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

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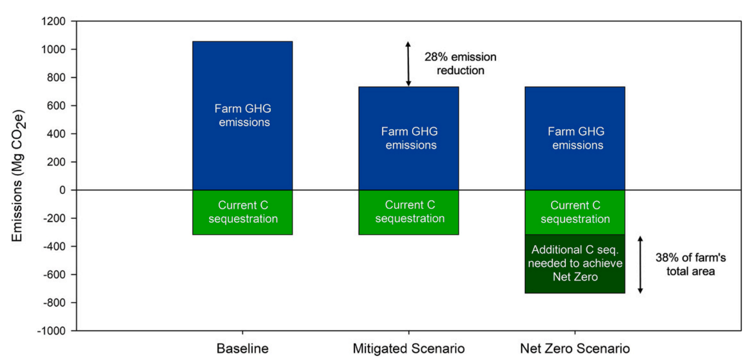
## HIGHLIGHTS

- Baseline GHG emissions were calculated for 20 grassland-based beef and sheep farms.
- Cost-effective abatement options could reduce GHG emissions by 28% on average.
- Large-scale land use change is needed to offset remaining GHG emissions.
- Woodland needed to achieve farm-level Net Zero equivalent to 8–85% of farms' area.
- Net Zero is more achievable and logical at a sector-level rather than a farm-level.

## GRAPHICAL ABSTRACT

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## ABSTRACT

*CONTEXT:* The UK Climate Change Committee has recommended a 64% reduction in greenhouse gas emissions from the agriculture and land-use sector to meet the 2050 Net Zero target in the UK. However, it is unclear how this reduction can be achieved at a farm level.
*OBJECTIVE:* Using detailed real farm data and novel modelling approaches, we investigated the management interventions and afforestation that would be required to deliver Net Zero within the farm boundary.
*METHODS:* Baseline carbon footprints were calculated for twenty Welsh beef and sheep farms using the Agrecalc carbon calculator, whilst carbon sequestration was estimated using Bangor University's Carbon Footprinting Tool. Scenarios were created to determine the emissions reductions achievable on each farm through implementation of cost-effective mitigation measures. Mitigation measures and their abatement potentials were sourced from the most recent UK Marginal Abatement Cost Curve, which allow emissions to be reduced mostly through improvements in efficiency thus maintaining the production of the system. Area footprints were calculated for production, with and without offset (afforested) areas needed to achieve Net Zero.

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

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

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

## 1. Introduction

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

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

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

The UK Climate Change Committee set out a "Further Ambition" scenario for agriculture, land use and peatlands in their 2019 Net Zero report, which specified emissions reductions of 64% by 2050 compared with 2017 (Stark et al., 2019). Although there is not a specific target for livestock sectors, it is presumed this should be in line with the wider agricultural sector. A 64% reduction from 2017 livestock emissions would mean an 37 Mt. $CO_2$e reduction (Climate Change Committee, 2020b). How this is achieved depends on the uptake of GHG mitigation measures. A range of mitigation measures are currently available for the livestock sector, all with varying abatement potentials and cost-effectiveness (Eory et al., 2020, 2015); the uptake for some of which has been incentivised or grant-aided through various schemes e.g., the Farming Investment Fund in England (UK Government, 2021), Small Grants – Efficiency scheme in Wales (Welsh Government, 2022a) and Agri-environment Climate Scheme in Scotland (Scottish Government, 2022).

Mitigation options include measures which address fuel and energy usage, for example, increasing fuel efficiency by actively monitoring fuel use, regular vehicle maintenance and improved driving techniques (Pellerin et al., 2013). Increasing fuel efficiency has a relatively low maximum technical abatement potential (MTP) for UK agriculture, estimated at 75 Gg $CO_2$e $yr^{-1}$ (with interactions) (Eory et al., 2015). More effective mitigation options could include measures relating to animal management such as improving breeding in cattle by directly measuring carcass traits (Bioscience Network Limited, 2012) or improving the health status of animals by targeting specific diseases to reduce morbidity and mortality (Bartley et al., 2016). These measures have the additional benefit of a negative net implementation cost as well as having comparatively high MTP for UK agriculture at 101 Gg $CO_2$e $yr^{-1}$, 784 Gg $CO_2$e $yr^{-1}$ and 363 Gg $CO_2$e $yr^{-1}$ for cattle breeding, cattle health and sheep health, respectively (Eory et al., 2015). Another measure which could result in net profit is through better animal nutrition e.g., improving the composition of animal diets through forage analysis or improving grazing management (Rooke et al., 2016), which could result in a MTP for UK agriculture of 98 Gg $CO_2$e $yr^{-1}$ in the UK (Eory et al., 2015). Other measures which relate to animal nutrition include feed additives, with one of the most promising being 3-nitrooxypropanol (3NOP), a chemical which inhibits enzymes in the rumen thereby decreasing $CH_4$ production (Duin et al., 2016). Although not included in the UK's most recent MACC, Eory et al. (2020) estimated 3NOP could reduce emissions by 0.855 Mg $CO_2$e $head^{-1}$ $yr^{-1}$ in Scotland. Manure management is another area which could be targeted to reduce emissions. For example, using an N planning tool or decreasing the margin of error on application of both synthetic and organic N sources could reduce $N_2O$ emissions. However, there may be a trade-off between abatement potential and cost, manure planning can save money but only has an estimated MTP of 18 Gg $CO_2$e $yr^{-1}$ for UK agriculture whereas low-emission manure spreading is one of the most expensive mitigation measures for beef and sheep farms but it has a high MTP of 163 Gg $CO_2$e $yr^{-1}$ (Eory et al., 2015). Finally, mitigation measures could involve altering land management, e.g., inclusion of legumes such as (*Trifolium repens* or red (*T. pratense*) clover in grass mixtures. Legumes fix nitrogen from the atmosphere, reducing the reliance on nitrogen fertiliser (Carswell et al., 2019). This means legumes can be introduced a negative net cost as well as having an abatement potential 170 Gg $CO_2$e $yr^{-1}$ (Eory et al., 2015). Many of these measures represent potential co-benefits, so-called "win-win" scenarios; for example, improved production efficiencies not only reduce GHG emissions from livestock but can also increase animal- or area-based yields. Similarly with increasing clover cover, as well as reducing $CO_2$ and $N_2O$ emissions associated with fertiliser production and application, they are also likely to increase digestibility and crude protein of pasture, therefore increasing animal yields (Jensen et al., 2012).

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

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

## 2. Methods

### 2.1. Farm data collection

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

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

### 2.2. Baseline footprint calculations

#### 2.2.1. Emission estimates: Agrecalc

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

Standardised emissions estimates were reported in units of carbon dioxide equivalents ($CO_2$e) using global warming potential over 100 years (GWP). Agrecalc uses GWP values from the fourth assessment report (AR4) which are consistent with National Inventory reporting. For $CH_4$, the value of $GWP_{100}$ is 25 and for $N_2O$ the value is 298 (IPCC, 2007). Model outputs are expressed as both total emissions per farm and GHG emissions per unit of product i.e., kg $CO_2$e kg$^{-1}$ of deadweight (dwt) (which equates to carcass weight) post slaughter. Baseline farm data were also expressed as production area footprints, defined as the area of land (in m$^2$) required to produce 1 kg of dwt per annum, i.e. m$^2$. yr kg$^{-1}$ dwt.

