samples were prepared using two stage HNO_3 / HCL digestion in a CEM MARS 6 microwave system. Liquids such as water and acids absorb microwave energy, which results in a rapid increase in temperature. A sample placed inside a microwave-transparent vessel with an acid is subjected to rapid heating allowing the sample to digest or dissolve in a short time. The digests were assayed for iron and zinc on an Agilent 5900 Synchronous Vertical Dual View Inductively Coupled Plasma Optical Emission Spectrometer (SVDV ICP-OES). Using an argon plasma, the sample is subjected to temperatures high enough to cause not only dissociation into atoms but to cause significant amounts of collisional excitation (and ionisation) of the sample atoms to take place. Once the atoms or ions are in their excited states, they can decay to lower states through thermal or radioactive (emission) energy transitions. In OES, the intensity of the light emitted at specific wavelengths is measured and used to determine the concentrations of the elements of interest. The wavelengths used for the iron and zinc analysis were 238.2 and 213.9 nm respectively, employing an indium internal standard and a caesium nitrate ionisation buffer. ERM-BB184 Bovine Muscle from the Joint Research Centre of the European Commission was used as a quality control material. All samples were analysed in duplicate.

Fatty acid composition was determined by the method of O'Fallon *et al.* (2007). Briefly, lean lamb muscle (1 g ± 0.01 g) with addition internal standard was saponified with KOH (10N, 1 ml) and methanol (5.3 ml). Samples were mixed by vortex before heating in an oven (minimum 14 hours, 60°C). Once cooled, H2SO4 (24N, 0.58 ml) was added. Samples were mixed by inversion and returned to the oven (90 mins, 60°C). FAMEs were extracted into hexane (3 ml) by mixing on a rotator for 15 mins at medium speed followed by centrifugation (2000 rpm, 5 minutes). An aliquot of the upper phase was analysed by GC-FID using a CP-SIL 88 column for FAME, 100 m ×250 µm ×0.2 µm. For reporting purposes, FAMEs were converted to FAs by applying a conversion factor for each FAME (AOAC Official Method 963.22 Methyl Esters of Fatty Acids in oils and fat, 41.1.29, 2019). Intramuscular fat was determined by the method of Folch *et al.* (1956). Homogenous lean lamb muscle (5 g ± 0.05 g) was extracted with chloroform: methanol (100 ml, 2:1 v:v) homogenising for 3 minutes with an ultra turrax homogeniser. The extract was filtered into a measuring cylinder and made up to the 100 ml mark with chloroform: methanol (2:1 v:v). KCL (20 ml, 0.37%) was added to aid separation and the samples were mixed by inversion before being left to separate overnight. The lower layer was transferred to a 200 ml tube and the solvent removed under nitrogen (water bath 40°C). Samples were dried to a constant weight, with the percentage of extracted fat calculated gravimetrically.

For total amino acid analysis, 100 mg of lamb (+/- 10mg) was weighed accurately to the nearest hundredth of a mg and hydrolysed to its constituent amino acids in constant boiling hydrochloric acid (5.8M) at 110°C for 24 hours under vacuum. Samples were then dried down, diluted and analysed on a Waters 2695 pump/injector system. The individual amino acids were separated by ion exchange chromatography on a strong cation exchange resin using sodium citrate buffer gradients of increasing pH. The ninhydrin reagent was pumped using a Waters 1515 isocratic pump. The ninhydrin reaction occurs in a heated reaction coil at 125°, and the derivatized amino acids are detected using a Waters 2487 variable wavelength UV/VIS detector. Data handling is performed with a Lab Systems 'Atlas' integration package. Cysteine is partially degraded under these conditions and is converted to the acid stable cysteic acid before standard acid hydrolysis. Tryptophan totally degraded during this acid diet but is stable in alkaline conditions, so samples are hydrolysed in barium hydroxide at 110°C for 24 hours under vacuum.

Table A 5.1: Estimated marginal mean (± standard error) nutritional composition of lamb per 100 g of meat from four finishing diets averaged over breed type and gender for longissimus dorsi and breed type for semimembranosus. Different lower-case letters indicate statistically significant differences between diets at the 5% level.

