European Innovation Partnership (EIP) Wales

Carbon Neutral Farming: Assessing opportunities and challenges

Contents

Executive Summary

This aim of this project was to establish the 'net' greenhouse gas (GHG) emissions position from agricultural production across 6 participating farms. The participating farms are all part of the 'Beacons Water Group'. The Beacons Water Group is a farmer cluster that has been established with the assistance and facilitation of Welsh Water to review, test and implement innovative solutions to address environmental challenges facing farming. One such challenge is in relation to climate action. This EIP funded activity set out to measure the baseline of GHG emissions and highlight opportunities for emissions reductions, and importantly to assess the usefulness and ease of the process and to highlight challenges faced.

The core element of the GHG analysis was undertaken by Bangor University. Data was collected across the 6 farms and processed through a GHG and carbon sequestration model. The results of the analysis are contained within this report which include an emissions balance estimate across beef, lamb, milk, and cereal crops. The emissions balance is quantified as an emissions intensity calculation which takes account of all the emissions generated per kg of output, with the carbon dioxide removals allocated and deducted from the gross emissions to provide a net emissions intensity calculation. The body of this report provides an aggregate view of the position across all participating farms and Appendix 1 provides farm specific information (anonymised).

In addition to the detailed GHG analysis, a comprehensive soil sampling and analysis programme was undertaken. This was to establish a robust and reliable (See appendix 3 for methodology) soil carbon baseline for participating farms so that the benefits of activities to improve soil organic matter.

Gap filling: in addition to the core GHG and soil analysis work, the project included physical measurement of carbon stock changes in hedgerows using a ground-based LIDAR measurement approach which was done by forest research. Part 2 of this report summarises the outcomes of that element of the work.

Key findings

- All the participating farmers found the outputs of the analysis useful in helping understand the origins of emissions on their farms and the links between production efficiency and emissions intensity.
- The project results demonstrate the challenge of achieving a net zero position within the ruminant livestock sectors with a maximum of a third of emissions being removed by sequestration and in most cases significantly less.
- The emissions intensity results are representative of efficient UK production systems. The emissions profiles for ruminant animal products are 54% methane and 27% from nutrient management on farm. The emissions of feed and fertiliser production are relatively small at 12% meaning that farms are relatively efficient with the resources brought on to the farm. With these biological processes

dominating the emissions, the opportunities for reductions need to focus on fertility and productivity of soils and livestock.

- CO_2 removals are generated from grassland (53%), woodland & trees (32%) and hedgerows (15%). There are high levels of uncertainty with these figures, and they should be treated as indicative. The soil carbon analysis was informative in establishing the baseline position to assess if these modelled outcomes are realistic when revisited in the future.
- Hedgerow management has a significant impact on woody biomass accumulation from from year to year with up to 117% increases in wood volumes.

Limitations of the analysis

- We only measured 1 year in the GHG analysis. While this is a useful snapshot it does not represent the multi-annual production systems. Farms with fluctuating stock numbers (destocking or increasing numbers) are not well served by tools as this has a significant impact on results (these effects 2 out of 6) farms in the group
- Tools should be better at representing the true lifecycle and lifetime efficiency of livestock production rather than inputs and outputs over a 12-month period.
- Activity data collection is time consuming and can lead to inaccuracy if errors occur.
- More farm specific actions are needed to generate activity to reduce GHG emissions. Information that can help prioritise and contextualise emissions are needed.
- Emissions estimates are not precise and there are many assumptions; we need to get better at communicating the uncertainty. We need to demonstrate the positive direction of the enterprises rather than the specifics of the numbers – these will change as science and methods improve.

Part 1: GHG Net Zero Assessment

Introduction

In 2019, the UK was the first country to legislate the net zero greenhouse gas (GHG) emissions by 2050 target, which will require considerable mitigation efforts from livestock production (Climate Change Committee, 2020). Moreover, Government targets have been overtaken by the National Farmers Union (NFU) setting a net zero target by 2040 for the agriculture sector. Net zero is defined by the Intergovernmental Panel on Climate Change (IPCC) as being when anthropogenic emissions (i.e., emissions derived from human activity) are equal to the anthropogenic removals over a specified timeframe. Net zero will be achieved on farms when on-farm GHG emissions are in equilibrium with on-farm carbon sequestration (e.g. from trees and soils). For farms to achieve net zero, the primary focus should be on reducing emissions, as it means less land is needed for sequestration to off-set those remaining emissions.

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

The IPCC treats all GHGs as "carbon dioxide equivalent" using a metric known as global warming potential (GWP). GWP is a relative measure of how much heat, relative carbon dioxide, a GHG traps in the atmosphere. GWP is expressed over 100 years, so to convert a non-CO_2 gas into its CO_2 equivalent, it is multiplied by its gas specific GWP100 factor. For methane, the value of GWP100 is 25 and for nitrous oxide the value is 298 (IPCC, 2014).

The European Innovation Partnership (EIP) Wales Carbon Neutral farming project aims to assess opportunities and challenges of the net zero target across six farms from the Brecon area. The farms involved represent a variety of enterprises, including dairy, beef and lamb systems. The key elements this project aims to address are:

1. Understanding what net zero is and what it means for farmers in Wales.
2. Assessing the baseline carbon emissions for participating farms, from which action can be taken and measured.
3. Improving evidence to demonstrate how actions taken on farm can help the industry move towards net zero.

Quantifying GHG emissions from livestock production systems is an important first step towards meeting these environmental targets. Many carbon accounting tools are available to quantify GHG emissions at the farm level. Of the current, commercially available tools, AgRE Calc, Cool Farm Tool and Farm Carbon Calculator have been shown to be amongst the most appropriate for use in UK farming systems (Sykes et al., 2017; Taft et al., 2018). The advantages of these tools are they are free to users, provide a complete account of GHG emissions at both farm and enterprise levels, and allow comparison with previous years and other similar farms. This enables benchmarking between similar farming systems, which can highlight opportunities for mitigation. Other tools, developed primarily for research, such as the Bangor University Carbon Footprint Tool, whilst not developed for commercial purposes, can also be useful for a more in-depth assessment of emissions and sequestration on farms. Tools vary in their inherent calculations, and the choice of tool depends on users' specific needs and aims. When calculating the carbon footprint of a farm, the choice of tool can have notable effects on the results, therefore it requires careful selection to match the intended aims of the carbon audit.

The aims of this work were:

- To produce a comprehensive carbon footprint per kg of deadweight (DW) product for beef and lamb for each of the six participating farms, and carbon footprint per kg of fat protein corrected (FPC) milk for the one dairy farm
- To contextualise data across the group and provide commentary on the factors which influence these footprints

Methods

Calculating a product's carbon footprint accurately is challenging, and is largely dependent on the accuracy of the data received from farmers. Farm-level data were collected through a detailed self-reported Excel spreadsheet, and, in most cases, follow up emails and phone calls to participants for verification of the information provided. All farms provided data from the year 2020. In cases where data were difficult to obtain, or where any data were missing, recently published UK data or standardised estimates were used in their place (Craig, 2020).

These data were then used to calculate baseline carbon footprints using **AgRE Calc** to calculate emission estimates (from the inputs used and livestock numbers over the study period), and the **Bangor University Carbon Footprinting Tool** to calculate carbon sequestration rates. AgRE Calc (Agricultural Resource Efficiency Calculator) was developed by Scotland's Rural College and has been found to be amongst the best-performing carbon accounting tool in terms of transparency, methodology and allocation for use on UK farms (Sykes et al., 2017). The tool uses a combination of IPCC (2006) Tier 1 and Tier 2 methodologies (Brown et al., 2019) and conforms to PAS2050 standards. All GHGs are converted to kg CO_2 equivalents (kg CO_2e) based on their IPCC GWP. Specifically, AgRE Calc employs GWP factors of 25 and 298 for methane and nitrous oxide, respectively.

The Bangor University Carbon Footprinting Tool (Edwards-Jones et al., 2009; Hyland et al., 2016; Jones et al., 2013) was selected for calculating carbon sequestration as it includes the most comprehensive set of sequestration measured, including via hedgerows, individual trees, trees in row systems and field boundaries as well as areas of pure woodland. The Bangor Tool also includes grassland and soil sequestration in its calculations at the time baseline footprints were calculated. In terms of woodland, the tool uses yield values from the Woodland Carbon Code (Read et al., 2009) as the basis for sequestration values for woodland. The values calculated for total emissions, minus sequestration, divided by the farm outputs (e.g. kg DW of lamb) enabled us to calculate total net CO_2e emissions per kg of product, known as the 'emission intensity' of a product.

As explained earlier, GHG emissions per kg of product are a reflection of the production efficiency of a system: farms that use lower inputs per unit of output will have a lower carbon footprint for their products, and vice versa. For instance, where livestock growth rates are burdened by disease pressure or poor diet, those animals will take longer to reach mature weights, meaning that total methane emissions for those animals will be greater. In addition, due to such animals being on farm for longer, this may require greater fertiliser usage to grow additional forage, and/or the purchase of supplementary feed – all of which contribute to the carbon costs of producing those animals.

Results and Discussion

Emissions

There was variability in GHG emissions per kg of DW lamb and beef. For lamb, product emissions ranged from **15-25 kg CO_2e/kg DW**, with an overall mean of **19 kg CO_2e/kg DW** (Figure 1).

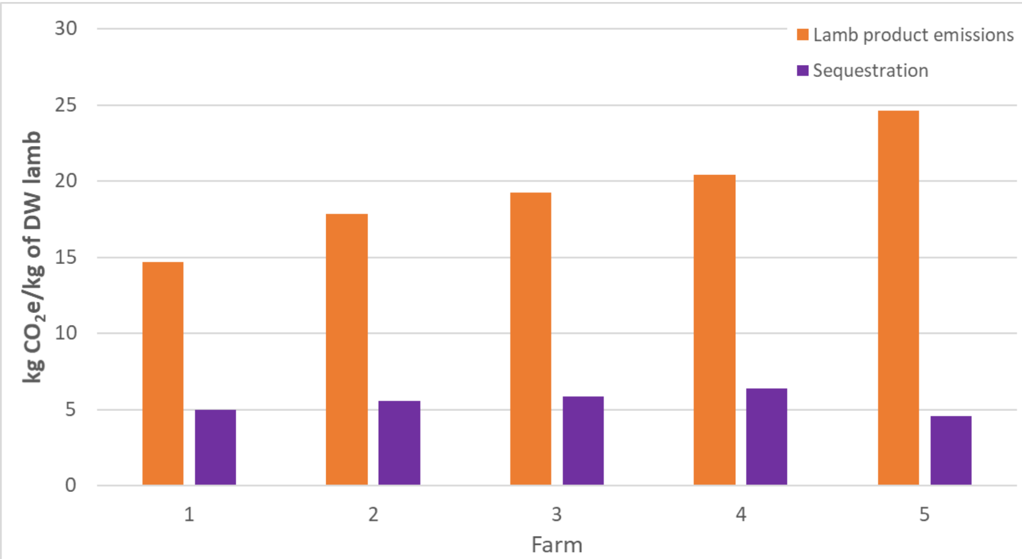


Figure 1: Average GHG emissions and sequestration per kg deadweight lamb across the study farms

The variation was more notable for beef with, product emissions ranging from **19-40 kg CO_2e/kg DW**, averaging **28 kg CO_2e/kg DW** (Figure 2). This variation in product emissions highlight the differences in efficiencies between study farms.

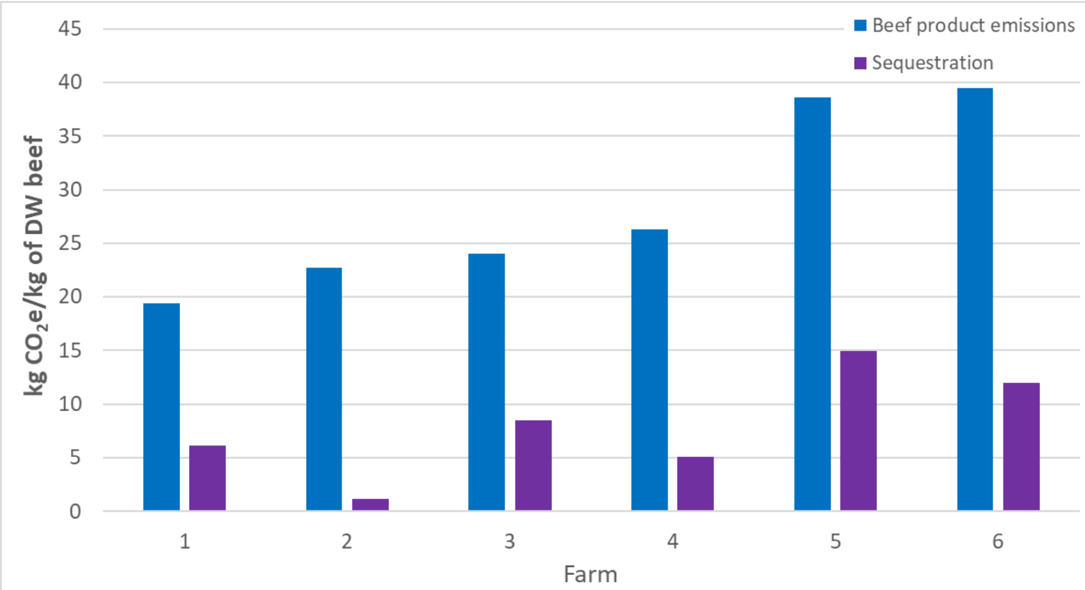


Figure 2: Average GHG emissions and sequestration per kg deadweight beef across the study farms

On the single dairy farm in this study, milk product emissions were **1.06 kg CO_2e/kg of fat protein corrected milk (FPC)** (Figure 3).

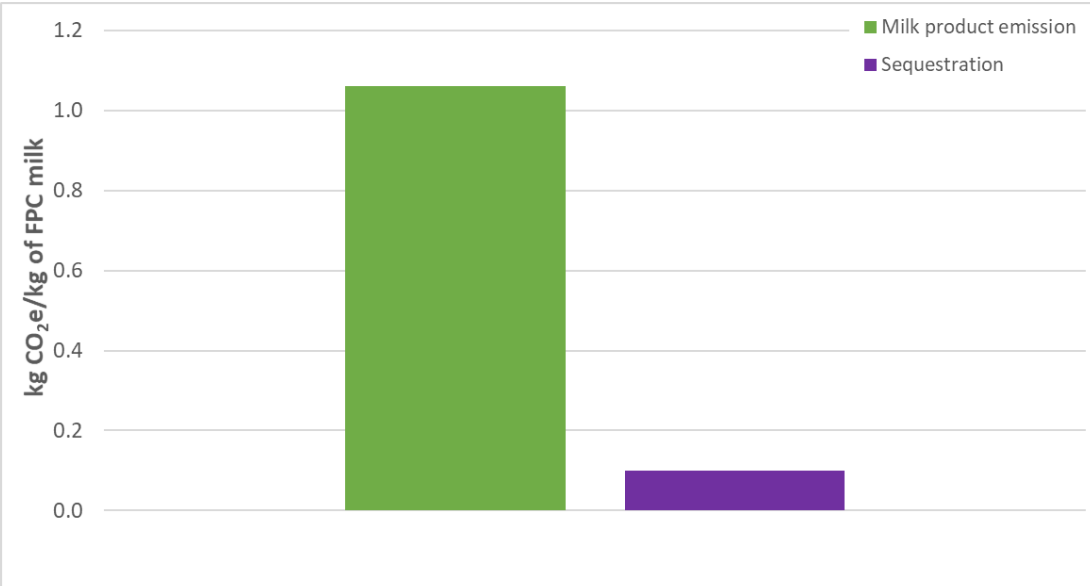


Figure 3: Average GHG emissions and sequestration per kg FPC milk on the single dairy farm in this study

Emission breakdowns were similar across participating farms as most farms have mixed beef and sheep enterprises, with the exception of one farm with a dairy enterprise which had slightly different emission breakdown. As expected, methane from enteric fermentation accounted for the majority of GHG emissions on all farms (Figure 4).

Methane emissions will increase with the number of ruminant animals on each farm, and total emissions will increase with farm flock and herd size. However, this may not be reflected here as results are expressed as emissions per kg of product. Some of the most densely stocked farms often had the lowest emission intensities. Compared to other farms, they use relatively high inputs (e.g. feed and fertiliser) to support higher stocking density, however despite the higher total emissions, these farms produce a higher volume of output so the total emissions will be divided by greater output. It is however important to note that these highly stocked farms, despite being efficient, will have a higher total emissions per hectare due to the greater number of animals and inputs per hectare relative to other farms.

