NET ZERO & LIVESTOCK

Centre for Innovation Excellence in Livestock

HOW FARMERS CAN REDUCE EMISSIONS

APRIL 2022

Contents

1. Preface

Delivering our UK ambition for net zero carbon by 2050 continues to be a major focus for all sectors of the economy and society. An output from COP26 was the commitment to science-based plans focused on recognised methodology, with regular reporting of progress against agreed targets. The need for rapid and coordinated action was the clear and consistent message.

Within agriculture, livestock production continues to receive considerable scrutiny. There is a lot of great work taking place within supply chains, but we need to accelerate the activity and help provide the information and tools that work at farm level.

We recognise that it is not just about emissions. Delivering holistic sustainability is a much broader concept, encompassing topics such as biodiversity and environmental management, rural communities and infrastructure, economics and continued provision of nutritious food. Farmed animals have an important role to play here. However, it is emissions that we are measured against. We can and must minimise emissions and reduce the carbon footprint of our livestock food products. This will be delivered through a focus on efficient use of resources, minimising waste and appropriate use of new technologies and practices. This report is focused on how we can reduce emissions at farm level.

CIEL's 2020 report, Net Zero Carbon & UK Livestock, established benchmarks for a range of farming systems across the main livestock types in the UK. This 2022 report builds on that by looking at a wide range of 'mitigations' - the strategies and technologies that can reduce emissions. This will provide farmers, their advisers, supply chain partners and policymakers with information on a range of options to consider, ultimately supporting better, evidence-based decision-making.

As with our 2020 report, we have commissioned an independent panel of expert scientists to provide evidence from which to assess the relative merit of this range of mitigation options. Absolute impacts will be dependent on an individual farm's situation, but this is the best evidence we have for comparing mitigations for cost, ease of implementation, impact and confidence in the evidence.

There is something useful for all types of farm systems in this report. Good animal husbandry to improve flock or herd efficiency will reduce emissions. Choosing lower carbon cost feedstuffs will deliver benefits. New products and technologies have the potential to advance us faster. Most likely, our journey towards net zero will involve some combination of available options. Farmers must choose those best suited to their individual situation.

In reading this report, it is important to consider the following points:

1. National Inventories for greenhouse gases (GHG) do not consider emissions occurring overseas. So, for global impact, we use life cycle assessment (LCA) of a product's carbon footprint. This methodology is employed by the majority of carbon calculators.
2. For some mitigations, the science is still evolving or evidence is sparse. This is reflected in assessments of 'certainty'. There is an urgent need for research to address critical knowledge gaps.
3 There is a great need for innovation – our 2020 report concluded that known technology can deliver less than half of the reductions sought, so new innovations are essential to deliver the remaining target reduction.

CIEL has a key role in delivering the innovations needed for the livestock-food sector. We have the capability required to address a range of issues and can call upon expertise to help drive innovation through industry-academic partnerships. Please contact us to explore and develop your research plans or innovation ideas.

Lyndsay Chapman, CEO at CIEL

Lyndsay

Lyndsay Chapman

2. Executive summary

This report provides a high-level guide, looking at key mitigations livestock farmers can adopt now or shortly, to reduce their carbon footprint and drive down net emissions reported through the National Inventory. It follows the CIEL report in 2020 on Net Zero Carbon & UK Livestock.

For dairy, beef and sheep systems, mitigations for improving production efficiency, through, for example, improved fertility, health and genetic gain, contributed significantly to reducing the carbon footprint and overall emissions. This often requires investment and system changes on farms. However, this practice has the advantage of requiring fewer animals for the same level of output. Fewer animals with improved efficiency result in more land being available for woodland and/or forestry, for example, capturing carbon within the farm. The scale of this carbon capture will depend on the nature of the afforestation or other strategies adopted, along with land type and location. For a typical 200 cow dairy herd, we estimated emissions could be lowered by 15% through improved production efficiency coupled with afforestation of land released.

More importantly, dietary methane inhibitors were found to be very effective at reducing the carbon footprint of dairy, beef and sheep farms, and on reducing methane emissions from ruminants at a national level. Dietary methane inhibitors should be available in the near future. However, while this report has made an assumption with regard to their efficacy, scientific investigation and innovation is still required to optimise their adoption and effectiveness for grass-based systems.

Prof. Elizabeth Magowan
Director, AFBI
and VP, British Society of Animal Science

Other mitigations, such as age at first calving, adoption of anaerobic digestion (AD) and use of nitrification inhibitors were addressed. Modelling found that they can all contribute positively within ruminant systems.

With regard to pigs and poultry, while their impact on national emissions is smaller than ruminants, their carbon footprint is greatly influenced by the source of feed ingredients. The effect of land use change (or not) associated with the protein ingredients within pig and poultry diets had the most significant impact on the carbon footprint within the farm case studies. For example, the carbon footprint of the pig and broiler farms modelled increased by over 100% when the protein ingredients were associated with land use change, compared to when no land use change was considered. It is noted that home-grown ingredients will be of most benefit if sourced from 'non-land use change' practices. Soya from 'non-land use change' practices grown in other countries should not be considered negatively.

Changes associated with manure management practices, such as using manure from pig and poultry farms in AD systems, should also be associated with reductions in carbon footprint.

Scenarios and mitigations described in this report are not exhaustive but demonstrate the potential reduction that might be achieved in the global warming impact of livestock farming in the UK. The way to measure this global warming potential will also be a critical factor in the years ahead, such as the conversion of methane emissions to CO_2 equivalents (CO_2-eq), i.e. the potential replacement of GWP100 with GWP* to better represent the short-lived nature of methane gas.

However, the 'global cooling' effect often shown by GWP* calculation will only cool the planet long-term if methane emissions continuously fall into the future.

Lastly, this report has highlighted that through wide-scale adoption (100% across the UK) of some of the most impactful mitigations, a 23% reduction in GHG and a 15% reduction in ammonia emissions from UK agriculture could be achieved. While this is encouraging, it also indicates much more innovation, adoption and the realisation of carbon capture is needed to contribute to the UK goal of net zero by 2050.

Overall, livestock farming can reduce its emissions significantly and capture more carbon in the years ahead. Achieving this will involve a combination of strategies and wide-scale adoption. It is also vital that farms measure and monitor their carbon footprint and act on the information it provides. Carbon calculators are essential tools to help farmers reduce their footprint. However, their benefits will only be optimised if overall emissions are reduced at the national level. Further detailed modelling is needed to establish how this can be achieved whilst supporting the food security of the UK.

Livestock farming can reduce its emissions significantly by a combination of strategies and wide-scale adoption.

3. Introduction

The UK is approximately 60% self-sufficient in terms of meat and milk.

As such, the livestock industry provides a vital source of high quality, nutritious food to the UK population and, in doing so, supports the food security of the UK.

Whilst climate change is a result of human activity, including global population growth and the affluence of that growing population, there are many ways in which livestock farming can reduce its carbon footprint to help achieve the ambition of slowing climate change.

In 2020, CIEL published their Net Zero Carbon & UK Livestock Report. The report was compiled by leading academics from across the UK and outlined the current state of the art knowledge on this topic and eight recommendations for the livestock industry to take forward.

To complement the 2020 report, this report now provides a high-level guide on the key interventions livestock farmers can make now or in the near future to reduce their carbon footprint and drive down net emissions as reported through the National Inventory. It also indicates their potential impact on 'case study' farms as estimated using an industry carbon calculator (Agrecalc carbon calculator (SRUC)) and applying GWP100 impact assessment method.

Furthermore, this report highlights the impact of some key mitigations when applied to the respective sectors and the UK agriculture industry as a whole, as determined through the Inventory of GHG and Ammonia Emissions from UK Agriculture (the National Inventory). While this report focuses mainly on quantifying the emission reductions that can be achieved, the magnitude of potential carbon sequestration is also suggested on case study farms, mainly as a result of releasing land and planting forestry.

In all the case studies modelled, the principle of maintaining output levels, mainly due to improvements in productivity, was adopted. This was to demonstrate the possibility of reducing the carbon footprint of livestock systems while also maintaining the overall current output from these systems since they play a vital role in the UK's food security.

This report is split by livestock type. For each species, key mitigations are described and their impact modelled. The results presented should be considered as case studies that highlight the potential on real farms. The case studies and list of mitigations are not exhaustive, and indeed, this work has flagged the need for more in-depth modelling across a wide range of possible scenarios.

Overall, this report highlights to farmers and personnel within the supply chain the key actions to start considering and adopting, if they haven't already done so, to drive towards a lower carbon livestock industry across the UK.

Background

The two main drivers in achieving a low carbon livestock industry and making a significant contribution to the net zero goal in the UK include management interventions that minimise GHG emissions whilst increasing carbon sequestration. Many of these key actions should also improve the circularity of nutrient use on farms and farm profitability.

The ruminant sector, especially beef and dairy, represent the main contributors of GHG emissions from UK livestock production (**Figure 1**). The two main GHG being emitted from livestock systems are methane (CH_4) and nitrous oxide (N_2O). Carbon dioxide (CO_2) is also emitted but is a minority gas compared with methane and nitrous oxide. Ammonia (NH_3) is also an important gas of consideration regarding the impact of livestock farming on air quality and can be considered an 'indirect' GHG. Methane emissions arise mainly from the digestion processes of ruminants (enteric fermentation) and the storage of slurry. Nitrous oxide emissions are primarily a result of nitrogen management and application in ruminants and monogastric systems (i.e. manure and fertiliser).

While the level of methane and nitrous oxide emissions are important in their own right, to standardise their impact the term 'carbon footprint' is often used and has a unit called 'carbon equivalents'. This is where the global warming potential of each gas is considered and converted to a figure which would be the equivalent global warming potential of carbon dioxide (CO_2).

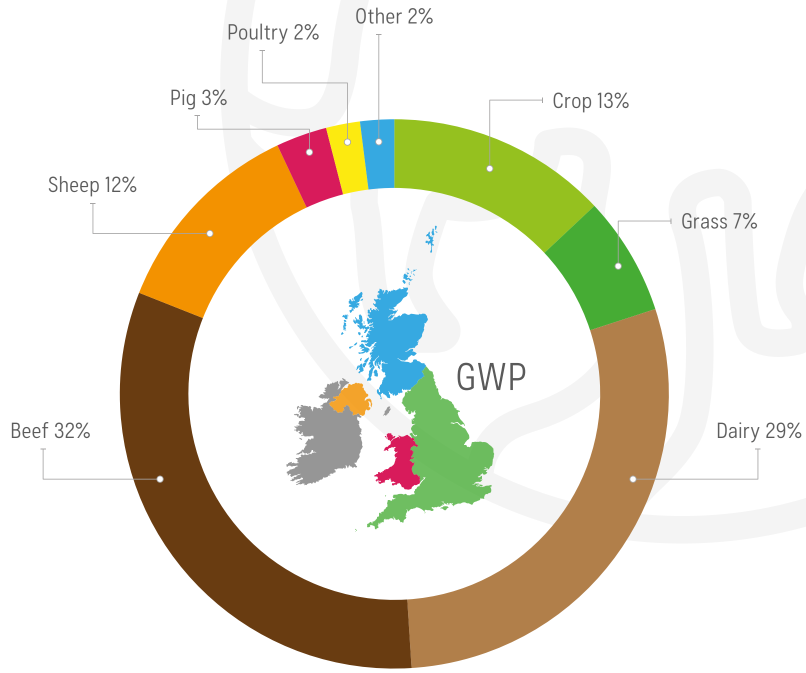


Figure 1
The percentage contribution of each livestock type to the total global warming potential as reported by the 2019 UK National Inventory.

Methane is considered to have 25 times the global warming potential of carbon dioxide, whereas nitrous oxide is considered to have 298 times the global warming potential (GWP100 methodology, version AR4). Alternative methods for capturing the climate change effect have been developed, such as GWP*. However, the most common methodology and that used in the National Inventory is GWP100 and therefore is the method used in this report.

Ruminants are the main contributors to livestock emissions (70-80%)

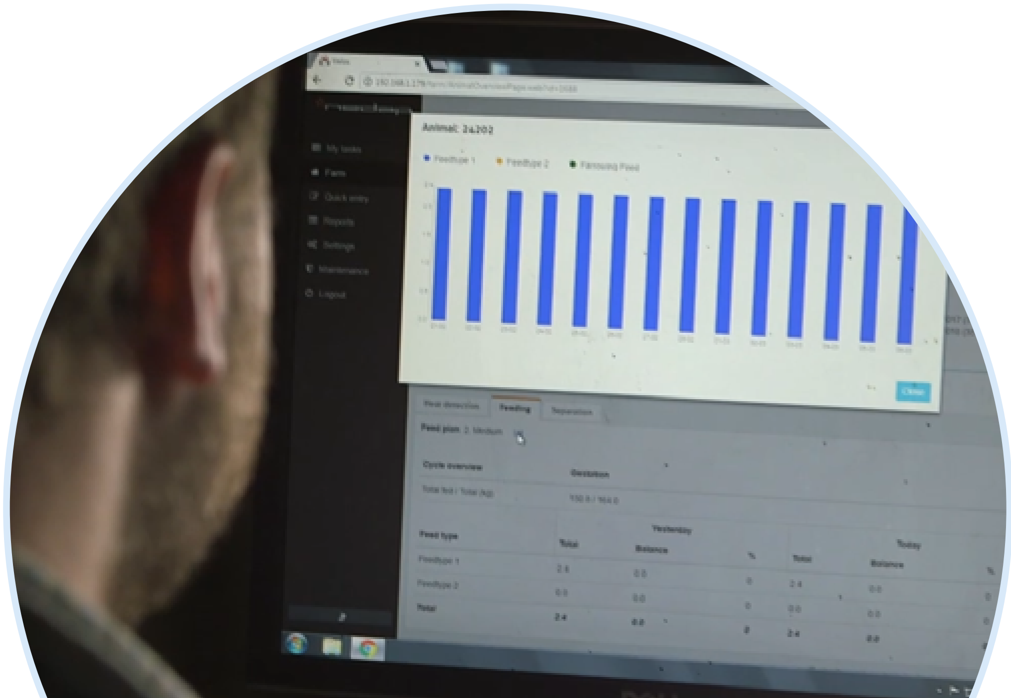
GWP* takes account of the fact that methane is a short-lived gas. This consideration generally amplifies the benefit of mitigation strategies that reduce methane emissions. Long-term, however, these mitigations are known to have a beneficial impact only under circumstances where annual methane emissions fall continuously rather than through a single measure.

This is an important consideration when reviewing the information presented in this report. The overall goal is to reduce the climate impacts arising from livestock farming by reducing GHG emissions and their global warming potential.

As noted above, this report uses both a carbon calculator and the National Inventory to demonstrate the impact of mitigations. **Section 4** explains in more detail the key differences between these two types of accounting and their use.

This report outlines how farmers can reduce emissions. It also quantifies the impact of these mitigations within a range of farm case studies.

Other publications which complement this document includes a report by Kite Consulting, which provides a detailed overview of carbon calculators and their use. While a brief description of mitigations is provided in the appendix of this report, a recent report published by Innovation for Agriculture and Eunomia provides detail on several mitigations from a farmer perspective. Lastly, it is recognised that soil management is also critical in the strive to achieve a lower carbon livestock industry. A recent report by the Soil Association provides good information on how to maximise soil health.



4. Overview to using this guide

This guide outlines key mitigations to reduce GHG emissions. It covers the main agricultural livestock types across the UK (dairy, beef, sheep, pigs and poultry) and is presented in a series of tables. The mitigations have been selected on a scientific basis, i.e. where the impact is best known as a result of scientific studies. As such, the mitigations listed do not represent an exhaustive list.

Given the variation in systems, scale and performance across farming sectors, it should be noted that the information provided is generalised. Individual farm circumstances will determine how easy it is to undertake specific mitigation measures as well as their impact. Nonetheless, this approach does support the identification of a range of options that could be adopted now, or soon, to support a low carbon livestock industry.

The reader should be aware that whilst there is a section per livestock type, the impact of some mitigations are common across several livestock types and further details on some of these are described separately in **Section 5.** Information specifically about farm landscape carbon sequestration is presented in **Section 7.**

The table on the next page lists criteria that different mitigations have been assessed against and includes background notes for each. Use this as a key for the tables presented for each livestock type.

Within each livestock type, the impact of a number of mitigations were modelled using real farm case studies.

This modelling considered the impact on the carbon footprint of the farm as calculated using a carbon calculator, as well as the impact of the mitigation if applied at a national level.

Table 1 Key to information contained in later tables of this report that characterise mitigations for each livestock type.

Criteria	Notes
Cost	High (H), Medium (M) or Low (L) rating has been assigned to provide an indication of the cost of the mitigation, relative to the costs of the other mitigations that could be adopted within each livestock type. Absolute cost and value from the mitigation will vary due to specific farm circumstances.
Ease of implementation	High (H), Medium (M) or Low (L) rating is applied to how easy it would be for a typical farmer to implement the mitigation at the present time.
State of readiness to implement	Assigned as 'Now' or 'Later', based on whether the technology or know-how is currently available or will be available in the future.
Potential GHG mitigating effect	Arrows indicate the specific GHG affected by the mitigation. The main gases detailed are CH_4 and N_2O since these are the main gases of consideration within livestock systems. To achieve the reductions, we assume that overall farm output remains constant. So, for mitigations aligned with improvements in efficiency, it is assumed that lower numbers of animals are required due to improved productivity i.e. total emissions decrease. Usually, the impact is a direct effect of the intervention, but in some situations, emissions are affected indirectly.
Impact on carbon footprint	High (H), Medium (M) or Low (L) rating has been assigned to the potential impact when applied as a mitigation through a carbon calculator. Note that the footprint is sometimes reported as 'carbon equivalents' CO_2-eq. CH_4 has a higher global warming effect (in the short-term) than CO_2, whilst N_2O has an even greater global warming effect than either CH_4 or CO_2. To standardise the global warming impact of gases, this 'carbon equivalent' metric effectively converts the global warming effect of CH_4 and N_2O to that of CO_2.
Agriculture Inventory	'Yes' (Y) is assigned whether the Inventory takes account of impact from the mitigation in either a direct or indirect manner. Where 'No' (N) is assigned, the Inventory does not currently take any account of this as a mitigation either directly or indirectly i.e. the mitigation may benefit the individual farm but will not count towards 'inventory accounting' (used by government to measure the carbon emissions and carbon capture at a sectoral and national level).
Certainty	High (H), Medium (M) or Low (L) rating is applied to indicate how confident science is about the impact of the mitigation. In some cases, there is a robust body of evidence to support the impact of the mitigation, but for others, more research is needed to provide a higher degree of confidence.
Other impacts	It is recognised that a singular focus on carbon could have both a positive impact on other environmental pressures, but also result in unintended consequences. Where this is the case, an indication is given where the science base suggests beneficial impacts on the other key environmental considerations such as biodiversity (B), ammonia emissions (NH_3) and phosphorus excretion (P).

Explaining the difference between carbon footprint and inventory accounting

A 'Life Cycle Assessment' (LCA) is commonly used to establish the carbon footprint at the farm level, with several 'carbon calculator' tools using this approach.

LCA aims to measure all emissions, including imported materials, but definitions of boundaries for the 'space' the assessment covers can differ between LCA for different products, processes or systems. In a LCA, the 'space' or 'system boundary' often includes upstream and downstream practices such as the growing and processing of feed, especially outside the UK and outside the relevant sector or industry.

There are several whole farm and sector-specific carbon calculators commercially available. The CIEL Net Zero Carbon & UK Livestock Report compared a number of these. However, they continue to evolve to fit commercial farms better, releasing updates as they are developed.

The Agrecalc carbon calculator was used in this report since Agrecalc has a strong link between industry usage and academic researchers (especially with those involved in this report). Furthermore, many of its underlying assumptions align with IPCC methodology, representing the core methodology used within inventory accounting.

The use of Agrecalc in this report is not an endorsement of this calculator over others. It is simply the one our consortium of scientists had direct access to.

By contrast, the national calculation of GHG emissions and carbon sequestration is calculated using the National Inventory. In simple terms, the National Inventory uses activity data from across the UK, e.g. animal numbers, age at slaughter, milk or meat yield etc, alongside 'emission factors' for key practices such as dietary characteristics, manure storage and spreading and the rate of uptake of these key practices.

Using this activity data, rates of uptake and emission factors, the total volume of GHG emitted and the total amount of carbon sequestrated by land use, land use change and forestry (LULUCF) are calculated. The National Inventory is used for national accounting purposes and aligns with national policy and international reporting obligations. However, it accounts only for the emissions produced within the UK and is aligned with a specific sector or industry.

Furthermore, as reported in the National Inventory, the agriculture sector accounts for emissions only from agriculture practices. However, other reporting sectors, such as LULUCF and energy, take account of other activities such as carbon sequestration and fuel use, respectively.

Establishing a farm's carbon footprint is a vital step to reduce emissions per unit of product. However, it will only count towards the UK goal of net zero if efforts are made to reduce overall total emissions, not just reducing emissions per unit of milk or meat produced.

The vast majority of mitigations will reduce the national volume of GHG emitted and the carbon footprint of a farm. However, there is potential for conflict between the two accounting systems if the number of livestock increases, even though their carbon footprint may be decreasing.

This report aimed to highlight scenarios where both the carbon footprint of the farm decreases, as well as the gross emissions at a national level.