		Diet				
	Muscle	*Forage crops*	*Grass*	*Concentrates*	*Grass and concentrates*	*p*-value
Amino acid (g/100g)	LD	-	-	-	-	-
	S	-	-	-	-	-
	GM	19.5 ± 6.89^{a}	19.3 ± 2.73^{a}	19.5 ± 4.88^{a}	19.8 ± 2.37^{a}	0.397
Fat (mg/100 g)	LD	3080 ± 167^{ab}	2816 ± 138^{ab}	3095 ± 144^{b}	2696 ± 133^{a}	0.016
	S	2291 ± 165^{a}	2398 ± 191^{a}	2117 ± 166^{a}	2083 ± 138^{a}	0.404
	GM	-	-	-	1903 ± 44.4	-
Saturated fat (mg/100 g)	LD	1399 ± 87.0^{ab}	1288 ± 71.9^{ab}	1404 ± 75.5^{b}	1208 ± 69.4^{a}	0.031
	S	1024 ± 83.1^{a}	1061 ± 95.7^{a}	902 ± 82.6^{a}	893 ± 69.2^{a}	0.324
	GM	-	-	-	834 ± 22.7	-
Iron (mg/100 g)	LD	1.64 ± 0.03^{a}	1.62 ± 0.02^{a}	1.64 ± 0.02^{a}	1.57 ± 0.02^{a}	0.325
	S	1.82 ± 0.04^{a}	1.82 ± 0.03^{a}	1.82 ± 0.03^{a}	1.77 ± 0.04^{a}	0.428
	GM	-	-	-	1.76 ± 0.05	-
Zinc (mg/100 g)	LD	2.29 ± 0.03^{a}	2.12 ± 0.03^{b}	2.29 ± 0.03^{ac}	2.03 ± 0.02^{bc}	<0.001
	S	3.16 ± 0.07^{a}	3.19 ± 0.05^{a}	3.16 ± 0.05^{a}	2.78 ± 0.03^{a}	0.1383
	GM	-	-	-	2.91 ± 0.03	-
Omega-3 (mg/100 g)	LD	132 ± 6.7^{ab}	137 ± 5.5^{b}	102 ± 6.1^{c}	117 ± 5.5^{bc}	<0.001
	S	138 ± 12.8^{a}	146 ± 13.7^{a}	103 ± 10.0^{a}	111 ± 9.1^{a}	0.067
	GM	-	-	-	100 ± 2.17	-

LD = *Longissimus dorsi*

S = *Semimembranosus*

GM = *Gluteus medius*

Table A 5.2: Effect of breed type and gender on fatty acid composition of longissimus dorsi and breed type for semimembranosus. Different lower-case letters indicate statistically significant differences between diets at the 5% level.

	Longissimus dorsi		*Semimembranosus*
Fatty acid (mg/100 g)	Breed Type	Gender	Breed Type
C12:0	0.259	0.013	0.278
C14:0	0.044	<0.001	0.419
C16:0	0.007	<0.001	0.025
C18:0	0.004	0.03	0.005
C18:1 t11	0.007	<0.001	0.43
C18:1 n-9 cis	0.002	<0.001	0.004
C18:2 n-6	0.424	0.675	0.129
C20:4 n-6	0.932	0.21	0.889
C18:3 n-3	0.217	<0.001	<0.001
C20:5 n-3	0.653	<0.001	0.096
C22:5 n-3	0.138	<0.001	0.002
C22:6 n-3	0.607	<0.001	0.427
Total SFA	0.009	<0.001	0.032
Total MUFA	0.002	<0.001	0.005
Total PUFA	0.105	<0.001	0.001
Total n-3	0.068	<0.001	<0.001
Total n-6	0.551	0.564	0.25
n-6/n-3	0.063	0.028	0.743
PUFA/SFA	0.073	0.033	0.115
Total FA	0.003	<0.001	0.017

Appendix 6 – Supplementary material to Chapter 6

A.6.1. Qualitative analysis – themes and respondents quotes

Respondents' answers to "Are you aware of any additional benefits of the GHG mitigation measures listed above (e.g. nitrogen planning, legumes, animal health or nutrition)?"

Economic

"Increase business resilience"

"Better use of inputs"

"More efficient and cost effective use of inputs"

"Efficiencies and improved sustainable profits"

"legumes sustainability"

"Reduction in inorganic N"

"So far they are essential to profitability"

"Better more resilient farm"

"Reduced input costs"

"Be aware of input nitrogen use compared to lamb price and weight difference."