Several factors can lead to a change in livestock numbers on farms, which will invariably influence the farm's carbon footprint. Changes in stock numbers on participating farms have likely skewed results from this study. For example, the farm with the lowest beef product emissions reduced stock numbers in the sample year. Conversely, the farm with the highest beef product emissions increased the number of cattle on their holding significantly in the sample year. This means the farm which is destocking will have a lower emission intensity than previous years as they will have sold more cattle and have less cattle on farm. The farm increasing its numbers will have an unusually higher estimate than previous years (or future years) as it will have the additional embedded emissions from bought-in stock as well as those animals not producing in the sample year. Such changes to animal numbers need to be considered when interpreting C-footprint results on farms, and is why sampling data over multiple years is preferable.

Nitrous oxide emissions from soils were the second most important contributor to emissions across all farms (Figure 4). All farms in this study handled manure as solid which has generally lower emissions than liquid slurry. Low emission manure spreading techniques e.g. incorporating manure within 24 hours or spreading manure in spring instead of autumn can also further reduce emissions from manure (Eory et al., 2015).

Emissions from inputs were dominated by fertiliser and feed (Figure 4). Given the greater use of fertiliser in cattle systems, both embedded emissions and nitrous oxide emissions from soil were greater than sheep systems. As expected on beef and sheep farms, energy usage on participating farms was generally low, therefore energy usage accounted for a very small proportion of total emissions, however, the energy usage from the dairy enterprise was understandably higher. Similarly, fuel use on farms did not account for a notable proportion of GHG emissions across production systems.

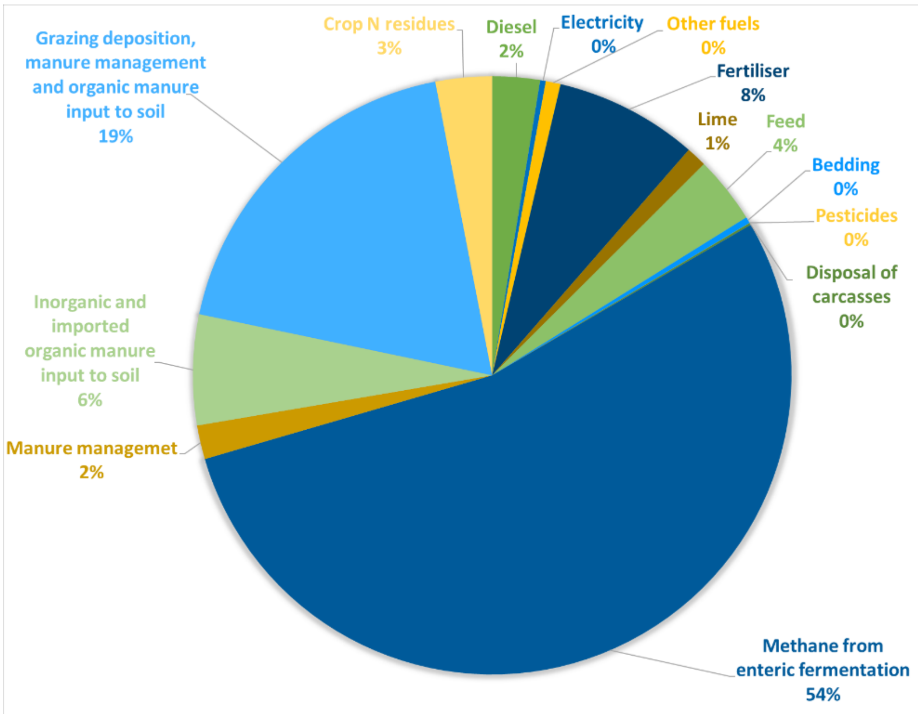


Figure 4: Breakdown of average whole farm GHG emissions sources across the study farms. Note values <0.5% appear as 0% due to rounding

Variability in GHG emissions generated per kg product (Figures 1, 2 and 3) reflect both differences in land quality between farms but also in efficiency and highlight the opportunities for efficiency gains on farms with higher product emissions. There was seemingly little influence of farm type (e.g. upland or lowland) on product emissions, however, due to the small sample size, this would need a larger sample size to be validated. Previous studies have also found farm type to have no significance on emission intensities (Jones et al., 2013). In general, lowland farms had more inputs which contribute to a greater liveweight of products over which those inputs can be divided. Livestock produced on upland systems were often a lower weight but required fewer inputs.

For cattle, upstream emissions (production of feed) accounted for notable proportions of total emissions. This was evident in the farm with the highest total emissions which had notably higher concentrate use (although this was not evident in product emissions with this farm having the second lowest). Conversely, some farms had little bought-in feed which highlights their emphasis on grassland utilisation and/or growing forage and high-protein crops for winter feed. Half of participating farms purchased no bedding as they produced their own straw from crops like wheat or oats. One farm also cut rushes for bedding, cutting their emissions from bought-in bedding.

There was also no clear association between farm emissions and farm size or stock numbers across all farm types. 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 GHG emissions.

For example, upland sheep systems are more likely to lamb outdoors and sell lambs as stores as opposed to purchasing feed to finish them, reducing their demand for concentrates and associated emissions. In cattle systems, lowland producers often buy store cattle for finishing on concentrates, but this is over a shorter time period. Upland producers often keep livestock housed over longer winters, meaning a greater requirement for feed. Some upland farmers often keep store or beef animals up to 2 years before selling, sometimes at relatively low weights due to the nature of their breed, which increases overall emissions per kg of product.

This study did not consider strategies to improve animal health, which will have a notable impact on production efficiencies. Implementing detailed animal health programmes and vaccinating against key diseases that impact productivity should be prioritised as they will both increase production efficiency and reduce emissions. Other areas such as reducing the burden of parasitic worms in both sheep and cattle which are known to have a majorly detrimental impact on livestock growth rates and feed conversion efficiency and therefore contribute to GHG emissions (CIEL, 2020).

Calving percentages on participating farms ranged from 90-99%. Lambing percentages ranged from 129-160%. Rearing percentages of both sheep and cattle reflect the different breeds kept, for example, lowland systems tend to have larger, more prolific ewes, but also management factors, for example, whether sheep are lambed indoors or outdoors. Rearing percentages are subject to multiple factors such as the weather at lambing on outdoor lambing systems. All farms provided data from 1 year, and although there will be some local variation in weather and its impacts on lambing survival, this could also mean the results are skewed by the favourable weather in spring 2020. Nevertheless, irrespective of management and system employed on farm, reducing losses and increasing rearing percentages should be prioritised across all production systems as a means to reduce the carbon footprint of farm products (ADAS UK Ltd, 2014).

In suckler beef systems, extended calving interval means the GHG burden of the unproductive adult cow has to be carried by other animals. Given the weight of an adult cow, this can account for a significant proportion of emissions. Measures that reduce calving intervals should therefore be implemented across all farms (e.g. shortening the bulling period, selling off cows of lower fertility, etc.). Dairy-beef systems also have a lower emission intensity than suckler beef systems, which was highlighted by the one dairy farm in this study. This is due to the emission burden associated with the adult cow in suckler systems. Similarly, lambing as ewe lambs is known to reduce emission intensity of lamb produced as it reduces the proportion of “unproductive” animals in the flock. This is more applicable on larger lowland breeds and may not be suitable on some upland farms where breeds are smaller and lambing as ewe lambs could be detrimental to growth rates.

Some participating farms have likely significantly invested in improving the genetic merit of their livestock, practising performance recording, switching to closed flocks/herds, regularly weighing of livestock to select for enhanced growth rates. Genetic improvement can help reduce days to slaughter and improve growth rates but may also lead to greater liveweight produced without increasing in inputs, reducing both total emissions and emissions intensity.

Re-seeding can also influence GHG emissions, and it is likely all farms re-seed a proportion of their land and/or grew an annual crop. Such tillage is likely to lead to carbon losses from soil as carbon accumulated in soil will be turned over by the soil microbial biomass (Fernández et al., 2010). Adopting practises such as direct drilling of seeds or crops will reduce such emissions (Mangalassery et al., 2014).

The choice of species included in grass re-seeds should be considered by farmers, as it can impact on the carbon footprint of farm products. Increasing the clover content in swards when re-seeding not only maintains sward productivity, but can bolster livestock performance due to enhanced forage quality (Jensen et al., 2012), thereby reduce associated methane emissions. Furthermore, legumes’ ability to fix nitrogen from the atmosphere reduces the need for artificial fertiliser and their associated emissions of nitrous oxide (Carswell et al., 2019). The higher protein content of swards that include legumes also reduce the need to buy in protein-rich feeds such as soya from South America, reducing environmental impacts there, such as deforestation (Sustainable Forage Protein, 2016).

Most farms in this study had invested in some form of renewable energy (mainly solar) which inevitably reduced electricity use on farm and therefore reduce emissions. However, under current GHG reporting frameworks, farmers do not gain any credit for reducing direct energy consumption and therefore emissions saved have not been counted against those emitted on farms in this study. Nevertheless, by producing renewable energy, which is supplied into the national grid, farms can help the broader economy move toward net zero.

Water data was not collected in this survey but is typically low on beef and sheep farms relative to other food sectors. If farms are on private water sources, this too will contribute to a reduction in GHG emissions through the avoidance of energy expenditure associated with the treatment and delivery of mains water.

Sequestration

Sequestration also differed across farms, with lamb **5-6 kg CO_2e/kg DW** and an average of **5 kg CO_2e/kg DW** offset (Figure 1). Sequestration for beef ranged from **1-15 kg CO_2e/kg DW** with an average of **8 kg CO_2e/kg DW** (Figure 2), and sequestration for the dairy farm in this study was **0.1 kg CO2e/kg FPC milk** (Figure 3). Sequestration on study farms was low compared to the level of emissions, offsetting on average **28%** of total emissions.

Breakdown of carbon sinks was similar across all farms, with the highest sequestration estimates from grassland and soils, at an average 53%, followed by sequestration in woodland at 24% (Figure 4). The contribution of carbon sequestration by woodland differed slightly between farm types, for example on lowland farms, isolated trees accounted for a considerably greater proportion of sequestration by woodland. This was due to the considerable variation in the percentage of tree cover on farms, with some reporting they had no trees or hedges. There is often a lack of detailed knowledge of the extent of hedges, individual trees and areas of woodland on farms, so the estimates of woodland cover have a high level of uncertainty. Woodland cover on all farms was relatively low, with woodland ranging from 1-11% of the farms' total area. Only one farm met the requirements of the new Sustainable

Farming Scheme, which recently outlined that all farms may be required to have at least a 10% of tree cover to receive the baseline universal payment (Welsh Government, 2022).

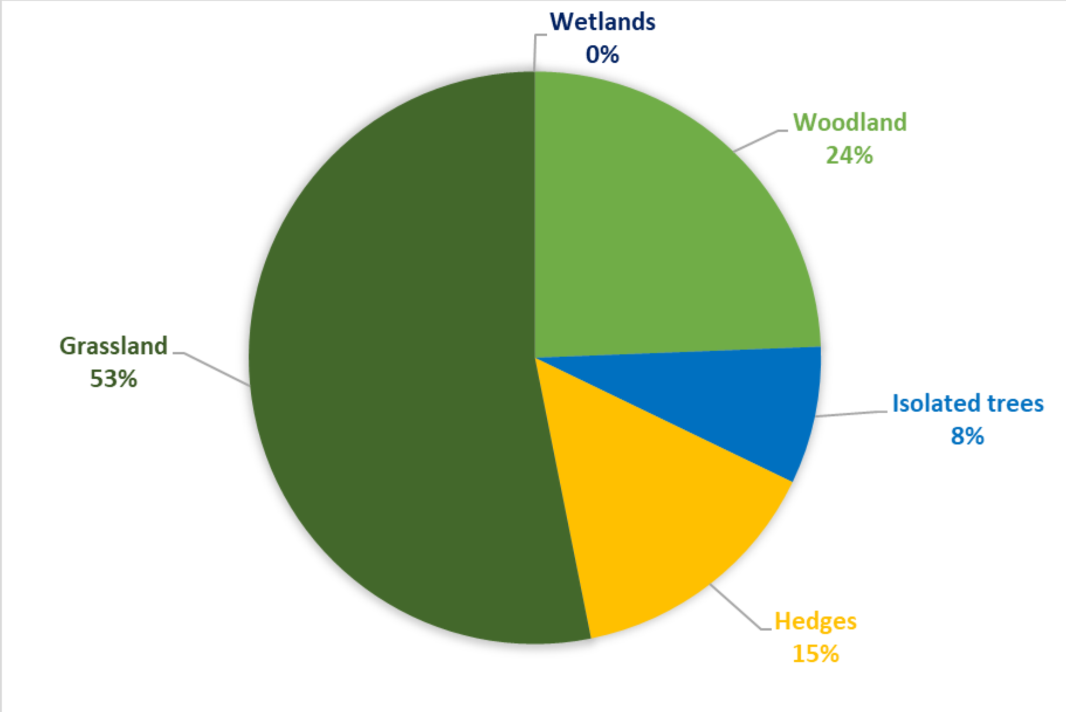


Figure 4: Breakdown of average whole farm carbon sequestration sinks across the study farms. Note values <0.5% appear as 0% due to rounding

Many factors influence these figures, for example, upland farms are more likely to have planted trees as shelter for their more exposed areas. Management of existing woodland is also important as there is a limit on how much trees can sequester, young trees sequester more and gradually sequester less over time, so if woodlands are not properly managed, carbon sequestration may not be effective. It is also worth highlighting here that in newly-planted woodland, trees are young and although over the years they will gradually sequester more carbon, this will not be reflected in the carbon accounting the year they are planted. Where financial incentives can be gained, tree planting can have a high carbon capture potential at a relatively low cost, whilst also having the potential to provide additional benefits in the form of biodiversity, flood management and improved animal welfare (Burgess, 2017).

Hedgerows are often thought to be an important contributor to sequestration on farms, however, their offsetting potential was relatively low in this study. The Bangor Tool assumes no net sequestration in hedges which are flailed in the sample year, meaning that managed hedges will not count towards any carbon sequestration. Letting hedges grow wider and taller, without annual flailing, could be a low-cost option to enhance carbon sequestration on farms.

Sequestration in wetlands was also not significant across study farms, contributing less than 1% of total sequestration across all farms. However, if farms have areas of degraded peat that could be restored to a better functioning state, then this could yield notable benefits for a farm's carbon footprint (Leifeld and Menichetti, 2018).

Grasslands accounted for the majority of sequestration on all farms, however, actual sequestration (or emissions) from soil depends on numerous variables including climate, soil type, land use/management, water availability and, most importantly, the actual organic matter content of the soil (Freibauer et al., 2004). Grassland systems are mainly regarded to represent a carbon sink, however, it is acknowledged that there is a lack of robust data for yearly carbon flows (Ostle et al., 2009). There is much debate around the potential for soil carbon sequestration in grassland systems in the UK, however, whether soils are carbon source or carbon sink is dependent on many factors including climate, soil type, management and organic matter content of soil. Without physical soil sampling repeatedly over many years, it is difficult to accurately estimate soil carbon sequestration, for several reasons. Firstly, any changes in soil carbon happen very slowly, therefore determining sequestration rates is inherently difficult. Secondly, soil carbon is highly dependent on soil type, and due to the heterogeity in Welsh soils, with many farms having multiple soil types, e.g. mineral and organic soils with contrasting properties, sequestration rates will be variable. Finally, management of soils is important for carbon sequestration rates, and there could be a high degree of variation in soil management even between different fields on the same farm. Together, these factors mean soil carbon sequestration calculations are based on many assumptions and estimations, which can partly explain the differences in values between different assessment tools.

Although the capacity to make significant further gains in sequestration in soils is uncertain, many of the participating farms here were implementing measures that could be promoting further sequestration of carbon in soils. Firstly, dung inputs from grazing animals on permanent pastures may enhance soil organic carbon levels, whilst the nutrient inputs from grazing animals facilitate biomass growth and the associated above-ground carbon, a proportion (dead leaves) will be returned to the soil and thereby contributing to soil carbon (Leake et al., 2006).

It is likely some participating farms were practising a rotational grazing approach in at least parts of their holdings. Compared to set-stocked systems, rotational systems allow 'rest' periods for grass to recover post-grazing, which can enhance overall grass yields. In turn, this should also increase root growth and therefore carbon inputs to soil, as indicated by a limited number of previous studies (Teague et al., 2011). As discussed earlier, re-seeding can give rise to carbon losses from soils; however, sequestration is likely to increase following re-seeding therefore recovering some of those carbon losses. Liming has also recently been shown to have marginal benefits to soil carbon by increasing the availability of key nutrients therefore reducing the requirement for fertiliser and improving yields (Gibbons et al., 2006). However, CO_2 is produced when lime is applied, and the PAS 2050 methodology adopted in this study requires to calculate all the carbonate-carbon content of applied to soil and convert it to CO_2e. Most farms in this study regularly limed soils to maintain target pH but the volumes applied during the sample year made a negligible contribution to GHG emissions.