5. Achieving net emissions by livestock type

5.1 Dairy cattle

Sector snapshot

- The dairy industry plays a significant role in UK agriculture, with milk production valued at £4.4bn in 2020 (16.4% of total agricultural output).
- Dairy's contribution to agricultural GHG emissions is dominated by CH_4 (from the digestion of feed and slurry management) and N_2O emissions (mainly from the application of manure and fertiliser).
- The UK dairy industry has made steady progress in mitigating GHG emissions over the last 30 years, in terms of both the efficiency of production and total emissions.
- Total emissions have fallen by 16.1% (1.12Mt CO_2-eq) between 1990 and 2020.
- This reduction was primarily due to increased average annual milk production per cow (from 5151l in 1990 to 8204l in 2020, representing a 59% increase) coupled with decreased dairy cow numbers (from 2.9m in 1990 to 1.9m in 2020, a 35% reduction).
- Additional improvement in milk production efficiency has supported a consequent reduction of 12.8% in the GHG emission intensity (based on CO_2-eq per unit of milk produced, g/kg).

Mitigation strategies for GHG emissions in dairy cattle

Although a number of overlaps exist between strategies, mitigation in dairy production can largely be divided into nutrition-based and management-based strategies (**Table 2**). Nutrition-based strategies achieve mitigation goals mainly through manipulation of dietary composition to increase milk production and feed utilisation efficiency, or dietary inclusion of feed additives to inhibit enteric CH_4 emissions. Nutrition-based strategies also include grassland management, mainly by offsetting the need for concentrates. Where nutritional strategies involve the use of home-grown crops, such as the increased use of forage maize with a potential reduction in grassland, such changes could then release significant carbon - therefore, it must be a consideration when assessing mitigation measures specific to a farm. However, grassland management can also drive a reduction in and/or improve the efficient use of fertilisers, which helps to reduce N_2O emissions or emissions associated with fertiliser application. Most of the management-based strategies work by means of animal, slurry and fertiliser management, e.g. genetic improvement. Genetic improvement in traits linked to productivity, health, feed efficiency, and in the future CH_4 production directly, will also be a positive step to improving the carbon footprint. Although the short-term impact may be relatively low, with the impact of genetics being cumulative year-on-year and permanent, it is an important strategic mitigation tool.

Table 2 Potential for mitigating GHG emissions in dairy cattle.

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Feed related								
Higher starch content diet	M	H	Now	CH_4 ↓	M	Y	H	
Increasing dietary oil and fat content, dietary inclusion of oilseeds	M	H	Now	CH_4 ↓	M	Y	H	
Low crude protein diets	L	H	Now	CH_4 ↓ N_2O ↓	M	Y	H	NH_3
Feeding tannin- and saponin-rich forage	M	H	Now	CH_4 ↓	M	N	H	
Feeding rumen CH_4 inhibitors								
3-NOP	Unknown	H	Later	CH_4 ↓	H	N	H	
Nitrate*	L	L/M	Now	CH_4 ↓	M	N	H	
Active compounds from seaweeds	Unknown	H	Later	CH_4 ↓	H	N	M	
Specialised feed ingredients/additives	M	H	Now	CH_4 ↓	L	N	M	
Forage related								
Grass-legume mixtures, multi-species swards	L	M	Now	N_2O ↓ CH_4 ↓	M	Y	H	B
Improved forage quality by early harvest, increasing grazing frequency, decreasing regrowth interval, etc	L	H	Now	CH_4 ↓	M	Y	H	
Increasing maize silage proportion in diet	L	M	Now	CH_4 ↓	M	Y	H	
See Section 4 of this report to support the interpretation of this table.								

*Extreme care required during incorporation to diets due to animal health concerns.

Table 2 Potential for mitigating GHG emissions in dairy cattle (continued).

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Animal related								
Genetic improvement in productivity (production, replacement rate longevity, health)	L	H	Now	CH_4 ↓ N_2O ↓	L	Y	H	NH_3
Improved fertility	L	M	Now	CH_4 ↓ N_2O ↓	M	Y	H	NH_3
Reducing age at first calving	L	M	Now	CH_4 ↓ N_2O ↓	M	Y	H	NH_3
Improved animal health	M	M	Now	CH_4 ↓ N_2O ↓	M	Y	H	NH_3
Manure/fertiliser related								
Covering slurry stores	H	L	Now	Depends on what cover is made of	L	Y	H	NH_3
Anaerobic digestion	H	L	Now	CH_4 ↓	M	Y	H	
Acidification	H	L	Now	CH_4 ↓ N_2O ↓	M	N	H	NH_3
Nitrification and urease inhibitors	M	H	Now	N_2O ↓	M	Y	H	NH_3
Low emission slurry spreading	H	H	Now	N_2O ↓	L	Y	H	NH_3

See Section 4 of this report to support the interpretation of this table.

Dairy cattle

Options

1. Complete regular (e.g. annual) carbon audits, using a reliable carbon calculator, to establish a baseline and identify hotspots to monitor emission reductions and changes in carbon footprint.
2. Maintaining a high level of production efficiency is essential through high health status for the herd, reducing age at first calving, optimising calving interval, replacement rate, cow longevity, and optimising feed inputs to match animal need.
3. Improve both quality and utilisation of forage as this is a major component of cow diets.
4. Reduce the need for artificial fertiliser whilst maintaining or enhancing sward productivity by including legumes in pasture mix and promoting soil health and fertility.
5. Increase starch and concentrate proportions in the diet within recommended guidance levels to reduce CH_4 production per unit of feed intake. Depending on baseline diet, management and animal factors, this strategy could increase milk output. Wider environmental considerations associated with carbon footprint of feed components and farm nutrient balance must be considered, not just financial impact.
6. Novel feed additives can reduce CH_4 production in the rumen, but many are not yet available or not yet proven on UK dairy farms.
7. Genetic improvement can help reduce emissions if focused on component traits, such as productivity relative to cow size, feed efficiency, fertility, longevity or health. This should be part of farm decision making now, to deliver long-term emission reductions.
8. How slurry or manure is stored and utilised can reduce emissions.
   a. Additives can reduce emissions from stored manure.
   b. Low emission spreading reduces NH_3 and N_2O emissions while improving nitrogen (N) usage efficiency, thereby reducing the need for artificial fertiliser.
   c. Precision application of manure and fertiliser can better match soil nutrient status with plant nutrient uptake. Soil testing for key nutrients will be essential to do this.

Modelling the impact of mitigations on UK farms

Dairy cattle

Mitigations identified within dairy systems as having the highest potential impact included:

- Use of methane inhibitors (i.e. to reduce the methane produced from the digestion process).
- Improved sward productivity.
- Improved herd efficiency resulting in fewer animals needed to produce a similar output.
- Slurry/fertiliser management.

While there are a range of dairy systems, this report specifically focused on two case studies:

- Lower-yielding, spring calving herd.
- Higher-yielding, indoor herd.

Key features of the lower-yielding, spring calving dairy herd case study

Farm facts

- 203.5ha grazing platform.
- 394 crossbred cows.
- Yielding 5267l/cow at 4.50% butterfat and 3.67% protein.
- Age at first calving: 24 months.
- Stocking rate: 2.64LU/ha.
- 242kg N/ha fertiliser.

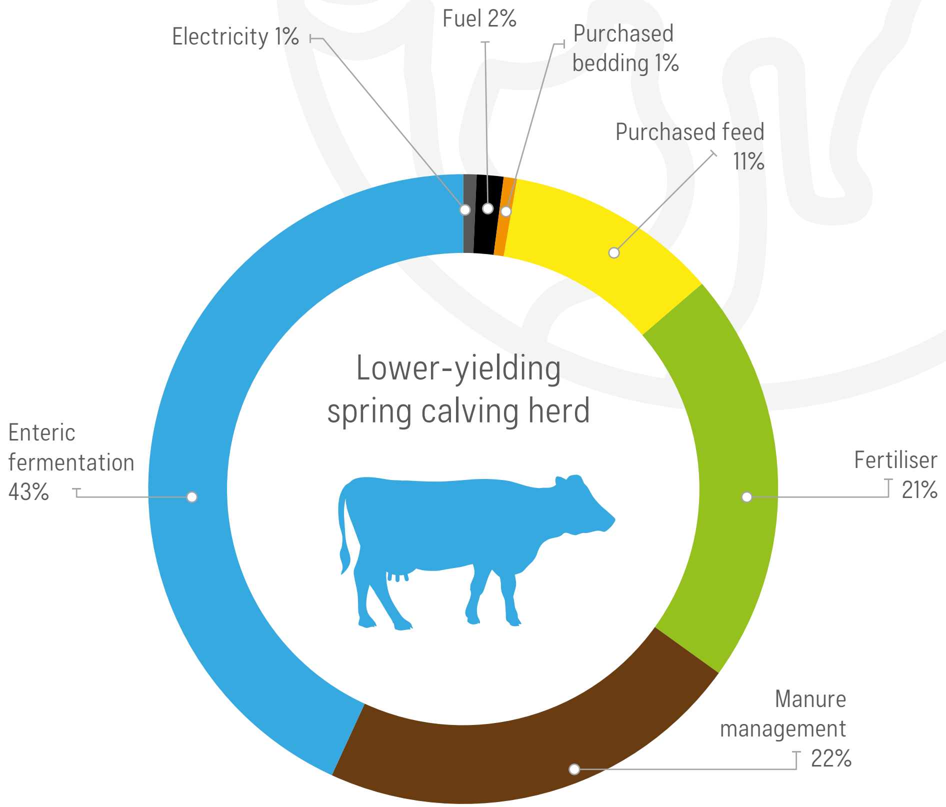


Figure 2

Contribution made by various parts of the lower-yielding spring calving herd to the overall carbon footprint.The main contributors to the carbon footprint are methane production from enteric fermentation (feed digestion) and nitrous oxide from fertiliser and manure management. The total emissions were 3374 t CO_2-eq which equated to 1.46 kg CO_2-eq/kg milk.

Farm mitigations modelled

Within the spring calving dairy herd, the following mitigations were modelled (see appendix for more details on the mitigations):

1. Earlier sale of surplus followers and enhanced grassland productivity.
2. Use of a urease inhibitor with urea-based fertiliser and use of a nitrification inhibitor with other N fertilisers use.
3. Inclusion of legumes in grassland to primarily reduce N fertiliser use.
4. Inclusion of a methane inhibitor in diets with methane reduction effectiveness of:
   a. 15% or
   b. 30%.
5. A combination of mitigation 1 and 4b (at 30% effectiveness).

Afforestation of agricultural land released as a result of a lower number of animals needed, due to the positive impact of the mitigation on production efficiency, was included as an additional option. This was to demonstrate the onward opportunity for carbon capture on the farm.

The impact of each mitigation on the gross emissions of CO_2, N_2O, and CH_4, as well as the net emissions and carbon footprint were calculated using the Agrecalc carbon calculator.

Modelling results

- The spring calving herd was holding significantly more heifers in the 12-24 age group than necessary. Sale of 50 of these surplus heifers earlier in life; under one year of age, was modelled.
- Coupled with this change, it was identified an increase in grassland productivity by 10% was feasible by increasing grass yields to 12.1t DM/ha with no increase in N fertiliser application required. As a result of the sale of heifers and enhanced grassland productivity, the carbon footprint of the farm reduced by 7.5% to 1.35kg CO_2-eq/kg milk.
- If the land released due to this mitigation was utilised for forestry, this could reduce net emissions by a further 354t CO_2-eq per annum and reduce the carbon footprint by 17.8% to 1.20kg CO_2-eq/kg milk.
- The inclusion of a dietary additive methane inhibitor with either 15% or 30% effectiveness reduced total emissions by 240 and 481t CO_2-eq, respectively. The adoption of fertiliser amendments reduced N_2O emissions by 94t CO_2-eq and the inclusion of legumes in grassland reduced emissions by 282t CO_2-eq. **Table 3** shows that it was possible to reduce the carbon footprint by up to 14.4% by adopting these mitigations.
- The combined effect of the dietary inhibitor, selling surplus heifers, plus increased grassland productivity resulted in a 21.2% reduction in associated carbon footprint. If the land released due to the mitigation was utilised for forestry, this could reduce net emissions by over 1000t CO_2-eq per annum and reduce the carbon footprint per litre of milk by 31.5%.

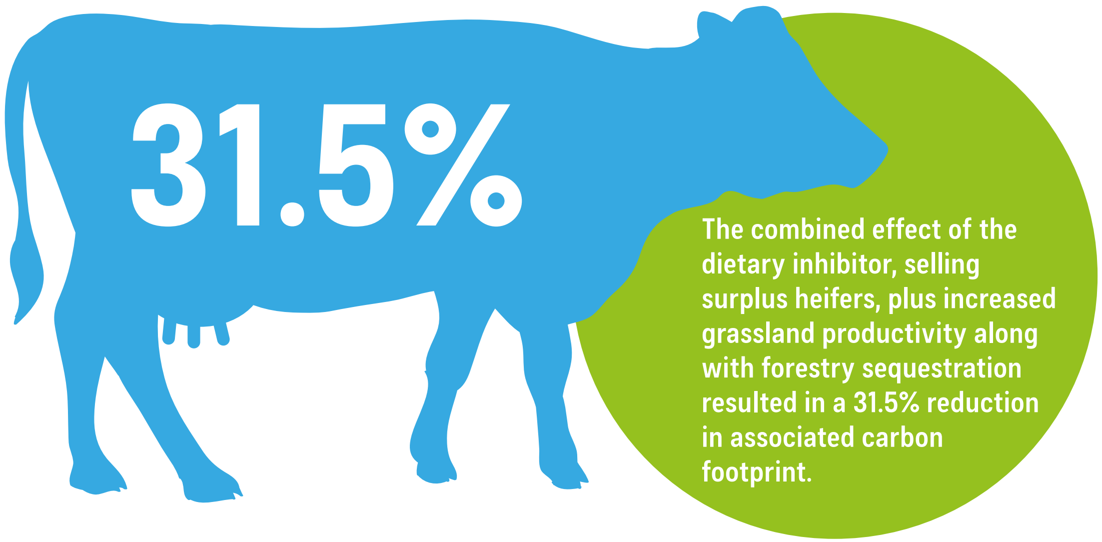


Table 3 Impact of mitigations singly or in combination on emissions and carbon footprint for a lower-yielding, spring calving dairy herd (all carbon footprinting results for dairy are reported on a fat and protein corrected basis).

Mitigation options Lower-yielding, spring calving herd	Total emissions ($t\ CO_2$-eq) and % change from baseline		Carbon footprint ($kg\ CO_2$-eq/kg milk) and % change from baseline	
Baseline	**3374**		**1.46**	
1. Sale of surplus followers and improved grassland	3116	-7.6%	1.35	-7.5%
If released land used for forestry	2762	-18.1%	1.20	-17.8%
2. Application of fertiliser amendments protected urea and N_2O inhibitors	3280	-2.8%	1.42	-2.7%
3. Inclusion of legumes in grassland	3092	-8.4%	1.34	-8.2%
4. Employing methane inhibitor:				
at 15% effectiveness	3134	-7.1%	1.36	-6.8%
at 30% effectiveness	2893	-14.3%	1.25	-14.4%
5. Combined effect:				
Sale of surplus followers, plus improved grassland plus dietary methane inhibitor (30% effective)	2662	-21.1%	1.15	-21.2%
If released land used for forestry	2308	-31.6%	1.00	-31.5%

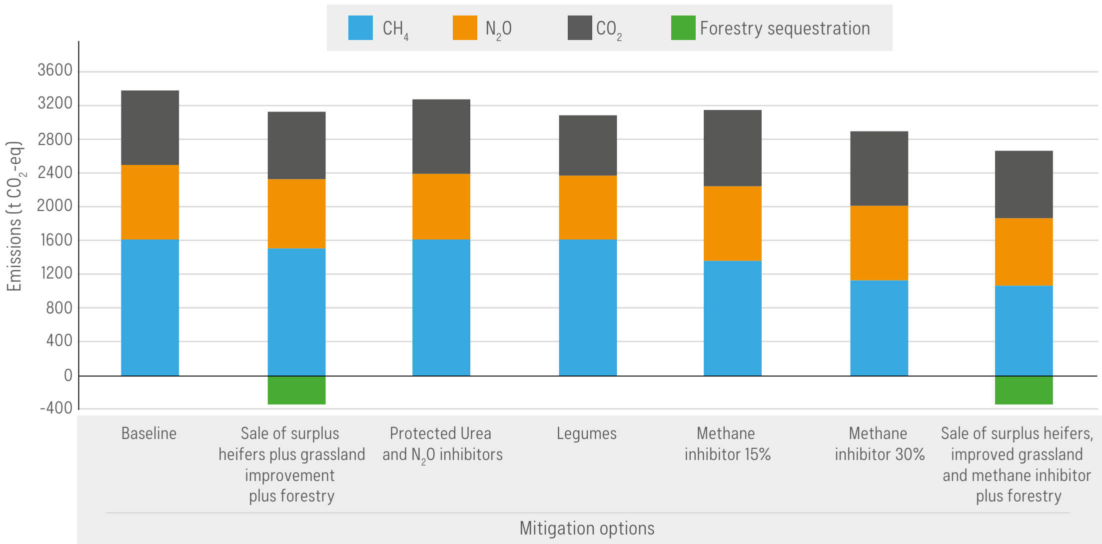


Figure 3

Spring calving dairy herd- Impact of mitigation strategies on emissions (including sequestration through forestry).

Key features of the higher-yielding indoor dairy herd case study

Farm facts

- 251.6ha grazing platform.
- 410 Holstein cows.
- Yielding 10,377l/cow with a butterfat of 3.49% and protein of 3.24%.
- Age at first calving: 25 months.
- Stocking rate: 2.27LU/ha.
- 159kg N/ha fertiliser.

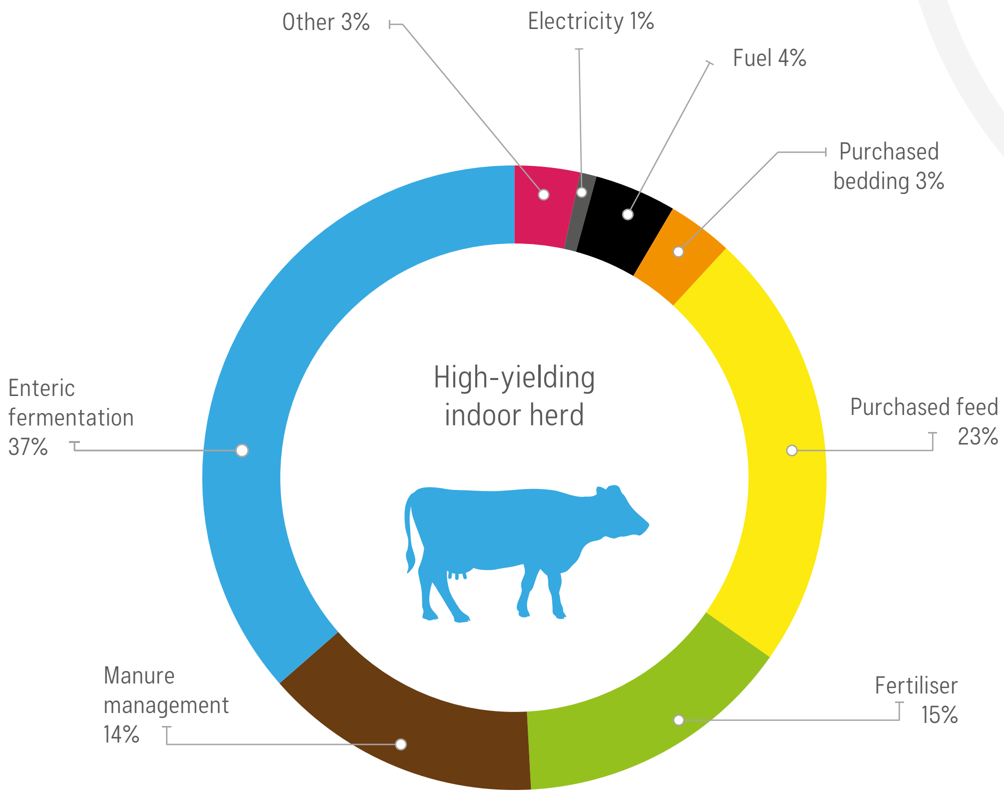


Figure 4

Contribution made by various parts of the higher-yielding indoor dairy system to the overall carbon footprint. The main contributors to the carbon footprint are methane production from enteric fermentation (feed digestion) and embedded emissions from purchased feed. The total emissions were 4851 t CO_2-eq which equated to 1.18 kg CO_2-eq/kg milk.

Farm mitigations modelled

In the higher-yielding indoor dairy herd, the following mitigations were applied **(see appendix for more details on the mitigations):**

1. Age at first calving reduced to 24 months.
2. Use of urease inhibitor with urea-based fertiliser and use of a nitrification inhibitor with other N fertilisers.
3. Inclusion of legumes in grassland to primarily reduce the need for N fertiliser.
4. Inclusion of a methane inhibitor in diets with methane reduction effectiveness of:
   a. 15% or
   b. 30%.
5. Combination of mitigations 1 and 4 (at 30% effectiveness).

Afforestation of agricultural land released as a result of a lower number of animals needed, due to the positive impact of the mitigation on production efficiency, was included as an additional option to demonstrate the onward opportunity for carbon capture on the farm.

The impact of each mitigation on the gross emissions of CO_2, N_2O, and CH_4, as well as the net emissions and carbon footprint were calculated.

Modelling results

- In the higher-yielding, indoor dairy herd, age at first calving was already good at 25 months. Therefore, it is unsurprising it had only a limited impact on GHG emissions (1% reduction).
- However, because the national average age at first calving is much higher (estimated at 29 months), the impact of reducing age at first calving from 29 to 24 months was modelled and is reported below. It is however, notable that the carbon footprint of the dairy enterprise reduced by 5% to 1.12kg CO_2-eq/kg milk when age of calving was improved and released land was utilised for forestry.
- As expected, the application of fertiliser amendments mainly affected N_2O emissions, reducing them by 17%. Inclusion of legumes in grassland reduced emissions by 193t CO_2-eq or 4%. Furthermore, the carbon footprint of the system reduced by 14% when the methane inhibitor (at 30% effectiveness) was applied.
- The combined effect of improving age at first calving and dietary methane inhibitor (30% effective) resulted in a 15% reduction in emissions and associated carbon footprint.
- If the land released due to the application of the combination of mitigations was utilised for forestry, this could reduce net emissions by over 811t CO_2-eq per annum and reduce the carbon footprint by 17% to 0.98kg CO_2-eq/kg milk.