"cost efficient ways of using natural fretilizer etc"

"Low nitregon in puts"

Animal Welfare/productivity

"Possible animal health benefits"

"herbal ley, animal health benefit"

"Animal health production "

"Better productivity with genetically improved sheep"

"animal health and nutrition"

"Clover - protein and it's benefits to parasite resilience."

"healthy animals will finish quicker, thereby reduce methane emissions (and costs!)"

Efficiency"

"Focusing on optimising genetics for your system also reduces input costs and time

genetically efficient animals/ health/ grassland management"

"increased productivity"

Other environmental benefits

"Fixing nitrogen from the atmosphere with legumes"

"soil health"

"Soil improvement"

"Soil health, biodiversity gains, reduced runoff, reduced inputs"

"Improved soil health and water retention"

"soil health and increased organic matter"

"Improving soil health and fertility, crop resilience through legumes and diverse awards"

"Legumes can reduce need for soya"

"Improved soil health"

"improved biodiversity"

"Legume fixing nitrogen"

"Legumes fix nitrogen in the soil"

Respondents' answers to "Are you aware of any additional benefits of the GHG sequestration measures listed above (e.g. afforestation or measures to increase soil carbon sequestration)?"

Economic

"High quality efficient grass leys and rotational grazing are excellent sequesters of carbon."

"wood for the log burner"

"I like scots pine trees, they smell nice"

"Farm resilience"

"increaed productivity"

"Improved resilience through strong ecosystems"

"Save money"

"improved crop yields"

Animal Welfare/productivity

"afforestation provides shade"

"Increased shelter and improved water resource that will provide a basis to deliver the 5 freedoms for my livestock."

"shelter for stock"

Other environmental benefits

“Biodiversity increase”

“Better soil health”

“As above but also improved biodiversity”

“Deeper rooting soil”

“Again, its working with natural systems.”

“Biodiversity & Landscape Management”

“Improved soil health, and soil biodiversity”

“improved habitats”

“Lower carbon footprint”

“Improved soil organic matter and health”

“In regards to grazing management, increased biodiversity and soil health”

“increased soil matter and carbon through grazing practices, debatable whether increased tree cover is as beneficial as practices aiming to increase soil organic matter”

“increasing soil OM has loads of benefits for holding water and nutrients”

“Soil health”

”improving wildlife habitats and habitat connectivity”

“Improving soil health, water management”

Respondents’ answers to “Are you aware of any additional benefits of the GHG sequestration measures listed above (e.g. afforestation or measures to increase soil carbon sequestration)?”

Loss of productive land

"Don't want to plant trees on land suitable for food production "

"Land too productive"

"Competing with large forests so no economy of scale"

"Trees are not the answer to all the climate’s woes. This survey seems bias in favour of tree planting."

"Loss of food producing land. We import nearly half our food. Are we making climate change worse by increasing imports?"

"Loss of productive area to spread fixed costs over."

"Reducing land available for food production"

"loss of grazing land, lower farm output to cover fixed costs"

"Our cattle are 100% grass fed - need grazing"

"Small farms can't 'spare' the land "

"loss of productive farm land"

"Loss of productive land"

"Taking productive land away forever. Shortsighted gains "

"Decrease in value of farmland."

"Reduction in farmland for grazing "

"Taking productive land out of production"

"perception of removal of productive land for trees"

"loss of fields"

Personal interest and values

"£££ write down time before timber is ready to harvest....you do realise that all the carbon these trees capture is going to be back in the atmospere in 100 years dopn't you? This means all you do, with the best will in the world, is defer the problem for my grandchildren, and while I don't care of your grandkids are boiled alive and eaten by rats, I do care that mine might one day walk safely on the land"

"No evidence about the benefits of afforestation against current practise. I don't t like the assumption in the questionke "

"Landscape spoilage"

"Don't want to plant trees! "

"Afforestation is generally badly thought through. "

"I believe mobgrazed pasture is far better for carbon sequestration "

"I don't believe trees on productive ground is better for the environment than well managed productive pasture."