#### 2.2.2. Sequestration estimates: the Bangor tool

The Bangor University Carbon Footprinting Tool (Edwards-Jones et al., 2009; Hyland et al., 2016; Jones et al., 2014) was selected for calculating carbon sequestration, as it includes the most comprehensive set of sequestration calculations (Sykes et al., 2017; Taft et al., 2018), including hedgerows, individual trees, trees in silvicultural systems and field boundaries, as well as areas of pure woodland. Additionally, the Bangor Tool includes potential grassland soil sequestration in its calculations. In terms of woodland, the tool uses yield values from the Woodland Carbon Code (WCC) (Forestry Commission, 2021). All biomass conversion and expansion factors are taken from IPCC (2006). For conifers, it uses mostly IPCC Tier I values, and for broadleaf, conversion factors were taken from Milne and Brown (1997), with above to below ground biomass ratios from Mokany et al. (2006). Hedge sequestration is calculated as the area not cut in the sample year (as they are considered to be in equilibrium (Axe, 2018)) and biomass sequestration rates are assumed to be equivalent to short rotation coppice using values from Laureysens et al. (2003).

In terms of soil carbon sequestration, all values were taken from Janssens et al. (2005), using the IPCC Tier 1 methodology. Under Tier 1 methodology, soil carbon in mineral soil under woodland is assumed to remain unchanged with management, due to incomplete scientific understanding (IPCC, 2006). For organic soils under woodland, only C emissions due to drainage of forest organic soils are considered under Tier 1(IPCC, 2006). For grassland soil sequestration rates, the Bangor Tool uses national net ecosystem C change under UK grasslands taken from Janssens et al. (2005). A full list of references for sequestration can be found in Table A3.

### 2.3. Mitigation scenario modelling

Scenarios were created to determine the emission reductions possible when a range of mitigation measures were implemented on each farm and the area of woodland needed to offset the residual emissions from each farm was calculated. Area footprints were calculated for production, with and without the offset (afforested) area needed to achieve Net Zero. Between five and seven mitigation measures were implemented on each farm depending on their applicability to the individual farms. Mitigation measures and initial abatement potentials with abatement cost of < £224 Mg $CO_2e^{-1}$ were sourced from the most recent UK Marginal Abatement Cost Curve (MACC) (Eory et al., 2015) (Table 1). It was assumed all measures were implemented in full across the study farms, and abatement was calculated in terms of annual emissions reduction at farm (or product) level. Measures were implemented in a sequential approach which aimed to minimise any potential influence of the order of measures. For example, any measure which reduced synthetic (fertiliser) N use, e.g. introducing legume-grass mixtures, were implemented before nitrification inhibitors, and measures which affected livestock emission intensities were implemented before measures such as $CH_4$ inhibitors or slurry acidification. Although cost was not directly assessed in this study (outside of scope), mitigation measures were chosen from the MACC to ensure that they had previously been deemed as cost-effective and practically feasible (Eory et al., 2015).

Although Agrecalc accounts for direct effects of some mitigation measures such as reduced fertiliser and fuel use, the remaining mitigation options exhibit indirect effects that may not be directly represented in farm-level emission calculators. For example, mitigation measures relating to animal breeding and husbandry manifest through increased production and are therefore likely to translate to reduced emissions intensities (and possibly reduced national emissions, at a given level of output) but not necessarily to reduced emissions at farm level (because production may increase). In this study, production was held constant and any increases in productivity following the implementation of mitigation measures were assumed to be translated into a reduction in emissions per hectare or emissions intensities. This is a model simplification but enables more consistent comparison across farms and measures, and is an approach used in other studies (ADAS UK Ltd, 2014; Rees et al., 2020). Similarly, feed additives or specific feed types do not have their own Efs and cannot be implemented in Agrecalc. Such mitigation measures effects were estimated through *post-hoc* calculations. Where possible, abatement potentials were estimated using calculations which reflect farm types and individual farm differences. A flow diagram for each mitigation measure was created to ensure all direct and indirect effects were considered (see Fig. 1 as an example). For robustness, only mitigation measure effects with a high level of certainty in abatement potential were considered i.e., effects for which published scientific literature was in general agreement. Effects with a higher level of uncertainty were excluded from these calculations, for example, any yield effects following improved organic nitrogen (N) use as this is highly dependent on the initial N rate.

**Table 1**
Mitigation measures taken from the UK's most recent Marginal Abatement Cost Curve (MACC) and the abatement potentials used in this study (Eory et al., 2015).

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

### 2.3.1. *Mitigation measures*

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

#### 2.3.1.1. *Energy and fuel*

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

#### 2.3.1.2. *Land and nutrient management*

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

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

#### 2.3.1.3. *Nitrification inhibitor – Dicyandiamide.*

Nitrification inhibitors (NIs) like *dicyandiamide* (DCD) reduce $N_2O$ emissions by altering biochemical processes, decreasing the activity of nitrifier bacteria, prolonging the retention of ammonium N in soil and increasing N use efficiency (Singh and Verma, 2007). NIs can be applied to the soil together with liquid fertilisers (Misselbrook et al., 2014), applied as a coating on granular fertilisers (Abalos et al., 2014) or mixed into slurry before application. Additionally, they can be spread onto pastures to reduce emissions from N fertilisers (Cardenas et al., 2019). To calculate

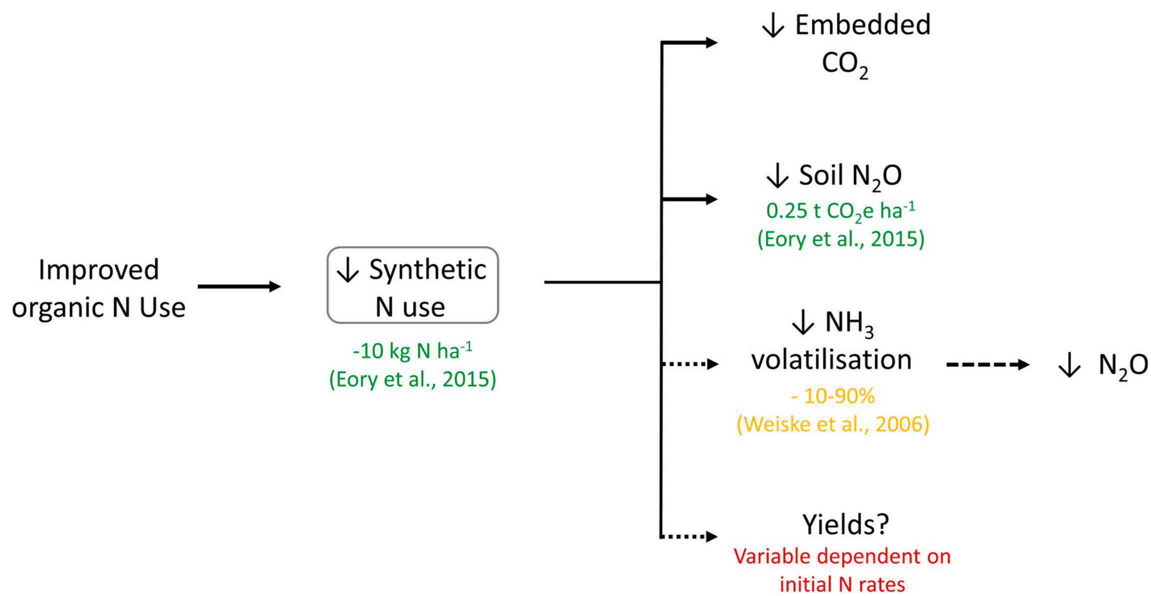


**Fig. 1.** An example of a flow diagram created for the mitigation measure *improved organic N use*, e.g. livestock manure, showing all effects of the measure with solid arrows depicting effects which were captured in the mitigation calculations and dashed arrows depicting effects which were not included in calculations due to a higher level of uncertainty in abatement potentials. Circled text represents the input variable.