Table 4 Impact of mitigations singly or in combination on emissions and carbon footprint for a higher-yielding, indoor dairy herd (all carbon footprinting results for dairy are reported on a fat and protein corrected basis).

Mitigation options– higher-yielding, indoor herd	Total emissions (t CO_2-eq) and % change from baseline		Carbon footprint (kg CO_2-eq/kg milk) and % change from baseline	
Baseline	**4851**		**1.18**	
1. Reducing age at first calving from 25 to 24 months	4784	-1.4%	1.17	-0.8%
If released land used for forestry	4721	-2.7%	1.12	-5.1%
2. Application of fertiliser amendments protected urea and N_2O inhibitors	4733	-2.4%	1.15	-2.5%
3. Inclusion of legumes in grassland	4659	-4.0%	1.14	-3.4%
4. Employing methane inhibitor:				
at 15% effectiveness	4508	-7.1%	1.10	-6.8%
at 30% effectiveness	4164	-14.2%	1.01	-14.4%
5. Combined effect:				
Reducing age cows first calf plus dietary methane inhibitor (30% effective)	4103	-15.4%	1.00	-15.3%
If released land used for forestry	4040	-16.7%	0.98	-16.9%

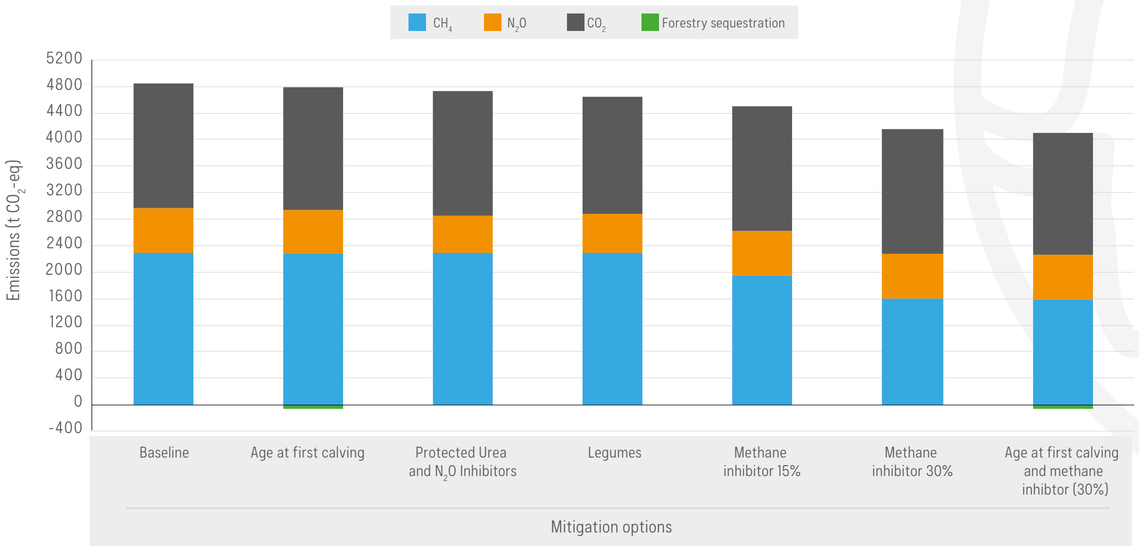


Figure 5

Indoor, higher-yielding system - Impact of mitigation strategies on emissions (including sequestration through forestry, although it had minor impact).

Application of the mitigations to the National Inventory

A number of mitigations were applied to the National Inventory (assuming 100% uptake rate across the UK) (**Table 5**). This was conducted to determine their impact on GHG emissions (and ammonia where applicable) within the UK dairy sector and the UK agricultural sector as a whole.

Farm mitigations modelled

1. Methane inhibitor used in all dairy animals:
   - Assumed effectiveness of 30% reduction.
2. Methane inhibitor used only in cows:
   - Assumed effectiveness of 30% reduction.
3. Increased productivity:
   - Assumed +15% in average milk yield per cow (genetic and/or health improvements). This resulted in 13% fewer dairy cows and followers for the same total output at national level.
   - Fertiliser nitrogen saving from land taken out of production accounted for.
4. Reduce age at first calving from 29 to 24 months:
   - Reduced number of followers required per dairy cow across UK. Same level of output at national level.
   - Fertiliser nitrogen saving on land taken out of production accounted for.
5. Use of nitrification inhibitor with dairy slurry application:
   - Nitrification inhibitor use with dairy cattle slurry (not FYM) was applied.
   - The inhibitor was assumed to reduce N_2O emissions from soils by 40% after spreading.
6. Dairy slurry processed by anaerobic digestion:
   - All dairy slurry processed through AD.
7. Use of nitrification inhibitor with all N fertiliser applied to all UK grassland:
   - In the National Inventory, grassland is reported separately from dairy, beef and sheep. For this exercise, use of inhibitors with nitrogen fertilisers was considered for all UK grassland.
   - Assumptions: 50% reduction in N_2O and 70% reduction in NH_3 by using urease and nitrification inhibitor with urea fertiliser, plus 25% reduction in N_2O by using nitrification inhibitor with AN (ammonium nitrate), CAN (calcium ammonium nitrate) and, AS (ammonium sulphate).
8. Combined effect of mitigations 1, 3, 4, 5, 6.

Modelling results

- A 20.3% reduction in GHG emissions was achieved within the dairy sector when a methane inhibitor (with an assumed effectiveness of 30% reduction) was applied to all dairy animals across the UK.
- This impact was halved when effectiveness of dietary methane inhibitors was assumed at 15%.
- Increasing productivity also had a notable impact on the sector (8.7% reduction in GHG), as did the reduction in age at first calving (4% reduction). With regard to ammonia emissions, increasing productivity had the most impact by reducing the emissions of ammonia from the dairy sector by 5.6kt, which equated to an 8.2% reduction at a sectoral level, and a 2.3% reduction within the overall Agricultural Inventory.
- Due to the assumed increase in milk yield to maintain overall output for the sector, the feed requirement and hence intake per cow increased in this scenario, increasing nitrogen excretion and methane emissions per cow. However, the overall impact of fewer cows was the main driver of reductions in emissions.
- When nitrification inhibitors were applied to nitrogen fertiliser, this also had a notable 9.7% reduction on GHG from grassland across the UK.
- All dairy slurry going to AD gave a 12% GHG reduction for the UK dairy sector and a 3.3% reduction for total Agricultural Inventory. However, it also increased ammonia emissions from the UK dairy sector by 6%.
- The combined effect of the main mitigations resulted in a 45% reduction in GHG (on CO_2-eq basis) within the UK dairy sector.
- A reduction in methane from enteric fermentation was the main contributor to this reduction, with a reduction in methane and nitrous oxide from storing and spreading liquid manure being secondary (because of fewer animals and the use of AD). This combination of mitigations also reduced ammonia emissions from the dairy sector by 12.3%.

Table 5 Impact of key mitigations on GHG emissions from the whole UK dairy sector and on the overall Agricultural Inventory.

	Impact on		
	GHG reduction for UK dairy sector		GHG reduction for whole of UK agriculture
Mitigation options	**kt CO_2-eq**	**%**	**%**
Methane inhibitor used in all dairy animals	2268	20.3	5.6
Methane inhibitor used only in cows	1764	15.8	4.4
Increased productivity	1006	8.7	2.5
Reduce age at first calving from 29 to 24 months	467	4.0	1.2
Use of nitrification inhibitor with dairy slurry application	178	1.6	0.4
Dairy slurry processed by AD	1343	12.0	3.3
Use of nitrification inhibitor with all N fertiliser applied to all UK grassland	246	9.7	0.6
Combined effect of mitigations 1,3,4,5,6	5030	45.0	12.5

Modelling the opportunity for carbon sequestration

In this scenario, we:

- Scaled down the National Inventory model to a realistic farm size (200 lactating cows).
- Implemented the mitigation of 'increased productivity'.
- Calculated the area of grassland that could be released due to improved productivity, without reducing milk production.
- The proportion of followers (all females before first calving entering the dairy herd) was calculated as 0.75 for every dairy cow in the herd (since this aligns with the ratio in the national herd, according to Inventory data).
- The net long-term rate of sequestration due to afforestation (i.e. grassland being converted to forestry) was assumed to be 3.8t C/ha/year, as previously suggested in a NERC-led report (Morison and Matthews, 2016[1]).
- As a result of increased productivity, 5.2ha could be freed up. Assuming this land was all suitable to be converted to forestry, 73t CO_2-eq could be sequestered on the farm per year. This, in addition to the GHG reduction realised due to the intervention itself on emissions (107t CO_2-eq reduction), creates an overall GHG reduction on the farm of 180t CO_2-eq i.e. 15% lower emissions overall.

Table 6 Key characteristics of the dairy farm before and after the impact of increased productivity was applied and resulting carbon sequestration potential.

Impact of increased productivity	Before	After	Change
Lactating cows			
Herd size – lactating cows	200	174	-13%
Yield per head (l)	8122	9340	+15%
Grass per head (kg)	3747	4137	+10%
Grass per herd (kg)	749,467	719,443	-4%
Land required (ha)	62.5	60.0	-4%
Total output (l)	1,624,400	1,624,400	No change
Followers			
Number of followers	150	130	-13%
Grass per head (kg)	1675	1675	No change
Grass per herd (kg)	251,303	218,531	-13%
Land required (ha)	20.9	18.2	-13%
Total land required (cows + followers)	83.4	78.2	-6%
Impact of increased productivity on carbon sequestration due to afforestation on net GHG emissions.			
	Before	**After**	**Change**
Herd size – lactating cows	200	174	-13%
GHG/cow/year (includes followers) – (t CO_2-eq)	6.14	6.44	+5%
GHG per herd – (t CO_2-eq)	1227	1120	-9%
Land available for forestry sequestration (ha)	0	5.2	
Assumed sequestration potential of 3.8t C/ha/year = 13.9t CO_2-eq/ha/year			
Realised sequestration – (t CO_2-eq)	0	73	-6%
Net GHG reduction (=1227-1120+73) – (t CO_2-eq)	0	180	-15%

- A review of literature (Dewar and Cannell, 1992[2]) suggests the upper and lower limits of carbon sequestration under forestry are in the region of 1.8 and 5.8t C/ha/year, respectively. If these were applied to this scenario, the amount of carbon reduction realised could range from 142t CO_2-eq (-12%) to 219t CO_2-eq (-18%).
- Within the current National Inventory, soil carbon sequestration under permanent grassland is assumed as zero (in equilibrium). However, science suggests under some circumstances, soil under permanent grassland could sequester carbon, although the values in literature represent a wide range. If we assume a moderate level of sequestration (200kg C/ha/year or 733kg CO_2-eq /ha/year), the permanent grassland on this farm could be reducing net emissions by 5.1%. It must be stressed this would be under specific circumstances and would not currently be captured in the National Inventory.

The carbon footprint on the case study farms showed a potential reduction of 14% through the use of methane inhibitors.

Take home messages

- These results are specific to these case study farms and will vary for other farm scenarios. Furthermore, the impact on the National Inventory assumed a 100% adoption rate across the UK, which is ambitious.
- Assuming dietary supplements designed as methane inhibitors could have high effectiveness in grazing systems (which is currently a challenge), this mitigation could significantly reduce GHG emissions. The carbon footprint on the case study farms showed a potential reduction of 14% and potentially 4-6% at a national level.
- Improved efficiency will also contribute considerably and will release land which can be used to capture carbon and therefore reduce the net emissions from the farm (potentially by 15%). The ability of the land to capture carbon will be dependent on the nature of afforestation adopted, which itself will be dependent on the land type and its location.
- Utilisation of forage legumes, protected fertilisers and nitrification inhibitors will reduce N_2O emissions and resultant GHG footprint (2-8% improvement).
- Processing of dairy slurry through AD is also an effective measure to reduce GHG emissions. While the National Inventory model can account for AD, it only accounts for changes in GHG emissions during manure storage and spreading and does not explicitly account for any fossil-fuel energy offsetting. This would be accounted for in the National Inventory for energy use.
- However, AD also increased ammonia emissions as a result of concentrating the nitrogen content in the digestate. Low emissions spreading (ideally trailing shoe or injection) of digestate is therefore essential to manage both GHG and ammonia emissions.
- Soil carbon sequestration under permanent grassland was not accounted for. Both the calculator and the Inventory align their methodology with IPCC, which does not assign a sequestration potential to the soil under grassland staying as grassland (i.e. permanent pasture). There is much uncertainty and debate regarding the potential quantities of carbon that soils under permanent grassland can sequester. This represents a major gap in knowledge to be addressed.

5.2 Beef cattle

Sector snapshot

- Beef and veal output in the UK totalled £2.9bn in 2020, accounting for about 11% of gross agricultural output in the UK.
- In common with dairy, the beef sector GHG impact is dominated by CH_4 (from the digestion of feed and slurry storage) and N_2O emissions (slurry and fertiliser application).
- The UK's beef production systems have improved their feed effciency gradually in recent years, through breeding programmes and nutritional management.
- The GHG intensity of UK produced beef is estimated to be around 48kg CO_2-eq/kg of meat from dedicated beef herds, equivalent to half of the global average (estimated at 99kg CO_2-eq/kg).
- The UK has efficient beef production by international standards (based on forage), while in some other countries land use change leads to emissions associated with clearing forests to grow forage and/or feed.
- Further improvements are required to contribute significantly to the UK's net zero 2050 goal, without having negative effects on animal welfare, health and beef production.

Mitigation strategies for GHG emissions in beef cattle

Although a number of overlaps exist between strategies, mitigation in beef production can largely be divided into nutrition-based and management-based strategies (**Table 7**). Nutrition-based strategies achieve mitigation goals mainly through manipulation of dietary composition to increase beef production and feed utilisation efficiency, or dietary inclusion of feed additives to inhibit enteric CH_4 emissions. Nutrition-based strategies also include grassland management, mainly by offsetting the need for concentrates. Where nutritional strategies involve the use of home-grown crops, such as the increased use of forage maize with a potential reduction in grassland, such changes could then release significant carbon - therefore it must be a consideration when assessing mitigation measures specific to a farm. Grassland management can also reduce and/or improve the efficient use of fertilisers, which helps to reduce N_2O emissions or emissions associated with fertiliser application. Most of the management-based strategies work by means of animal, slurry and fertiliser management. Genetic improvement in traits linked to productivity, health, feed efficiency, and in the future CH_4 production directly, will also be a positive step to improving the carbon footprint. Although the short-term impact may be relatively low, with the impact of genetics being cumulative year-on-year and permanent, it is an important strategic mitigation tool.

The estimated GHG intensity of UK produced beef is equivalent to half of the global average. However, further improvements are required to contribute significantly to the UK's net zero 2050 goal.

Table 7 Potential for mitigating GHG emissions in beef cattle.

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Feed related								
Higher starch content diet	M	M	Now	CH_4 ↓	M	Y	H	
Increasing dietary oil and fat content, dietary inclusion of oilseeds	M	M	Now	CH_4 ↓	M	Y	H	
Low crude protein diets	L	M	Now	CH_4 ↓ N_2O ↓	L	Y	H	NH_3
Feeding tannin- and saponin-rich forage	M	M	Now	CH_4 ↓	M	N	H	
Feeding rumen CH_4 inhibitors								
3-NOP	Unknown	M	Later	CH_4 ↓	H	N	H	
Nitrate*	L	M	Now	CH_4 ↓	M	N	M	
Active compounds from seaweeds	Unknown	M	Later	CH_4 ↓	H	N	M	
Specialised feed ingredients/additives	M	M	Now	CH_4 ↓	L	N	M	
Forage related								
Grass-legume mixtures, multi-species swards	L	M	Now	CH_4 ↓ N_2O ↓	M	Y	H	B
Improved forage quality by early harvest, increasing grazing frequency, decreasing regrowth interval, etc.	L	H	Now	CH_4 ↓	M	Y	H	
See Section 4 of this report to support the interpretation of this table.								

*Extreme care required during incorporation to diets due to animal health concerns.

Table 7 Potential for mitigating GHG emissions in beef cattle (continued).

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Animal related								
Genetic improvement in female productivity (fertility, health, longevity and early calf growth/survival)	L	M	Now	CH_4↓ N_2O↓	L	Y	H	NH_3
Genetic improvement in terminal productivity traits (e.g. growth rate)	L	M	Now	CH_4↓ N_2O↓	L	Y	H	NH_3
Genetic improvement in direct feed efficiency	L	L	Later	CH_4↓ N_2O↓	L	Y	H	
Improved animal health	M	M	Now	CH_4↓ N_2O↓	M	Y	H	NH_3
Reducing age at first calving	L	M	Now	CH_4↓ N_2O↓	M	Y	H	NH_3
Reducing the age at slaughter	L	M	Now	CH_4↓ N_2O↓	M	Y	H	NH_3
Manure/fertiliser related								
Covering slurry stores	H	L	Now	CH_4↓ N_2O↓	L	Y	H	NH_3
Anaerobic digestion	H	L	Now	CH_4↓	M	Y	H	NH_3
Acidification	H	L	Now	CH_4↓ N_2O↓	M	N	H	NH_3
Nitrification and urease inhibitors	M	H	Now	N_2O↓	M	Y	H	NH_3
Low emission slurry spreading	H	H	Now	N_2O↓	L	Y	H	NH_3

See Section 4 of this report to support the interpretation of this table.

Beef cattle

Options

1. Complete regular (e.g. annual) carbon audits, using a reliable carbon calculator, to establish a baseline and identify hotspots to monitor emission reductions and changes in carbon.
2. Delivering high production efficiency is essential through maintaining high health status of the herd, reducing age at first calving, optimising calving interval and reducing days to slaughter.
3. Forage represents the major part of the diet for cows and growing animals, so improving both the quality and utilisation of forage is critically important.
4. Reduce the need for artificial fertiliser, while maintaining or enhancing sward productivity, by including legumes in pasture mix and promoting soil health and fertility.
5. Increase starch and concentrate proportions in the diet within recommended guidance levels to reduce CH_4 production per unit of feed intake. Depending on baseline diet, management and animal factors, this strategy should increase liveweight gain. Wider environmental considerations associated with the carbon footprint of feed components and farm nutrient balance must be considered, not just financial impact.
6. Novel feed additives can reduce CH_4 production in the rumen, but many are not yet available or not yet proven on UK beef farms. Use within grazed grass systems is a challenge yet to be overcome. These are considered in more detail in **Section 6**.
7. Genetic improvement can help to reduce emissions from the herd if focused on component traits, such as productivity relative to cow size, feed efficiency, fertility, longevity or health. Similarly, genetic information for growth and carcass traits should be used in both dairy beef and suckler beef systems. Such information should be part of farm decision making now, to deliver long-term emission reductions.
8. How slurry or manure is stored and utilised can reduce emissions:
   a. Additives can reduce emissions from stored manure.
   b. Low emission spreading reduces NH_3 and N_2O emissions while improving N usage efficiency, thereby reducing the need for artificial fertiliser.
   c. Precision application of manure and fertiliser can better match soil nutrient status with plant nutrient uptake. Soil testing for key nutrients will be essential to do this.

Forage represents the major part of the diet for cows and growing animals, so improving both the quality and utilisation of forage is critically important.

Modelling the impact of mitigations on UK farms

Beef cattle

Within the beef sector, the case study being demonstrated was based on a spring calving suckler breeder-finisher system. This work was taken from a report by Bell et al. 2020[3] and more details of the work from which this scenario was taken can be found here. This case study focused on a beef suckler herd because it is a simpler system. However, close to half of UK beef is produced from the dairy herd. Beef bred from dairy cows offers substantial reductions in beef carbon footprint because the cows produce both milk and a beef calf. The implications of sexed-semen and effects on cow longevity can further reduce carbon footprint but this is a more complex set of interactions to model.

Key features of the beef case study

To assess the potential impact of the key mitigations for beef, the following parameters were assumed as a baseline:

- 100 cow herd.
- Cows average 700kg liveweight (LW).
- Silage-based winter diet.
- Calving rate 86%.
- 79 animals slaughtered per year.
- All pasture >10 years old.
- Rearing rate 80%.
- Beef animals slaughtered at 21 months old, weighing 650kg liveweight, 364kg deadweight.
- Homebred heifers, first calving at three years old.
- Forage quality: 10MJ ME and 11% crude protein (CP) under set stocking grazing.
- 28,756kg deadweight sold a year.