"scenery in the open countryside and trash"

Policy

"Mistrust of regulatory regime"

"Hostile policy environment, lack of joined up approach from government departments"

"To much NRW and Private forestry in the area and they will not work together for the good of the environment by working together to save fuel cost and the CO /2 emissiones "

A6.2. Survey questions – Barriers and opportunities to achieving Net Zero on UK beef and sheep farms

Barriers and Opportunities to achieving Net Zero on UK Beef and Sheep Farms

Page 1: Participants Information Sheet

Study Information

This short survey relates to the **Net Zero target** on **beef and sheep farms** in the UK as part of a PhD research project at Bangor University funded through the Knowledge Economy Skills Scholarship (KESS2) programme and Hybu Cig Cymru – Meat Promotions Wales (HCC).

In 2019, the UK was the first country to legislate the Net Zero greenhouse gas emissions by 2050 target, which will require the livestock sectors to adapt their systems. Net Zero will be achieved on farms when on-farm greenhouse gas emissions (e.g. from livestock and fertiliser use) are in balance with on-farm carbon sequestration (e.g. in trees and soils). For farms to achieve Net Zero, the primary focus should be on reducing emissions, as it means less land is needed for sequestration to off-set those remaining emissions. However, it is important to better understand the likely adoption of measures to reduce greenhouse gas emissions.

The information collected from the survey will form an important chapter of this PhD study and benefit the industry more widely by gaining a better understanding of farmers' attitudes towards the Net Zero target and identifying both opportunities and barriers the target may create. The questions are centred around carbon footprinting and the uptake of greenhouse gas mitigation measures on your farm.

The survey should take approximately 20-30 minutes to complete. The majority of these questions are simple "checkbox" questions, where you select answers from a list of choices.

Data protection statement

This survey is confidential, and no personally identifiable information will be collected in the survey. All information provided will be protected under the terms of General Data Protection Regulation (2018) which ensures that the data is securely recorded, used for a legitimate purpose and there is a compelling justification for processing the data. The data collected will be stored on a password protected University computer and will be discarded after a period of 5 years from the end of this project.

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The results will be included in a PhD thesis and may form part of further published work.

Your participation is voluntary, and you are under no obligation to complete this survey; however, it would be very much appreciated to maximise the values of responses.

If at any point you have questions or concerns about this survey, please contact Louise McNicol at lsm20fqj@bangor.ac.uk or Dr Prysor Williams at prysor.williams@bangor.ac.uk

Participation Consent

Please read the following statements and check you agree with them before consenting to take part in the study. You have read the participant information above and agree to participate in this study You have been given the opportunity to ask questions about the study You have been given adequate time to consider your decision and agree to take part in the study You understand that you are free to withdraw consent for involvement, however, as the survey is anonymous, once the 'submit' button is clicked, it will not be possible to withdraw.

1. Do you agree to participate in this survey? The data collected will be used to improve understanding of attitudes, opportunities and barriers to achieving the Net Zero target in the beef and sheep sector.

○ I agree to take part in this survey

Page 2: General farm information

2. Do you own, rent or manage your farm?

- Wholly owned
- Wholly tenanted/rented
- Mostly owned with some rented land
- Mostly tenanted/rented land
- Manage/employed on a farm

3. How are your livestock marketed?

Please select between 1 and 3 answers.

- Livestock market
- Abattoir
- Direct Sales
- Other

3.a. If you selected Other, please specify:

4. Does your farm have a direct link to the supply chain? For example, a contract with a supermarket or meat processor.

- Yes
- No

5. Please select the region of your main holding.

- England
- Northern Ireland

- Scotland
- Wales

6. Please specify your holding type. If you have land across different types, please select the type where the majority of your land falls.

- Hill
- Upland
- Lowland

7. Please specify the area of your holding (in hectares or acres)

	Area	Unit	
		Acres	Hectares
Total Area		☐	☐
Woodland		☐	☐

8. Types of livestock enterprise

- Beef only
- Sheep only
- Mixed (cattle and sheep)
- Other

8.a. If you selected Other, please specify:

9. Number of breeding ewes

Please enter a whole number (integer).

10. Number of suckler cows

Please enter a whole number (integer).

11. Number of store cattle

Please enter a whole number (integer).

12. Is your land registered as organic?

- Yes
- No

13. Do you run any diversification activities on your farm?

- Yes
- No

13.a. If yes, please state which diversitifcation activities you run on your farm.