NI effects, any ammonium nitrate-based fertilisers were first switched to urea-based fertilisers (which generally have lower $N_2O$ Efs) (Smith et al., 2012) then were applied with DCD as well as spread on grazed pastures. NIs are assumed to reduce $N_2O$ emissions associated with synthetic N by 66% (Cardenas et al., 2019). In this study, DCD also reduced $N_2O$ emissions from cattle urine by 46% (Chadwick et al., 2018) and cattle slurry by 56% (Misselbrook et al., 2014). Due to a lack of well-established literature, reductions in $N_2O$ from sheep urine were not included in these calculations, however, current evidence suggests this would be similar to cattle urine.

*2.3.1.4. Animal management*

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

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

*2.3.1.5. Manure management*

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

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

*2.3.1.6. Nutrition and feed additives*

*2.3.1.6.1. Improving beef and sheep nutrition.* This measure describes the improvement of ration nutritional values (i.e., digestibility of the ration), in order to improve yield and reduce enteric $CH_4$ emissions. It involves improving the composition of the diet, complemented with forage analysis and improved grazing management. Specifically, digestibility of animal feed can be increased in a number of ways such as grazing younger grasses, harvesting grass earlier and reseeding grass varieties with a higher digestibility (Bruinenberg et al., 2002). In line with the MACC analysis (Eory et al., 2015), in this study, improved diet formulation and grazing management was assumed to increase the digestibility of roughage and concentrates by 2% of their original values (Eory et al., 2015). However, yields were kept constant to reduce uncertainty in calculations to estimate liveweight gain following mitigation measures (a conservative approach, discussed later in Section 4.2).

*2.3.1.6.2. 3NOP as a feed additive.* 3-Nitrooxypropanol (3NOP) is a chemical that reduces the production of enteric $CH_4$ by ruminants when added to their rations (or introduced via a bolus). It does so by reducing the rates at which rumen archaea convert hydrogen released from ingested feed into $CH_4$ (Duin et al., 2016). Although there is little research on the effects of NOP on sheep, and although not commercially available yet, it was assumed 3NOP could be administered to all animals as a bolus (Rooke et al., 2016), which resulted in a 20% reduction in the enteric $CH_4$ conversion factor (Eory et al., 2015).

#### 2.3.2. Afforestation

Afforestation was the only measure modelled to increase carbon sequestration. Once the reduction in emissions of GHGs due to implementing the mitigation measures was applied to each farm, the area of woodland planting needed to offset the remaining emissions was calculated. Additional planting was assumed to be a mixed broadleaf woodland over 20 years old at 2 m spacing with no clearfell or thinning. Sequestration in trees and soil carbon losses from planting were based on the WCC lookup tables (Forestry Commission, 2021), through the Bangor Tool. This calculation includes $CO_2$ from land use change, $CO_2$ from soil carbon losses from tree planting, $CO_2$ from soil carbon sequestered in forests post-planting, and $CO_2$ carbon sequestered in growing trees.

## 3. Results

### 3.1. Baseline scenarios

Whole-farm GHG emissions varied considerably between farms in the baseline situation. Baseline emissions at the farm level ranged from 347 to 2326 Mg $CO_2$e $yr^{-1}$, in part reflecting a wide range of management intensities and farm sizes, from 55 to 540 ha. Farms also varied in efficiencies, with product emissions intensities ranging from 13.8 to 38.5 kg $CO_2$e $kg^{-1}$ dwt (Table 2). Although the farms had notably different baseline emissions, all farms showed similar emission profiles, with $CH_4$ emissions from enteric fermentation accounting for the majority of GHG emissions (mean of 57% across all farms) followed by $N_2O$ from soils (mean of 24%) (Fig. 2). The relative sinks for carbon (i.e., carbon sequestration) were also similar between farms, with grasslands being the biggest carbon sink, accounting for on average 72% of total sequestration (Fig. 2).

### 3.2. Mitigation scenarios

Mitigation measures were implemented in a sequential approach, culminating in a Net Zero GHG scenario for each farm through GHG removals via afforestation; an example farm is shown in Fig. 3. Mitigation scenarios for each farm can be found in Figs. C.1–19. Implementing the mitigation measures alone was not sufficient to reduce total farm emissions to zero on any farm. Emission reductions following the implementation of five to seven mitigation measures ranged from 19.7 to 35.0%, with an average of 27.9%. Individual mitigation measures resulted in an average 0.8 to 11.9% reduction in overall emissions across farms (Table 3) with 3-NOP contributing to the largest reduction. Total emissions following mitigation measures ranged from 264 to 1512 Mg $CO_2$e $yr^{-1}$. Mitigated product emissions ranged from 9.3 to 29.4 kg $CO_2$e $kg^{-1}$ dwt, with a mean of 18.9 kg $CO_2$e $kg^{-1}$ dwt (Table 4).

### 3.3. Afforestation

The area of woodland needed to offset the remaining emissions to achieve Net Zero on each farm ranged from 8 to 85% of the farm's area, with an average of 38% (Table 4); making woodland the primary carbon sequestration (and, indeed, Net Zero) measure for all mitigated scenarios. This offset area was equivalent to 10.5 to 35.0 $m^2$.yr $kg^{-1}$ dwt, with an average of 17.4 $m^2$.yr $kg^{-1}$ dwt. Average area footprints for production plus offset (afforested) area required to reach Net Zero ranged from 25.8 to 231.7 $m^2$.yr $kg^{-1}$ dwt. A scatterplot of production area footprints plotted against production plus offset area footprints which depicts changes in the area efficiency ranking from baseline compared with Net Zero scenarios can be found in Fig. C.20.

## 4. Discussion

### 4.1. Baseline scenarios

#### 4.1.1. Emissions

In order to achieve Net Zero in any sector, it is essential to first gain an understanding of the magnitude of baseline emissions. This not only allows us to consider total emissions but also highlights sources of emissions where there is potential for mitigation. Considerable variation was seen between farms in this study, reflecting large differences in size, land quality, management systems and efficiency. The farm with the highest product emissions – Farm K, at 38.5 kg $CO_2$e $kg^{-1}$ dwt, had product emissions almost three times that of the farm with the lowest product emissions – Farm N, at 13.8 kg $CO_2$e $kg^{-1}$ dwt, indicating the opportunity for efficiency gains (Table 2). Hyland et al. (2016)

**Table 2**
Farm characteristics, baseline farm-level emissions, baseline product emissions and baseline emissions per unit area.

| Farm | Farm size (ha) | Livestock enterprise | Baseline farm-level emissions (Mg $CO_2$e $yr^{-1}$) | Baseline product emissions (kg $CO_2$e $kg^{-1}$ dwt) | Baseline emissions per unit area (kg $CO_2$e $ha^{-1}$ $yr^{-1}$) |
|---|---|---|---|---|---|
| A | 262 | Hill | 952 | 22.1 | 3635 |
| B | 117 | Hill | 385 | 29.2 | 3293 |
| C | 157 | Hill | 875 | 23.0 | 5575 |
| D | 270 | Hill | 1241 | 26.2 | 4598 |
| E | 93 | Hill | 347 | 15.5 | 3729 |
| F | 116 | Hill | 1078 | 36.1 | 9292 |
| G | 71 | Hill | 463 | 26.3 | 6519 |
| H | 258 | Hill | 1212 | 23.7 | 4698 |
| I | 288 | Hill | 783 | 21.4 | 2718 |
| J | 200 | Hill | 2061 | 24.8 | 10,305 |
| K | 540 | Hill | 889 | 38.4 | 1647 |
| L | 233 | Lowland | 950 | 26.4 | 4076 |
| M | 55 | Lowland | 476 | 21.7 | 8661 |
| N | 111 | Lowland | 1411 | 13.8 | 12,716 |
| O | 128 | Upland | 743 | 38.0 | 5802 |
| P | 290 | Upland | 2326 | 24.3 | 8021 |
| Q | 296 | Upland | 1423 | 38.5 | 4806 |
| R | 278 | Upland | 1326 | 23.8 | 4777 |
| S | 205 | Upland | 1375 | 25.3 | 6708 |
| T | 189 | Upland | 803 | 22.0 | 4248 |
| Average | | | **1056** | **26.0** | **5791** |