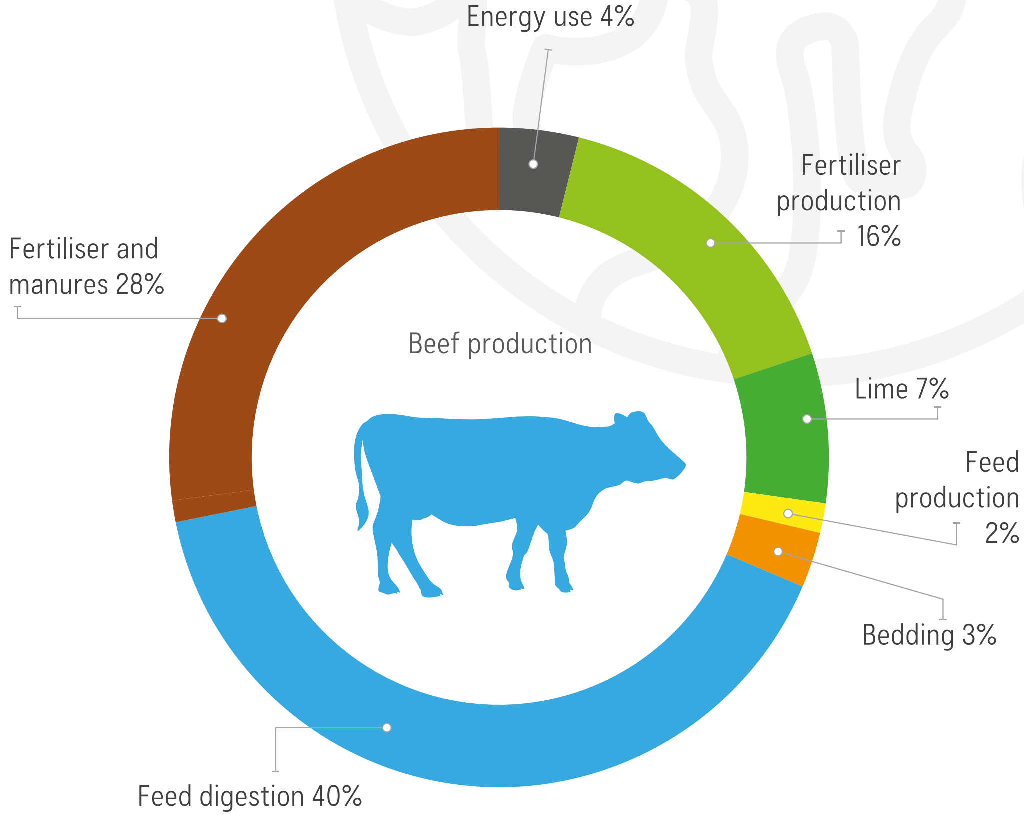


Figure 6

Baseline beef carbon footprint by activity (percentage of footprint calculated as kg CO_2-eq/kg deadweight) The main contributors to the carbon footprint are methane production from enteric fermentation (feed digestion) and nitrous oxide from fertiliser and manure management. The total emissions were 1027t CO_2-eq, which equated to 35.73kg CO_2-eq/kg deadweight.

Farm mitigations modelled

Within the beef system, the following mitigating strategies were considered **(see appendix for more details):**

1. Increase number of calves successfully reared.
2. Reduce age at first calving to two years.
3. Reduce cow weight by 10%.
4. Reduce age at slaughter from 21 to 18 months.
5. Improve grassland management.
6. Use methane inhibitors (3-NOP), assuming 10% effectiveness for grazing beef cattle.
7. Improve nutrient management.
8. Use nitrification inhibitors in artificial fertiliser.

In this exercise, all mitigations were run together sequentially within the model (i.e. stacked), instead of one at a time. The outcomes may have been affected due to their order of adoption within the model. This has raised the need for additional research to evaluate the carbon footprint reductions on an individual basis and to evaluate the interplay between mitigations and the impact this has on the rank of each mitigation within the stacked model.

Modelling results

- Reducing age at first calving from three to two years reduced all gas emissions, particularly methane, which reduced by 6.9%.
- Reducing age at slaughter from 21 to 18 months followed 'age at first calving' within the stacked order. It had a marked impact on all gases, with a reduction in the carbon footprint of 12.4%.
- Nitrification inhibitors further reduced the N_2O emissions from the farm by 6.2%.
- Reductions in enteric methane emissions by 20-30% using methane inhibiting feed additives is possible, however, given limited supplementary feeding when at grass, a 10% effectiveness was assumed in this case study. When this mitigation was included in this stacked case study, methane inhibitors reduced methane emissions from the total farm by 4.8%.
- Other mitigations, including improved grassland management and improved nutrient management reduced the overall carbon footprint by 8.0% and 3.9%, respectively.
- Overall, within this beef system, it was possible to reduce the carbon footprint by 37.2% when all mitigations were implemented (i.e. to 22.4kg CO_2-eq/kg deadweight).

Overall, within this beef system, it was possible to reduce the carbon footprint by 37.2% when all mitigations were implemented.

Table 8 Impact of mitigations on total herd emissions and beef carbon footprint. (Note that mitigations were added sequentially, so improvements were 'stacked' on those added before, meaning emission reductions increased in size as each mitigation was added).

Stacked mitigation for spring calving suckler breeder-finisher system

Mitigation options	Emissions (t CO_2-eq) and cumulate % change from baseline		Carbon footprint (kg CO_2-eq/kg deadweight) and cumulate % change from baseline	
Baseline	**1027**		**35.73**	
+ Increase number of calves reared by 5%	1051	+2.3%	35.23	-1.4%
+ Reduce age at first calving to two years	990	-3.6%	32.80	-8.2%
+ Reduce cow weight by 10%	943	-8.2%	32.45	-9.2%
+ Reduce age at slaughter to 18 months	844	-17.8%	28.41	-20.5%
+ Improve grassland management	777	-24.3%	26.15	-26.8%
+ Use methane inhibitor (3-NOP)	740	-27.9%	24.90	-30.3%
+ Improve manure and nutrient management	711	-30.8%	23.92	-33.1%
+ Nitrification inhibitor in artificial fertiliser	667	-35.1%	22.44	-37.2%

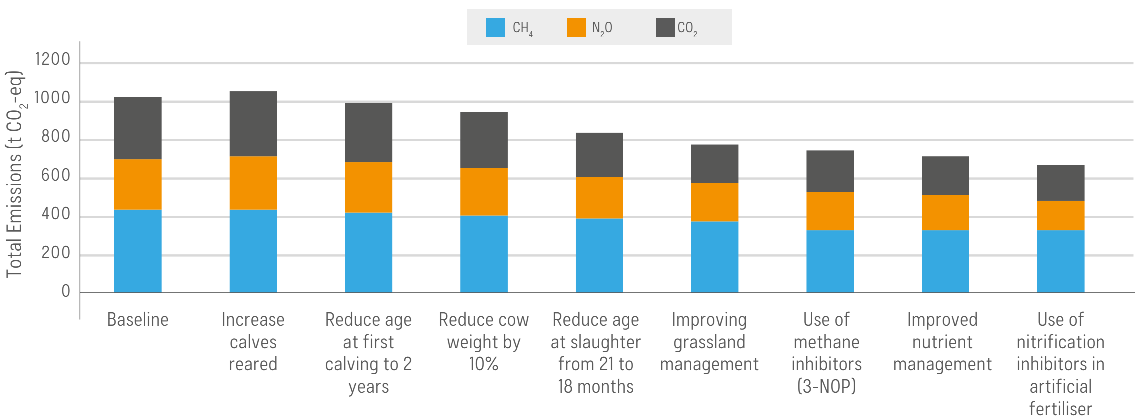


Figure 7

Beef – Stacked impact of mitigation strategies on methane, nitrous oxide and carbon dioxide.

Application of the mitigations to the National Inventory

A number of the key mitigations were applied to the National Inventory to determine their impact on GHG emissions within the UK beef sector and the UK agricultural sector as a whole.

Farm mitigations modelled

1. Methane inhibitor A: Applied to all lowland beef cattle:
   - Assumed effectiveness 30%.
2. Methane inhibitor B: Applied to all lowland beef cattle:
   - Assumed effectiveness 30%.
3. Increased productivity:
   - Leading to a 5% reduction in suckler cow numbers for the same total output at a national level. Gains may come from genetics, health or fertility.
4. Nitrification inhibitor with N fertiliser:
   - Grassland is a separate sector in the National Inventory, combined for dairy, beef and sheep.
   - Assumptions for all N fertiliser for all grassland: 50% reduction in N_2O and 70% reduction in NH_3, 25% reduction in N_2O.
5. Combination of mitigations 1 and 3.

Modelling results

- The level of adoption and effectiveness of modelled mitigations is highly ambitious for the UK beef sector.
- A 22% reduction in GHG emissions was achieved within the beef sector when a methane inhibitor (with an assumed effectiveness of 30% reduction) was applied to all beef animals across the UK.
- When the methane inhibitor was not offered to animals in the uplands, this impact reduced to 13.2% for the UK beef sector.
- Increasing productivity, resulting in a reduction of 5% in suckler cow numbers in the UK, reduced emissions from the beef sector by 1.6%.
- The application of nitrification inhibitors to nitrogen fertiliser had a notable 9.7% reduction on GHG from grassland across the UK (across dairy, beef and sheep).
- When the impact of methane inhibitors and increasing productivity was combined, they achieved a 23.2% reduction in GHG (on a CO_2-eq basis) within the UK beef sector. A reduction in methane from enteric fermentation was the main contributor to this reduction.

When the impact of methane inhibitors and increasing productivity was combined, they achieved a 23.2% reduction in GHG's within the UK beef sector.

Table 9 The impact of some key mitigations on the GHG emissions from the beef sector as a whole across the UK and their impact on the overall Agricultural Inventory.

		Effect on beef sector	Effect on total Agriculture Inventory
Mitigation options	**GHG reduction (kt CO_2-eq)**	**% reduction GHG**	**% reduction GHG**
Methane inhibitor A	2655	22.0	6.6
Methane inhibitor B	1593	13.2	4.0
Increased productivity	190	1.6	0.5
Use of nitrification inhibitor with all N fertiliser applied to all UK grassland	246	9.7	0.6
Combination of mitigations 1 and 3	2802	23.2	7.0

Modelling the opportunity for carbon sequestration

Mitigations modelled

- For a 100 cow suckler herd, a 5% reduction (as noted above for the National Inventory due to increased productivity), would result in a 95 cow herd post intervention.
- While maintaining farm output, the GHG emissions for the herd would reduce by 1.6% from 806t CO_2-eq to 793t CO_2-eq. Five less suckler cows would also free up 2.1ha of land.
- Assuming a sequestration potential of 3.8t C/ha/year, this would equate to a total of 13.9t CO_2-eq/ha/year sequestrated due to afforestation of the land released. As a result, the overall reduction in GHG emissions from sequestration and lower livestock emissions would be equivalent to 41.3t CO_2-eq, which represents a 5.1% reduction on the farm.

Take home messages

- Improving grassland management and reducing the age at first calving from three to two years significantly reduced the carbon footprint by 8 and 6%, respectively.
- Methane inhibitors will also play an important role in reducing the methane emissions from beef cattle. However, their adoption and effectiveness in beef systems will likely be more challenging than dairy systems due to the pasture-based nature of beef farming and lower levels/regularity of supplementary feeding.
- Improved production efficiency whilst maintaining total levels of beef output will release land, which can be used to capture carbon and reduce the net emissions from the farm. Using a 100 cow herd, a 5% reduction in GHG (carbon equivalents) was calculated when reductions of herd size, while maintaining overall output.
- While the impact of individual mitigations is highlighted, it is important to acknowledge that the order in which the mitigations were modelled in this case study may determine their impact. As such, further modelling is required to independently assess the impact of individual mitigations and the adoption of various other combinations of mitigations.

5.3 Lamb

Sector snapshot

- Mutton and lamb production in the UK was valued at £1.3bn in 2020 (accounting for 5% of the UK's gross agricultural output).
- CH_4 emissions produced as a result of digestion (enteric CH_4) are the largest component of on-farm emissions from UK sheep production, followed by N_2O emissions due to fertiliser and manure application to pasture.
- GHG emission intensity from sheep production is influenced greatly by farm type.
- There are lower emissions in lowland systems than in upland systems in the UK. This is due to higher outputs (kg of meat produced) per ha of land used and/or per breeding ewe in lowland systems.
- The average GHG emissions intensity of lamb produced by lowland systems was measured in a scientific study to be 11kg CO_2-eq/kg of liveweight and 13-18kg CO_2-eq/kg of liveweight for upland and hill systems, respectively.

Mitigation strategies for GHG emissions in lamb

Although a number of overlaps exist between strategies, mitigation in sheep production can be divided into nutrition-based and management-based strategies (**Table 10**). Nutrition-based strategies achieve mitigation goals mainly through manipulation of dietary composition to increase sheep production and feed utilisation efficiency, or dietary inclusion of feed additives to inhibit enteric CH_4 emissions. Nutrition-based strategies also include grassland management, mainly by offsetting the need for concentrates. However, grassland management can also reduce and/or improve the efficient use of fertilisers, which helps to reduce N_2O emissions or emissions associated with fertiliser application. Most of the management-based strategies work by means of animal and fertiliser management, e.g. genetic improvement, and precision farming. Genetic improvement in traits linked to productivity, health, feed efficiency, and in the future CH_4 production directly will also be a positive step to improving the carbon footprint. Although the short-term impact may be relatively low, with the impact of genetics being cumulative year-on-year and permanent, it is an important strategic mitigation tool.

Table 10 Potential for mitigating GHG emissions in lamb.

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Feed related								
Higher starch content diet	M	M	Now	CH_4 ↓	M	Y	H	
Increasing dietary oil and fat content, dietary inclusion of oilseeds	M	M	Now	CH_4 ↓	M	Y	H	
Low crude protein diets	L	M	Now	CH_4 ↓ N_2O ↓	M	Y	H	NH_3
Feeding tannin- and saponin-rich forage	M	M	Now	CH_4 ↓	M	N	H	
Feeding CH_4 inhibitors								
3-NOP	Unknown	M	Later	CH_4 ↓	H	N	H	
Nitrate*	L	M	Later	CH_4 ↓	M	N	H	
Active compounds from seaweeds	Unknown	M	Later	CH_4 ↓	H	N	M	
Specialised feed ingredients/additives	L	M	Now	CH_4 ↓	L	N	M	
Forage related								
Grass-legume mixtures, multi-species swards	L	M	Now	CH_4 ↓ N_2O ↓	M	Y	H	B
Improved forage quality by early harvest, increasing grazing frequency, decreasing regrowth interval, etc.	L	H	Now	CH_4 ↓	M	Y	H	
See Section 4 of this report to support the interpretation of this table.								

*Extreme care required during incorporation to diets due to animal health concerns.

Table 10 Potential for mitigating GHG emissions in lamb (continued).

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Animal related								
Genetic selection for inherently low enteric methane emissions	L	L	Later	CH_4↓	L	Y	H	
Genetic improvement in female productivity (fertility, lower mature weight, health, longevity and early lamb growth/survival)	L	L	Now	CH_4↓ N_2O↓	L	Y	H	NH_3
Genetic improvement in terminal productivity traits (e.g. growth rate)	L	M	Now	CH_4↓ N_2O↓	L	Y	H	NH_3
Improved animal health	L	M	Now	CH_4↓ N_2O↓	M	Y	H	NH_3
Finish lambs at a younger age	L	M	Now	CH_4↓ N_2O↓	M	Y	H	NH_3
First mating of ewes as lambs rather than yearlings	L	M	Now	CH_4↓ N_2O↓	M	Y	H	NH_3
Manure/fertiliser related								
Nitrification and urease inhibitors	M	H	Now	N_2O↓	H	Y	H	NH_3

See Section 4 of this report to support the interpretation of this table.

Lamb

Options

1. Complete regular (e.g. annual) carbon audits, using a reliable carbon calculator, to establish a baseline and identify hotspots to monitor emission reductions and changes in carbon pools.
2. Maintaining a high level of production efficiency is essential through high health status for the flock, reducing age at first lambing, increasing lambing rate, reducing lamb losses and enabling high lamb growth rates.
3. Forage represents the majority of the diet for breeding, growing and finishing sheep, so improving both quality and utilisation of forage is critically important.
4. Reduce the need for artificial fertiliser, while maintaining or enhancing sward productivity, by including legumes in pasture mix and promoting soil health and fertility.
5. Increase starch and concentrate proportions in the diet within recommended guidance levels to reduce CH_4 production per unit of feed intake. Depending on baseline diet, management and animal factors, this strategy should increase liveweight gain and ewe litter size. Wider environmental considerations associated with the carbon footprint of feed components and farm nutrient balance must be considered, not just financial impact.
6. Novel feed additives can reduce CH_4 production in the rumen, but many are not yet available or not yet proven on UK sheep farms. Use within grazed grass systems is a challenge yet to be overcome. These are considered in more detail in **Section 6**.
7. Genetic improvement can help reduce emissions for the ewe flock if focused on component traits, such as productivity relative to ewe size, feed efficiency, longevity, health, lamb growth and carcass traits. Such information should be part of farm decision making now, to deliver long-term emission reductions.
8. Consideration should be given to the use of controlled release fertilisers and protected urea fertilisers. Applications of manure and fertiliser should be timed to optimise plant nutrient uptake and taking account of soil nutrient status. Soil testing will be essential to this optimisation.

Genetic improvement can help reduce emissions for the ewe flock if focused on component traits, such as productivity relative to ewe size, feed efficiency, longevity, health, lamb growth and carcass traits.

Modelling the impact of mitigations on UK farms

Lamb

Within the sheep sector, three case studies were modelled; two hill farms and one lowland farm to demonstrate the diversity of systems. Enterprise types varied with a mixture of early and late lambing and store/finishers.

Key features of case study

To assess potential impact of key mitigations for sheep, the following baseline parameters were assumed:

- **Hill**
  - Farm one - 117ha platform, organic, 690 Welsh ewes.
  - Farm two - 93ha platform, 428 Mule and 133 Texel ewes.
- **Lowland**
  - 233ha platform, 900 Lleyn and 500 Abermax ewes.

Agrecalc was used to estimate the baseline carbon footprint and a Bangor University tool was used to calculate potential sequestration levels (Williams et. al., 2020) [6].

For each case study, the impact of each mitigation on the quantity of gross emissions (CO_2, N_2O, and CH_4) is reported. In this exercise, all mitigations were run together sequentially within the model (stacked) rather than one at a time. The outcomes may have been affected due to their order of adoption within the model. This highlights the need for additional research to evaluate carbon footprint reductions on an individual mitigation basis and to evaluate interactions between mitigations.

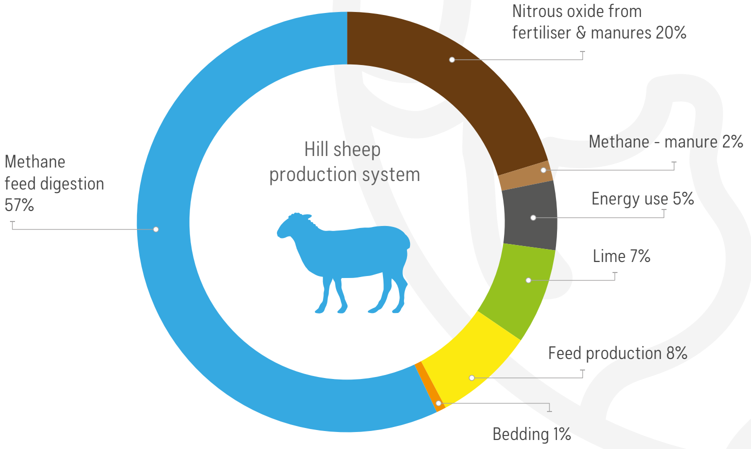


Figure 8

Baseline hill farm one carbon emissions by activity. Baseline total annual emissions were 385 and 347t CO_2-eq / year, for hill farms one and two, respectively. Not depicted is carbon captured by sequestration occurring in grassland, hedgerows and woodland, which amounted to 163 and 97t CO_2-eq / year, respectively.

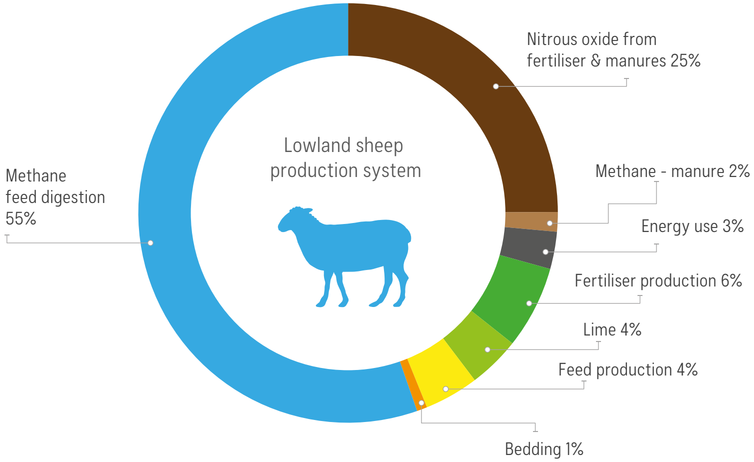


Figure 9

Baseline lowland sheep farm carbon emissions by activity. Baseline total annual emissions was 912t CO_2-eq / year. Not depicted is carbon captured by sequestration occurring in grassland, hedgerows and woodland which amounted to 226t CO_2-eq / year.

Farm mitigations modelled

Within the hill and lowland sheep systems, the following mitigating strategies for reducing gross emissions were assessed

Hill farm one

1. Improved fuel efficiency.
2. Legume grass mixtures.
3. Improved sheep health.
4. Improved sheep nutrition.
5. Methane inhibitors.

Hill farm two

1. Improved fuel efficiency.
2. Improved fertiliser use.
3. Legume grass mixtures.
4. Improved sheep productivity.
5. Methane inhibitors.

Lowland farm

1. Improved fuel efficiency.
2. Improved fertiliser use.
3. Nitrification inhibitors.
4. Improved sheep productivity.
5. Methane inhibitors.

For further details on these mitigations, please see appendix.

Modelling results

- A hill sheep system can reduce total GHG emissions primarily by reducing methane and N_2O emissions. The inclusion of dietary methane inhibitors and legumes greatly reduced total emissions by 19-22 and 10-14%, respectively. When stacked mitigations were applied, the carbon footprint of sheep meat was reduced by up to 67% on hill case study farms. For a lowland sheep system, it is possible to reduce total GHG emissions primarily through reducing methane and N_2O emissions. The inclusion of dietary methane inhibitors and improved sheep productivity (improved health and nutrition) greatly reduced total emissions by 19 and 7%, respectively. The carbon footprint of sheep meat was reduced by 37% on this lowland farm when stacked mitigations were applied.