Despite the uncertainties in carbon sequestration estimates, the data indicates that many farms were storing significant amounts of carbon in both their soils and woodland. The potential for this to be enhanced further will help participating farms move towards net zero.

Limitations

It must be reiterated that the results presented here are based on data provided by participating farmers.

As highlighted throughout this report, it is important to remember the many assumptions and limitations of the carbon footprinting process. One of the major uncertainties, as previously mentioned, is in sequestration estimates especially soil sequestration which is partly due to the limited knowledge of soil carbon but also partly due to the uncertainty in the input data. Data in this study was self-reported and despite the effort to verify data, the potential for errors must be acknowledged. All tools are based on a number of assumptions, for example, despite the chosen tool in this study, AgRECalc, using inventory-derived EFs to generate footprints, emissions will depend on animal weights and weight gain – the measuring of which would require much more work for participants.

Another area of uncertainty relates to the mixed nature of participating farms, as it is more challenging to generate robust footprints for mixed farm enterprises because inputs and emissions must be allocated by economic output which can skew footprints for particular product. This becomes more apparent on farms where one enterprise is responsible for a considerable proportion of farm income, for example, a pedigree breeder selling high value animals of one species.

Finally, although sampling in one year allows a fairer comparison between farms, there are many factors, such as extreme weather, that can change from year to year, resulting in high inter-annual variability of footprints. To mitigate this, data would ideally be collected over multiple years for all farms.

Conclusions

Calculating baseline whole-farm carbon footprints is the key first step to reduce GHG emissions and move towards net zero. Carbon footprinting can help identify which management practices have either a positive or negative impact on a farm's carbon balance. As well as enabling farmers to monitor changes to their C-footprint over time, it also allows benchmarking between farms and can highlight areas of inefficiency where there is potential for emission reductions. This facilitates the sharing of best-practise between farms, especially within a close group such as within this EIP project, each helping others in the group move towards net zero. The importance and value of such discussion between farms should not be underestimated (Hyland et al., 2016).

Participating farms produced levels of emission typical of beef and sheep (and one dairy) in the UK (Craig, 2020). However, caution should be exercised when citing a single precise due to the variability, uncertainty, and subjectivity of the process all potentially impacting on the accuracy of the final result. It is also important not to over-interpret the figures or take them too literally. Comparing results from different studies should be avoided due to the methodological differences between tools and their effects on the resulting footprint.

Although the small sample size made it difficult to draw a solid conclusion, it appeared farm type was not an important factor affecting total or net emissions, however it did impact on the inputs used and outputs produced. Farms across all production systems appeared to vary in efficiencies, however, it should be noted that changes in stock numbers, particularly on two farms (one destocking and one increasing cattle numbers), have likely skewed results.

Many farms were clearly efficient producers, generating relatively low emission intensities. There are many ways for farmers to achieve efficiency gains including improving genetic merit of livestock, optimising diets of different livestock classes, reducing the disease burden, improving grassland management, and reducing purchased feed and introducing legumes to reduce fertiliser usage. Many of these options represent win-win scenarios and deliver productivity and economic gains as well as GHG abatement.

The majority of GHG emissions from participating farms were derived from ruminant livestock (methane from enteric fermentation) and nitrous oxide from soils, with emissions from inputs (e.g. fuel, feed, and fertiliser) were relatively low. These emissions are hard to reduce, therefore achieving net zero will not be possible through efficiency gains alone. A smaller, more productive farm herd and flock may reduce total emissions, and if it leads to efficiency gains, then it would also reduce emission intensities.

This study highlights the importance of sequestration in woodland and soils to offset GHG emissions. Sequestration generally made a minor difference to overall emissions, equating to on average 28% of total GHG emissions. Residual emissions will always exist therefore sequestration will always be needed to achieve net zero on farms. Increasing tree cover on farms will play an important role in increasing sequestration and moving towards net zero. Targeting afforestation on less productive land can reduce emissions intensity of lamb and beef through improving overall system efficiency, whilst also reducing total farm net emissions.

Part 2: Hedgerow management

The management of farmland hedgerows is a promising strategy to promote carbon sequestration for climate change mitigation, but empirical data in terms of *spp*. composition, structure and carbon content are lacking. Hedgerows managed by hedge laying and triennial trimming using a mechanical flail forms a dense coppiced structure of about hundred-thousands of stems per hectare displaying values in height, width and carbon stock ranging respectively from about 2–6 m, 2–4 m and 20–40 t C ha^{-1} (*e.g.*, Axe *et al*. 2017, Drexler *et al*. 2021).

This report summarises the results from a pioneer work on the application of a terrestrial Light Detection and Ranging (tLiDAR) technology to measure non-destructively above ground woody volumes in broadleaved hedgerows. In this project, a well-established method for reconstructing automatically the Quantitative Structure Model (QSM) of every tree in a forest plot from tLiDAR data (Raumonen *et al.* 2013, 2015) was applied to hedgerow structures in Wales.

Broadleaved hedgerows were 3D mapped nearby Llangasty Tal-y-llyn in the winters of 2022 and 2023 (Figures 1 and 2). The hedgerows were composed of mixed *spp*. dominated at 85–90% by blackthorn (*Prunus spinosa* L.), hawthorn (*Crataegus monogyna* Jacq.) and hazel (*Corylus avellana* L.) with the presence of some alder (Alnus glutinosa [L.] Gaertn.), bramble (*Rubus fruticosus* L.), dog rose (*Rosa canina*) and holly (*Ilex aquifolium* L.) plants. In addition, one isolated mature oak (*Quercus robur* L.) and one Ash tree located in one of the selected hedgerow sections were also laser scanned during this project. Hedgerows in Wales are generally managed through trimming and cutting cycles and are, therefore, relatively heterogeneous in terms of form and shape (Figure 1).

Large data sets of point clouds were analysed in this project (Figure 2). Although the methods used here have been in regular use for some time in forestry (*e.g.*, Casella *et al.* 2020*a*, 2020*b*, 2022), limitations were acknowledged from their introduction and the comparison between the reported results in this report highlights one such issue related to the accurate estimation of stem volumes when distributed in such dense and complex coppiced structures.

The final part of this report makes suggestions for follow-on work, including ground-truth measurements of above-ground carbon stocks and wood nominal specific gravities for the studied hedgerows and species to allow a direct validation of the estimates reported here.

Figure 1. Satellite photograph showing the location of the selected hedgerows (sections 1-10), the oak and the Ash tree (in section 8) used in this project (51°55'10.42"N - 3°15'55.07"O, Llangasty Tal-y-llyn, Wales). Source: Google Earth Pro © 2013 Google LLC.

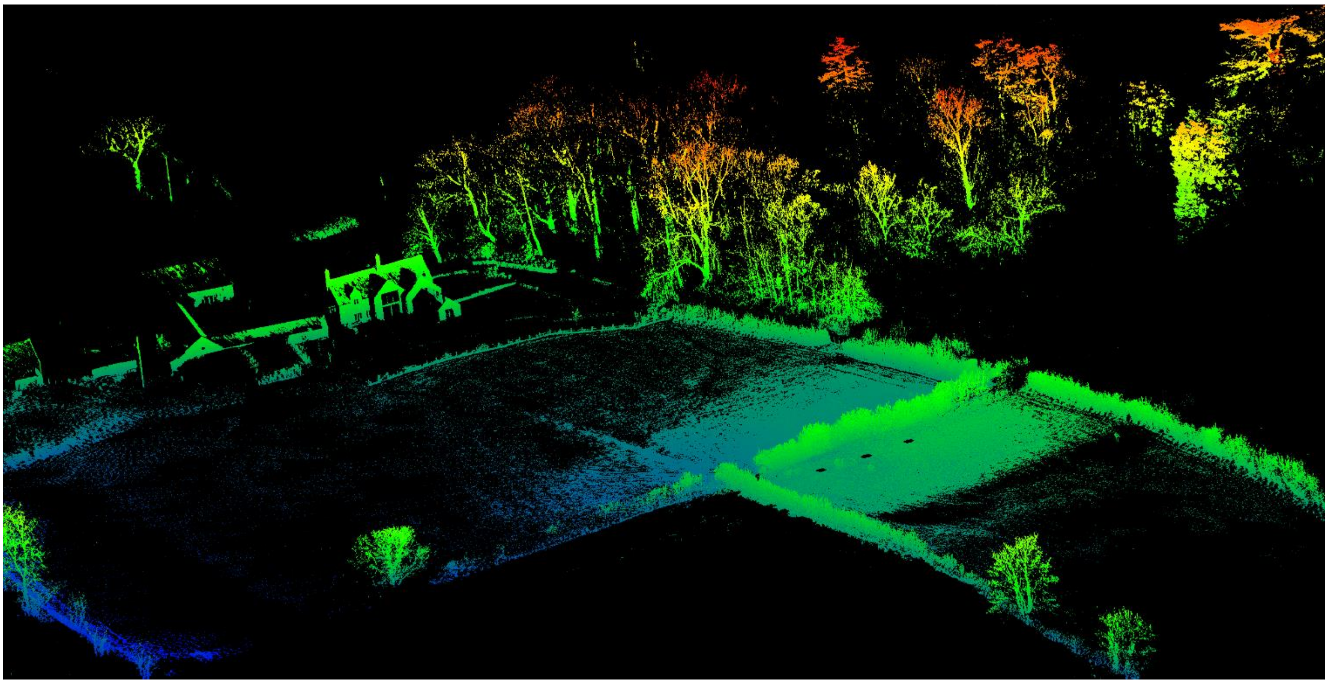


Figure 2. An example of the 3D map of a farmland area computer-generated from recorded tLiDAR point clouds in January 2023 at the hedgerow section number 5 (see Figure 1). Colours represent a height ramp with z values ranging from 0–47 m (n ~ 285M points).

Material and Methods

The study was conducted in the winters of 2022 and 2023 at a farmland site located in the Brecon Beacons National Park, south-eastern Wales. Ten 30-m-long hedgerow sections, representative of the observed ranges in structure and carbon stock, were selected and geo-localised (Figure 1) prior to be 3D mapped in March 2022 and January 2023.

Terrestrial LiDAR data were acquired in dry and low wind speed (up to 4.5 m s^{-1}) conditions with a field portable single-return phase-shift $Focus^S$ 350 scanner (FARO Technologies Inc., FL, USA). The scanner had a rotating mirror system that covers a 360° in azimuth by 310° in elevation field-of-view. The laser beam wavelength is within the infra-red band of the light spectrum (~1550 nm). The angular sampling resolution of the scanner was 0.018° in both directions, with a range accuracy of about 0.001 m for a maximum unambiguous detection range of 350 m. The scanner settings were kept the same across the entire acquisition campaigns. During scans, the scanner was mounted on a heavy-duty tripod with the laser source located at about 1.5 m above ground level and fine-levelled using its built-in electronic tilt sensor system.

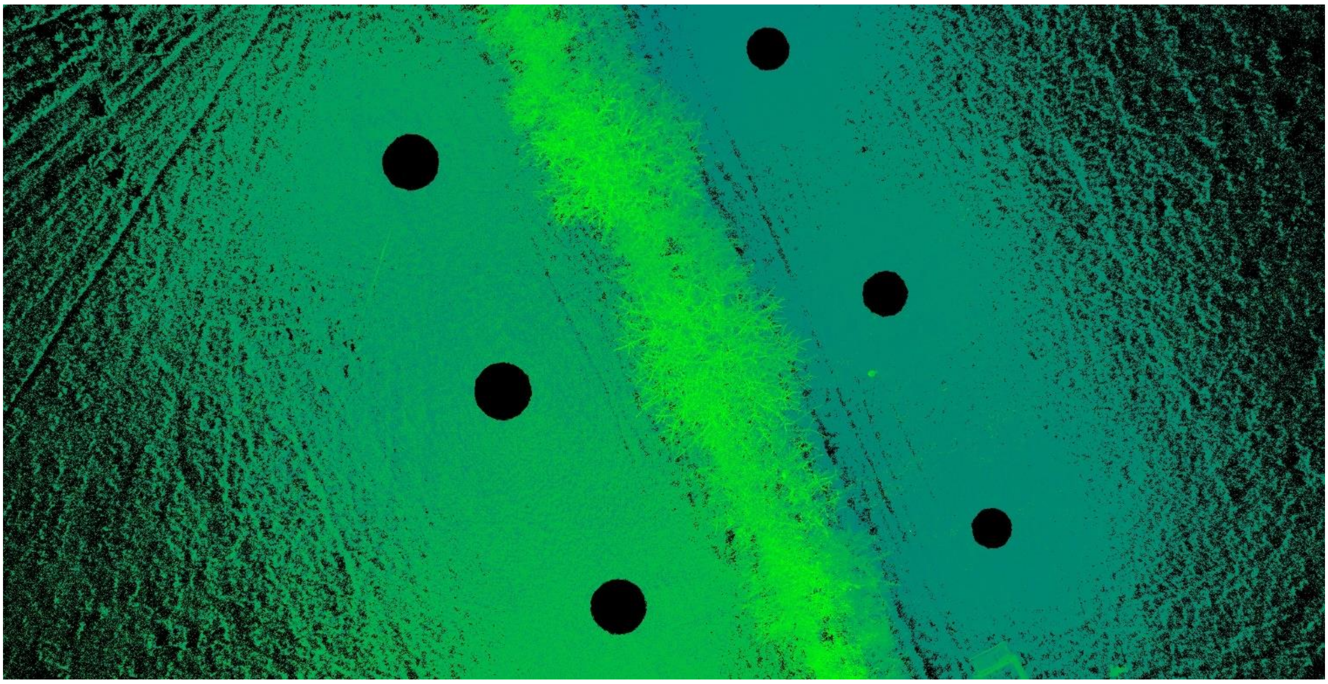


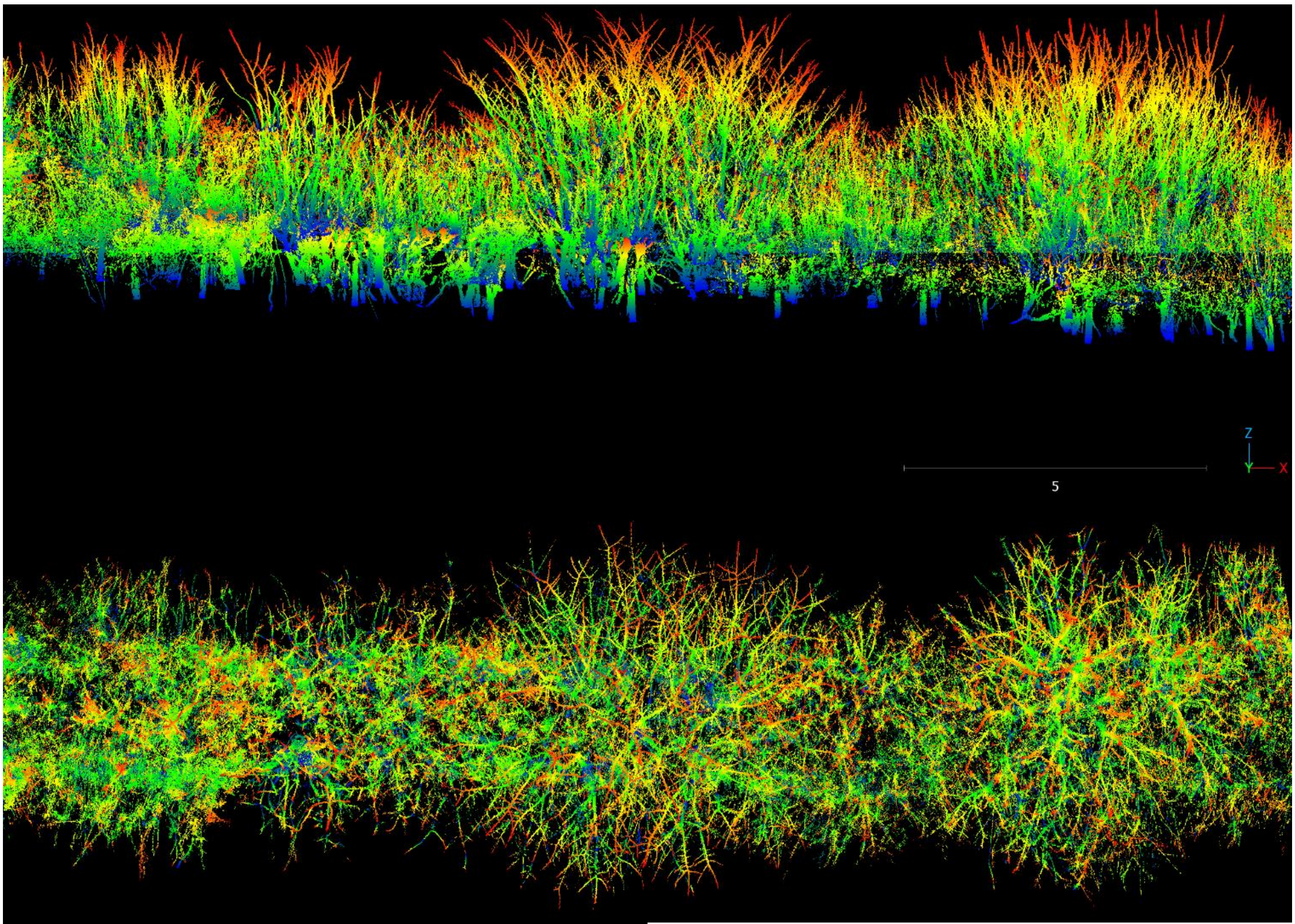
Figure 3. A zoom-in on a hedgerow (section number 5, see Figures 1 and 2) showing the point cloud acquisition setup used in this project: black dots are the six scan locations from either side of the hedgerow.