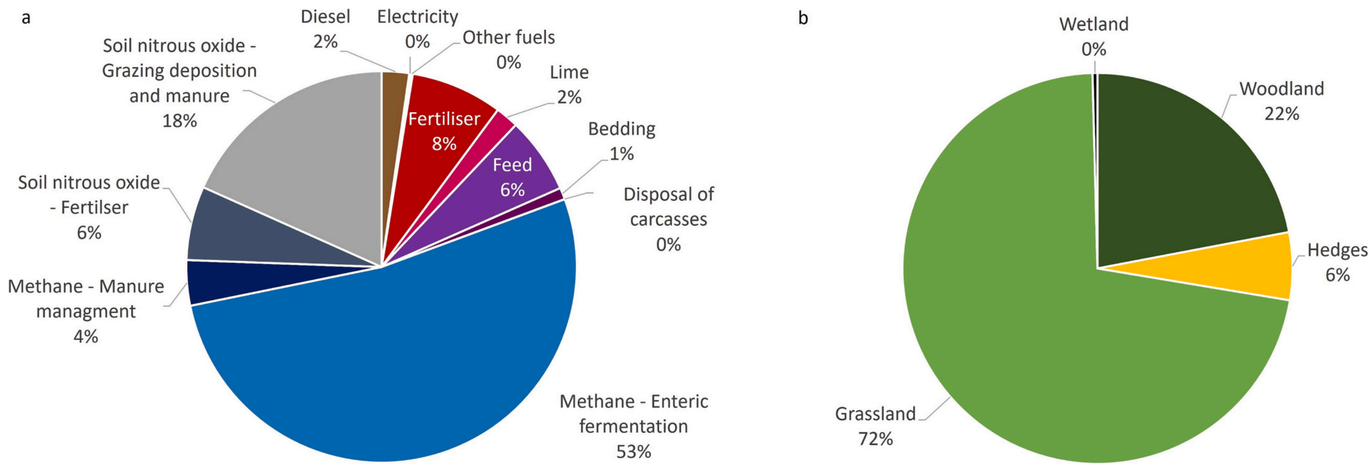


**Fig. 2.** Average [a] emission breakdown of greenhouse gases and [b] sequestration breakdown across the twenty farms. Some numbers appear as 0 due to rounding.

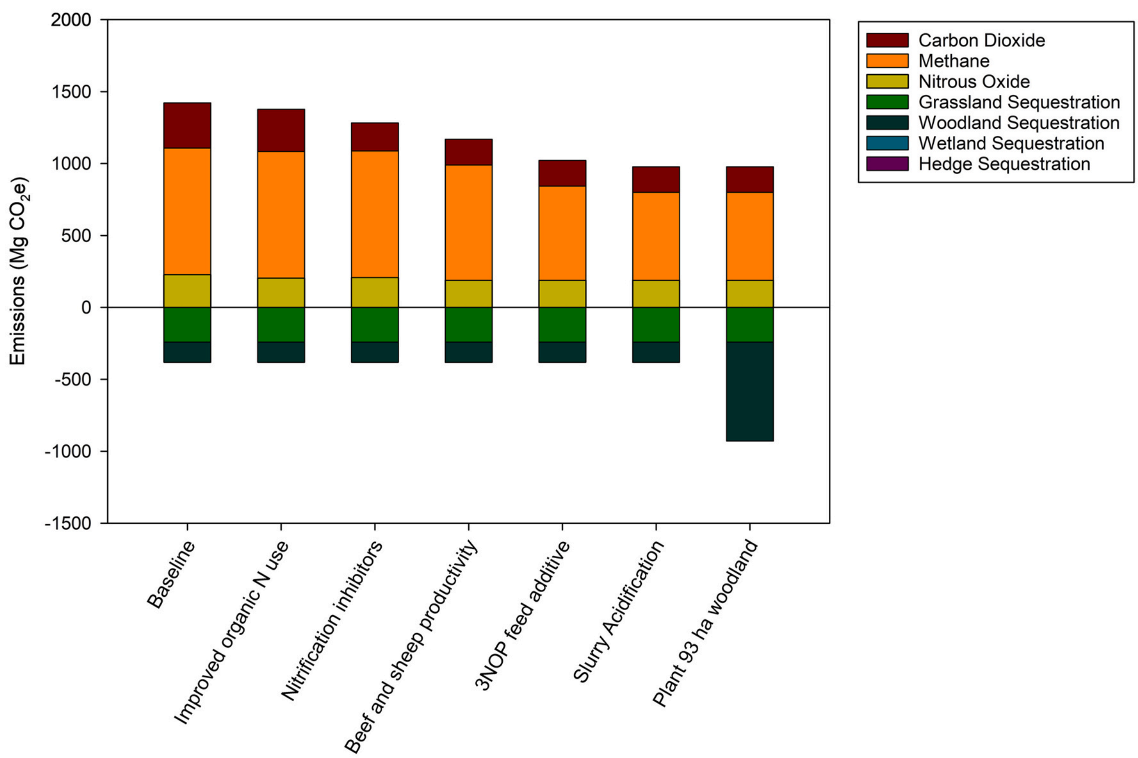


**Fig. 3.** An example of one hill farm – Farm Q's (farm characteristics in Table A.1) mitigation scenario with mitigation measures implemented sequentially and cumulative emissions reduction shown (31%). The area of additional woodland needed to offset residual emissions to achieve Net Zero for this farm was calculated at 93 ha. Sensitivity analysis was carried out on a subsample of data and found little effect of the order of mitigation measures.

demonstrated this potential for emission reductions in the production of Welsh beef and lamb if all enterprises replicated the efficiency levels of the highest-performing producers. Although this modelling was carried out on 20 case study farms in Wales, and therefore the aim was not to generate statistically scalable results, this principle applies at a global as well as local level. For example, Costa et al. (2022) found global food systems could reduce emissions by 45% if all food production was shifted to the 30th-percentile of the least emission-intensive systems. However, these efficiency gains must be made sustainably to avoid an unintended increase in total emissions, i.e., by increasing livestock numbers across the sector as a whole.

Despite Farm N having the lowest product emissions, it also had a notably high farm-level GHG emissions – mostly a reflection of the enteric emissions associated with their large livestock numbers (Table 2). This shows that the most efficient farms in terms of emissions intensity are not always those with the lowest farm-level emissions due to higher stocking densities. This highlights an important global issue that although food production must be increased to feed a growing population, this must be done sustainably to avoid increasing net GHG emissions (Costa et al., 2022).

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

Farm type had little apparent influence on product emissions, with considerable overlap in values between hill, upland and lowland farms

**Table 3**
Average emissions reductions and standard error of the mean (SEM) for individual mitigation measures across the twenty farms. Measures ordered from largest to smallest emissions reductions.