- Agroforestry
- Alternative crops
- Alternative livestock e.g. poultry, dairy sheep/goats
- Alternative production systems e.g. regenerative, organic
- Energy production e.g. wind or hydro power

- [ ] Hosting weddings and conferences
- [ ] Letting out buildings
- [ ] Marketing skills/offering experience days e.g. wood, metal, leather working, rural crafts
- [ ] Providing animal services e.g. kennels, cattery, dog grooming/training, livery
- [ ] Selling farm produce e.g. farm shop, pick your own
- [ ] Tourism e.g. accommodation, camping, tourist attraction
- [ ] Other

13.a.i. If you selected Other, please specify:

____

14. Have you previously been involved in or are you currently part of an agri-environment scheme?

- ○ Yes
- ○ No

14.a. If yes, in which scheme(s) have you been involved in and for how long?

____

Page 3: Farm management and decision making

15. Which of these factors will have the biggest impact on your decision-making regarding your farming business over the next 5 years? (Please rank these answers in order of importance, with 1 being most important and 8 being least important)

Please don't select more than 1 answer(s) per row.

Please select exactly 8 answer(s).

Please don't select more than 1 answer(s) in any single column.

	1	2	3	4	5	6	7	8
Animal health e.g. bovine TB	☐	☐	☐	☐	☐	☐	☐	☐
Climate change	☐	☐	☐	☐	☐	☐	☐	☐
Post-Brexit trade deals	☐	☐	☐	☐	☐	☐	☐	☐
Market prices	☐	☐	☐	☐	☐	☐	☐	☐
Regulatory change e.g. NVZ	☐	☐	☐	☐	☐	☐	☐	☐
Extreme weather	☐	☐	☐	☐	☐	☐	☐	☐
Subsidy reform	☐	☐	☐	☐	☐	☐	☐	☐
Parasite control/resistance	☐	☐	☐	☐	☐	☐	☐	☐

16. What are the main opportunities you think climate change could bring to your farm? (Please select up 3 answers)

Please select between 1 and 3 answers.

- ☐ Better conditions for livestock
- ☐ Better prices for produce
- ☐ Carbon capture and storage
- ☐ Diversification e.g. tourism or farm shop
- ☐ Increased biodiversity
- ☐ Longer growing season
- ☐ New markets
- ☐ No opportunities
- ☐ Producing energy

- [ ] Reduced costs
- [ ] Other

16.a. If you selected Other, please specify:

[ ]

17. What are the main risks you think climate change may bring to your farm? (Please select up to 3 answers)

Please select between 1 and 3 answers.

- [ ] Animal husbandry issues e.g. heat stress, disease
- [ ] Crop failure/reduces yields
- [ ] Increased costs
- [ ] Increased taxes/regulations
- [ ] Lower price for produce
- [ ] Nutrient loss through run-off
- [ ] Price/profit volatility
- [ ] Soil erosion
- [ ] Unpredictable/extreme weather
- [ ] No risk
- [ ] Other

17.a. If you selected Other, please specify:

[ ]

18. Have there been any significant changes in stock numbers or land management on your farm in the last 5 years? Examples: changes in stocking density or type, land use change, crop production

- ( ) Yes
- ( ) No

18.a. If yes, please specify the change(s) and why these changes have occurred.

19. Do you have any firm plans to make significant changes to your farm business over the next 5 year? Examples: area farmed, farming infrastructure, enterprise type, livestock numbers

- Yes
- No

19.a. If yes, please specify the change(s) and why it is being planned.

Page 4: Carbon footprinting and carbon calculators

20. Has your farm ever been carbon footprinted?

- Yes, once
- Yes, more than once
- No

20.a. What motivated you to carbon footprint your farm? (Select all that apply)

Please select between 1 and 4 answers.

- Personal intrest
- Retailer/processor requirement
- Pressure from consumers
- Pressure from industry
- Other

20.a.i. If you selected Other, please specify:

20.b. If no, why haven't you had your farm carbon footprinted? (Select all that apply)

Please select between 1 and 4 answers.

- Cost
- Knowledge
- Lack of perceived benefit
- Time
- Other

20.b.i. If you selected Other, please specify:

21. What are your biggest concerns regarding the carbon footprinting process and carbon calculators?

(Select all that apply)

Please select between 1 and 4 answers.