- It is important to note the effectiveness of methane inhibitors in grazed grass systems remains challenging due to limited supplementary feeding and the fibrous nature of the diet. In this modelling, an ambitious effectiveness of 33% was assumed. Excluding the impact of dietary methane inhibitors gave a stacked GHG footprint reduction between 27-38% and 14% on hill and lowland case study farms, respectively.

The effectiveness of methane inhibitors in grazed grass systems is challenging due to limited supplementary feeding and the fibrous nature of the diet.

Table 11 Sheep system case studies: Emissions and carbon footprints for different scenarios. NB: Results are for stacked mitigations i.e. cumulated as mitigations are added. Changes are relative to the baseline and cumulate.* *Carbon sequestration included in footprint calculation.

Hill farm one					Hill farm two					Lowland farm				
Mitigation options	Emissions (t CO_2-eq) and cumulative % change		Carbon footprint (kg CO_2-eq/kg meat) and cumulative % change		Mitigation options	Emissions (t CO_2-eq) and cumulative % change		Carbon footprint (kg CO_2-eq/kg meat) and % change		Mitigation options	Emissions (t CO_2-eq) and cumulative % change		Carbon footprint (kg CO_2-eq/kg meat) and cumulative % change	
Baseline	**385**		**16.09**		**Baseline**	**347**		**23.7**		**Baseline**	**912**		**16.73**	
+ Improved fuel efficiency	**381**	-1.1%	**15.78**	-1.9%	+ Improved fuel efficiency	**345**	-0.6%	**23.5**	-0.9%	+ Improved fuel efficiency	**906**	-0.7%	**16.58**	-098%
+ Legume-grass mixtures	**328**	-15.0%	**11.91**	-26.0%	+ Legume-grass mixtures	**338**	-2.5%	**22.9**	-3.4%	+ Legume-grass mixtures	**896**	-1.8%	**16.34**	-2.4%
+ Improved sheep health	**308**	-20.1%	**10.49**	-34.8%	+ Improved sheep health	**303**	-12.6%	**19.6**	-17.5%	+ Improved sheep health	**877**	-3.8%	**15.88**	-5.1%
+ Improved nutrition	**302**	-21.7%	**10.04**	-37.6%	+ Improved nutrition	**279**	-19.6%	**17.3**	-27.2%	+ Improved nutrition	**816**	-10.6%	**14.38**	-14.1%
+ Methane inhibitors	**235**	-39.0%	**5.21**	-67.6%	+ Methane inhibitors	**225**	-35.2%	**12.1**	-49.0%	+ Methane inhibitors	**661**	-27.6%	**10.60**	-36.7%

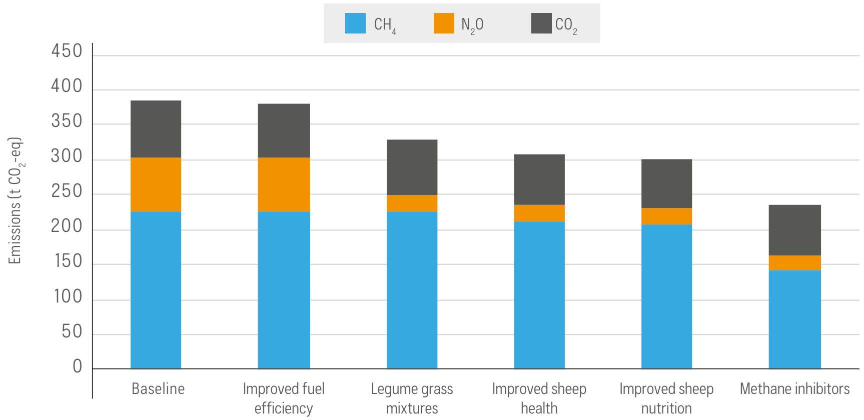


Figure 10
Hill sheep farm one – Stacked impact of mitigation strategies on emissions.

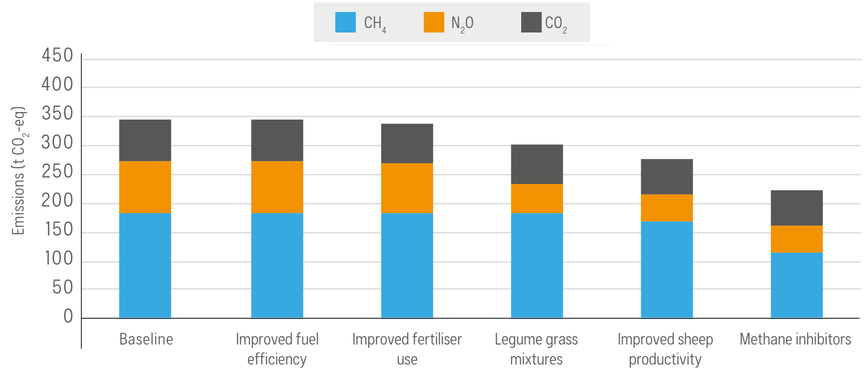


Figure 11
Hill sheep farm two – Stacked impact of mitigation strategies on emissions.

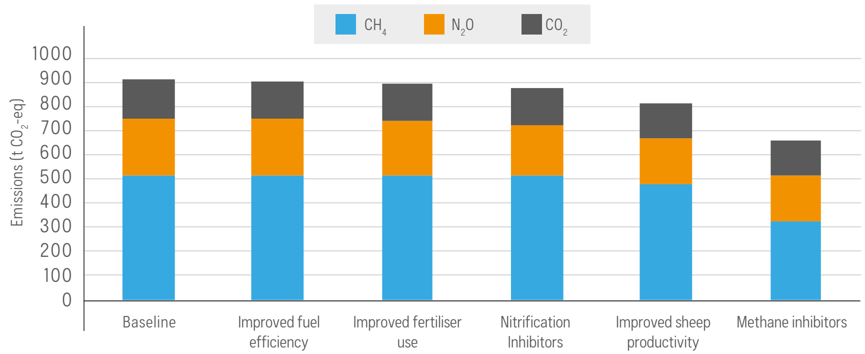


Figure 12
Lowland sheep –Stacked impact of mitigation strategies on emissions.

Application of the mitigations to the National Inventory

The impact of offering lowland sheep in the UK a methane inhibitor (with an assumed effectiveness of 30%) was applied to the National Inventory. This level of effectiveness is ambitious for the sheep sector, given the low levels of supplementary feeding and bolus delivery systems not yet available.

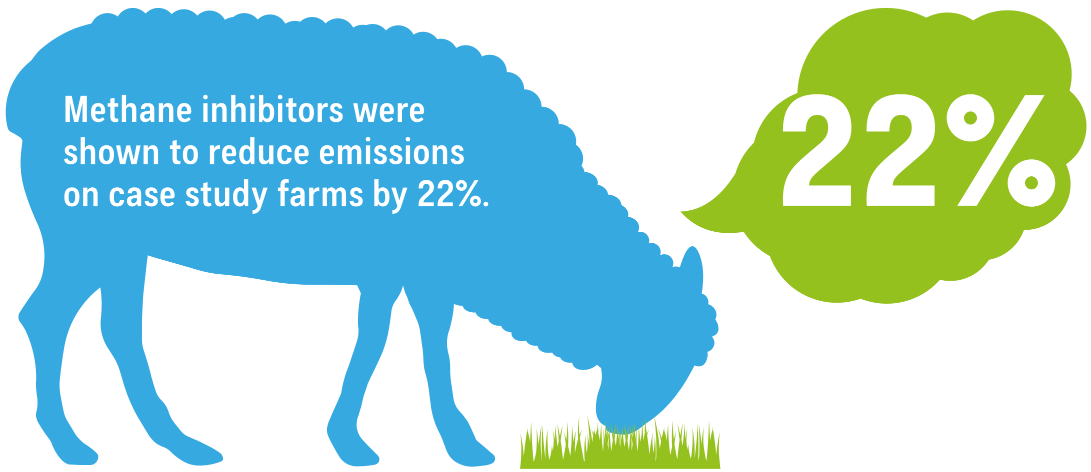
However, the impact of this scenario equated to a reduction of 471kt CO_2-eq (10.2% reduction in GHG emissions) from the UK sheep sector. This had the onward impact of lowering overall GHG in the Agricultural Inventory by 1.2%.

Table 12 The impact of a key mitigation on the GHG emissions from the sheep sector as a whole across the UK and their impact on the overall Agricultural Inventory.

	Impact on		
	GHG reduction for UK sheep sector		GHG reduction for whole of UK agriculture
Mitigation options	**kt CO_2-eq**	**%**	**%**
Methane inhibitor to lowland sheep	471	10.2	1.2

Take home messages

- Methane inhibitors will have a marked impact on GHG emissions and the carbon footprint of sheep farms if they can be effectively incorporated into sheep diets (22% reduction on case study farms).
- The inclusion of legumes in sheep pasture reduced total emissions by up to 14% based on the case study hill farms.
- Improved productivity can also contribute considerably (case study reduction in emissions of up to 7% on hill and lowland farms) and will release land, which can be used to capture carbon and therefore reduce the net emissions from the farm.



5.4 Pork

Sector snapshot

- Pig meat production in the UK is valued at £1.4bn in 2020.
- The GHGs impact contributions per unit of pig meat from the pig industry are relatively low compared with dairy, beef and sheep systems.
- Key challenges include the sector's contribution to acidification and eutrophication due to emissions of N and P from manure. So reducing the excretion of N and P is of key importance.
- Pork is one of the sectors where the differences in carbon footprinting at farm level versus the National Inventory approach are relevant.
- GHG emissions, as determined through LCA (using a carbon calculator), are mainly attributed to feed production (approximately 75-80%).
- Yet direct emissions from UK pigs systems, as accounted for under inventory accounting, are mainly aligned with CH_4 from manure and enteric fermentation (digestion), and N_2O as a result of manure application.

Mitigation strategies for GHG emissions in pork

Mitigation strategies in the pig industry can be divided into three categories: mitigations that relate to the animal, the feed and the manure, with feed being by far the main category (**Table 13**). When considering the pig system, due to the fact that a large component of the feed offered to UK pigs is imported, the carbon footprint compared to 'local emissions', as reported through the Inventory, can be quite different. As such, the GHG associated with land use change (mainly N_2O) are the main ones associated with feed within the carbon footprint of pig systems, since the emissions are realised in the country that the feed ingredient is grown in. However, overall feed use efficiency in terms of how well the animal and herd as a whole utilises the feed, as well as reducing feed wastage on-farm, should be a key area of focus to reduce the carbon footprint and overall emissions from pig systems. Improvements in feed efficiency will increase the volume of pork produced from less feed used and, as such, will reduce the emissions of CH_4 and N_2O within the UK. Improvements in feed efficiency mainly come from the enhancement of animal genetic traits associated with maintenance requirements, growth rates and the ratio of protein to fat in the body of the animal. Other ways to reduce feed use, and therefore the carbon footprint, align with improved genetics and management to improve animal health and welfare, sow longevity and reproductive rate, as well as piglet survival. The actual carbon footprint of the feed itself can be decreased by using lower carbon footprint feed ingredients, e.g. replacing soybean meal (which commonly has a higher global warming potential as a result of land use change in the country it is grown), and additives with the potential to improve efficiencies of utilisation for energy and protein. Improvements in overall reduction in feed waste due to management and feeding strategies, such as precision feeding, are key in further reducing the environmental impact of pig systems. With regard to manure application, the adoption of low emission spreading techniques are key to reducing the emissions of N_2O, alongside novel uses of manure such as AD.

Table 13 Potential for mitigating GHG emissions in pork.

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Animal related								
Genetic improvement	L	H	Now	CH_4 ↓ N_2O ↓	L	Y	H	P NH_3
General health improvement	L	H	Now	CH_4 ↓ N_2O ↓	L	Y	H	P NH_3
Feed related								
Precision feeding and management to improve feed use efficiency	H	M	Later	CH_4 ↓ N_2O ↓	L	Y	H	P NH_3
Specialist ingredients focused on improving feed utilisation	L	H	Now	CH_4 ↓ N_2O ↓	L	Y	H	P NH_3
Higher co-product inclusion level	L	M	Now	Up or down, depends on product	M	N	H	
Use alternative ingredients to soybean meal	M	M	Now	Up or down, depends on product	H	Y	H	
Lower crude protein diet	L	H	Now	N_2O ↓	L	Y	H	NH_3
Manure/fertiliser related								
Anaerobic digestion	H	M	Now	CH_4 ↓	M	Y	H	Odour NH_3
Acidification	H	L	Now	CH_4 ↓	L	N	H	Odour NH_3
Covered stores	H	H	Now	Depends on what cover is made of	L	Y	H	Odour NH_3
Low emission spreading and precision application of manure	H	H	Now	N_2O ↓	M	Y	H	NH_3

See Section 4 of this report to support the interpretation of this table.

Pork

Options

Strategies to reduce the environmental impact of pigs should focus on finishing pigs. They consume the highest proportion of feed because of their size and use nutrients less efficiently compared to other pig classes.

There is little difference between the carbon footprints of indoor and outdoor breeding systems in the UK, mainly because weaned pigs from both systems are managed in a similar way. Consequently, the options described below apply to pigs produced by both systems.

1. Genetic improvement can reduce emissions mostly through reductions in carcass fatness. Other trait improvements, such as increases in piglets per sow per year deliver smaller reductions.
2. Improvements in pig health improve feed efficiency and reduces maintenance requirement, mortality and culling.
3. Improved feed efficiency reduces both CH_4 and N_2O from pig systems, directly impacting on Inventory GHG. This has great impact for reducing emissions on-farm.
4. Replacement of soybean meal in the diet is critically important due to the high carbon footprint of soy. Replacing soybean meal with protein not associated with land use change has the greatest impact for reducing overall carbon footprint of pig production.

   While replacement of soybean meal normally reduces carbon footprint of pig systems, it does not significantly reduce GHG emissions from UK pigs because those attributed to protein production are emitted in other countries.
5. Reverting pigs to their traditional role as recyclers of "waste" could reduce their carbon footprint and overall environmental impact by playing a major role in circular agriculture, utilising former foods and other co- and by-products. Benefits would be greatest in finisher pigs.
6. Improvements in feed processing technologies and inclusion of specialist ingredients, such as synthetic amino acids, enzymes and probiotics, will be associated with some reductions in the carbon footprint from pig systems.
7. Precision feeding and management strategies have the potential to reduce emissions but come at a high cost. Technological advances may make such strategies cheaper and more readily available in the longer term.
8. For slurry, covering stores, acidification and AD all reduce GHG emissions from manure. They also reduce emissions of NH_3 and other odours. These emission reductions are directly accounted for in inventory accounting.
9. Application of manure using low emission spreading methods reduces N_2O emissions.

Modelling the impact of mitigations on UK farms

Pig

The main emissions occurring from pig systems are methane and nitrous oxide as a result of manure management, but also some methane via enteric fermentation.

However, most of the carbon footprint in pig systems is aligned with feed.

Much of the feed for pigs, especially protein ingredients, is sourced from outside the UK. This means that while the emissions resulting from growing this feed do not impact directly on the reported UK GHG emissions in the National Inventory, they are important to consider at a global level.

Therefore, for this exercise, the key mitigation modelled through the carbon calculator was using non-soya alternative protein sources.

Key features of case study

- 552 sows.
- 342kg of feed per head.
- Farrow to finish system.
- Base finisher diet 19.2% soya.
- 110kg slaughter liveweight.
- 1109t/year of pig meat produced.

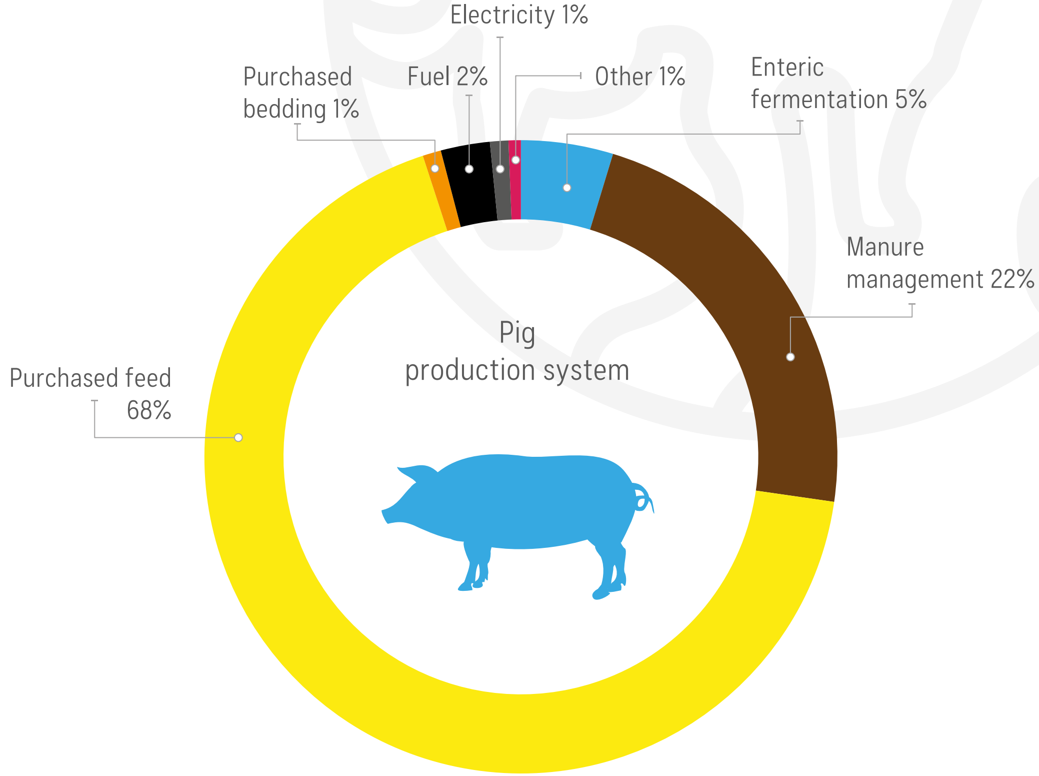


Figure 13

Contribution of key practices on this farm to the overall carbon footprint (kg CO_2-eq/kg deadweight), based on soya in the diet not being associated with land use change. This farm had total annual emissions of 3785t of CO_2-eq/year and an overall carbon footprint of 3.18kg CO_2-eq/kg deadweight.

Farm mitigations modelled

Within this system, the impact of replacing soya with rapeseed meal in the finisher diet whilst maintaining constant levels of dietary amino acids was modelled. Considerations concerning whether the protein sources were associated with land use change or not were also made. Relevant details are presented with results in **Table 14**.

The following therefore represents the scenarios modelled:

- Soya in the finisher diet was reduced to 11% and 14% rapeseed meal was included as an alternative protein source. This level of inclusion did not affect the feed intake or performance of the pigs (as evidenced through trial work).
- For both the soya and rapeseed-based diets, the impact of whether the protein component was associated with land use change (LUC) or not, was examined. The assumptions about the emissions associated with the LUC were based on the values as reported in the GLFI Inventory.

Modelling results

Given the majority of emissions arise from feed, impacts for feed are reported in more detail. Total carbon footprint is presented for reference.

- Contributions from manure, energy sources etc were identical for the modelled scenarios. Under both the no LUC and LUC scenarios, the footprint values associated with feed are considered high compared to what has recently been reported for average UK pig systems. In this case study, it appears the farm's performance (which was lower than expected) was the main factor contributing to its higher than expected carbon footprint.
- The carbon footprint for the soya (no LUC) scenario was 3.18kg CO_2-eq/kg deadweight, and within this, the footprint aligned with feed was 2.16kg CO_2-eq/kg deadweight.
- When the soya was associated with LUC, the footprint of the feed increased to 4.39kg CO_2-eq/kg deadweight and for the system as a whole to 5.41kg CO_2-eq/kg deadweight (70% increase).
- The aligned increase in emissions was 5224t CO_2-eq from feed alone (i.e. double that of the feed component when the soya was not associated with LUC in the base scenario).
- When rapeseed replaced soya (on a no LUC basis), the footprint and emissions were broadly the same as when soya (with no LUC) was used.
- However, when rapeseed with LUC was used instead of soya, whilst being associated with LUC, the footprint aligned with feed was 7% lower (4.05kg CO_2-eq/kg deadweight) and emissions were 8% lower (4816t CO_2-eq).

Table 14 Impacts on emissions and carbon footprint of dietary protein source including the effect of land use change (LUC).

Mitigation options – Pig production system (finisher)1,2	Impacts from feed component			Total
	Emissions from feed t CO_2-eq	Carbon footprint from feed kg CO_2-eq/ kg deadweight	% difference for emissions and for carbon footprint from feed	Total Carbon footprint from Feed kg CO_2-eq/ kg deadweight
Base diet – no LUC Soya 19.2%	2568	2.16		3.18
Alternate diet – no LUC Soya 11%, rapeseed meal[3] 14%	2556	2.15	Alternate no LUC vs. Base, no LUC **0.5%**	3.17
Base diet with LUC[4]	5224	4.39	Base, LUC vs. Base, no LUC **+103%**	5.41
Alternate diet with LUC[3,4]	4816	4.05	Alternate, LUC vs Base, LUC **8%** Alternate, LUC vs. Alternate, no LUC **+88%**	5.07

[1]Diets offered from 40kg (12 weeks of age) to slaughter.
[2]Diets based on wheat and barley and formulated to be iso-energetic (13.6MJ/kg), iso-nitrogenous (17% N, 1.1% Lysine and similar amino acid profile).
[3]No effect of feed on intake or performance of pigs (proven through trial work).
[4]Assumptions about emissions associated with LUC based on values reported in GLFI Inventory.