For each section of the selected hedgerows, point clouds were acquired from six scan positions (three from either side) at a distance of about 15 m from each other (Figure 3). Prior to scanning, six reflective polystyrene spheres (0.25 m diameter) were set out from either side of the hedgerow to align multiple point clouds. The spheres were mounted on 0.02 m diameter aluminium poles at about 5 m above ground level.

For the oak, point clouds were acquired from six scan positions around the tree for α (the azimuth) ranging from 0 (North) to 300° following a clockwise 60° interval step at a distance of about 10 (for α = 0, 120 and 240°) and 30 m from the stem. The six reflective polystyrene spheres were set out around the tree with α ranging from 30 to 330°, 10 m from the stem. The targets were mounted on the poles at about 1 m above ground level. Prior to scanning, the stem diameter at breast height (dbh, 1.3 m above ground level) was measured with a research girth tape (precision of ± 0.001 m).

Data were then manipulated in the following ways: *i*) artefacts caused by range averaging or edge effects (*i.e.*, where partial interception of the beam occurs at the edge of an object) were addressed through pre-filtering and post-processing software programs (Rombourg, 2019; SCENE, FARO Technologies Inc., FL, USA); *ii*) all filtered single point clouds were aligned in a common Cartesian coordinate system using the SCENE program (version 10.2.0.10355); *iii*) SCENE was then used to extract the individual hedgerow sections from the global point cloud (hereafter called hedgerow point cloud) by manually removing ground, unrelated vegetation and fence components from the scene; *iv*) hedgerow point clouds were then segmented in elementary units using the method described in Raumonen *et al*. (2015) (Figure 4) and *v*) mean values in height, width and above ground woody volume were finally inferred from the segmented hedgerow point cloud through the 2.5D Delaunay triangulation plugin in the CloudCompare software program (Version 2.14.4) (Figure 5) and the reconstruction of Quantitative Structure Models (Version 2.4.1) presented by Raumonen *et al*. (2013) and Åkerblom *et al*. (2015) (Figure 6). The same process was applied to the oak and the hawthorn tree data. Moreover, five QSM models were produced in each case due to the randomness involved in the processing steps of this method.

The process was implemented in MATLAB (R2023a) using a 4.9 GHz AMD Ryzen 9 based Windows 10 64-bit operating system with 128 GB of RAM.



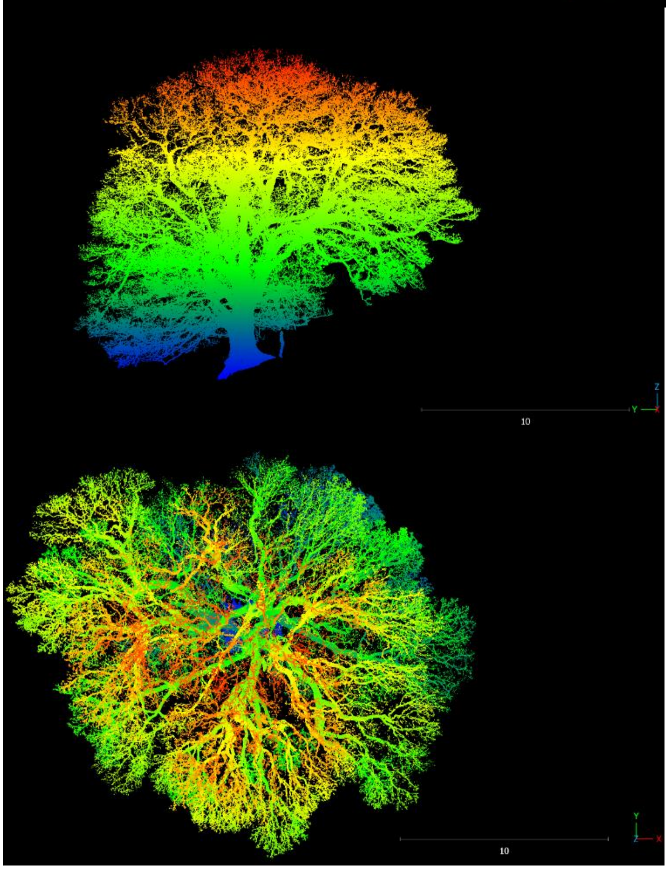
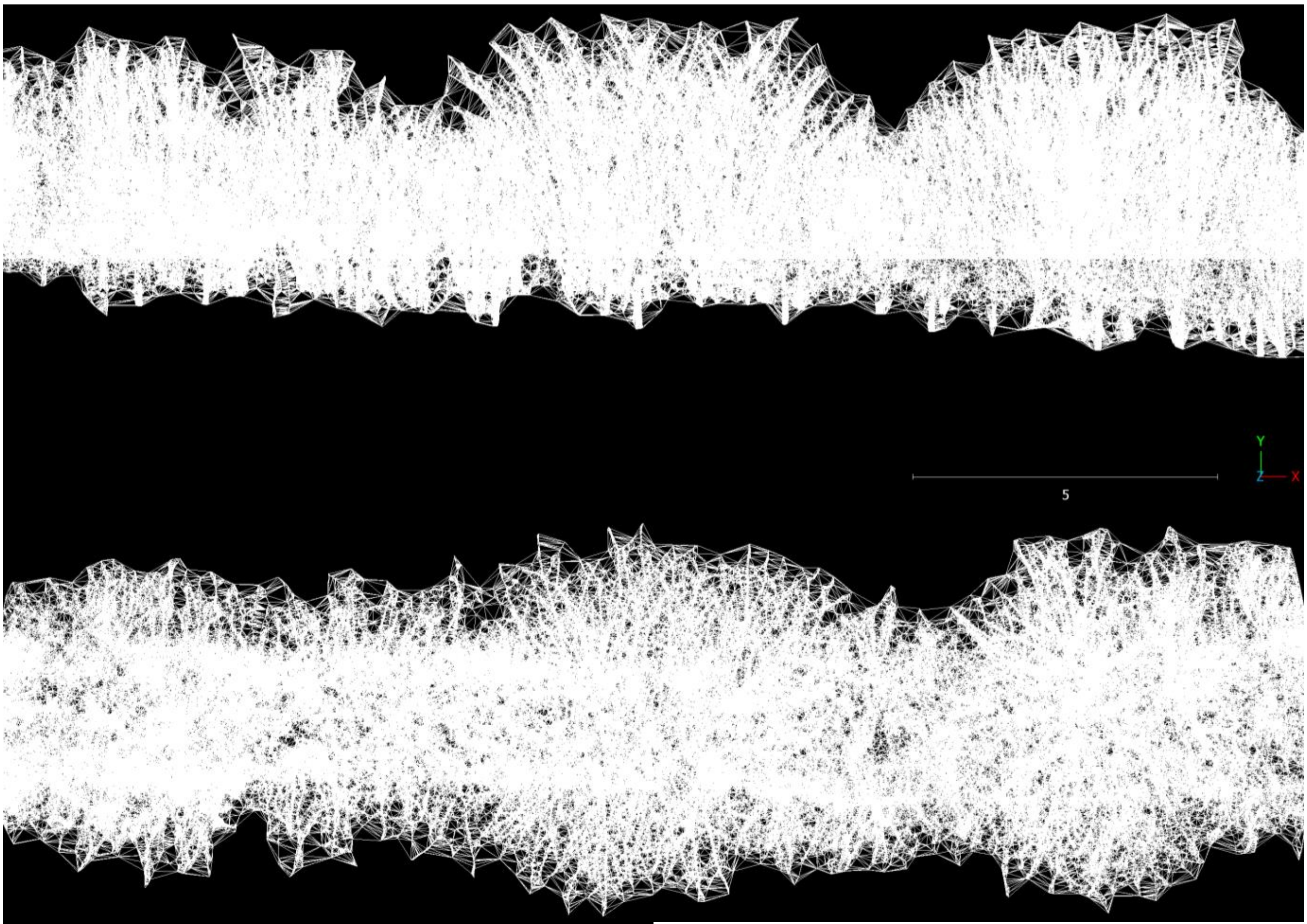


Figure 4. Examples of 3D maps showing segmented point clouds (side and aerial views) obtained after applying the Raumonen *et al*. (2015) method to the data for the hedgerow section number 5 (top and middle lines) and the oak tree (bottom line) in 2023. Colours represent height ramps with *z* values ranging from about 0–5 m (*n* ~ 10M points) and 0–23 m (*n* ~ 66M points) for the hedgerow and the oak tree, respectively.



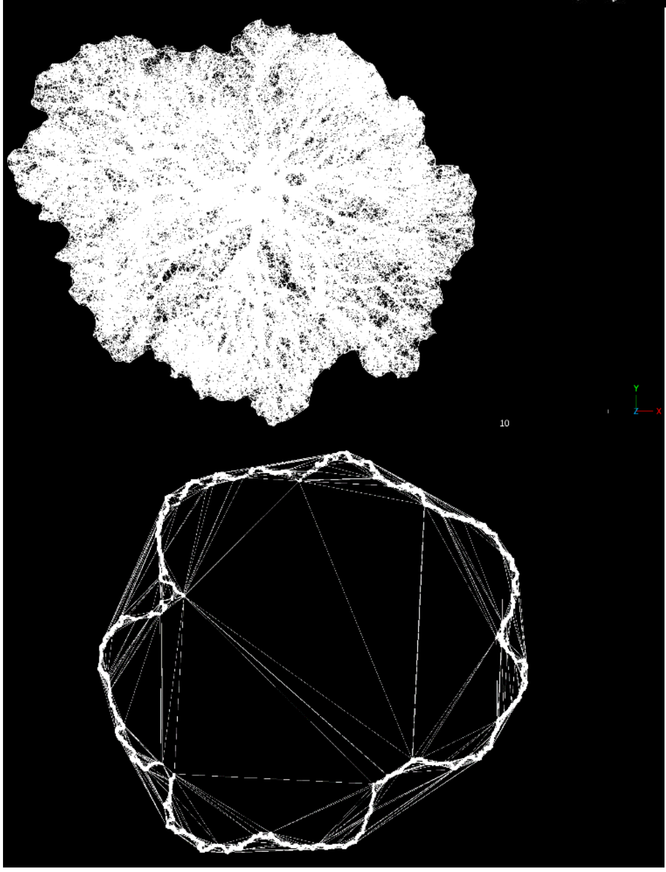


Figure 5. Examples of 2D maps showing mesh networks obtained after applying the 2.5D Delaunay triangulation method to the data for the hedgerow section number 5 (top line: side view, *n* ~ 20M triangles, 94 m^2; middle line: aerial view, *n* ~ 19M triangles, 109 m^2) and the oak tree (bottom left: orthogonal projection of the crown to a plan, *n* ~ 130M triangles, 580 m^2; bottom right: stem cross section at the dbh mark, *n* ~ 16K triangles, 3 m^2) in 2023.

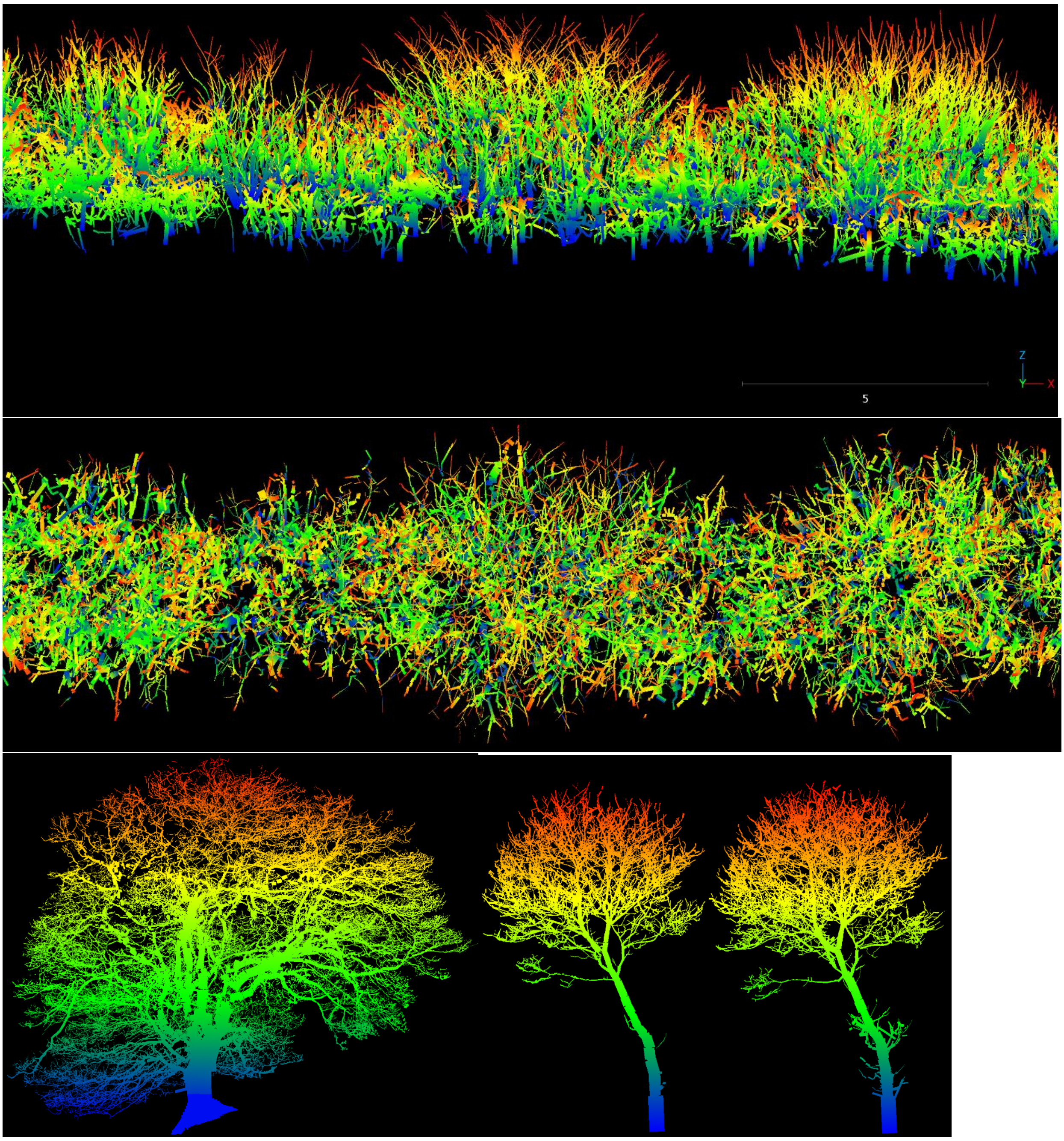


Figure 6. Examples of 3D maps showing the Quantitative Structure Models (side and aerial views) obtained after applying the Raumonen *et al*. (2013) method to the data for the hedgerow section number 5 (top and middle lines), the oak tree (bottom left, 2023) and the Ash tree (bottom right, in 2022 and 2023). Colours represent height ramps with z values ranging from about 0–5 m (n ~ 34M cylinders), 0–22 m (n ~ 94M cylinders) and 0–11 m (n ~ 12M cylinders) for the hedgerow, the oak and the Ash trees, respectively.

Results and discussion

Results for sample hedgerows

The individual estimates of the above-ground structure and the woody volume for the ten hedgerow sections are shown in Table 1.

Table 1. Estimates of the above-ground structure and woody volume for the ten hedgerow sections. Volumes are expressed in cubic meters per unit of hedgerow length ($m^3\ m^{-1}$) or per unit of ground area ($m^3\ m^{-2}$). Values in bold are recorded changes (%) between the two acquisition dates.