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

(Table 2). In general, lowland farms used more inputs which contributed to a greater weight of products over which those inputs were divided. Hill farms required fewer inputs, however, livestock produced on hill systems were often sold at a lower weight. Moreover, the farms with the highest and lowest total emissions were both the same farm type (hill). There was also no clear association between farm product emissions and farm size or stock numbers across farm types (Table 2). This may in part reflect the small sample size in some categories, however, farm size has also been shown in other studies to have no effect of emission intensity (Hyland et al., 2016). These results reiterate the importance of management systems as opposed to geographical factors on product carbon footprints.

Production area footprints appear to be lower on lowland farms at 42.3 $m^2.yr\ kg^{-1}$ dwt than on hill and upland (66.3 $m^2.yr\ kg^{-1}$ dwt and 53.2 $m^2.yr\ kg^{-1}$ dwt, respectively) (Fig. C.20). However, although study farms were deemed by sectoral stakeholders to be representative of their respective "types", with only three lowland farms in this study, there are not enough data points to be conclusive. Production area footprints did not appear to be associated with total emissions or product emissions, instead this metric addresses a separate issue - competition for land. In order to reach current policy targets, Welsh farms (and indeed farms across the world) will need to reduce both emission intensity and total emissions as well as prioritise land use, especially with the increased demand for land-based $CO_2$ removal activities (Beauchemin et al., 2020; Rosa and Gabrielli, 2023).

#### 4.1.2. Sequestration

On balance, baseline carbon sequestration on these farms was low compared to the level of emissions, offsetting an average 22% of total emissions (Table 2). Of this offsetting, the majority was attributed to soil sequestration under grassland, accounting for 67% of total sequestration (Fig. 2). There is much debate around the potential for soil carbon sequestration in ruminant production systems (Abdalla et al., 2018; Arca et al., 2021; Batalla et al., 2015; Hammer et al., 2016; Soussana et al., 2010). Within the UK, it is widely considered that long term grasslands will have reached an approximate equilibrium in carbon exchange with the atmosphere resulting in a small potential for any additional carbon sequestration (Smith, 2014). Accurately estimating soil carbon sequestration (without field sampling to measure actual change in soil carbon) is difficult, therefore, sequestration estimates must be interpreted with caution.

Existing farm woodland and hedgerow sequestration accounted for relatively little of the total carbon sequestration at only 28% (Fig. 2), representing an average 7% offset of total farm emissions – however, this was higher than reported in other studies (e.g., Emmett et al., 2017). The contribution of carbon sequestration by woodland differed between farm types, for example on lowland farms, isolated trees (19% of total sequestration) accounted for a considerably greater proportion of sequestration than woodland (7% of total sequestration). This was due to the considerable variation in tree cover on farms (0 to 27%) (Table A.1), with some farms reporting they had no trees or hedges. Farmers often had little detailed knowledge of the extent of hedges, individual trees and areas of woodland on their farms, so the estimates of woodland cover have a high level of uncertainty. Upland farms had the highest woodland cover at 8%, with lowland farms having the lowest at 2% (Table A.1). Many factors influenced these figures, for example upland farms were more likely to have planted trees as shelter for their more exposed areas. Tree cover was lower on hill farms due to the exposed nature of the land, and lowest on lowland farms despite their soil and climatic conditions favouring tree growth.

Hedgerows are often thought to be an important contributor to sequestration on farms (Blair, 2018), however, their offsetting potential was relatively low in this study. The Bangor Tool assumes no net sequestration in hedges which are cut in the sample year. This means that managed hedges will not count towards any carbon sequestration. Additionally, this management practice could skew carbon

**Table 4**
Emission reductions, mitigated emissions and area of woodland needed to offset residual emissions following mitigation scenarios on each farm. Offset areas are expressed as a percentage of farm's total area as well as specific annual area occupation per unit meat output (in $m^2.yr\ kg^{-1}$ dwt) to indicate magnitude.

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

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

sequestration and offset values depending on whether the hedge was flailed in the same year as the footprint was carried out. Allowing hedgerows to grow taller and wider increase the hedge's capacity to sequester carbon in above- and below-ground biomass (Axe, 2018; Axe et al., 2017).

### 4.2. *Mitigation scenarios*

#### 4.2.1. *Emission reductions*

The implementation of mitigation measures was found to reduce emissions by an average of 28% across all farms. Emission reductions were similar across all farm types, with average emission reductions of 26%, 30% and 29% for hill, upland and lowland, respectively (Table 4). Farms with only sheep had lower emission reductions of 24%, most likely reflecting the more limited number of mitigation measures applicable to these farms. Nitrous oxide emissions from sheep only farms were generally lower than those of cattle, so the effectiveness of measures targeting $N_2O$ are limited. Measures relating to manure management are not applicable for sheep farms which are primarily extensive systems with short (or no) periods of animal housing. Sheep farms also have lower levels of inputs including fertiliser and fuel, which limited the potential from mitigation measures in such areas.

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

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

#### 4.2.2. *Woodland needed to achieve Net Zero*

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

In this study, the area of woodland needed to achieve Net Zero at a farm level was found to be affected by farm type. Hill and upland farms required on average a lower proportion of woodland to reach Net Zero (Table 4). This could be due to the extensive nature of these systems with larger size and generally lower baseline emissions (per hectare) due to fewer inputs and lower livestock numbers. Lowland farms needed on average higher percentages of their total area to be converted to woodland to achieve GHG neutrality. Lowland farms not only had on average higher inputs and total baseline emissions, but they were also smaller in size, making the proportion of land required for woodland planting for Net Zero to appear particularly high. When converted from percentages, the area of woodland needed to achieve Net Zero across farms was on average equivalent to 58 ha, 80 ha and 68 ha for hill, upland and lowland, respectively.

As noted, Farm N - one of the lowland farms - had a notably high farm-level GHG emissions (Table 2). Even following mitigation, with this farm having one of the highest levels of emission reductions, it would still require the equivalent of 85% of its total area to be planted to offset the remaining emissions (Table 4). Despite this, Farm N was also the most efficient (when ranked by emissions intensity) of the twenty participating farms. If all the study farms were to produce at this level of efficiency, the same level of output could be produced on 28% of the current land area, saving 2984 ha across these 20 farms alone. Although this could result in higher emissions per hectare on the farmed land, such a land 'sparing' approach would make large areas available for carbon sequestration or biodiversity provisioning. As highlighted earlier for Farm N, it is important to interpret farm emissions data with caution and nuance to avoid the potential of displacing production from more efficient farms to less efficient farms, which would likely increase overall emissions (Bateman and Balmford, 2023).

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

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

### 4.3. Alternative land use mitigation measures

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

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

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

The competition for land use is highlighted in the difference between the baseline area footprints of farms and the area footprint when the offset needed to achieve Net Zero is included. The area footprint notably increases from the baseline average of 58.8 $m^2$.yr $kg^{-1}$ dwt to an average of 76.1 $m^2$.yr $kg^{-1}$ dwt when including offset area. The apparent area efficiency decreased linearly when comparing baseline area footprints with footprints from Net Zero scenarios which include the offset area. However, the ranking of farms was largely unaffected, even following mitigation (Fig. C.20). Significantly more land will be needed if the same quantity of meat is to be produced in a carbon neutral manner, however, it is unclear where this additional land could come from. Reducing food production on UK farms for sequestration purposes would not be a sensible mitigation strategy if it results in importing food from more GHG-intensive production systems. Moreover, this would have huge social, economic, and environmental implications which were also not considered in this study. The purpose of this paper was to focus on the potential for GHG mitigation at a farm level; many other studies have identified broader changes to global food systems that are needed to achieve Net Zero. These changes often relate to reducing the demand for meat through reducing food waste or dietary change (Costa et al., 2022; Rosa and Gabrielli, 2023). Recently, there have been calls for a complete transformation in our food systems, which traditionally focus on food security alone, to a more integrated approach which ensures security without undermining the environment (Bhunnoo and Poppy, 2020; FAO, 2020; Webb et al., 2020).