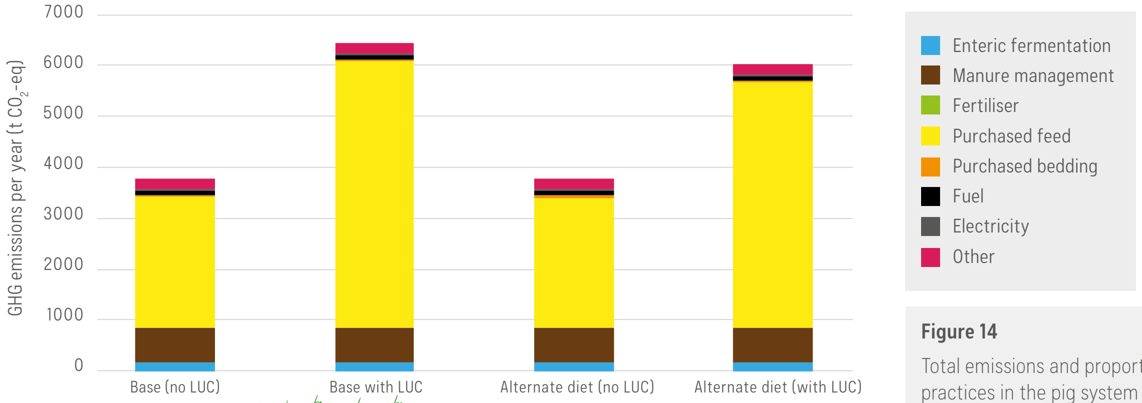


Figure 14

Total emissions and proportions from different farm inputs and practices in the pig system considered.

Application of the mitigations to the National Inventory

The mitigations applied to the UK sector included reducing crude protein (CP), use of anaerobic digestate A(D) and nitrification inhibitors.

- The application of the nitrification inhibitor to pig slurry had a small effect on GHG emissions from the UK pig herd (1.7%), mainly due to lower N_2O emissions.
- The application of AD to all pig slurry in the UK reduced GHG emissions by 15%, mainly as a result of the recapture and use of the (enhanced) methane emissions generated during the AD process compared with those emitted during slurry storage. It also reduced ammonia emissions by 7.1%, mainly due to the covered slurry storage assumed to be associated with AD processing, offset to a small extent by increased emissions following spreading.
- When the crude protein (CP) content of the diet was lowered, GHG emissions were reduced by 2.4%, mainly due to lower N excretion and, therefore, lower N_2O emissions resulting from manure management.
- Ammonia emissions were also reduced by 6.1% across the pig sector in the UK, again as a direct result of lower N excretion.
- A reduction in CP content would also equate to a decrease in protein ingredients such as soya. However, embedded emissions in feed sourced from outside the UK are not reported as UK emissions and are not included in the National Inventory.
- This highlights an important difference between the reported impact of potential management changes in the carbon footprints of farms and products and the impact reflected in the UK National Inventory report. It is important to acknowledge the impact on global emissions as well as nationally reported emissions.
- When all three mitigations were combined, they achieved a 20.3% reduction in GHG (on a CO_2-eq basis), mainly due to a reduction in methane from slurry storage and reduced nitrous oxide emissions from storage and spreading of the liquid manure. The combination also reduced ammonia emissions by 12.8% within the UK pig sector, mainly from housing and manure storage.

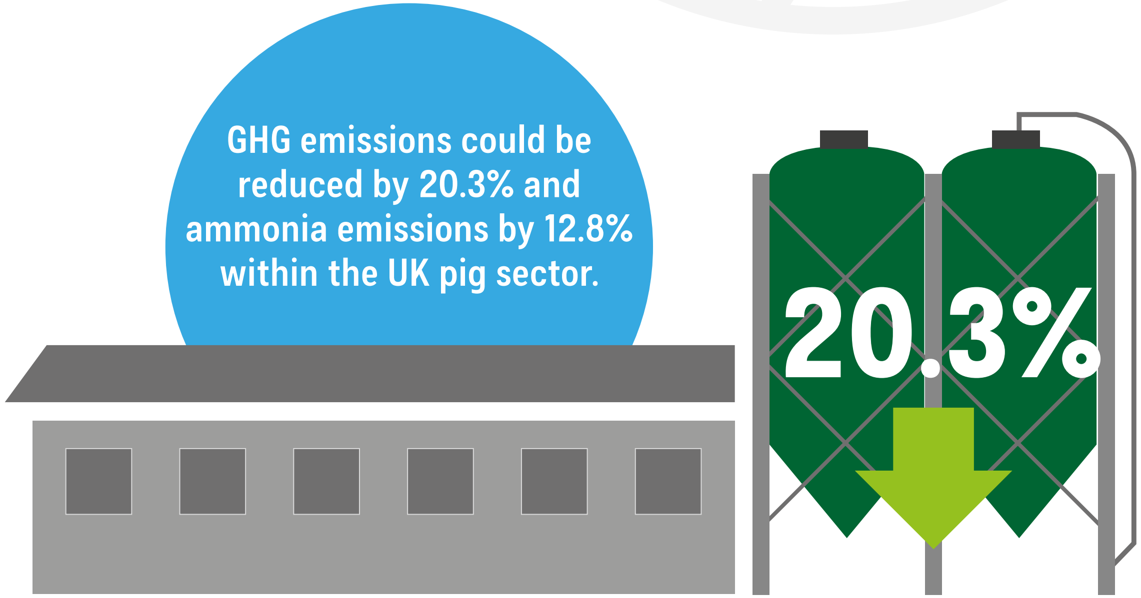


Table 15 The GHG and ammonia reductions achieved within the UK pig herd by reducing the CP content of diets, application of AD and use of a nitrification inhibitor.

			% reduction for pig sector		% reduction for Agriculture Inventory	
Mitigation options		**GHG kt CO_2-eq**	**GHG**	**NH_3**	**GHG**	**NH_3**
1% reduction in CP content	Applied to all growing and finisher pig feed in UK (100% adoption) Assumed reduction of 8% in N excretion from grower and finisher pigs	29	2.4	6.1	0.1	0.5
All pig slurry to AD (not farm yard manure)	Methane conversion factor of 4% assumed to account for 'escaped' emissions	192	15.9	7.1	0.5	0.6
Nitrification inhibitor used with pig slurry application*	Assumed to reduce N_2O emissions from soils after spreading by 40%.	21	1.7	0.0	-0.1	0.0
Combined effect of above three mitigations		242	20.3	12.8	0.6	1.0

Take home messages

- The use of protein ingredients associated with land use change or not had the biggest impact on the carbon footprint of the farm.
- However, replacing soybean meal with rapeseed meal resulted in reductions of 7% of the GHG emissions from pig systems, when both were associated with land use change.
- There was essentially no change in the GHG emissions from pig systems through this replacement, when the soy or rapeseed were not associated with land use change.
- From the strategies considered for their effect on the National Inventory, the greatest reductions were achieved by processing slurry through AD. However, this excludes the offsetting of fossil fuel usage, which would be accounted for in the National Inventory aligned with energy use.
- Both the reduction of CP in finisher pig diets and nitrification inhibitor use with pig slurry application led to a smaller reduction in GHG emissions from the sector (~2% in each case). However, reducing CP content had a marked impact on ammonia emissions, at a national level which is important.
- It is likely UK grown ingredients will be of greatest benefit in terms of their climate change impact if sourced from 'non land use change' practices. Soya from 'non land use change' practices grown in other countries should not be considered negatively.

5.5 Poultry

Sector snapshot

- The UK's poultry industry has seen huge growth, with the value of poultry meat and eggs reaching £3.5bn in 2020.
- Dominated by chicken production, the poultry sector accounts for about 13% of the UK's gross agricultural output.
- Although the poultry industry has a low carbon footprint compared with the dairy, beef and lamb sectors, it presents a challenge with regard to air and water quality resulting from N, NH_3 and P emissions.
- In common with pork, a key focus for the poultry industry is the reduction of N and P excretion from animals and the use of technologies to reduce the release of these nutrients.
- Feed production, processing and transport is the main contributor (approximately 70%) to the carbon footprint of both poultry egg and meat production systems.

Mitigation strategies for GHG emissions in poultry

Mitigation strategies (**Table 16** and **17**) are similar for poultry and pigs and, again, due to the fact that a large component of the feed offered to the UK poultry sector is imported, the carbon footprint compared to 'local emissions', as reported through the Inventory, can be quite different. With regard to direct emissions from poultry systems in the UK, N_2O from manure management and application are notable. However, the GHG associated with land use change are the main ones associated with feed within the carbon footprint of poultry systems, since the emissions are realised in the country that the feed ingredient is grown in. CO_2 aligned with the processing and transport of feed is also of consideration.

Feed use efficiency in terms of how well the animal and flock as a whole utilises the feed, as well as reducing feed wastage on-farm, is therefore the main area of focus to reduce the carbon footprint of poultry systems. Improvements in feed efficiency mainly come from enhancement of animal genetic traits associated with maintenance requirements, growth rates and the ratio of protein to fat in the body of the animal. These all result in the need for less feed to produce each kilogram of eggs or poultry meat. This, along with an overall reduction in feed waste due to management and feeding strategies, such as precision feeding, is key. Other ways to reduce feed use, and therefore the carbon footprint, align with improved genetics and management to improve animal health and welfare, longevity of laying hens and reproductive rate, as well as chick survival. The actual carbon footprint of the feed itself can be decreased by using lower carbon footprint feed ingredients, e.g. replacing soybean meal (which commonly has a higher global warming potential as a result of land use change in the country it is grown), and additives with the potential to improve efficiencies of utilisation for energy and protein.

Table 16 Potential for mitigating GHG emissions in meat producing poultry (broilers).

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Animal related								
Genetic improvement	L	H	Now	N_2O ↓	L	Y	H	P NH_3
General health improvement	L	H	Now	N_2O ↓	L	Y	H	P NH_3
Feed related								
Precision feeding and management to drive feed use efficiency	H	M	Later	N_2O ↓	L	Y	H	P NH_3
Specialist ingredients focused on improving feed utilisation	L	H	Now	N_2O ↓	L	Y	H	P NH_3
Higher co-product inclusion level	L	M	Now	Up or down, depends on product	M	N	H	
Use alternative ingredients to soybean meal	M	M	Later	Up or down, depends on product	H	Y	H	
Lower crude protein diet	L	H	Now	N_2O ↓	L	Y	H	NH_3
Manure related								
Anaerobic digestion	H	M	Now	N_2O ↓	M	Y	H	Odour
Acidification	H	L	Now	N_2O ↓	L	N	H	Odour NH_3
Precision manure application	M	M	Now	N_2O ↓	L	N	H	Odour NH_3
Using poultry litter as a fuel instead of fertiliser	H	L	Now	N_2O ↓	L	Y	H	P Odour NH_3

See Section 4 of this report to support the interpretation of this table.

Table 17 Potential for mitigating GHG emissions in egg producing poultry (layers).

Strategy	Cost	Ease of implementation	State of readiness to implement	Potential GHG mitigating effect	Impact on carbon footprint	Inventory	Certainty	Other impacts
Animal related								
Genetic improvement	L	H	Now	N_2O ↓	L	Y	H	P NH_3
General health improvement	L	H	Now	N_2O ↓	L	Y	H	P NH_3
Feed related								
Precision feeding and management to drive feed use efficiency	H	M	Later	N_2O ↓	L	Y	H	P NH_3
Specialist ingredients focused on improving feed utilisation	L	H	Now	N_2O ↓	L	Y	H	P NH_3
Higher co-product inclusion level	L	M	Now	Up or down, depends on product	M	N	H	
Use alternative ingredients to soybean meal	M	M	Now	Up or down, depends on product	H	Y	H	
Lower crude protein diet	L	H	Now	N_2O ↓	L	Y	H	NH_3
Manure related								
Physical treatment of manure (e.g. proper stacking, pelleting)	H	L	Now	N_2O ↓	L	Y	H	P
Anaerobic digestion	H	M	Now	N_2O ↓	M	Y	H	Odour
Acidification	H	L	Now	N_2O ↓	L	N	H	Odour NH_3
Precision manure application	M	M	Now	N_2O ↓	L	N	H	Odour NH_3
Using poultry litter as a fuel instead of fertiliser	H	L	Now	N_2O ↓	L	N	H	P Odour NH_3

See Section 4 of this report to support the interpretation of this table.

Meat producing poultry

Options

1. Like pig meat, replacement of soya bean associated with land use change in the diet is critically important due to the typically high carbon footprint of soya. Home-grown protein not associated with land use change (e.g. rapeseed meal and legumes) has the greatest impact in reducing the carbon footprint of poultry meat. However, this will not significantly reduce UK GHG emissions because most emissions for soya occur in other countries.
2. Genetic improvement to increase feed efficiency and enhance animal health will lead to only small reductions in carbon footprint. This is because such traits have already been subjected to intense genetic selection.
3. A number of alternative protein sources, such as insect meal, algae and microbial protein, may have the potential to reduce the carbon footprint of poultry production and are being considered for use in the UK.
4. Improvements in feed processing technologies and inclusion of specialist ingredients, such as synthetic amino acids and enzymes, can deliver some reduction in the carbon footprint of poultry meat production systems.
5. Precision feeding and management strategies have the potential to reduce emissions but come at a high cost. Technological advances may make such strategies cheaper and more readily available in the longer term.
6. Physical treatment of manure, such as improved stacking, pelleting, etc., reduces GHG emissions. These can be reduced further by chemical and biological means. However, information about the optimal design and economic feasibility is lacking for these mitigations.
7. Alternative manure management systems such as using litter as fuel or as a substrate for AD, instead of spreading it on fields, can reduce GHG emissions. These can also deliver other environmental benefits, through the reduction of emissions of NH_3 and other odours.

Egg producing poultry

Options

Egg production is the least environmentally impacting livestock commodity, in terms of UK GHG emissions.

1. Past genetic improvement in feed efficiency, animal health and productivity, at the level of pullet and eggs, have already reduced the carbon footprint of poultry egg production systems. Further improvements are more likely to come from enhancements in bird health leading to hen longevity.
2. The contribution of pullets to the environmental impact of egg production is considerable (20-25% of carbon footprint). Options for reducing GHG emissions from pullets include management and dietary mitigations, such as the use of home-grown protein sources.
3. Although laying hens' diets include relatively low amounts of soybean meal, like meat producing poultry, replacement of soybean meal associated with land use change with home-grown alternatives not associated with land use change is the most effective mitigation to reduce the carbon footprint of the egg producing poultry sector. Whilst this reduces carbon footprint, it will not reduce emissions from the sector, as accounted for by the Inventory, since soya bean emissions largely occur outside the UK. However, reductions in global emissions are likely to be critical for UK farm sustainability.
4. Dietary manipulation, such as reducing the crude protein content of feed, improvements in feed processing technology and inclusion of specialist ingredients, such as synthetic amino acids and enzymes, are associated with some reduction in the carbon footprint of egg production.
5. Precision feeding and management strategies have the potential to reduce emissions but come at a high cost. Technological advances may make such strategies cheaper and more readily available in the longer term.
6. Physical treatment of manure, such as improved stacking, pelleting, etc., can reduce GHG emissions. These may be reduced further by chemical and biological means. Information about economic feasibility and optimal design is still lacking for these mitigations.
7. Alternative manure management systems such as using litter as fuel or as a substrate for AD, instead of spreading it on fields, can reduce GHG emissions. These can also deliver other environmental benefits, through the reduction of emissions of NH_3 and other odours.

Modelling the impact of mitigations on UK farms

Poultry

Within the National Inventory the main gas of concern in poultry systems is nitrous oxide from manure management.

However, the main factor contributing to the carbon footprint of poultry systems is feed.

Much of the feed for poultry, especially protein ingredients, is sourced from outside the UK. This means that while the emissions resulting from growing this feed do not impact directly on the reported UK GHG emissions in the National Inventory, they are important to consider at a global level.

Therefore, for this exercise, the key mitigation of focus to model through a carbon calculator was the use of alternative protein sources.

Meat producing poultry

Key features of case study

In this broiler case study, beans were used to replace soybean meal as an alternative protein source since the baseline diets already contained some rapeseed meal (up to 10% in the finisher diets). It was not considered appropriate to increase it further, as it may affect the feed intake of the birds (Leinonen et al, 2013[4]).

- 20,785 birds.
- 294t broiler meat/ year.
- 3.54kg feed per bird.
- 2.2kg liveweight-endpoint.
- Feeds wheat-based and formulated to be iso-energetic and iso-nitrogenous.
- Animal performance similar for diets modelled.

Table 18 Key ingredients (protein sources) and dietary characteristics of the diets modelled.

	Soya-based diet				Alternative protein diet			
	Starter	Grower	Finisher	Withdrawal	Starter	Grower	Finisher	Withdrawal
Age offered (days)	0-10	11-24	25-32	33+	0-10	11-24	25-32	33+
Key ingredients of interest (% of diet unless otherwise stated)								
Whole rapeseed	5.0	7.5	10.0	10.0	5.0	7.5	10.0	10.0
Soya	33.5	25.5	18.0	17.0	25.5	16.0	9.0	7.5
Beans					10.0	15.0	20.0	20.0
Energy (MJ/kg)	12.7	13.1	13.4	13.4	12.7	13.1	13.4	13.4
Protein (%)	22.8	20.0	18.5	18.0	21.5	18.7	17.0	16.5
Total Lysine (%)	1.44	1.20	1.08	1.04	1.42	1.21	1.09	1.06

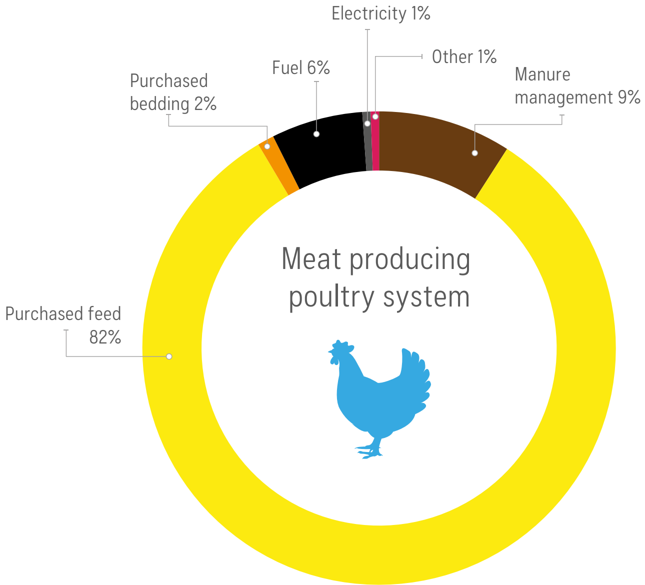


Figure 15

Contribution made by various parts of the poultry farm to its overall carbon footprint when the diet was soya-based (sourced from no land use change practices). It had an overall carbon footprint of 1.76kg CO_2-eq/kg deadweight).

Farm mitigations modelled

The impact of replacing imported soya with home-grown beans was modelled as an alternative protein source for the broiler case study (**Table 19**). Considerations concerning whether the protein sources were associated with land use change or not were also made.

The following scenarios were therefore modelled:

- Broadly half of the soya in the base diet was replaced with beans as an alternative protein source; the amino acid contents of all diets were balanced with the addition of pure amino acids.
- For both of the dietary scenarios, the impact of whether the soya, rapeseed or beans were associated with land use change or not was compared. The assumptions about the emissions associated with the LUC were based on the values reported in the GLFI Inventory.

Modelling results

- The carbon footprint for the soya (no LUC) scenario was 1.76kg CO_2-eq/kg deadweight, and within this, the footprint aligned with feed was 1.45kg CO_2-eq/kg deadweight. The total annual emissions of this farm were 519t CO_2-eq/year, of which 429t CO_2-eq/year were aligned with the feed component, **Table 19** and **Figure 16**.
- The carbon footprint for the bean-based (no LUC) scenario was 1.84kg CO_2-eq/kg deadweight, and within this, the footprint aligned with feed was 1.56kg CO_2-eq/kg deadweight. The emissions from this scenario totalled 541t CO_2-eq/year, of which 461t CO_2-eq/year were aligned with the feed component.
- When beans partially replaced soya (no LUC), the footprint and level of emissions were broadly the same.
- When soya and rapeseed in the diet was assumed to be associated with LUC, the footprint of the feed increased to 3.52kg CO_2-eq/kg deadweight and for the system as a whole to 3.82kg CO_2-eq/kg deadweight. This represented a 117% increase compared with when the soya and rapeseed were sourced from non-LUC practices. The aligned increase in emissions was 1037t CO_2-eq/year from feed alone (i.e. over double that of the feed component when soya and rapeseed were not from LUC practices).
- However, when beans (with LUC) partially replaced soya (with LUC), the footprint aligned with feed were 20% lower (2.80kg CO_2-eq/kg deadweight), as were the total emissions aligned with feed (826t CO_2-eq/year).
- The assumptions used to calculate the changed emissions associated with LUC to produce beans and rapeseed (e.g. whether the LUC occurs in the UK or overseas) will alter the carbon footprint of the resulting feeds.

Table 19 Broiler case study: Impacts on emissions and carbon footprint of dietary protein source including the effect of land use change (LUC).