	Structure							Woody material		
Year	Section number	Length (l, m)	Mean height (h, m)	Mean width (w,m)	Mean volume† ($m^3\ m^{-1}$)	Mean volume‡ ($m^3\ m^{-1}$)		Mean volume ($m^3\ m^{-1}$)		Mean volume ($m^3\ m^{-2}$)
2022	1	31.03	3.19	3.82	12.184	9.570		0.0705		0.0185
	2	31.96	3.37	3.08	10.378	8.151		0.0593		0.0193
	3	27.96	2.26	2.77	6.256	4.914		0.0313		0.0113
	4	10.25	2.36	3.36	7.916	6.217		0.0444		0.0132
	5	21.74	3.88	4.20	16.316	12.815		0.0655		0.0156
	6	22.18	2.45	3.23	7.895	6.201		0.0332		0.0103
	7	31.16	4.97	4.01	19.958	15.675		0.0594		0.0148
	8	29.04	2.06	2.40	4.938	3.878		0.0297		0.0124
	9	30.48	4.20	5.02	21.087	16.562		0.0798		0.0159
	10	29.85	2.22	2.05	4.540	3.566		0.0272		0.0133
2023	1	31.03	3.43	3.88	13.321	10.463	**9**	0.0670	**-5**	0.0173
	2	31.96	3.94	3.79	14.926	11.723	**44**	0.0773	**30**	0.0204
	3	27.96	2.88	3.40	9.808	7.703	**57**	0.0589	**89**	0.0173
	4	10.25	2.73	3.64	9.930	7.799	**25**	0.0416	**-6**	0.0114
	5	21.74	4.34	4.99	21.649	17.003	**33**	0.0756	**15**	0.0151
	6	22.18	3.50	4.28	14.974	11.761	**90**	0.0662	**99**	0.0155
	7	31.16	5.52	4.79	26.421	20.751	**32**	0.1092	**84**	0.0228
	8	29.04	2.87	3.09	8.853	6.953	**79**	0.0559	**89**	0.0181
	9	30.48	4.91	5.85	28.739	22.572	**36**	0.1285	**61**	0.0220
	10	29.85	2.82	2.77	7.799	6.125	**72**	0.0588	**117**	0.0213

Estimated values based on a †rectangular ($v = h \cdot w$) or an ‡elliptical ($v = ¼ \cdot h \cdot w \cdot \varpi$) cross section of the hedgerow.

The sampled hedgerows were relatively heterogeneous in terms of form and shape (see also the 3D maps reported in Annex 1). Values in mean height, width and volume ranged respectively from 2.06–5.52 m, 2.05–5.85 m and 3.9–22.6 $m^3\ m^{-1}$. These ranges were consistent with those reported by Axe *et al*. (2017) and Drexler *et al*. (2021) when hedges were untrimmed for a period of about three years. In most cases, our hedgerows were well mapped by the tLiDAR system (Annex 1), but not for the section number 4. At both sampling dates, this section was characterised by a thick layer of mixed bramble and grasses that occluded substantially more the lower than the upper parts of this hedge structure during tLiDAR acquisitions (Annex 1). Additionally, section number 1 was accidentally trimmed during the growing season of 2022 (Annex 1), which influenced the resolving power of this technique in estimating volume changes between the two acquisition dates.

The best fit parameters for volumes (Figure 7 and 8) were assessed by running a sensitivity analysis across the different parameter options. Running the sensitivity analyses for each of the six parameters indicated a consistent pattern across volumes when expressed in cubic meters per unit of hedgerow length (m^3 m^{-1}) with mean height driving improved fits for volume. Estimated wood volumes ranged from 0.030–0.129 m^3 m^{-1} and from 0.010–0.023 m^3 m^{-2}. These ranges were consistent with those reported by Axe *et al*. (2017) and Drexler *et al*. (2021) (Figure 8). Therefore, an average 1.6-fold increase in wood volume (ranging from 0.9–2.2) was detected here between the two tLiDAR acquisition dates.

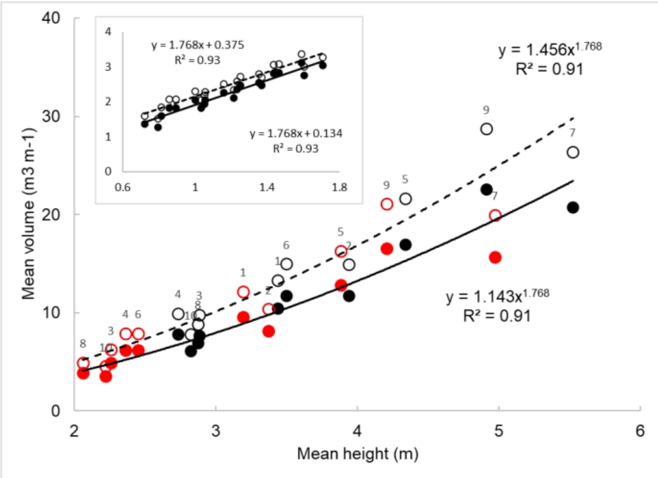


Figure 7. Estimated total above-ground volume against mean height for the ten hedgerow sections (data reported in Table 1). Volumes were estimated based on a rectangular (open symbols) or an elliptical (closed symbols) cross section of the hedgerows in 2022 (red symbols) and in 2023 (black symbols). Inset: $\log_n$ transformation of the data.

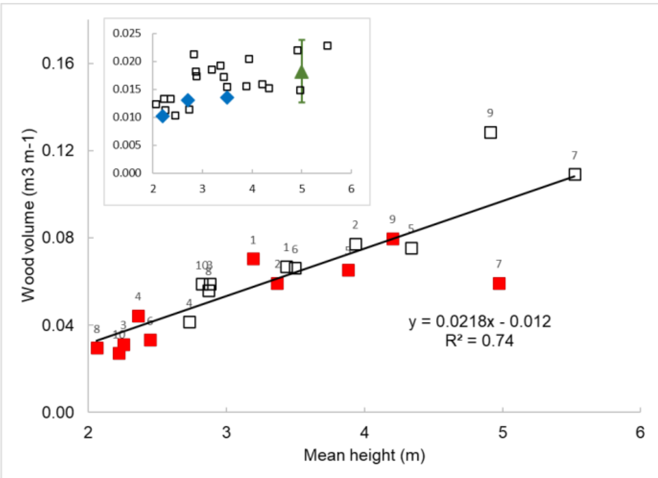


Figure 8. Estimated total above-ground woody volume against mean height for the ten hedgerow sections in 2022 (red symbols) and in 2023 (open symbols). Inset: inter-comparison with published data in Axe *et al*. (2017, blue symbols) and in Drexler *et al*. (2021, green symbols ± 1σ) when volumes are expressed in cubic meters of wood per unit of ground area (m^3 m^{-2}).

Results for sample trees

The individual estimates of the above-ground structure and the woody volumes for the two trees are shown in Table 2.

To date, the accuracy of the QSM method used here exceeds a level of 95% on total tree above-ground volume estimates (Casella *et al*. 2020*a*, 2020*b*, 2022).

Table 2. Individual tree estimates (± 1σ) of the above-ground structure and woody volume. Values in bold are recorded changes (%) between the acquisition dates.

		Tree							Crown			
Year	Species	dbh† (m)	dbh (m)		Height (m)		Wood volume (m^3)		Area (m^2)		Mean diameter (m)	
2022	Ash	0.43	0.44		10.99		1.61±0.02		38.5		7.0	
2023	Ash	0.46	0.46	**5**	11.09	**2**	2.02±0.05	**25**	43.0	**12**	7.4	**6**
Pooled data	Oak	2.01	1.99	-	22.45	-	43.54±1.35	-	580.2	-	27.2	-

†*Actual values measured with a research girth tape.*

When compared to 2022, highly significant ($P<0.001$) increases in both the wood volume and the structural parameters were detected in 2023 for ash, being the mature oak the exception.

Conclusions and recommendations for next steps

Based on the limited comparison possible at this stage, both the tLiDAR technology and the method considered appear to be valid for estimating non-destructively above ground biomass and carbon stocks in broadleaved hedgerows when leaf-off. This method estimates directly volumes from measurements of stem and hedgerow structures rather than using a general relationship between height and stem mass.

Comparison of the per cubic meters of wood volume per unit of ground area estimates from this method to available ground-truth data identified in the literature (*e.g.*, Axe *et al*. 2017, Drexler *et al*. 2021) show good agreement.

The following list recommends further investigations that add values to the work described here:

- Convert the volumes into biomasses using suitable wood nominal specific gravities and multiply the biomass estimates by 0.5 to give an approximation of carbon contents.
- Proceed to a sensitivity analysis of the automated chain (the method) to better tune relevant parameters when this method is applied to hedgerow structures.
- Adapt the point cloud acquisition protocol to progress the performance of this LiDAR technology when applied to complex 3D woody structures where the level of signal occlusion is the key factor which may influence its resolving power (*e.g.*, for section number 4).

Appendices

Appendix 1: Individual Farmer Reports

Farm 1

Background

Greenhouse gases (GHG) are known to accelerate the process of climate change. The agriculture sector was responsible for 14% of Wales' total GHG emissions in 2019 (Welsh Government, 2019). Of all agricultural GHG emissions, a large proportion of this percentage is generated from ruminant livestock, including beef cattle and sheep, with enteric fermentation and fertiliser use being important GHG sources. Wales is committed to a target of 95% reduction in greenhouse gas (GHG) emissions (of 1990 levels) by 2050 (Welsh Government, 2019). At the same time, consumers are becoming increasingly conscious of the impacts of their diet choice on GHG emissions, with some choosing to eliminate, or at least reduce the amount of red meat they consume, based on the notion that this will reduce their environmental impacts. The red meat sector is therefore under considerable pressure to reduce its GHG emissions. This is why we are very grateful to you for taking part in this study, as it will help the industry understand where positive changes can be made.

What are carbon footprints?

Farm carbon footprints (CF) provide detail regarding the amount of GHGs that are emitted both directly and indirectly because of farming-related activities. The information provided in this report relates to your farm's carbon footprint. In addition to this, it highlights areas for improvement, and provides further information on potential measures and practices that will lower your farm's carbon footprint and increase farm efficiency. Our carbon footprinting approach makes use of your farm data for one or more year to calculate GHG emissions from your farm's major products, e.g. lamb, beef and/or dairy, with your carbon footprint expressed per kilogram (kg) of product during that period. Your results are then compared to other farms included in this audit. We also estimate the farm's sequestration (i.e., the amount of carbon added to soils and vegetation such as trees and hedges over the study period).

There are multiple tools that can be used for determining carbon footprints. As explained in other reports (e.g., CIEL, 2020; Taft et al., 2018), each have their merits, and in general, a trade-off exists in terms of the level of detail required (and therefore how onerous the process is), and the accuracy. Because different tools use different methodologies (e.g., what they choose to include, and what they omit), the results of carbon footprints generated using different tools **should not and cannot be directly compared to each other**.

How are carbon footprints calculated?

All inputs to a farm have GHG emissions associated with them, e.g., every litre of diesel or tonne of concentrate feed used will have generated some emissions during their production. These 'upstream' (or 'off-farm') GHG emissions need to be included in your product's carbon footprint. Our questionnaire was designed to capture adequate data to quantify the upstream emissions and GHG emissions produced on your farm, expressed as a 'cradle to gate' footprint. This means that all emissions produced from the farm's sources (e.g., livestock, manure management, soils, and energy use) are included in the footprint. Furthermore, levels of carbon sequestration in soils and vegetation (trees and hedges) on your farm were estimated. We did not consider what happens to your livestock once they pass your 'farm gate', for example, selling or processing.

This audit calculates a comprehensive carbon footprint per kg of deadweight (DW) of product for your farm outputs (i.e., lamb and beef). The GHG emissions associated with all of your farm inputs are calculated, as are the emissions generated by your livestock during their time on farm. All these emissions are added, then divided by your farm outputs, enabling us to present the results expressed as GHG emission per unit of DW product (e.g., kg CO_2e/kg of lamb DW). Sequestration values are expressed in the same way (the sequestration associated with your farm is divided by the outputs), with the sequestration values subtracted from the emissions to generate the overall net emissions. It is important to note that this unit of measurement is different to **total emissions**, whereby your farm **product's** carbon footprint is determined here, as opposed to the **whole farm's** footprint. The product's carbon footprint can be compared with other farms (as done so in this audit), whereas the whole farm's footprint would depend on farm size, total livestock numbers, etc.

Accurately calculating a product's carbon footprint is challenging, and is very dependent on the accuracy of the data received. There were some data that participants found difficult to provide. In this case, national data sources, published UK reference examples, or standardised estimates were used in their place.

The data provided by you was input into AgRE Calc and the Bangor Tool's sequestration calculations, and results were exported from both tools and combined to complete the final footprint. Both tools are validated to approved standards (PAS2050) and use internationally accepted figures to estimate the emissions from certain farm practises to generate carbon footprints. There is limited understanding of the potential of vegetation and soils to sequester carbon, and therefore your farm's sequestration estimations are based on current scientific understanding.

Carbon footprints are influenced by several fixed factors as well as management options. Variability in farm emissions, and consequently carbon footprints, are influenced by livestock numbers, soils, the amount of inputs used (e.g. feed and fertiliser), etc. As explained above, the GHG emissions associated with these inputs are divided with the kg DW produced on a farm in the same year. Some systems may be high inputs but high outputs, whereas other systems will have much fewer inputs, but lower outputs (and all combinations in between). Essentially, more efficient systems use a smaller amount of inputs per unit output generated, meaning that their product carbon footprint will be lower. Such factors should be considered when comparing your product's footprint with others, as well as when assessing what measures to reduce the carbon footprint are appropriate and relevant to your farm type.

Carbon footprints can vary on the same farm from year to year, e.g. due to bad weather meaning more concentrates were used in some years and/or that the growth rates of livestock was lower than usual. For this reason, capturing data from the same year across all farms was best to allow a fair comparison but ideally data would be provided for a number of years then averaged to ensure accuracy of the resulting footprint.

Your footprint is presented below alongside the other five farms from this project. Although this allows a comparison to farms in your area, **caution must be exercised analysing the results comparison** as farms vary significantly in size, type (e.g., hill, upland and lowland) and enterprise type (e.g., breeders, finishers etc.) – all of which will affect both their emission and sequestration estimates.

Your carbon footprint

Carbon footprints are presented as 'carbon dioxide equivalents', or CO_2e, which is all of the measured GHGs converted to and expressed as a single GHG equivalent, based on their Global Warming Potential (GWP) values used internationally by the Intergovernmental Panel on Climate Change (IPCC). The GHGs that are included in your footprint, and are converted to CO_2e, are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The gases with the most impact are CH_4, which is largely produced by livestock and released into the atmosphere via enteric fermentation, and N_2O, which occurs mainly from soil, following applications of nitrogen fertiliser and livestock manures, as well as urine and dung deposition by grazing livestock (included in the "Soil Nitrous Oxide – Manure" section of your footprint). Storage of manure also releases both gases manure. These two gases are very potent in terms of their GWP, with the tool employing GWP factors of 25 and 298 for CH_4 and N_2O, respectively (IPCC, 2006). This equates to CH_4 having a GWP that is 25 greater than CO_2, and N_2O having a GWP that is 298 times greater than CO_2, over a 100-year period. Some scientists argue that this artificially inflates the contribution of CH_4 to climate change as the CH_4 breaks down after 12-20 years; however, as explained earlier, we have used the internationally-recognised GWP of 25 for CH_4, to comply with the methods employed by the IPCC. Using recognised methods is important to ensure credibility of results.

As your farm produced more than one output (lamb and beef), emissions from the farm enterprise were allocated between different outputs on an economic basis, as the percentage of total farm income earned from the relevant output. Such use of economic allocation allows common burdens (e.g., from the manufacture and use of fertiliser on mixed farms) to be “shared” on individual farms between lamb and beef deadweight outputs (BSI, 2011). For instance, where you apply fertiliser on land grazed by both cattle and sheep, if 60% of your farm income is from cattle, then 60% of the emissions caused by that fertiliser would be allocated to cattle, and 40% to lamb. Similarly, sequestration values have been “shared” between different enterprises based on economic allocation. It is important to reiterate that the results presented here are based on data provided to us. The accuracy of the results is therefore dependent on the accuracy of the data you provided.

Your lamb carbon footprint

In Figure 1, we present the total CO_2e output per kg of <u>lamb</u> product on your farm for a year. A breakdown of the farm’s carbon sequestration is also presented. Your total GHG emissions equated to 17.8 kg CO_2e/kg of DW lamb (i.e., for every kg of DW of lamb you produced, this resulted in the emissions of 17.8 kg of CO_2e). This was below the average of 19.4 kg CO_2e/kg of DW lamb for sheep farms in this project. Your sequestration levels were roughly average, at 5.6 kg CO_2e/kg of DW lamb (where the average was 5.5 kg CO_2e/kg of DW lamb).