- ☐ Accuracy of results from carbon calculators
- ☐ Difference in results between carbon calculators
- ☐ Don't understand the results
- ☐ The amount of input data required
- ☐ Other

21.a. If you selected Other, please specify:

Page 5: The Net Zero target

In 2019, the UK was the first country to legislate the Net Zero greenhouse gas emissions by 2050 target, which will require the livestock sectors to adapt their systems. Net Zero will be achieved on farms when on-farm greenhouse gas emissions (e.g. from livestock and fertiliser use) are in balance with on-farm carbon sequestration (e.g. in trees and soils). For farms to achieve Net Zero, the primary focus should be on reducing emissions, as it means less land is needed for sequestration to off-set those remaining emissions.

22. Do you think the government Net Zero target is achievable for the beef and sheep sector?

- ○ Yes
- ○ No
- ○ Don't know

23. Do you think Net Zero is achievable on your farm?

- ○ Yes
- ○ No
- ○ Don't know

23.a. If no, why do you think the Net Zero target is not achievable on your farm? (Select all that apply)

Please select between 1 and 8 answers.

- ☐ Already highly efficient so hard to achieve efficiency gains
- ☐ Current emissions are too high
- ☐ There are only a few measures that I can apply on my farm
- ☐ Lack of knowledge on mitigation/sequestration options
- ☐ Livestock emissions are hard to reduce
- ☐ Not enough land for sequestration
- ☐ Restricted by management control e.g. tenanted farm
- ☐ Too expensive
- ☐ Other

23.a.i. If you selected Other, please specify:

23.b. Are you aware of what you need to do on your farm to move towards the Net Zero target?

- Very aware
- Aware
- Somewhat aware
- Not aware
- Unsure

23.c. Has the Net Zero target influenced your decision-making or farming practices in the last 5 years?

- Yes
- No

Page 6: Mitigation measures

24. Listed below are a series of measures which have the potential to reduce net greenhouse gas (GHG) emissions and may be relevant to your farm. Please rate each measure on the likelihood you would implement them on your farm.

Please don't select more than 1 answer(s) per row.

	Already implemented	Currently considering	Would consider in future	Would not consider	Not applicable on my farm	Don't know
Improved synthetic nitrogen use e.g. soil analysis, N planning tool, decreasing margin of error of N fertiliser application and not applying in wet conditions	☐	☐	☐	☐	☐	☐
Low emission spreading of slurry (e.g. slurry injection) or incorporating FYM within 24 hrs	☐	☐	☐	☐	☐	☐
Shifting autumn manure application to spring	☐	☐	☐	☐	☐	☐
Introducing legumes (e.g. clovers) in grass mixtures – legumes fix N from atmosphere, reducing need for N fertilisation	☐	☐	☐	☐	☐	☐
Use of nitrification inhibitors – compounds applied to soils which reduce nitrogen losses	☐	☐	☐	☐	☐	☐
Improving cattle and sheep nutrition e.g . increasing digestibility of feed can decrease enteric methane emissions and improve yields	☐	☐	☐	☐	☐	☐

Improving cattle and sheep health e.g. improving the feed conversion ratio and reducing the herd/flock breeding overhead (through improved fertility and reduced mortality)	☐	☐	☐	☐	☐	☐
Selection for balanced breeding goals in cattle – genetic improvement in beef cattle (increases yields but also reduces emission intensity through e.g. directly measuring carcass weights)	☐	☐	☐	☐	☐	☐
Slurry acidification – adding strong acid to slurry in house, in storage tank or before field application to achieve optimal pH, which can lower nitrogen losses	☐	☐	☐	☐	☐	☐
Feeding methane inhibitors – feed additives which inhibit enteric fermentation and therefore reduce methane emissions e.g. 3NOP	☐	☐	☐	☐	☐	☐
Anaerobic digestion – manure is converted into digestate which can be spread as well as biogas which can be used as energy	☐	☐	☐	☐	☐	☐

Behavioural change in fuel efficiency e.g. actively managing fuel use, regular maintenance, improved driving style	☐	☐	☐	☐	☐	☐
Reducing stock numbers	☐	☐	☐	☐	☐	☐
Increased afforestation	☐	☐	☐	☐	☐	☐
Management practices to increase soil carbon sequestration e.g. reduced tillage, cover crops, manure application	☐	☐	☐	☐	☐	☐
Grazing management e.g. rotational grazing	☐	☐	☐	☐	☐	☐
Biochar – adding a charcoal-like substance to soil which can store more carbon	☐	☐	☐	☐	☐	☐

25. What are the most important factors to you when considering mitigation measures for your farm? (Please rank these answers in order of importance, with 1 being most important and 6 being least important)

Please don't select more than 1 answer(s) per row.