Mitigation options – Meat producing poultry system [1,2]	Impacts from feed component			Total
	Emissions from feed t CO_2-eq	Carbon footprint from feed kg CO_2-eq/ kg deadweight	% difference for emissions and for carbon footprint from feed	Total Carbon footpring from Feedkg CO_2-eq/ kg deadweight
Base diet – no LUC Soya and rapeseed	429	1.27		1.76
Alternate diet – no LUC Beans replaced ≈ 50% of soya[3]	461	1.32	Alternate, no LUC vs Base, no LUC **+5%**	1.84
Base diet with LUC[4]	1037	2.75	Base, LUC vs Base, no LUC **+117%**	3.82
Alternate diet with LUC[3,4]	826	2.21	Alternate, LUC vs Base, LUC **-20%** Alternate, LUC vs Alternate, no LUC **+67%**	3.07

[1]Diet used were wheat-based, were formulated to be iso-energetic and iso-nitrogenous so far as possible.
[2]The principles of diet formulations were taken from Leinonen et al (2013[4]). Key ingredients available in the appendix.
[3]No effect of feed on intake or performance of birds (proven through trial work).
[4]Assumptions about emissions associated with LUC based on values reported in GLFI Inventory.

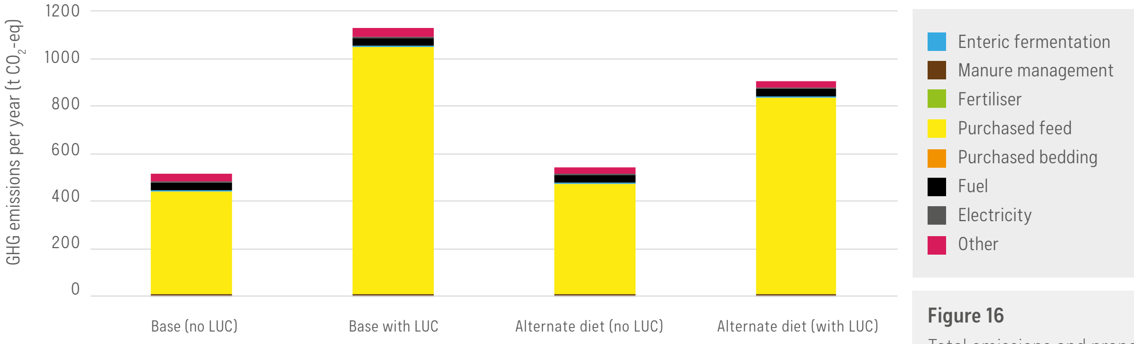


Figure 16
Total emissions and proportions from different farm inputs and practices in the poultry broiler system considered.

Take home messages

- The greatest impact on the carbon footprint arose from when the protein was associated with land use change or not.
- However, there was essentially no change in the GHG emissions from broiler systems when approximately 50% of soybean meal in the diet was replaced by beans (when these ingredients were not associated with land use change). Under this scenario, the GHG emissions were relatively similar whether soya or beans were used.
- However, when ingredients were associated with land use change, replacing soybean meal with beans resulted in a reduction of 20% of the GHG emissions from the broiler system.
- The source of raw materials and the assumptions aligned with LUC or not are critical when calculating the carbon footprint of broiler systems. Therefore, further investigation into these assumptions is warranted within carbon calculators.
- UK grown ingredients will likely be of greatest benefit in terms of their climate change impact if sourced from 'non land use change' practices. Soya from 'non land use change' practices grown in other countries should not be considered negatively.

UK grown ingredients will likely be of greatest benefit in terms of their climate change impact if sourced from 'non land use change' practices.

Egg producing poultry

Key features of case study

- 4251 laying hens.
- 1.186m eggs/year.
- 279 eggs/hen/year.
- 56kg feed/hen/year.
- Feeds wheat-based and formulated to be iso-energetic and iso-nitrogenous.
- Animal performance similar for diets modelled.

Farm mitigations modelled

Within this system, the impact of replacing soya with rapeseed meal was modelled, and considerations concerning whether the protein sources were produced as a result of land use change or not were also made.

The following scenarios were therefore modelled:

- Broadly half of the soya in the base diet was replaced with rapeseed as an alternative protein source. The amino acid contents of all diets were balanced with the addition of pure amino acids.
- For both of the dietary scenarios, the impact of whether the protein sources i.e. soya or rapeseed were produced as a result of land use change or not was compared.

Table 20 Key ingredients (protein sources) and dietary characteristics of the diets modelled.

	Soya-based diet					Alternative protein diet				
	Starter crumb	Rearer	Developer	Early lay	Late lay	Starter crumb	Rearer	Developer	Early lay	Late lay
Age Range	0-6w	6-15w	15-20w	20-35w	35-60w	0-6w	6-15w	15-20w	20-35w	35-60w
Dietary characteristics (% unless otherwise stated)										
Wheat	63.52	67.11	67.53	64.06	68.53	54.68	52.89	55.91	52.13	52.01
Wheatfeed	7.35	9.26	12.18	3.34		10	15	15	10	13
Soya	20.09	9.69	6.67	14.51	11.95	15	4		10	6
Sunflower	4	10	10	6	7	7	15	16	7.5	8
Whole rapeseed						10	10	10	10	10
Energy (MJ/kg)	12	11.6	11.6	11.4	11.3	12.1	11.7	11.7	11.4	11.3
Protein (%)	19.0	16.5	15.4	16.3	15.4	18.9	16.5	15.1	16.2	15.1
Total Lysine (%)	0.98	0.78	0.68	0.79	0.74	1.00	0.80	0.69	0.80	0.75

Modelling results

- The carbon footprint for the soya (no LUC) scenario was 1.92kg CO_2-eq/kg eggs, and within this, the footprint aligned with feed was 1.54kg CO_2-eq/kg eggs. The total annual emissions of this farm were 151t CO_2-eq/year, of which 121t CO_2-eq / year were aligned with the feed component (**Table 21** and **Figure 18**).
- The carbon footprint for the rapeseed based (no LUC) scenario was 1.99kg CO_2-eq/kg eggs, and within this, the footprint aligned with feed was 1.61kg CO_2-eq/kg eggs. The emissions from this scenario totalled 157t CO_2-eq/year, of which 126t CO_2-eq / year were aligned with the feed component.
- When the soya in the diet was assumed to be sourced from LUC, the footprint of the feed increased by 80% to 3.08kg CO_2-eq/kg eggs and for the system as a whole to 3.46kg CO_2-eq/kg eggs compared with when the soya was sourced from non-LUC practices.
- The aligned increase in emissions was to 242t CO_2-eq/year from feed alone (i.e. double that of the feed component when the soya is associated with LUC).
- When rapeseed partially replaced soya (no LUC), the footprint and level of emissions were broadly the same compared with when soya/rapeseed (with no LUC) was used.
- However, when rapeseed (associated with LUC) partially replaced soya (associated with LUC), the footprint aligned with feed was 24% lower (2.33kg CO_2-eq/kg eggs), as was the total emissions aligned with feed (183t CO_2-eq/year).

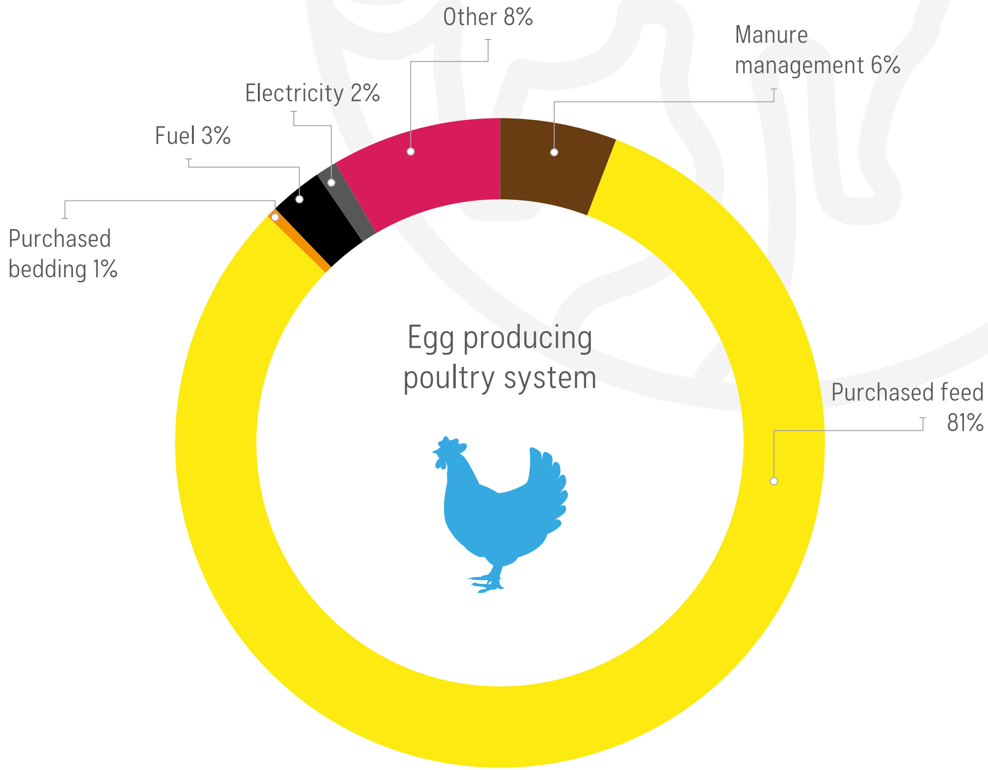


Figure 17

Contribution made by the various parts of the layer enterprise to its overall carbon footprint when the diet was soya-based (sourced from no land use change practices). It had an overall carbon footprint of 1.92kg CO_2-eq/kg eggs.

Table 21 Layer case study: Impacts on emissions and carbon footprint of dietary protein source including the effect of land use change (LUC).

Mitigation options – Egg producing poultry system[1,2]	Quantity from feed component			Total
	Emissions from feed t CO_2-eq	Carbon footprint from feed kg CO_2-eq/ kg deadweight	% difference for emissions and for carbon footprint from feed	Total Carbon footprint from Feed kg CO_2-eq/ kg deadweight
Base diet – no LUC Soya and rapeseed	122	1.54		1.92
Alternate diet – no LUC Beans replaced ≈ 50% of Soya[3]	126	1.61	Alternate, no LUC vs. Base, no LUC **+4%**	1.99
Base diet with LUC[4]	242	3.08	Base, LUC vs. Base, no LUC **+80%**	3.46
Alternate diet with LUC[3,4]	183	2.33	Alternate, LUC vs Base, LUC **-22%** Alternate, LUC vs. Alternate, no LUC **+36%**	2.71

[1]Diet used were wheat-based, were formulated to be iso-energetic and iso-nitrogenous so far as possible.
[2]The principles of diet formulations were taken from Leinonen et al (2013[4]). Key ingredients available in the appendix.
[3]No effect of feed on intake or performance of birds (proven through trial work).
[4]Assumptions about emissions associated with LUC based on values reported in GLFI Inventory.

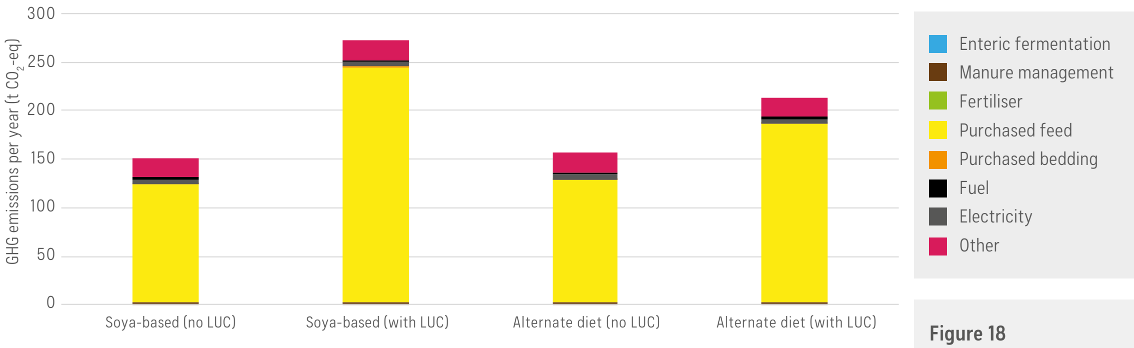


Figure 18
Total emissions and proportions from different farm inputs and practices in the poultry layer system considered.

Take home messages

- The greatest impact on the carbon footprint arose from when the protein was associated with land use change or not.
- There was essentially no change in the GHG emissions from layer systems when almost all soybean meal in the diet was replaced with rapeseed, these ingredients were not associated with land use change. Under this scenario, the GHG emissions associated with the production of soya and rapeseed were relatively similar.
- However, replacing the soybean meal with rapeseed resulted in reductions of 22% of the GHG emissions from layer systems, when the ingredients were not associated with land use change.
- The source of raw materials and the assumptions aligned with LUC or not are critical when calculating the carbon footprint of broiler systems.
- UK grown ingredients will likely be of greatest benefit in terms of their climate change impact if sourced from 'non land use change' practices. Soya from 'non land use change' practices grown in other countries should not be considered negatively.

Soya from 'non land use change' practices grown in other countries should not be considered negatively.

Application of the mitigations to the National Inventory

The impact of lowering CP and the use of AD were applied as mitigations within the National Inventory to determine their impact on GHG (and ammonia) emissions within the UK poultry sector and the UK agricultural sector as a whole (**Table 22**).

- When the CP of broiler and layer diets were reduced, the GHG within the poultry sector were reduced by 4.6% and the ammonia emissions were reduced by 5%, as a direct result of lower N excretion and therefore lower N_2O and ammonia from manure management.
- Processing poultry manure through AD resulted in a 17.5% reduction in ammonia emissions (lower emissions associated with the liquid digestate than solid poultry manure) but increased GHG emissions by 11.7%. This is because the methane emissions for poultry manure storage are the same as the assumed fugitive emissions from poultry AD processing (both have a methane conversion factor of 1.5). However, it is greater than manure spread directly from the house without further storage; hence an increase is found when this practice is applied within the Agriculture Inventory.
- However, offsetting fossil fuel-derived energy by that produced through AD is not explicitly considered in the Agriculture Inventory (would be implicitly captured in the energy sector of the National Inventory), and so is not reflected in the results of this scenario.
- When both these practices were combined, the overall impact was an increase in GHG emissions by 11.8% (on CO_2-eq basis), mainly due to the reasons noted above aligned with AD.
- The combination also reduced ammonia emissions by 30.9% within the UK poultry sector, again mainly from the storage and spreading of the litter, aligned with the reduction in N content of the diets.

Take home messages

- From the strategies considered for their effect on the National Inventory, using manure for AD was associated with increases in the GHG emissions and significant decreases in NH_3 emission. However, since this exercise only considered the agricultural emissions, it therefore excluded the potential of AD to generate energy and offset fossil fuel usage.
- The reduction of CP in the diets of both the broilers and layers led to relatively small GHG and ammonia emissions reduction from the poultry sector as a whole.

Table 22 The GHG and ammonia reductions achieved by reducing CP in the diet and the application of AD within the UK poultry sector. Negative values indicate an increase in the emissions.

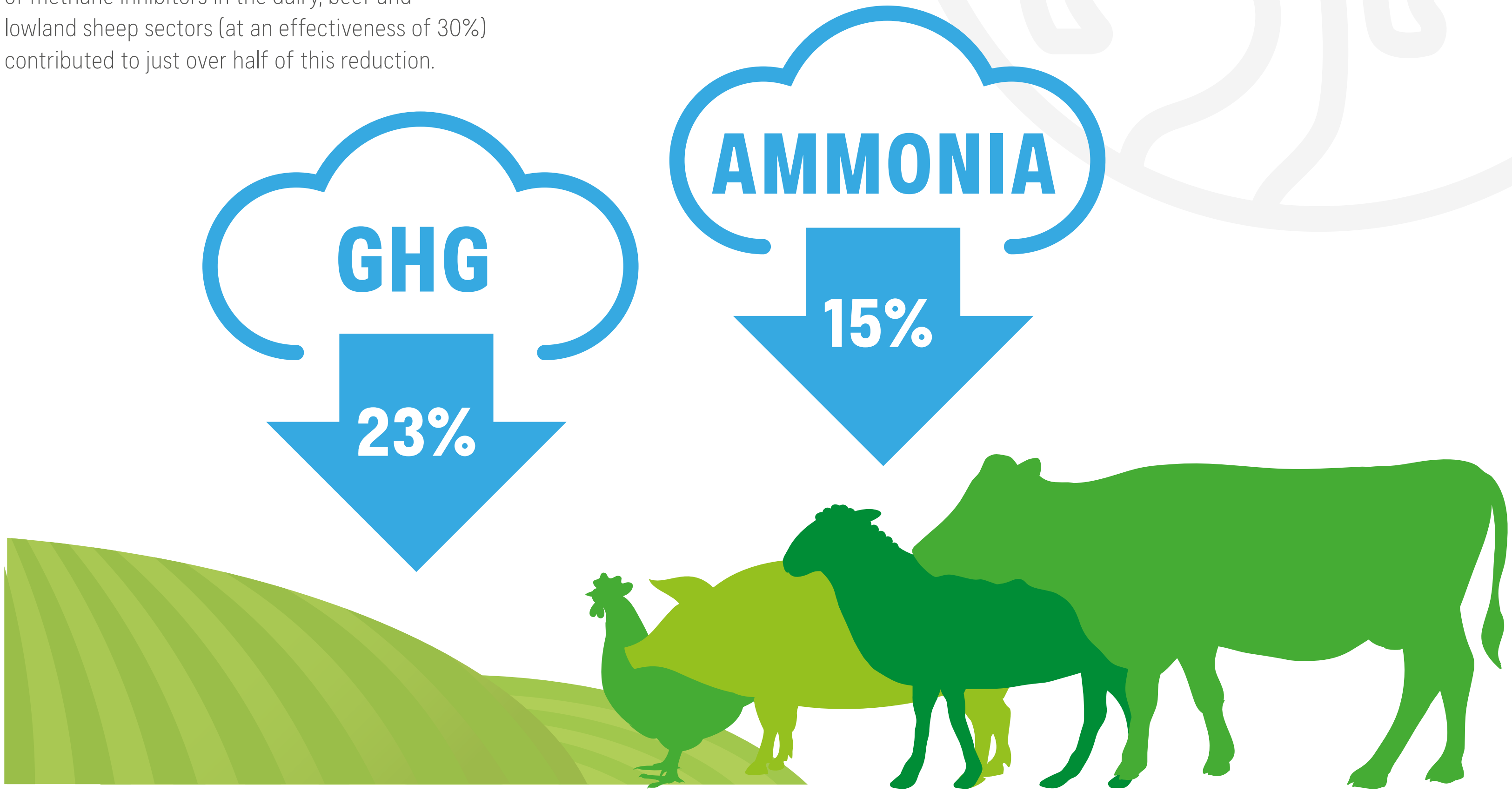
		Effect on sector		Effect on total Agricultural Inventory	
Mitigation Options	GHG reduction (kt CO_2-eq)	GHG % reduction	NH_3% reduction	GHG % reduction	NH_3 % reduction
Lower CP % by 1% for broilers and layers[1]	33	4.6	5.0	0.1	0.7
Layer and broiler manure to AD at the point of storage[2,3]	-84	-11.7	17.5	-0.2	2.5
Combined effect of the two mitigations	-85	-11.8	30.9	-0.2	4.4

[1] Lower Crude Protein (CP) diet decreases N excretion by 8% and assumed used by whole of industry.
[2] Baseline scenario manure would be spread directly from house without storage.
[3] Litter going to power stations excluded.

5.6 Application of the mitigations across all livestock sectors to the National Inventory

Across the five main livestock types mentioned in this report, the combined effect of a range of mitigations were modelled and their impact assessed when applied to the National Inventory.

In combination, they reduced emissions of GHG by 23% and ammonia emissions by 15%. The application of methane inhibitors in the dairy, beef and lowland sheep sectors (at an effectiveness of 30%) contributed to just over half of this reduction.



6. Emerging dietary methane inhibitors

3-NOP

3-NOP (3-nitrooxypropanol) is a novel and specific small molecule that can stop the action of an enzyme called 'methyl-coenzyme M reductase' (MCR). This enzyme is key in the last step of the process which generates CH_4 in the rumen of animals.

3-NOP has been found to reduce CH_4 from ruminants (cattle and sheep), although the dose and application strategy needs to be tailored depending on the types of animals. Currently, 3-NOP can only be used in conjunction with concentrate feeding, with only a very small amount (100-200mg/kg dry matter per day) needed. Studies have found long-lasting improvements in animal performance (increased production of milk fat or milk protein). As a feed additive, 3-NOP requires regulatory approval by various countries.

Nitrate

Nitrate (NO_3–) is another feed additive that intercepts the methanogenesis process and therefore reduces enteric CH_4 production. However, nitrate poisoning of ruminants and rumen microbes has been reported, in particular through inhibition of fibrolytic bacteria and methanogens. Furthermore, feeding nitrate might increase the concentration of nitrate and nitrite in milk and urine. Nitrate tastes bitter which lowers the palatability of nitrate-based diets and may cause lower feed intake, leading to lower levels of production. Recent promise shown in the use of nitrate as a feed additive in precision indoor feeding systems. Use within grazing or non total mixed ration systems presents a major challenge. More work is required on the use of nitrate as a CH_4 reducing mitigation to manage any unintended detrimental impacts on the animal and its outputs.

Seaweeds

Seaweeds provide a large group of essential nutrients as well as numerous secondary plant compounds. Some of these secondary compounds have been found to reduce CH_4 emissions when offered to cattle and sheep. Much work continues to identify raw seaweed products as well as the active compounds responsible for the reduction in CH_4 emissions. Certain seaweeds also contain omega-3, omega-6 and other polyunsaturated fatty acids. Algae-based feeds may improve the fatty acid profile of diets, increase the fat content and reduce somatic cell counts in milk. However, seaweeds may also contain inorganic elements and heavy metals that, at high levels, may cause toxicity in animals and humans. As such, work on seaweeds continues, but the use of the active compounds contained within them shows promise to be a future key mitigation strategy to reduce emissions from cattle and sheep.