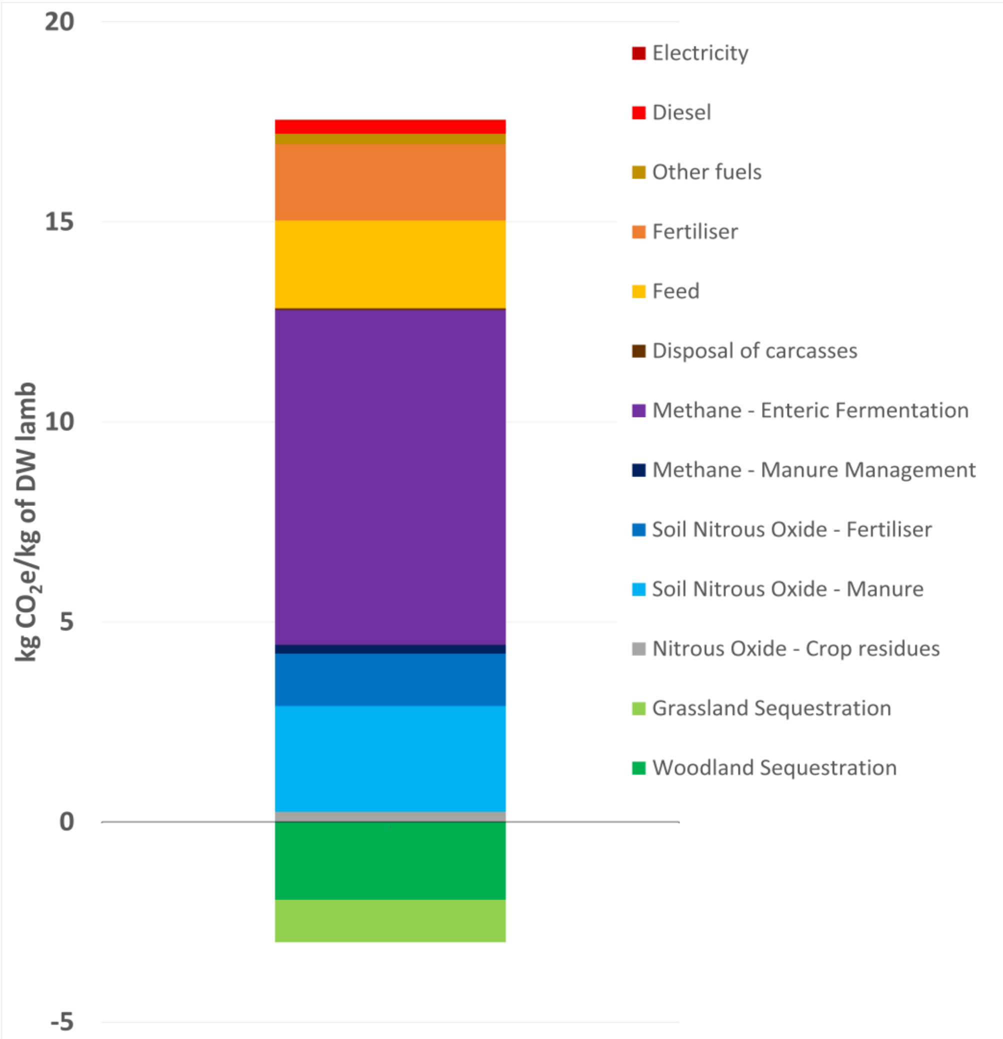


Figure 1: Your lamb carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW lamb.

Both the GHG emissions produced for your lamb footprint and the sequestration occurring on-farm **resulted in net emissions (kg CO_2e emissions minus sequestration) of 12.2 kg CO_2e/kg of DW lamb**. This is displayed as the bar in red in Figure 2, along with the values for all farms.

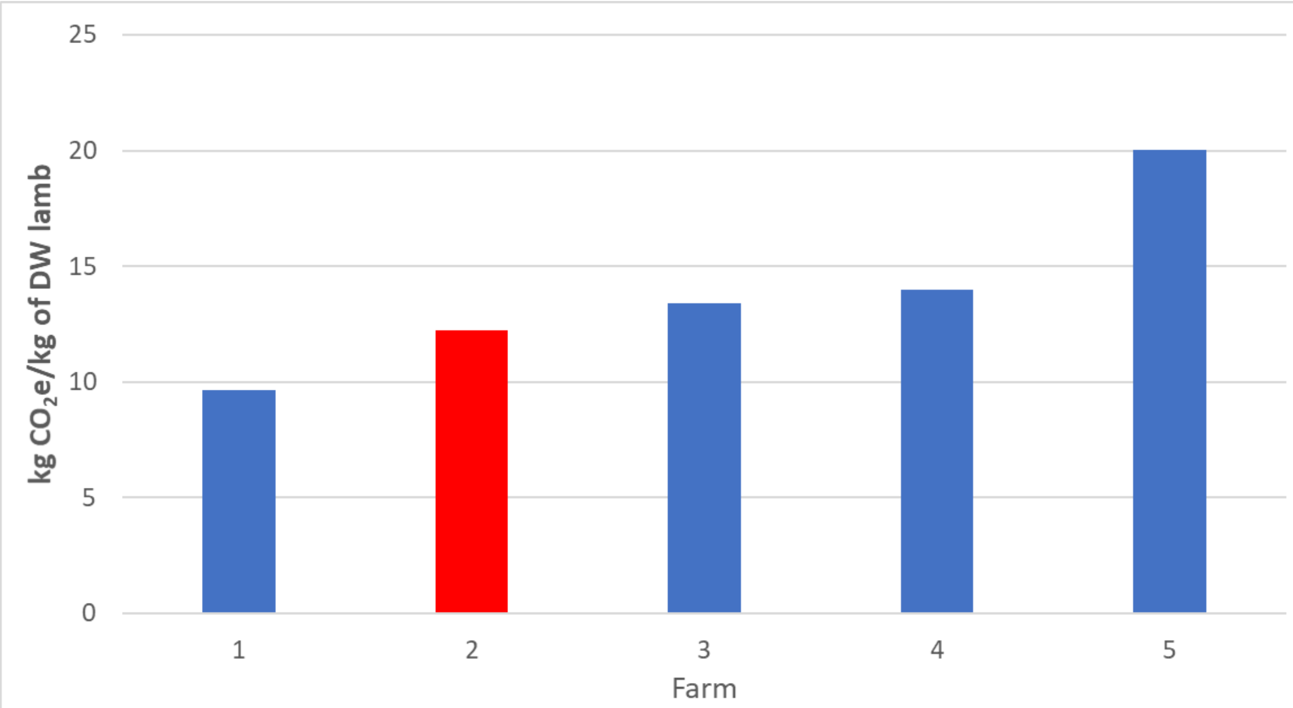


Figure 2: Lamb net emissions in kg CO_2e/ kg of DW lamb of the five sheep farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Your beef carbon footprint

In Figure 3, we present the total CO_2e output per kg of <u>beef</u> product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 39.5 kg CO_2e/kg of DW beef, and above the average of 28.4 kg CO_2e/kg of DW beef for beef farms in this project. Your sequestration levels were higher than the average for all farms, at 12.0 kg CO_2e/kg of DW beef (where the average was 8.0 kg CO_2e/kg of DW beef). It should be noted that as emissions are expressed in per kg of product, due to the increase in cattle numbers on your farm in the sample year, your footprint may be higher than it would be on a normal year.

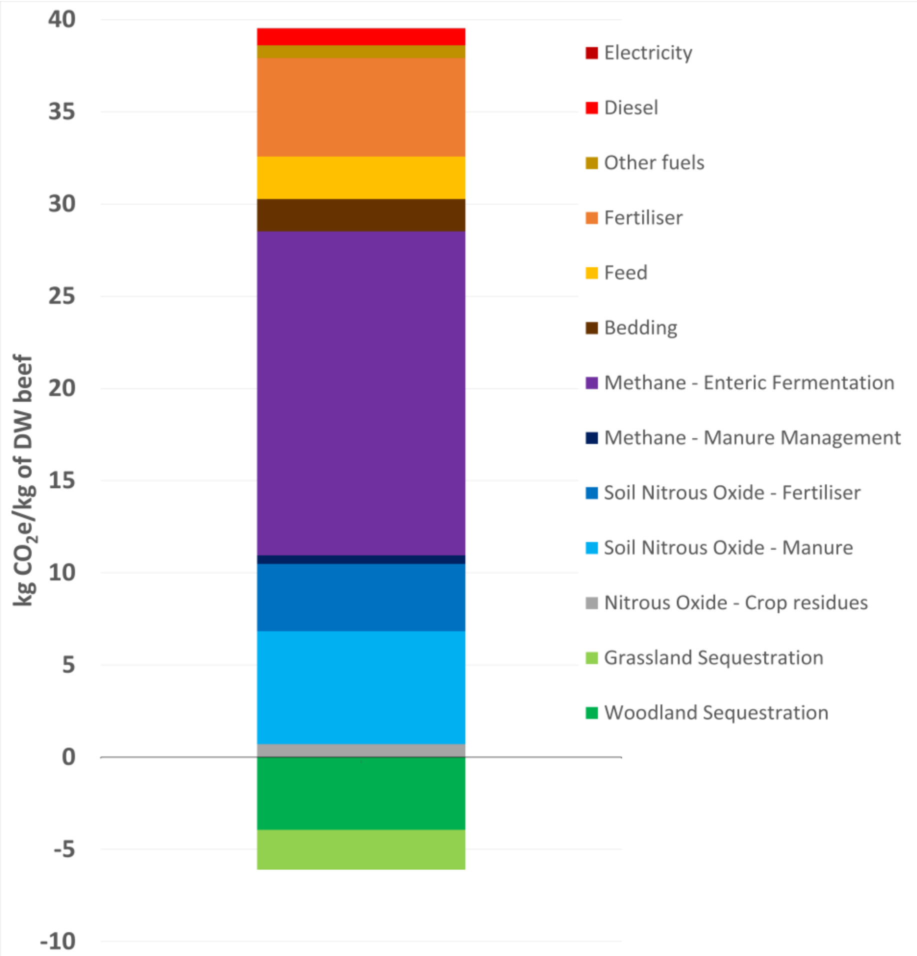


Figure 3: Your beef carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW beef.

In terms of your beef enterprise, **the net emissions (kg CO_2e emissions minus sequestration) was 27.4 CO_2e/kg of DW beef**. This is displayed as the bar in red in Figure 4, along with the values for all of farms.

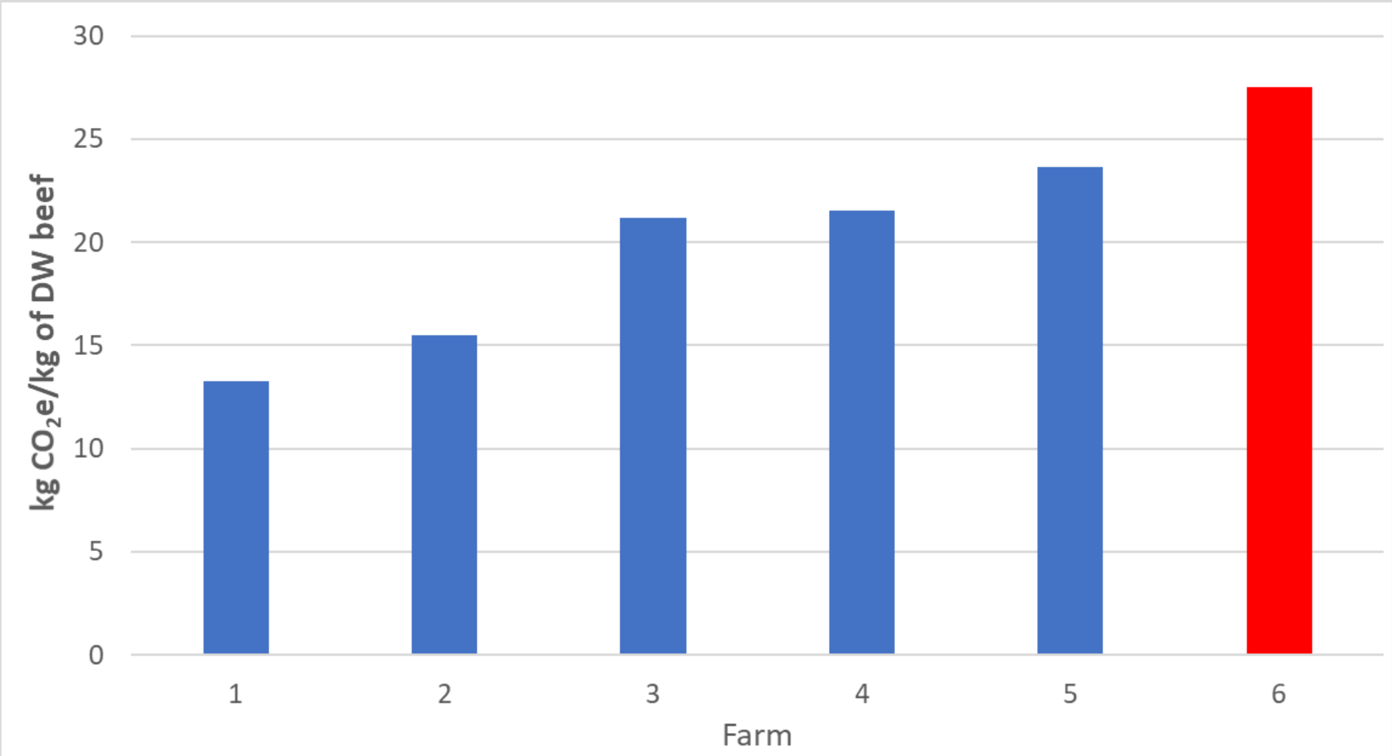


Figure 4: Beef net emissions in kg CO_2e/ kg of DW beef of the six beef farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Reducing your product's carbon footprint

Improving efficiency

Measures intended to reduce your product's carbon footprint may also lead to an improvement in livestock performance, and potentially, an increase in the farm's profitability. Some of the measures may be farm-specific, and may not be as effective or applicable to your farm as others. An example of this could be the cost, effort and impracticality associated with cultivating and reseeding hill pasture as opposed to lowland, where the economic and environmental costs may be greater than the potential returns. Due to this, prioritisation should be given to those measures deemed both effective and practical for your farm. Potential measures for improving efficiency are as follows:

- One of the most effective strategies are related to *optimising the diet of animals*, which can potentially reduce concentrate feed requirements, lower feed costs, and increase growth rates, meaning days to finishing are reduced (therefore less CH_4 is emitted over the lifetime of the animal)

- *Genetic improvement* will aid to reduce days to slaughter and improve growth rates, resulting in less emissions associated during the animal's lifetime. This measure may also lead to increased DW produced without an increase in feed requirements
- *Increasing the lamb/calf rearing percentage*, leading to greater kg produced per ewe/cow, and therefore a reduction in the emissions associated with the ewe/cow
- *Reducing the calving interval* in suckler cow systems. An extended calving interval means that the GHG burden of unproductive adult cows has to be borne by other animals. Given the high body mass of adult cows, they can account for a significant proportion of emissions associated with feed use and enteric fermentation. A protracted calving period may also lead to further inefficiencies at later stages of production, such as issues around optimal feeding for animals at different growth stages
- *Lambing as ewe lambs* where practical and feasible as well as *reducing heifer age when first put in calf*, leading to greater output (kg produced) at a younger age (otherwise 'unproductive'), and therefore a reduction in GHGs associated with the ewe lamb/heifer at this period of its life (and consequently, its lifetime)
- *Reducing the burden of disease* (e.g., reducing losses through abortions, lameness, pneumonia) or parasites (e.g. gastrointestinal worms) can have very significant impacts on livestock performance, value, and reduce GHG emissions per kg produced
- *Improving the way that manure/slurry is stored and applied* (e.g., avoiding spreading during winter) can decrease emissions and simultaneously reduce the need for bought-in fertiliser as better use is made of the nutrients within the product
- *Improving grassland management*, thereby reducing the need for bought-in concentrates and improving growth rates
- *Using legumes* (plants that increase nitrogen in soils naturally, such as clover) can provide a valuable source of high quality, home-grown fodder, and reduce the need for bought-in fertiliser
- When re-seeding, *grasses of a high water-soluble carbohydrate* (WSC) concentration ("high-sugar grasses") have been shown to reduce N_2O emissions from pasture systems through reduced excretion of nitrogen in animals feeding on such grasses compared to conventional grass
- *Introduction of a forage crop within a grass rotation or arable crop* can reduce the burden of pests and weeds, thereby saving on the use of herbicides and pesticides and their associated emissions (although the use of these agro-chemicals was deemed too low to be included in this audit).

Enhancing sequestration

Carbon sequestration in both soils and vegetation (trees and hedges) provides a valuable opportunity to off-set GHG emissions produced on-farm. We estimate that sequestration offset roughly 38% of your farm's total footprint. Grassland makes up a significant percentage of the sequestration on your farm. This is to be expected, as a large proportion of your land is managed as grassland. However, sequestration of carbon in woodland was also responsible for offsetting 24% of your farm's footprint.