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

### 4.4. Limitations

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

The main limitation of this mitigation modelling is the exclusion of some of the effects of mitigation measures due to the uncertainty of their abatement potentials. For both reducing synthetic and organic N use, it was assumed there was no effect on yields. This is most likely to be valid where targeted N use allows the N is used more efficiently or there are only small reductions in N application where it is currently over-applied. The yield effects of reducing fertiliser use will depend on baseline N rates and will be different for each farm, but without data/soil analysis it is not possible to predict this for individual farms. However, most mitigation measures under this category, such as better N planning and timing of N application, are unlikely to negatively affect yield. Moreover, in this study we assumed production was held constant. In practice, as mentioned earlier, if production efficiencies were increased, it is possible that farmers would increase livestock numbers, leading to an increase in net GHG emissions. It is also possible that emissions reductions potential we applied from adopting some of the mitigation measures are conservative estimates. This will vary between farms and will depend on the attributes of their current production system. For instance, Fox et al. (2018) showed that parasitic worms can increase methane emissions from lambs by 33%. Where such disease burdens exist on farms, resolving such issues could therefore lead to a much greater reduction in emissions than the estimates used in this study (Table 1).

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

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

## 5. Conclusions

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

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

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

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

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## CRediT authorship contribution statement

**Louise C. McNicol:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Non G. Williams:** Data curation, Investigation, Writing – review & editing. **Dave Chadwick:** Conceptualization, Supervision, Writing – review & editing. **David Styles:** Conceptualization, Supervision, Writing – review & editing. **Robert M. Rees:** Conceptualization, Supervision, Writing – review & editing. **Rachael Ramsey:** Writing – review & editing. **A. Prysor Williams:** Conceptualization, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.103852.

## References

Abalos, D., Jeffery, S., Sanz-Cobena, A., Guardia, G., Vallejo, A., 2014. Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use