Please select exactly 6 answer(s).

Please don't select more than 1 answer(s) in any single column.

	1	2	3	4	5	6
Abatement potential (potential GHG reduction)	☐	☐	☐	☐	☐	☐
Cost	☐	☐	☐	☐	☐	☐
Your knowledge of the change needed	☐	☐	☐	☐	☐	☐
Labour	☐	☐	☐	☐	☐	☐
Management control e.g. tenant farmer	☐	☐	☐	☐	☐	☐

Time	☐	☐	☐	☐	☐	☐

26. If you have already implemented any mitigation measures, what were your main reasons/motivations to do this? (Select all that apply)

Please select between 1 and 5 answers.

- ☐ Economic gains
- ☐ Productivity gains
- ☐ Reducing GHG emissions
- ☐ Retailer requirement
- ☐ I have not implemented any mitigation measures

27. Are you aware of any additional benefits of the GHG **mitigation** measures listed above (e.g. nitrogen planning, legumes, animal health or nutrition)?

- ○ Yes
- ○ No

27.a. If yes, what are the additional benefits of the GHG **mitigation** measures listed above?

28. Are you aware of any additional benefits of the GHG **sequestration** measures listed above (e.g. afforestation or measures to increase soil carbon sequestration)?

- ○ Yes
- ○ No

28.a. If yes, what are the adiditonal benefits of the GHG **sequestration** measures listed above?

29. What do you consider the main barriers to increased afforestation on farms? (Select all that apply)

Please select between 1 and 5 answers.

- ☐ Cost
- ☐ Lack of experience/management skill
- ☐ Lack of perceived benefit
- ☐ Management control e.g. tenant farmer
- ☐ Time
- ☐ Other

29.a. If you selected Other, please specify:

Page 7: Improving uptake of mitigation measures

30. Who do you think should be responsible for improving the uptake of mitigation measures and driving a reduction in on farm GHG emissions? (Please rank these answers in order of importance, with 1 being most important and 6 being least important)

Please don't select more than 1 answer(s) per row.

Please select exactly 6 answer(s).

Please don't select more than 1 answer(s) in any single column.

	1	2	3	4	5	6
Farmers	☐	☐	☐	☐	☐	☐
Farming unions	☐	☐	☐	☐	☐	☐
Government	☐	☐	☐	☐	☐	☐
Levy boards	☐	☐	☐	☐	☐	☐
Processors	☐	☐	☐	☐	☐	☐
Retailers	☐	☐	☐	☐	☐	☐

31. What would be needed for you to amend your farming practices to reduce GHG emissions? (Select all that apply)

Please select between 1 and 5 answers.

- ☐ Additional training
- ☐ Financial incentives
- ☐ Knowledge exchange events e.g. farm open days, webinars
- ☐ New skills
- ☐ Compliance with new regulations
- ☐ Other

31.a. If you selected Other, please specify:

32. How satisfied are you that the new proposed schemes (Environmental Land management (ELMS) in England or Sustainable Farming Scheme (SFS) in Wales) will support farmers to reduce emissions

and adopt mitigation measures?

- Very satisfied
- Satisfied
- Neither satisfied nor dissatisfied
- Dissatisfied
- Very dissatisfied
- Don't know

Page 8: Personal information

33. Gender identity

- Male
- Female
- Other
- Prefer not to say

34. Your age

- 16-17
- 18-25
- 26-35
- 36-45
- 46-55
- 56-65
- >66

35. What is your position in the farming business?

- Sole trader
- In partnership (family business)
- In partnership (non-family business)
- Farm manager/employee
- Part of a co-operative/joint venture

36. What is your employment status?

- Full-time farming
- Part-time farming and part time work off-farm
- Full-time work off-farm and farming in spare time