7. Carbon sequestration

Carbon sequestration – an introduction

Carbon (C) can be captured from the atmosphere using a range of technological and biological approaches. Many of these are still in development and are expensive. However, C sequestration refers to the process of capturing, securing and storing atmospheric CO_2 mainly by biological processes. There are two main types of C sequestration: biological and geological. Biological C sequestration is the act of capturing atmospheric CO_2 as C in plants (vegetation and woody products), soils and aquatic environments. Geological C sequestration refers to the storage of CO_2 in underground geological formations. In this report, only biological C sequestration is considered where C is stored in plant biomass and soil. Storage of C contained in plants is measured by quantifying above ground biomass, i.e. leaves and wood, while soil C comprises organic C (including below ground plant biomass, e.g. roots) and inorganic C. The main process of C capture described in this report is of organic C derived from biological activity in the soil. Soil organic C stocks are the largest land-based C stock and have an important role to play in combating climate change. The C contained in soils at a global scale is almost three times that in biomass and woody vegetation.

Carbon reservoir

Land use (e.g. cereal or grassland production), land use change (e.g. moving from grassland to cereals or even developments) and forestry are responsible for large flows of C (both direct and indirect) between the atmosphere, vegetation biomass and soil C, which in turn, affects the balance between C sequestration and C losses.

The vegetation C stock of the UK is about 117.9Mt. Forests and woodland account for most UK vegetation C stocks (55% in Northern Ireland and 80% in the other three nations). However, the amount of C contained in above ground biomass, e.g. forestry and grass, is small compared with the soil C pool. The total stock of soil C in the UK to 100cm depth is 4566Mt. Of this, 1345 (30%), 734 (16%) and 400 (9%) Mt are held under grassland, cropland and woodland, respectively. The other 45% of soil C in the UK is held mostly by peatlands and moorlands - although it is notable that many of these latter environments are also emitting C in the form of CH_4.

The impacts of land use, land use change and forestry on carbon sequestration

Soil C losses occur when grasslands, managed forests or native ecosystems are converted to croplands. Soil C gains are made when croplands are converted to grasslands, forest or native ecosystems. For cropland, improved crop rotations and cover crops, application of no-tillage and other conservation tillage and manure application are the strategies commonly used for increasing C inputs in soil. For grassland, the effective approaches include conversion to perennial grasses and legumes, improved grazing land management and well managed manure application.

In addition to land use change, various management activities such as tillage, grazing management and cover cropping can be used to increase C stocks through C sequestration (**Table 23**). Following a change in land use, losses of C will occur more quickly than gains, and thus changes between land use categories are not symmetrical. There is also an assumption by policymakers that after 20 years of a land use change, a new soil C equilibrium value will be achieved. Furthermore, some scientists within the UK consider there to be limited opportunities for increasing existing C stocks of soils not undergoing land use change, due to the relatively high soil C contents of agricultural soils (particularly those already in long-term grassland). However, there is much debate across the UK about the ability of soils to sequester C. Long-term trials (50 years old), in Northern Ireland at AFBI Hillsborough have shown soil C continues to accumulate under well managed grassland.

Table 23 Potential changes in carbon sequestration from land use change.

(Data adapted from Moxley et al, (2014)[7] & Ostle et al., (2009)[8] and could vary with on-farm practices & soil types).

Land use, land use change, forestry and management type	Change in soil C stock
Grassland to plantation forest	-10%
Native forest to plantation forest	-13%
Native forest to cropland	-42%
Grassland to cropland	-59%
Native forest to grassland	+8%
Cropland to grassland	+19%
Fallow to grassland	+150 to 236%
Cropland to plantation	+18%
Cropland to forestry	+50%
Multi-species pasture rotations	+66%
Cover cropping	+6%
Liming	+30%

Options

At present, on many farms the amount of C being sequestered by the land is not offsetting the emissions produced on-farm. Indeed, in some soil types under some circumstances, for example peatland, the soil is very likely to be a net source of GHG emissions. While much more knowledge is required in the area of C sequestration, the following options represent some key actions that could be taken to maximise C sequestration on farms.

1. Less productive areas of land on-farm can be identified and alternative uses considered. On many farms, there is opportunity to increase productivity from improved grassland. Increasing productivity on this more productive land could offset the land that is committed to storing C through land use change.
2. Hedges offer an opportunity to sequester C, as well as creating wildlife corridors supporting biodiversity. As such, hedgerow management to maximise growth and therefore C sequestration should be considered.
3. Manure application to grassland, in a manner that reduces N_2O emissions, can increase soil C stocks.
4. There is evidence that demonstrates C sequestration can be increased by the incorporation of biochar into soils, but high costs currently limit its application. It is also unknown what impact this may have on soil health, although this is currently being investigated.
5. The use of multi-species swards, due to deeper rooting, can also increase C stocks and contribute to resilience.
6. Restoration of peatlands will reduce emissions associated with their degradation, and increase their potential to store C.

8. Conclusions

This report was designed to demonstrate the impact of some key mitigations that could be applied to the five main livestock types farmed in the UK. The impact of the mitigations will be dependent on individual farm circumstances and how feasible they are to implement under those circumstances. However, this report has provided some indication of what is and/or could be possible on UK farms and even at a national level.

The main take-home messages are:

- A reduction of methane emissions from the enteric fermentation (digestion of feed) in dairy, beef cattle and sheep is a key driver in many scenarios, both on-farm and at a national level. Dietary methane inhibitors with an effectiveness of 30% was assumed for this mitigation. The inclusion of dietary methane inhibitors and at this level of effectiveness should be possible within current dairy systems. However, it may be more challenging for beef and sheep systems due to the greater reliance on grazing at pasture. Work is ongoing to bring these technologies to market and develop delivery mechanisms that are better suited to grazing systems and less dependent on concentrate feeding. As such, the challenge of adopting such inhibitors into mainly forage-based systems needs to be addressed urgently for the UK. Their licensing and verification for acceptance to national accounting is also required.
- Improving production efficiency will require system changes on many farms, but it will reduce emissions at the farm and national levels, assuming overall output remains the same. Furthermore, this will also free up land that can be converted to woodland or forestry, which generally have a greater ability to sequester carbon than grassland. The scale of this carbon capture will depend on the nature of the afforestation adopted and the land type and location.

- This report has highlighted some considerations regarding the source of feed ingredients, i.e. associated with land use change or not. It is noted that home-grown ingredients will be of most benefit in terms of their climate change impact when they are not associated with land use change. Soya from 'non-land use change' practices grown in other countries should not be considered negatively.
- AD of manure also has an important role to play. This report has evidenced that the National Inventory, due to its boundaries being for agriculture, does not take account of the fossil fuels that AD could offset. This is an area that warrants further modelling through carbon calculators and at a national level. Collaboration with other industries, such as the energy and transport sector, is also warranted, especially regarding this mitigation and others similar to it, which create energy from the farm platform.
- The report did not estimate soil carbon sequestration for grassland, as its calculations aligned their methodology to IPCC which assumes that soil sequestration under permanent grassland is net zero (i.e. the level of sequestration is equal to the level of emissions).
- However, it is recognised this is an important area of consideration. As such, we did make some attempt to estimate the potential soil carbon sequestration under permanent grassland for a dairy or sheep enterprise. Overall, it is important to highlight the high level of uncertainly in the scientific literature, due to a lack of data and modelling on the ability of soils across the UK to sequester carbon. This presents a major knowledge gap yet could have a notable positive impact for some areas of the UK.

This report has highlighted that through the wide-scale adoption (100% across the UK) of the most impactful mitigations currently or soon to be available, a 23% reduction in GHG and a 15% reduction in ammonia emissions from UK agriculture could be achieved. While this is encouraging, it also suggests much more innovation, adoption and the realisation of carbon capture is needed to contribute to the UK goal of net zero by 2050.

To deliver significant emissions reductions, combining strategies will be essential.

To deliver significant emissions reductions, combining strategies will be essential, and core to all changes is the need to maintain a high level of production efficiency. A high degree of carbon capture will also be required and farmers should carefully consider their land use to optimise production and sequester carbon.

A 23% reduction in GHG and a 15% reduction in ammonia emissions from UK agriculture could be achieved.

Overall, livestock farming can reduce its emissions and capture more carbon in the years ahead, but significant reductions will need wide-scale adoption of many interventions. It is also vital farms measure and monitor their carbon footprint and act on the information it provides. Carbon calculators are essential tools to help farmers reduce their footprint. However, their benefits will only be optimised if overall emissions also reduce at the national level. This will likely mean producing the same amount or more product from fewer animals. Further innovation and detailed modelling are needed to establish how this can be achieved in the long-term whilst also supporting the food security of the UK.

Farms must measure and monitor their carbon footprint and act on results.

9. CIEL commentary

By Mark Young and Harry Kamilaris, CIEL

This report provides a clear call for action across the industry. Substantial change is required if the UK's livestock industry is to help deliver our shared ambition for carbon net zero by 2050. The need is urgent, so change must be widespread and rapid. Fortunately, there are things we can do on all farms to initiate change.

For farmers, the modelling of mitigations on case study farms reported here offers a useful guide to the scale of emission reductions that can be obtained on typical farms. However, the size of the reductions will be affected by the unique features of each farm, so the impact realised will vary somewhat between farms or between different mitigations on-farm.

Information presented highlights that few mitigations can deliver significant emission reductions, so a range of mitigations need to be implemented on-farm – adopting single or minimal options will not deliver all the change possible or needed. A great start is to look to improving herd, flock or farm production efficiency, which has the added benefit of impacting positively on farm profitability. Increasing productivity per animal while reducing input costs, and maintaining overall productivity at the same level, is something we can do right now. Farmers can focus on aspects such as:

- The age at which females first breed as well as their productive lifespan.
- Number of offspring produced and their growth rate.
- Rate of milk or egg production.
- Maintaining high health and welfare status.
- Maximising feed efficiency.
- Managing resources like manure to reuse nutrients and reduce reliance on artificial fertiliser inputs.

We will need to exploit new, promising technologies as they become available. For example, rumen methane inhibitors, new feed plant varieties (e.g. high quality feed protein grown in the UK), redefined animal genetics for future farm systems and emission capture with nutrient recycling for manure.

We must account for all emissions associated with inputs. While our National Inventory targets do not consider emissions occurring overseas, we must consider these as well if we are to reduce global warming. Land use change is of particular significance here. There is a need for robust carbon calculator tools to estimate carbon footprints that account for all significant emissions, all nutrient pools on-farm, critically for both carbon and nitrogen, amount of carbon captured, inputs brought in and carbon in farm products. Some resources such as manures should be looked at as nutrient resources or potential sources of energy to spare fossil fuel usage.

We urgently need to develop cost-effective, easy to use methods to measure soil carbon, as well as developing carbon calculator models. There is a strong case for defining the basic features that all carbon calculators should include to provide standards that can be used for rewarding good practice, as well as feeding accurate consistent information into national emission assessments.

Delivering such changes on-farm will require a collective effort. Farmers cannot and should not be expected to deliver this on their own. All those within the supply chains must work together to reduce emissions while still producing the nutritious, safe food we need. Advisers and consultants specialising in feed, health, soil fertility, business profitability or environmental management, as well as all other supply chain partners, have much to gain by working together. Improving our position for net zero will deliver widespread benefits.

Finally, the report re-confirms, from the latest modelling, that we can currently deliver less than half the change needed for net zero carbon by 2050, and that requires universal adoption of the various known mitigations described in this report - something we are not achieving. This emphasises the critical and urgent need for:

- New innovations that will deliver the greater part of our net zero goal.
- Change to be rapid and widespread, actively supporting adoption of known and new mitigations.

10. Glossary

Terms	Abbreviation	Definition
Ammonia	NH_3	A colourless gas released mainly during naturally occurring processes created when faeces and urine mix i.e. during breakdown of urea excreted by farm livestock or of uric acid excreted by birds.
Anthropogenic		Environmental impact originating in human activity.
Carbon	C	A natural element that forms the backbone of molecules used for energy transactions in biology. It has become shorthand for 'efficiency' and emissions due to carbon dioxide (CO_2) being the standard unit for emissions related to global warming potential.
Carbon dioxide	CO_2	A greenhouse gas that is used by plants to capture energy from the sun and emitted by animals when they use energy in their food, or by combustion of plant and animal matter.
Carbon equivalent	CO_2-eq	A unit of greenhouse gas expressed as a carbon dioxide equivalent and used to compare global warming potential of different GHG on a common scale.
Carbon sequestration		The removal and subsequent storage of carbon dioxide from the atmosphere by nature. If the carbon dioxide sequestered is more than the carbon dioxide emitted, the store is increasing and is known as a carbon sink.
Greenhouse gas	GHG	Gases produced by human activity that contribute to warming of the earth's atmosphere.
Methane	CH_4	A greenhouse gas produced by ruminant livestock from enteric fermentation in the digestion process and during manure storage. It has 28 times the global warming potential of carbon dioxide.
Mitigation		A process to reduce the greenhouse gas emissions created by human activities.
Net zero carbon		A situation where anthropogenic emissions of carbon (as a greenhouse gas) to the atmosphere are balanced by anthropogenic removals over a specified period.
Nitrous oxide	N_2O	A greenhouse gas produced largely as a result of the use of nitrogen fertilisers and manures. It has a global warming potential 298 times that of carbon dioxide.
Soil carbon		Carbon stored in organic matter in the soil. It comes from decomposing plant and animal material and is important for soil health. About 58% of soil organic matter is carbon.

11. Acknowledgements

This report was commissioned by CIEL and delivered by a consortium led by Prof. Elizabeth Magowan of AFBI. Dr. Steven Morrison and Prof. Magowan of AFBI are acknowledged as lead authors of the report. Significant contributions were made to the report by Dr. Xianjiang Chen (AFBI), Prof. Ilias Kyriazakis (QUB), Prof. Bob Rees (SRUC), Dr. Taro Takahashi (Rothamsted Research) and Prof. Tom Misselbrook (Rothamsted Research), who provided expert input, guidance and critical modelling work.

Julian Bell, Rachael Ramsey and Kaia Waxenberg (SAC Consulting) provided critical input associated with producing outputs from the Agrecalc carbon calculator. Louise McNicol (SRUC/Bangor University), with funding from Hybu Cig Cymru (HCC), kindly provided access to results from her PhD studies.

afbi AGRI-FOOD & BIOSCIENCES INSTITUTE

QUEEN'S UNIVERSITY BELFAST

ROTHAMSTED RESEARCH

SRUC

12. Endorsements

As well as the authors, industry experts from the following academic institutions have endorsed this work.

- Duchy College (Dr. Robin Jackson)
- Harper Adams University
- University of Bangor (Prof. Dave Chadwick)
- University of Leeds (Prof. Frank Dunshea)
- University of Nottingham (Prof. Phil Garnsworthy)
- University of Reading (Prof. Christopher Reynolds and Dr. Les Crompton)
- University of Aberystwyth (Dr. Christina Marley)

This endorsement recognises that compiled data from different sources does not provide precise comparisons, but it presents a useful picture of what we know and what we don't. The value lies in helping farmers consider options to then seek more detailed information on, to implement a mitigation on their farm.

Collectively with the authors, these represent eleven academic and research institutions from across the UK.

DUCHY COLLEGE

Harper Adams University

PRIFYSGOL BANGOR UNIVERSITY

UNIVERSITY OF LEEDS

The University of Nottingham UNITED KINGDOM · CHINA · MALAYSIA

University of Reading

1872 PRIFYSGOL ABERYSTWYTH UNIVERSITY

13. References

1. Morison, JIL and Matthews, RB (2016) Agriculture and Forestry Climate Change Impacts, NERC Living with Environmental Change Programme report card.
2. Dewar, RC and Cannell, MGR (1992) Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples. Tree Physiology 11: 49-71.
3. Bell, J., Beaton, C., Young, M., Hill, G., Stout, D., Sellars, A., Thomson, S., Spencer, M. and Mozey, A. (2020). Suckler beef climate change group Farm carbon case studies. An SRUC Publication 2020.
4. Leinonen, I., Williams, A.G., Waller, A. and Kyriazakis, I. (2013). Comparing the environmental impacts of alternative protein crops in poultry diets: the consequences of uncertainty. Agricultural Systems 121: 33-42.
5. Data adapted from Moxley et al, (2014) & Ostle et al., (2009).
6. G Williams, Colm Duffy, David Styles, Dave R Chadwick, A Prysor Williams, School of Natural Sciences, Bangor University, Bangor, Gwynedd 2 School of Engineering, University of Limerick, Limerick. November 2020. The carbon footprint of twenty Welsh beef and lamb farms. Unpublished Report.
7. Moxley, J., Anthony, S., Begum, K., Bhogal, A., Buckingham, S., Christie, P., Datta, A., Dragosits, U., Fitton, N., Higgins, A., Myrgiotis, V., Kuhnert, M., Laidlaw, S., Malcolm, H., Rees, B., Smith, P., Tomlison, S., Topp, K., Watterson, J., Webb, J., and Yeluripati, J. 2014. Capturing Cropland and Grassland Management Impacts on Soil Carbon in the UK LULUCF Inventory . SP1113. 2014. DEFRA. Final Report of the SP1113 project, prepared for the Department for Environment, Food and Rural Affairs.
8. Ostle, Nicholas and Levy, Peter and Evans, C. and Smith, P.. (2009). UK land use and soil carbon sequestration. Land Use Policy 26:S274-S283. Land Use Policy. 26. 10.1016/j.landusepol.2009.08.006.

14. Appendix

Mitigation measures	Explanation
High starch, oil or fat diets	The reduced CH_4 emission can be attributed to increased supply of non-fermentable highly digestible energy, a decreased feed intake and fibre digestibility as well as inhibition of methanogenesis by unsaturated fatty (oil). However, feeding diets that are too high in starches, oil and fats can have adverse effects on animal health and thus yields.
Feeding tannin-, saponin- rich forage	Tannins bind to proteins at a ruminal pH, thus preventing access by microbes. Saponins hamper the activity of microbes at different steps of protein degradation. Though both tannins and saponins have been reported to be effective against ruminal methane and ammonia emissions.
Using lower carbon footprint feed ingredients	The carbon footprint of the feed itself can be lowered through using lower carbon footprint feed ingredients, e.g. replacing soya bean with home-grown protein sources, inclusion of co- and by-products in the feed, and inclusion of specialist ingredients with the potential to improve efficiencies of utilisation for energy and protein.
Rumen methane inhibitors	Several dietary methane inhibitors are at varying stages of development with scientifically published additives including 3-NOP, nitrate and active compounds from seaweeds. Common mode of action includes interception of the methanogenesis process or act as the alternative electron acceptors that can redirect hydrogen from methanogens towards metabolically beneficial sinks in the rumen, and therefore reduce enteric CH_4 production. How to incorporate into grazing systems and magnitude of impact on commercial diets is a current area of research.
Grass-legume mixtures, multi-species swards	Using grass legumes major biological fixation of N could replace artificial fertiliser and the associated CO_2 in production and N_2O emissions at application. Multi-species swards have shown promise both with reduced N_2O emissions through less fertiliser but also reduced CH_4. Potential impacts on soil carbon sequestration.
Optimised grassland management	Management practices, such as early harvest, increasing grazing frequency, decreasing regrowth interval, etc can improve the forage quality and provide methane emissions reduction potential.
Precision feeding	Precision feeding and management strategies have the potential for some reductions in carbon footprint by improving feed use efficiency but can be associated with high investment.
Genetic improvement	Livestock genetic improvement in traits linked to productivity, health, feed efficiency and CH_4 production will also be a positive step to improving the carbon footprint. Although the short-term impact may be relatively low, with the impacts of genetics being cumulative year-on-year and permanent, it is an important strategic mitigation tool.
Slurry management	Covering slurry stores and acidification are the most effective practices on reducing ammonia emissions from slurry or manure, but will have relatively small impacts on GHG emissions. The principal benefit of AD is the conversion of CH_4 to CO_2, in effect reducing the global warming potential and potential offsetting fossil fuel use.

Mitigation measures	Explanation
Nitrification and urease inhibitors	Nitrification inhibitors depress the activity of nitrifying bacteria and reduce conversion of ammonium to nitrate, reducing N_2O emissions. Urease inhibitors delay urea hydrolysis to NH_3, reducing NH_3 emissions. Using urea in combination with urease inhibitors and nitrification inhibitors can therefore further reduce N_2O emissions. Within the sheep case study farms, the paper assumed adopting nitrification inhibitors delivered 48% reduction in the soil emission factor emission factor across fertiliser and manure types.
Low emission slurry spreading	Low emission slurry spreading largely related to reducing NH_3 emission and may have reduction potential in N_2O while improving N usage efficiency, thereby reducing the need for artificial fertiliser.
Improved fertiliser N use	Reduction in N fertiliser use by: soil analysis for pH and the application of lime; using an N planning tool; decreasing the error of margin on N fertiliser application and not applying the fertiliser in waterlogged conditions. Within the sheep case study farms, adopting recommended N application rate: 10% reduction of the applied synthetic N.
Improving 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.
Improving sheep health	Improving animal health could, in principle, lead to significant reductions in emissions intensity by, for example, improving the feed conversion ratio of individual animals and reducing the flock breeding overhead (through improved fertility and reduced mortality).

NET ZERO
& LIVESTOCK

CIEL
Centre for Innovation
Excellence in Livestock

CIEL
Innovation Centre
York Science Park
YO10 5DG

Email: enquiries@cielivestock.co.uk
Telephone: 01904 567716

www.cielivestock.co.uk

@CIELivestock1

Centre for Innovation Excellence in Livestock (CIEL)

Innovate
UK