efficiency. Agric. Ecosyst. Environ. 189, 136–144. https://doi.org/10.1016/j.agee.2014.03.036.
Abdalla, M., Hastings, A., Chadwick, D.R., Jones, D.L., Evans, C.D., Jones, M.B., Rees, R.M., Smith, P., 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agric. Ecosyst. Environ. 253, 62–81. https://doi.org/10.1016/j.agee.2017.10.023.
ADAS UK Ltd, 2014. Study to Model the Impact of Controlling Endemic Cattle Diseases and Conditions on National Cattle Productivity. Agricultural Performance and Greenhouse Gas Emissions.
AHDB, 2022. Nutrient Management Guide (RB209). Agriculture and Horticulture Development Board, Kenilworth, UK.
Arca, P., Vagnoni, E., Duce, P., Franca, A., 2021. How does soil carbon sequestration affect greenhouse gas emissions from a sheep farming system? Results of a life cycle assessment case study. Ital. J. Agron. 16 https://doi.org/10.4081/ija.2021.1789.
Axe, M.S., 2018. Hedgerow agroforestry in England and Wales: Increasing width to sequester additional carbon. In: European Agroforestry Conference-Agroforestry as Sustainable Land Use, 4th. EURAF.
Axe, M.S., Grange, I.D., Conway, J.S., 2017. Carbon storage in hedge biomass—a case study of actively managed hedges in England. Agric. Ecosyst. Environ. 250, 81–88. https://doi.org/10.1016/j.agee.2017.08.008.
Balmford, A., 2021. Concentrating vs. spreading our footprint: how to meet humanity's needs at least cost to nature. J. Zool. 315, 79–109. https://doi.org/10.1111/jzo.12920.
Bartley, D.J., Skuce, P.J., Zadoks, R.N., MacLeod, M., 2016. Endemic sheep and cattle diseases and greenhouse gas emissions. Adv. Anim. Biosci. 7, 253–255. https://doi.org/10.1017/S2040470016000327.
Batalla, I., Knudsen, M.T., Mogensen, L., del Hierro, Ó., Pinto, M., Hermansen, J.E., 2015. Carbon footprint of milk from sheep farming systems in northern Spain including soil carbon sequestration in grasslands. J. Clean. Prod. 104, 121–129. https://doi.org/10.1016/j.jclepro.2015.05.043.
Bateman, I., Balmford, A., 2023. Current conservation policies risk accelerating biodiversity loss. Nature 618, 671–674. https://doi.org/10.1038/d41586-023-01979-x.
Beauchemin, K.A., Ungerfeld, E.M., Eckard, R.J., Wang, M., 2020. Review: fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation. animal 14, s2–s16. https://doi.org/10.1017/S1751731119003100.
Beef Improvement Federation, 2018. Guidelines For Uniform Beef Improvement Programs, Ninth Edition.
BEIS, 2022. Final UK Greenhouse Gas Emissions National Statistics: 1990 to 2020. Department for Business, Energy & Industrial Strategy.
Bhunnoo, R., Poppy, G.M., 2020. A national approach for transformation of the UK food system. Nat. Food 1, 6–8. https://doi.org/10.1038/s43016-019-0019-8.
Bioscience Network Limited, 2012. Developing Options to Deliver a Substantial Environmental and Economic Sustainability Impact Through Breeding for Feed Efficiency of Feed use in UK Beef Cattle (DEFRA No. IF0207.).
Blair, J., 2018. Hedgerows as form of agroforestry to sequester and store carbon in agricultural landscapes: A review. In: European Agroforestry Conference-Agroforestry as Sustainable Land Use, 4th. EURAF.
Bonn, A., Reed, M.S., Evans, C.D., Joosten, H., Bain, C., Farmer, J., Emmer, I., Couwenberg, J., Moxey, A., Artz, R., Tanneberger, F., von Unger, M., Smyth, M.-A., Birnie, D., 2014. Investing in nature: developing ecosystem service markets for peatland restoration. Ecosyst. Serv. 9, 54–65. https://doi.org/10.1016/j.ecoser.2014.06.011.
Brack, D., King, R., 2021. Managing land-based CDR: BECCS, forests and carbon sequestration. Global Pol. 12, 45–56. https://doi.org/10.1111/1758-5899.12827.
Brancalion, P.H.S., Holl, K.D., 2020. Guidance for successful tree planting initiatives. J. Appl. Ecol. 57, 2349–2361. https://doi.org/10.1111/1365-2664.13725.
Brtnicky, M., Datta, R., Holatko, J., Bielska, L., Gusiatin, Z.M., Kucerik, J., Hammerschmiedt, T., Danish, S., Radziemska, M., Mravcova, L., Fahad, S., Kintl, A., Sudoma, M., Ahmed, N., Pecina, V., 2021. A critical review of the possible adverse effects of biochar in the soil environment. Sci. Total Environ. 796, 148756 https://doi.org/10.1016/j.scitotenv.2021.148756.
Bruinenberg, M.H., Valk, H., Korevaar, H., Struik, P.C., 2002. Factors affecting digestibility of temperate forages from seminatural grasslands: a review. Grass Forage Sci. 57, 292–301. https://doi.org/10.1046/j.1365-2494.2002.00327.x.
Burgess, P.J., 2017. Agroforestry in the UK. Q. J. For. 111.
Cardenas, L.M., Thorman, R., Ashlee, N., Butler, M., Chadwick, D., Chambers, B., Cuttle, S., Donovan, N., Kingston, H., Lane, S., Dhanoa, M.S., Scholefield, D., 2010. Quantifying annual N2O emission fluxes from grazed grassland under a range of inorganic fertiliser nitrogen inputs. Agricult. Ecosyst. Environ. Estim. Nitrous Oxide Emiss. Ecosyst. Mitigat. Technol. 136, 218–226. https://doi.org/10.1016/j.agee.2009.12.006.
Cardenas, L.M., Bhogal, A., Chadwick, D.R., McGeough, K., Misselbrook, T., Rees, R.M., Thorman, R.E., Watson, C.J., Williams, J.R., Smith, K.A., Calvet, S., 2019. Nitrogen use efficiency and nitrous oxide emissions from five UK fertilised grasslands. Sci. Total Environ. 661, 696–710. https://doi.org/10.1016/j.scitotenv.2019.01.082.
Carswell, A.M., Gongadze, K., Misselbrook, T.H., Wu, L., 2019. Impact of transition from permanent pasture to new swards on the nitrogen use efficiency, nitrogen and carbon budgets of beef and sheep production. Agric. Ecosyst. Environ. 283, 106572 https://doi.org/10.1016/j.agee.2019.106572.
Chadwick, D.R., Cardenas, L.M., Dhanoa, M.S., Donovan, N., Misselbrook, T., Williams, J.R., Thorman, R.E., McGeough, K.L., Watson, C.J., Bell, M., Anthony, S.G., Rees, R.M., 2018. The contribution of cattle urine and dung to nitrous oxide emissions: quantification of country specific emission factors and implications for national inventories. Sci. Total Environ. 635, 607–617. https://doi.org/10.1016/j.scitotenv.2018.04.152.
Chapman, S.J., Bell, J.S., Campbell, C.D., Hudson, G., Lilly, A., Nolan, A.J., Robertson, A.H.J., Potts, J.M., Towers, W., 2013. Comparison of soil carbon stocks in Scottish soils between 1978 and 2009. Eur. J. Soil Sci. 64, 455–465. https://doi.org/10.1111/ejss.12041.
CIEL, 2022. Net Zero Carbon & UK Livestock Report: How Farmers Can Reduce Emissions.
Clark, M.A., Domingo, N.G.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., Azevedo, I.L., Hill, J.D., 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science 370, 705–708. https://doi.org/10.1126/science.aba7357.
Climate Change Committee, 2020a. The Sixth Carbon Budget The UKs Path to Net Zero.
Climate Change Committee, 2020b. Land use: Policies for a Net Zero UK.
Coomes, D.A., Allen, R.B., 2007. Effects of size, competition and altitude on tree growth. J. Ecol. 95, 1084–1097. https://doi.org/10.1111/j.1365-2745.2007.01280.x.
Costa, C., Wollenberg, E., Benitez, M., Newman, R., Gardner, N., Bellone, F., 2022. Roadmap for achieving net-zero emissions in global food systems by 2050. Sci. Rep. 12, 15064. https://doi.org/10.1038/s41598-022-18601-1.
Craig, K., 2020. Farm Management Handbook 2020/21. FAS.
Darusman, T., Murdiyarso, D., Impron, Anas, 2023. Effect of rewetting degraded peatlands on carbon fluxes: a meta-analysis. Mitig. Adapt. Strateg. Glob. Chang. 28, 10. https://doi.org/10.1007/s11027-023-10046-9.
DEFRA, 2012. Guidelines to Defra Greenhouse Gas (GHG) Conversion Factors for Company Reporting. Department for Environment, Food and Rural Affairs, London, UK.
DEFRA, 2021. Agriculture in the United Kingdom 2020. Department for Environment, Food and Rural Affairs Department of Agriculture, Environment and Rural Affairs (Northern Ireland) Welsh Government, Knowledge and Analytical Services The Scottish Government, Rural and Environment Science and Analytical Services.
DEFRA, 2022. The British Survey of Fertiliser Practice.
Doelman, J.C., Stehfest, E., van Vuuren, D.P., Tabeau, A., Hof, A.F., Braakhekke, M.C., Gernaat, D.E.H.J., van den Berg, M., van Zeist, W.-J., Daioglou, V., van Meijl, H., Lucas, P.L., 2020. Afforestation for climate change mitigation: potentials, risks and trade-offs. Glob. Chang. Biol. 26, 1576–1591. https://doi.org/10.1111/gcb.14887.
Duin, E.C., Wagner, T., Shima, S., Prakash, D., Cronin, B., Yáñez-Ruiz, D.R., Duval, S., Rümbeli, R., Stemmler, R.T., Thauer, R.K., Kindermann, M., 2016. Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol. Proc. Natl. Acad. Sci. U. S. A. 113, 6172–6177. https://doi.org/10.1073/pnas.1600298113.
Edwards-Jones, G., Plassmann, K., Harris, I.M., 2009. Carbon footprinting of lamb and beef production systems: insights from an empirical analysis of farms in Wales, UK. J. Agric. Sci. 147, 707–719. https://doi.org/10.1017/S0021859609990165.
Emmett, B.E., Abdalla, M., Anthony, S., Astbury, S., August, T., Barrett, G., Beckmann, B., Biggs, J., Botham, M., Bradley, D., Brown, M., Burden, A., Carter, H., Chadwick, D., Cigna, F., Collier, R., Cooper, D., Cooper, J., Cosby, B.J., Creer, S., Cross, P., Dadam, D., Edwards, F., Edwards, M., Evans, C., Ewald, N., Fitton, A., Garbutt, A., Giampieri, C., Gooday, R., Grebby, S., Greene, S., Halfpenney, I., Hall, J., Harrison, S., Harrower, C., Henrys, P., Hobson, R., Hughes, P., Hughes, S., Illian, J., Isaac, N., Jackson, B., Jarvis, S., Jones, D.L., Jones, P., Keith, A., Kelly, M., Kneebone, N., Korenko, J., Lallias, D., Leaver, D., Robinson, I., Malcolm, H., Maskell, L., McDonald, J., Moxley, J., Norton, L., O'Hare, M., Oliver, T., Owen, A., Parkhill, K.A., Pereira, M., Peyton, J., Pogson, M., Powney, G., Pritchard, N., Prochorskaite, A., Prosser, M., Pywell, R., Rawlins, B., Reuland, O., Richards, M., Robinson, D.A., Rorke, S., Rowland, C., Roy, D., Scarlett, P., Scholefield, P., Scott, A., Scott, L., Scott, R., Sharps, K., Siriwardena, G., Smart, S., Smith, G., Smith, P., Stopps, J., Swetnam, R., Taft, H., Taylor, R., Tebbs, E., Thomas, A., Todd-Jones, C., Tordoff, G., Turner, G., Van Breda, J., Vincent, H., Wagner, M., Waters, E., Walker-Springett, K., Wallace, H., Watkins, J., Webb, G., White, J., Whitworth, E., Williams, B., Williams, P., Wood, C., Wright, S., 2017. Glastir Monitoring & Evaluation Programme. Final report (Publication - Report). NERC/Centre for Ecology & Hydrology, Bangor, UK.
El-Naggar, A., El-Naggar, A.H., Shaheen, S.M., Sarkar, B., Chang, S.X., Tsang, D.C.W., Rinklebe, J., Ok, Y.S., 2019. Biochar composition-dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: a review. J. Environ. Manag. 241, 458–467. https://doi.org/10.1016/j.jenvman.2019.02.044.
Eory, V., Topp, C.F.E., Moran, D., 2013. Multiple-pollutant cost-effectiveness of greenhouse gas mitigation measures in the UK agriculture. Environ. Sci. Policy 27, 55–67. https://doi.org/10.1016/j.envsci.2012.11.003.
Eory, V., MacLeod, M., Topp, C.F.E., Rees, R.M., Webb, McVittie, Wall, Borthwick, Wiltshire, Watson Waterhouse, 2015. Review and update the UK Agriculture Marginal Abatement Cost Curve to Assess the Greenhouse Gas Abatement Potential for the 5th Carbon Budget Period and to 2050. (Final Report Submitted for the Project Contract "Provision of Services to Review and Update the UK Agriculture MACC and to Assess Abatement Potential for the 5 Th Carbon Budget Period and to 2050"). SRUC.
Eory, V., Topp, K., Rees, B., Leinonen, I., Maire, J., 2020. Marginal Abatement Cost Curve for Scottish Agriculture. https://doi.org/10.7488/ERA/755.
Fangueiro, D., Hjorth, M., Gioelli, F., 2015. Acidification of animal slurry– a review. J. Environ. Manag. 149, 46–56. https://doi.org/10.1016/j.jenvman.2014.10.001.
FAO, 2013. Mitigation of Greenhouse Gas Emissions in Livestock Production: A Review of Technical Options for Non-CO2 Emissions, FAO Animal Production and Health Paper. Food and Agriculture Organization of the United Nations, Rome.
FAO, 2020. The State of Food Security and Nutrition in the World 2020: Transforming Food Systems for Affordable Healthy Diets. Food & Agriculture Org.
Forestry Commission, 2021. Woodland Carbon Code: Carbon Lookup Tables.
Forster, E.J., Healey, J.R., Dymond, C., Styles, D., 2021. Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. Nat. Commun. 12, 3831. https://doi.org/10.1038/s41467-021-24084-x.