We estimated your soil's sequestration, based on the current science. There is much discussion about the potential for off-setting livestock-derived GHG emissions through the sequestration of carbon in grassland systems that dominate Wales. However, whether agricultural soils are a carbon sink (sequestering carbon) or source (release carbon) depends on a number of wide-ranging variables, including climate, soil type, land use/management, water availability and, most importantly, the actual organic matter content of the soil (Freibauer et al., 2004). Accurately estimating sequestration, without field sampling to measure actual change in soil carbon, is difficult. Firstly, changes in soil carbon tend to occur slowly (over many years), therefore determining sequestration rates is challenging (whereas in contrast, calculating the GHG emissions associated with farm inputs is comparatively much easier). Secondly, soil carbon (and the potential for sequestration) is very dependent on soil type, with sequestration potential in lighter, mineral soils being many times greater than in organic-rich soils, as the rate of sequestration slows with time (Ostle et al., 2009). The heterogeneous nature of soils in Wales, with many farms with varying areas of more than one soil type, of different bulk densities, adds to this complexity. Thirdly, management of those soils will have a notable impact on the rate of carbon sequestration or loss, and in some cases, though less so in pasture systems, management may be subject to frequent change (differences in cropping cycles, inputs, etc.). Fourthly, even where soil data exists, variation in sampling protocols to measure changes in soil carbon can have very notable impacts on results; for instance, sampling at different depths, and due to within-field variability of soils, etc. (Dawson and Smith, 2007). Collectively, these factors mean that there is therefore a high dependence on assumptions and estimations when predicting the sequestration potential of grassland systems. Such challenges at least partly explain why estimates of the sequestration values of soils on farms notably vary between different carbon assessment tools (Taft et al., 2018), and should always be interpreted with caution. The capacity to make significant further gains in sequestration may be limited in soils under permanent grasslands as many are likely to be at a state of carbon equilibrium (where emissions and sequestration are balanced) (CIEL, 2020). Some advocate that rotational grazing can increase soil carbon; however, currently, there is not enough robust science to determine this. Where a rotational grazing approach is practised, this was not accounted for within this audit, as estimating sequestration rates in soils managed in this way is very difficult without detailed soil sampling, as previously mentioned.

The potential and rate of sequestration in woodland and hedges will vary with factors such as species planted, rotation length of woodland, the frequency of flailing and laying hedges, soil types, and climate (Ostle et al., 2009). However, a recent study concluded that the New Zealand beef and lamb sectors were close to achieving carbon neutrality due to the relatively high woodland cover on such farms (mean of 15%) accounting for considerable sequestration to off-set emissions (Beef and Lamb New Zealand, 2020). This emphasises the important role that trees can play in sequestering carbon on farms. Measures that protect, and indeed enhance soil carbon, are to be encouraged, as are opportunities for better management of existing trees and hedges, alongside the strategic planting of trees on Welsh livestock farms. Potential measures to enhance sequestration levels include:

- *Leaving hedges to grow taller and wider* could offer a simple and cost-neutral way to increase sequestration rates on farm, as well as delivering enhanced shelter for both livestock and wildlife
- *Establishing additional hedges and trees in suitable locations*, e.g. along fence lines, on unproductive land could make important contributions in reducing whole farm footprints once trees reach the phase where sequestration rates are high. As well as sequestering carbon above-ground and in soil, trees and hedges planted appropriately can also improve the efficiency of production by reducing losses and energy losses through improving shelter provision
- Tillage prior to re-seeding is likely to give rise to carbon losses from soils, as some of the accumulated carbon will be lost as it is respired by soil bacteria. From a carbon perspective, it is better to *reduce the frequency of re-seeding* (and the primary focus should be on managing older leys well, so that they remain productive and reduce the need to re-seed). However, the rate of sequestration is likely to be increased following re-seeding due to higher yield from a new ley, thus recovering some of the carbon lost, until the soil again reaches equilibrium. In the event of re-seeding, minimum tillage approaches such as direct drilling or scarification of seeds is preferred to reduce soil losses of carbon and the risk of soil erosion
- *Incorporation of multi-species swards* on-farm that typically have a deeper-rooting growth structure than ryegrass-only swards. Such deep-rooting species can deliver ‘deep sequestration’ of carbon in soils, given that soil carbon is concentrated in the plant root zone (Thorup-Kristensen et al., 2020)

- *Permanent pastures generally also have deeper-rooting systems* than annual crops as plant species grow a larger rooting network over time, thus will accumulate deeper layers of carbon sequestration in soils (Thorup-Kristensen et al., 2020)
- *Implementing a precise rotational grazing system* that is carefully managed. Compared to set-stocked systems, rotational systems allow 'rest' periods for grass to recover post-grazing, which can enhance overall grass yields if grazing occurs at the optimal grass growth stage (Dawson and Smith, 2007). In turn, this should also increase root growth and therefore carbon inputs to soil. However, further research is greatly needed to validate this, as the scientific evidence currently does not exist. It is also important to note that where ground conditions are not suitable, rotational grazing can lead to soil compaction and run-off, which would ultimately negatively affect soil sequestration levels. Further, where such systems lead to an increase in livestock numbers, there is a need to consider how the resulting greater emissions of CH_4 may outweigh any positive effects associated with increased soil carbon storage. Whilst this may reduce the emissions intensity of <u>their products</u>, it clearly has the opposite effect in terms of <u>total farm</u> emissions, which would not help Welsh agriculture reach its ambition of being net zero emissions.

<u>Conclusions and recommendations</u>

Estimating the net emissions associated with the production of lamb and beef on Welsh farms through carbon footprinting is a valuable exercise to help farmers consider how their management impacts their farm's carbon balance. As well as potentially reducing the costs of production, farmers that are able to demonstrate their environmental credentials may be better placed to market their produce more positively to consumers in the future. It should also be noted that future private and public funding schemes may reward good practise. There has never been a greater need to improve our understanding of how farm GHG emissions can be reduced and/or off-set through sequestration.

The results of your carbon audit presented here are an estimation based on the data that you provided. To reiterate, the findings of this audit is expressed as GHG emission per unit of DW product (kg CO_2e/kg of lamb or beef DW), and is not the farm's total emissions. Your lamb enterprise resulted in net emissions (kg CO_2e emissions minus sequestration) of 12.2 kg CO_2e/kg of DW lamb. In terms of your beef enterprise, the net emissions (kg CO_2e emissions minus sequestration) was 27.5 kg CO_2e/kg of DW beef.

Welsh agriculture has an ambition to be net zero in terms of GHG emissions, meaning it sequesters at least as much carbon as it emits. The net emissions (kg CO_2e emissions minus sequestration) was positive on all farms that participated in the study, i.e., no farm sequestered more carbon than the GHGs their activities emitted. Whilst there were a few exceptions, sequestration generally made only a modest difference to overall net emissions, off-setting equal to 30% of GHG emissions across all production systems. Although our sample size was small in this study, these results indicate that Welsh farms therefore have a considerable challenge to deliver the net zero ambition. There is scope for every farm that participated in this study to implement measures to reduce their product's carbon footprint. **To achieve this, farms will need to both i) reduce emissions, and ii) enhance sequestration.**

In terms of efficiency measures, a well-managed flock or herd will optimise livestock growth rates, reducing their days on farm and the associated GHG emissions. This also necessitates fewer inputs such as feed, and reduces mortalities. Livestock growth rates are a function of many products – the genetic merit of animals, their diet, animal health, and the influence of variables such as the weather, to name a few. Strategies that optimise these would make both economic and environmental sense for Welsh farms.

In terms of sequestration levels, strategically increasing woodland cover on Welsh farms is to be encouraged as it can offer many environmental benefits over and above carbon sequestration, and in many cases, benefits to the economic viability of farm businesses, particularly where farmers can capitalise on schemes to pay for establishment and/or management costs. Ultimately, trees will likely play an important part in helping the Welsh livestock sector move towards net zero GHG emissions. Measures that retain carbon in soil should be implemented, and further research to prove how to enhance sequestration in soils under grassland systems would be very worthwhile. Nevertheless, it is also important to remember that enhanced sequestration should not substitute overall emission reduction, which should be the primary aim to achieving a net zero livestock sector in Wales.

Farm 2

Your carbon footprint

Carbon footprints are presented as ‘carbon dioxide equivalents’, or CO_2e, which is all of the measured GHGs converted to and expressed as a single GHG equivalent, based on their Global Warming Potential (GWP) values used internationally by the Intergovernmental Panel on Climate Change (IPCC). The GHGs that are included in your footprint, and are converted to CO_2e, are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The gases with the most impact are CH_4, which is largely produced by livestock and released into the atmosphere via enteric fermentation, and N_2O, which occurs mainly from soil, following applications of nitrogen fertiliser and livestock manures, as well as urine and dung deposition by grazing livestock (included in the “Soil Nitrous Oxide – Manure” section of your footprint). Storage of manure also releases both gases manure. These two gases are very potent in terms of their GWP, with the tool employing GWP factors of 25 and 298 for CH_4 and N_2O, respectively (IPCC, 2006). This equates to CH_4 having a GWP that is 25 greater than CO_2, and N_2O having a GWP that is 298 times greater than CO_2, over a 100-year period. Some scientists argue that this artificially inflates the contribution of CH_4 to climate change as the CH_4 breaks down after 12-20 years; however, as explained earlier, we have used the internationally-recognised GWP of 25 for CH_4, to comply with the methods employed by the IPCC. Using recognised methods is important to ensure credibility of results.

As your farm produced more than one output (lamb and beef), emissions from the farm enterprise were allocated between different outputs on an economic basis, as the percentage of total farm income earned from the relevant output. Such use of economic allocation allows common burdens (e.g., from the manufacture and use of fertiliser on mixed farms) to be “shared” on individual farms between lamb and beef deadweight outputs (BSI, 2011). For instance, where you apply fertiliser on land grazed by both cattle and sheep, if 60% of your farm income is from cattle, then 60% of the emissions caused by that fertiliser would be allocated to cattle, and 40% to lamb. Similarly, sequestration values have been “shared” between different enterprises based on economic allocation. It is important to reiterate that the results presented here are based on data provided to us. The accuracy of the results is therefore dependent on the accuracy of the data you provided.

Your lamb carbon footprint

In Figure 1, we present the total CO_2e output per kg of lamb product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 20.4 kg CO_2e/kg of DW lamb (i.e., for every kg of DW of lamb you produced, this resulted in the emissions of 20.4 of CO_2e). This was slightly above the average of 19.4 kg CO_2e/kg of DW lamb for sheep farms in this project. Your sequestration levels were just above average at 6.4 kg CO_2e/kg of DW lamb (where the average was 5.5 kg CO_2e/kg of DW lamb).

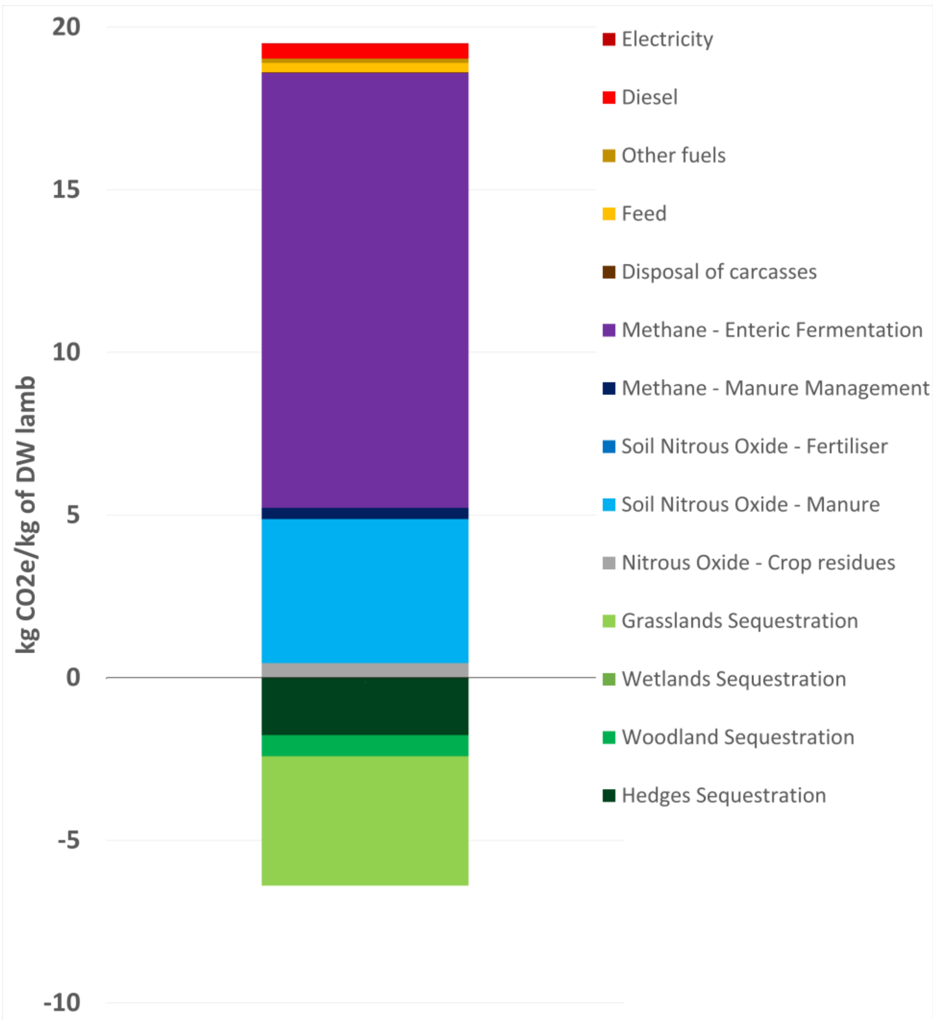


Figure 1: Your lamb carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW lamb.

Both the GHG emissions produced for your lamb footprint and the sequestration occurring on-farm **resulted in net emissions (kg CO_2e emissions minus sequestration) of 14.0 kg CO_2e/kg of DW lamb**. This is displayed as the bar in red in Figure 2, along with the values for all farms.

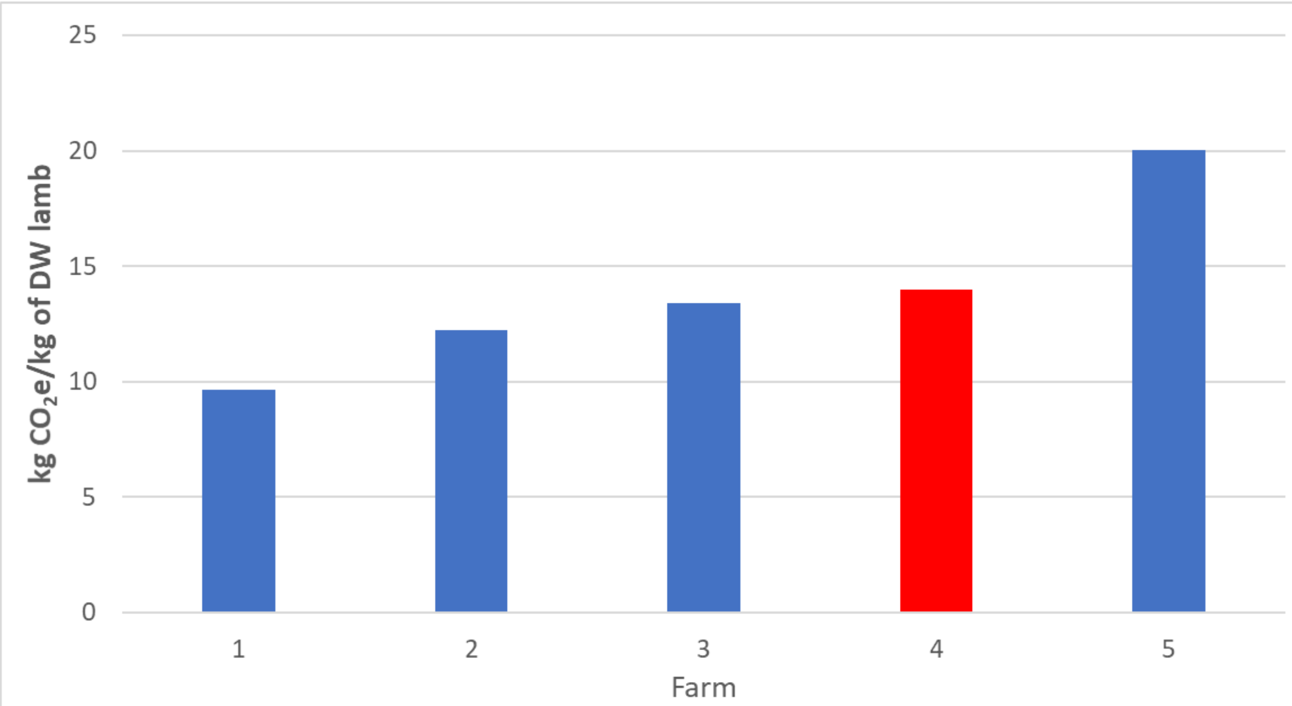


Figure 2: Lamb net emissions in kg CO_2e/ kg of DW lamb of the five sheep farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Your beef carbon footprint

In Figure 3, we present the total CO_2e output per kg of <u>beef</u> product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 38.6 kg CO_2e/kg of DW beef, and above the average of 28.4 kg CO_2e/kg of DW beef for beef farms in this project. Your sequestration levels were higher than the average for all farms, at 15.0 kg CO_2e/kg of DW beef (where the average was 8.0 kg CO_2e/kg of DW beef).