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

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

Green, R., Cornell, S., Scharlemann, J., Balmford, A., 2005. Farming and the Fate of Wild Nature. Science (New York, N.Y.) 307, 550–555. https://doi.org/10.1126/science.1106049.

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

Hammer, T.J., Fierer, N., Hardwick, B., Simojoki, A., Slade, E., Taponen, J., Viljanen, H., Roslin, T., 2016. Treating cattle with antibiotics affects greenhouse gas emissions, and microbiota in dung and dung beetles. Proc. R. Soc. B Biol. Sci. 283, 20160150. https://doi.org/10.1098/rspb.2016.0150.

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

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

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

Hilber, I., Bastos, A.C., Loureiro, S., Soja, G., Marsz, A., Cornelissen, G., Bucheli, T.D., 2017. The different faces of biochar: contamination risk versus remediation tool. J. Environ. Eng. Landsc. Manag. 25, 86–104. https://doi.org/10.3846/16486897.2016.1254089.

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

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

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate. In: Miller, H.L. (Ed.), M.Tignor and. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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

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

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

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

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

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

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

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

Jordon, M.W., Willis, K.J., Harvey, W.J., Petrokofsky, L., Petrokofsky, G., 2020. Implications of temperate agroforestry on sheep and cattle productivity, environmental impacts and enterprise economics. A systematic evidence map. Forests 11, 1321. https://doi.org/10.3390/f11121321.

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

Kool, A., Marinussen, M., Blonk, H., Consultants, B., 2012. LCI Data for the Calculation Tool Feedprint for Greenhouse Gas Emissions of Feed Production and Utilization, p. 20.

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

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

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

Li, D., Lanigan, G., Humphreys, J., 2011. Measured and simulated nitrous oxide emissions from ryegrass- and ryegrass/White clover-based grasslands in a moist temperate climate. PLoS One 6, e26176. https://doi.org/10.1371/journal.pone.0026176.

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

Milne, R., Brown, T.A., 1997. Carbon in the vegetation and soils of Great Britain. J. Environ. Manag. 49, 413–433. https://doi.org/10.1006/jema.1995.0118.

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

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

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

Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333, 1289–1291. https://doi.org/10.1126/science.1208742.

Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D., 2018. Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: evidence from long-term experiments at Rothamsted research, United Kingdom. Glob. Chang. Biol. 24, 2563–2584. https://doi.org/10.1111/gcb.14066.

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

Rees, R.M., Eory, V., Bell, J., Topp, C.F.E., Sykes, A., Misselbrook, T., Cardenas, L.M., Chadwick, D.R., Sohi, S., Manning, A.C., Smith, P., 2020. How Far Can Greenhouse Gas Mitigation Take us towards Net Zero Emissions in Agriculture?, p. 8.

Rooke, J.A., Miller, G.A., Flockhart, J.F., McDowell, M.M., MacLeod, M., 2016. Nutritional Strategies to Reduce Enteric Methane Emissions.

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

Ryan, M., O'Donoghue, C., 2016. Socio-Economic Drivers of Farm Afforestation Decision-Making. Irish Forestry.

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

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

Singh, S.N., Verma, A., 2007. ENVIRONMENTAL REVIEW: the potential of nitrification inhibitors to manage the pollution effect of nitrogen fertilizers in agricultural and other soils: a review. Environ. Pract. 9, 266–279. https://doi.org/10.1017/S1466046607070482.

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

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

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

Sokolov, V., Habtewold, J., VanderZaag, A., Dunfield, K., Gregorich, E., Wagner-Riddle, C., Venkiteswaran, J.J., Gordon, R., 2021. Response curves for Ammonia and methane emissions from stored liquid manure receiving low rates of sulfuric acid. Front. Sustain. Food Syst. 5.

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

Stark, C., Thompson, M., Andrew, T., Beasley, G., Bellamy, O., Budden, P., Cole, C., Darke, J., Davies, E., Feliciano, D., 2019. Net Zero: The UK's Contribution to Stopping Global Warming.

Stott, A., MacLeod, M., Moran, D., 2010. Reducing greenhouse gas emissions through better animal health rural policy centre. SAC 8.

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

Taft, H., Chadwick, D., Styles, D., Kipling, R., Newbold, J., Moorby, J., 2018. A Review of Greenhouse Gas Calculators for Use in the Welsh Agricultural Sector, a Climate Smart Agriculture (Wales) Report.

Thorman, R.E., Nicholson, F.A., Topp, C.F.E., Bell, M.J., Cardenas, L.M., Chadwick, D.R., Cloy, J.M., Misselbrook, T.H., Rees, R.M., Watson, C.J., Willimas, J.R., 2020. Towards country-specific nitrous oxide emission factors for manures applied to arable and grassland soils in the UK. Front. Sustain. Food Syst. 4, 62. https://doi.org/10.3389/fsufs.2020.00062.

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

Veldman, J.W., Overbeck, G.E., Negreiros, D., Mahy, G., Le Stradic, S., Fernandes, G.W., Durigan, G., Buisson, E., Putz, F.E., Bond, W.J., 2015. Where tree planting and Forest expansion are bad for biodiversity and ecosystem services. BioScience 65, 1011–1018. https://doi.org/10.1093/biosci/biv118.

Vellinga, T.V., Blonk, H., Marinussen, M., van Zeist, W.J., Starmans, D.A.J., 2013. Methodology used in FeedPrint: A Tool Quantifying Greenhouse Gas Emissions of Feed Production and Utilization (no. 674). Wageningen UR Livestock Research, Lelystad.

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

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

Welsh Government, 2021a. Survey of Agriculture and Horticulture: June 2021. Welsh Government.

Welsh Government, 2021b. Net Zero Wales Carbon Budget 2 (2021 to 2025). Welsh Government.

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

Welsh Government, 2022b. Farming Facts and Figures: 2022. Welsh Government.

Welsh Government, 2023. Survey of Agriculture and Horticulture: June 2023. Welsh Government.

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

Yu, G., Beauchemin, K.A., Dong, R., 2021. A review of 3-Nitrooxypropanol for enteric methane mitigation from ruminant livestock. Animals (Basel) 11, 3540. https://doi.org/10.3390/ani11123540.