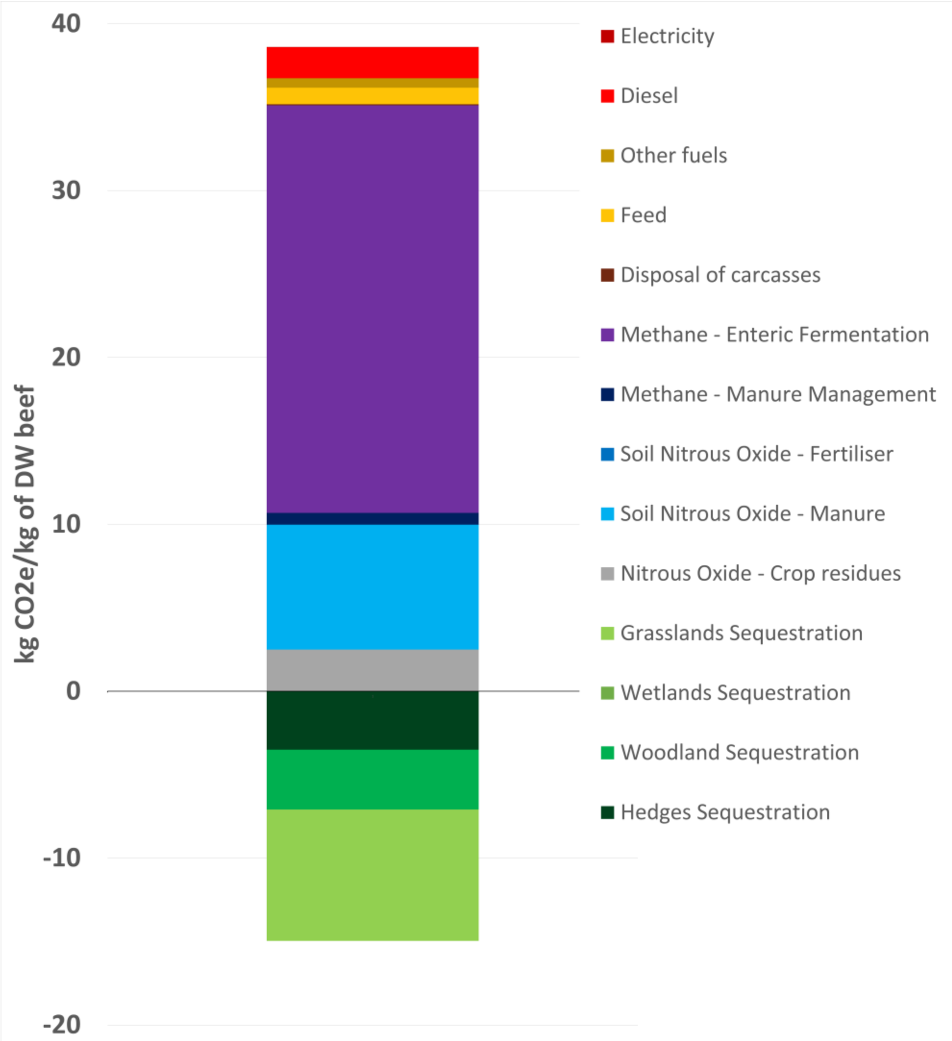


Figure 3: Your beef carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW beef.

In terms of your beef enterprise, **the net emissions (kg CO_2e emissions minus sequestration) was 23.6 kg CO_2e/kg of DW beef**. This is displayed as the bar in red in Figure 4, along with the values for all of farms.

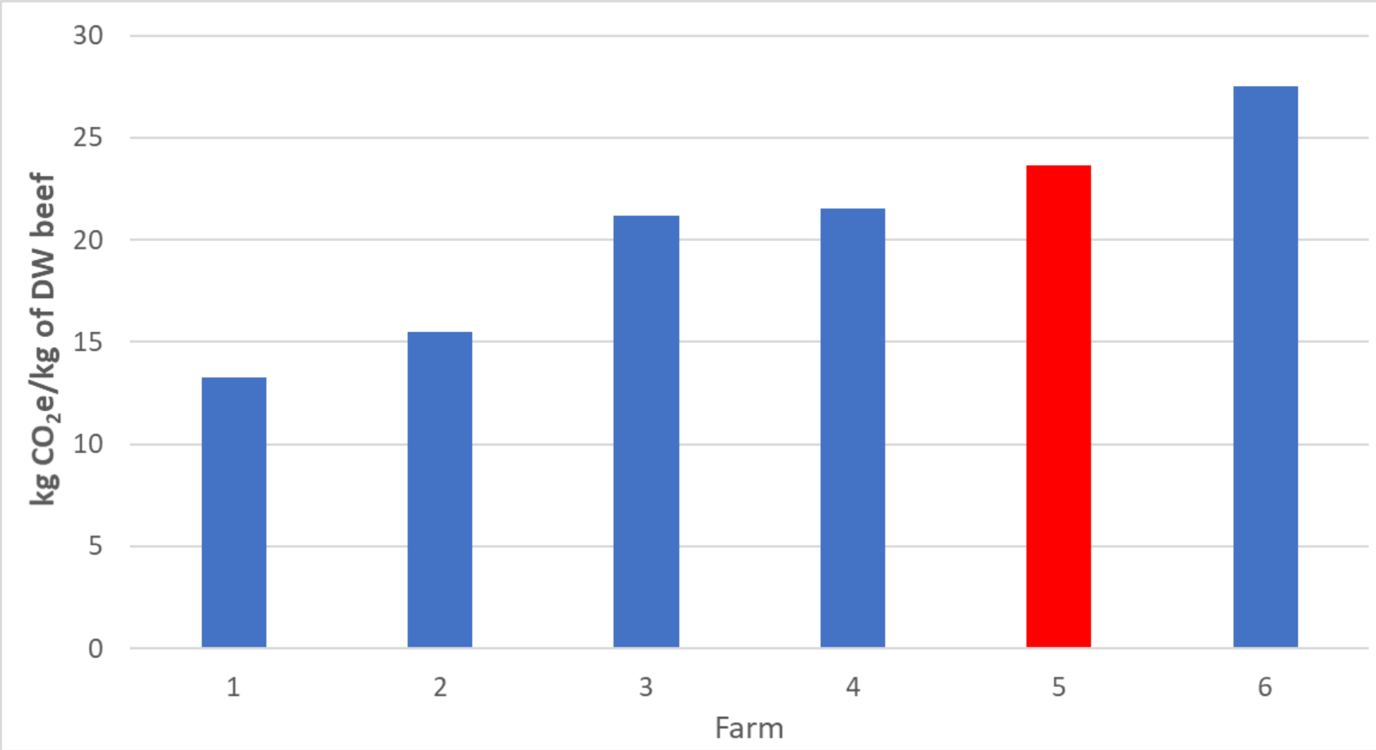


Figure 4: Beef net emissions of the six beef farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Reducing your product's carbon footprint

Improving efficiency

Measures intended to reduce your product's carbon footprint may also lead to an improvement in livestock performance, and potentially, an increase in the farm's profitability. Some of the measures may be farm-specific, and may not be as effective or applicable to your farm as others. An example of this could be the cost, effort and impracticality associated with cultivating and reseeding hill pasture as opposed to lowland, where the economic and environmental costs may be greater than the potential returns. Due to this, prioritisation should be given to those measures deemed both effective and practical for your farm. Potential measures for improving efficiency are as follows:

- One of the most effective strategies are related to *optimising the diet of animals*, which can potentially reduce concentrate feed requirements, lower feed costs, and increase growth rates, meaning days to finishing are reduced (therefore less CH_4 is emitted over the lifetime of the animal)

- *Genetic improvement* will aid to reduce days to slaughter and improve growth rates, resulting in less emissions associated during the animal's lifetime. This measure may also lead to increased DW produced without an increase in feed requirements
- *Increasing the lamb/calf rearing percentage*, leading to greater kg produced per ewe/cow, and therefore a reduction in the emissions associated with the ewe/cow
- *Reducing the calving interval* in suckler cow systems. An extended calving interval means that the GHG burden of unproductive adult cows has to be borne by other animals. Given the high body mass of adult cows, they can account for a significant proportion of emissions associated with feed use and enteric fermentation. A protracted calving period may also lead to further inefficiencies at later stages of production, such as issues around optimal feeding for animals at different growth stages
- *Lambing as ewe lambs* where practical and feasible as well as *reducing heifer age when first put in calf*, leading to greater output (kg produced) at a younger age (otherwise 'unproductive'), and therefore a reduction in GHGs associated with the ewe lamb/heifer at this period of its life (and consequently, its lifetime)
- *Reducing the burden of disease* (e.g., reducing losses through abortions, lameness, pneumonia) or parasites (e.g. gastrointestinal worms) can have very significant impacts on livestock performance, value, and reduce GHG emissions per kg produced
- *Improving the way that manure/slurry is stored and applied* (e.g., avoiding spreading during winter) can decrease emissions and simultaneously reduce the need for bought-in fertiliser as better use is made of the nutrients within the product
- *Improving grassland management*, thereby reducing the need for bought-in concentrates and improving growth rates
- *Using legumes* (plants that increase nitrogen in soils naturally, such as clover) can provide a valuable source of high quality, home-grown fodder, and reduce the need for bought-in fertiliser
- When re-seeding, *grasses of a high water-soluble carbohydrate* (WSC) concentration ("high-sugar grasses") have been shown to reduce N_2O emissions from pasture systems through reduced excretion of nitrogen in animals feeding on such grasses compared to conventional grass
- *Introduction of a forage crop within a grass rotation or arable crop* can reduce the burden of pests and weeds, thereby saving on the use of herbicides and pesticides and their associated emissions (although the use of these agro-chemicals was deemed too low to be included in this audit).

Enhancing sequestration

Carbon sequestration in both soils and vegetation (trees and hedges) provides a valuable opportunity to off-set GHG emissions produced on-farm. We estimate that sequestration offset roughly 39% of your farm's total footprint. Grassland makes up a significant percentage of the sequestration on your farm. This is to be expected, as a large proportion of your land is managed as grassland.

We estimated your soil's sequestration, based on the current science. There is much discussion about the potential for off-setting livestock-derived GHG emissions through the sequestration of carbon in grassland systems that dominate Wales. However, whether agricultural soils are a carbon sink (sequestering carbon) or source (release carbon) depends on a number of wide-ranging variables, including climate, soil type, land use/management, water availability and, most importantly, the actual organic matter content of the soil (Freibauer et al., 2004). Accurately estimating sequestration, without field sampling to measure actual change in soil carbon, is difficult. Firstly, changes in soil carbon tend to occur slowly (over many years), therefore determining sequestration rates is challenging (whereas in contrast, calculating the GHG emissions associated with farm inputs is comparatively much easier). Secondly, soil carbon (and the potential for sequestration) is very dependent on soil type, with sequestration potential in lighter, mineral soils being many times greater than in organic-rich soils, as the rate of sequestration slows with time (Ostle et al., 2009). The heterogeneous nature of soils in Wales, with many farms with varying areas of more than one soil type, of different bulk densities, adds to this complexity. Thirdly, management of those soils will have a notable impact on the rate of carbon sequestration or loss, and in some cases, though less so in pasture systems, management may be subject to frequent change (differences in cropping cycles, inputs, etc.). Fourthly, even where soil data exists, variation in sampling protocols to measure changes in soil carbon can have very notable impacts on results; for instance, sampling at different depths, and due to within-field variability of soils, etc. (Dawson and Smith, 2007). Collectively, these factors mean that there is therefore a high dependence on assumptions and estimations when predicting the sequestration potential of grassland systems. Such challenges at least partly explain why estimates of the sequestration values of soils on farms notably vary between different carbon assessment tools (Taft et al., 2018), and should always be interpreted with caution. The capacity to make significant further gains in sequestration may be limited in soils under permanent grasslands as many are likely to be at a state of carbon equilibrium (where emissions and sequestration are balanced) (CIEL, 2020). Some advocate that rotational grazing can increase soil carbon; however, currently, there is not enough robust science to determine this. Where a rotational grazing approach is practised, this was not accounted for within this audit, as estimating sequestration rates in soils managed in this way is very difficult without detailed soil sampling, as previously mentioned.

The potential and rate of sequestration in woodland and hedges will vary with factors such as species planted, rotation length of woodland, the frequency of flailing and laying hedges, soil types, and climate (Ostle et al., 2009). However, a recent study concluded that the New Zealand beef and lamb sectors were close to achieving carbon neutrality due to the relatively high woodland cover on such farms (mean of 15%) accounting for considerable sequestration to off-set emissions (Beef and Lamb New Zealand, 2020). This emphasises the important role that trees can play in sequestering carbon on farms. Measures that protect, and indeed enhance soil carbon, are to be encouraged, as are opportunities for better management of existing trees and hedges, alongside the strategic planting of trees on Welsh livestock farms. Potential measures to enhance sequestration levels include:

- *Leaving hedges to grow taller and wider* could offer a simple and cost-neutral way to increase sequestration rates on farm, as well as delivering enhanced shelter for both livestock and wildlife
- *Establishing additional hedges and trees in suitable locations*, e.g. along fence lines, on unproductive land could make important contributions in reducing whole farm footprints once trees reach the phase where sequestration rates are high. As well as sequestering carbon above-ground and in soil, trees and hedges planted appropriately can also improve the efficiency of production by reducing losses and energy losses through improving shelter provision
- Tillage prior to re-seeding is likely to give rise to carbon losses from soils, as some of the accumulated carbon will be lost as it is respired by soil bacteria. From a carbon perspective, it is better to *reduce the frequency of re-seeding* (and the primary focus should be on managing older leys well, so that they remain productive and reduce the need to re-seed). However, the rate of sequestration is likely to be increased following re-seeding due to higher yield from a new ley, thus recovering some of the carbon lost, until the soil again reaches equilibrium. In the event of re-seeding, minimum tillage approaches such as direct drilling or scarification of seeds is preferred to reduce soil losses of carbon and the risk of soil erosion
- *Incorporation of multi-species swards* on-farm that typically have a deeper-rooting growth structure than ryegrass-only swards. Such deep-rooting species can deliver 'deep sequestration' of carbon in soils, given that soil carbon is concentrated in the plant root zone (Thorup-Kristensen et al., 2020)
- *Permanent pastures generally also have deeper-rooting systems* than annual crops as plant species grow a larger rooting network over time, thus will accumulate deeper layers of carbon sequestration in soils (Thorup-Kristensen et al., 2020)

- *Implementing a precise rotational grazing system* that is carefully managed. Compared to set-stocked systems, rotational systems allow 'rest' periods for grass to recover post-grazing, which can enhance overall grass yields if grazing occurs at the optimal grass growth stage (Dawson and Smith, 2007). In turn, this should also increase root growth and therefore carbon inputs to soil. However, further research is greatly needed to validate this, as the scientific evidence currently does not exist. It is also important to note that where ground conditions are not suitable, rotational grazing can lead to soil compaction and run-off, which would ultimately negatively affect soil sequestration levels. Further, where such systems lead to an increase in livestock numbers, there is a need to consider how the resulting greater emissions of CH_4 may outweigh any positive effects associated with increased soil carbon storage. Whilst this may reduce the emissions intensity of their products, it clearly has the opposite effect in terms of total farm emissions, which would not help Welsh agriculture reach its ambition of being net zero emissions.

Conclusions and recommendations

Estimating the net emissions associated with the production of lamb and beef on Welsh farms through carbon footprinting is a valuable exercise to help farmers consider how their management impacts their farm's carbon balance. As well as potentially reducing the costs of production, farmers that are able to demonstrate their environmental credentials may be better placed to market their produce more positively to consumers in the future. It should also be noted that future private and public funding schemes may reward good practise. There has never been a greater need to improve our understanding of how farm GHG emissions can be reduced and/or off-set through sequestration.

The results of your carbon audit presented here are an estimation based on the data that you provided. To reiterate, the findings of this audit is expressed as GHG emission per unit of DW product (kg CO_2e/kg of lamb or beef DW), and is not the farm's total emissions. Your lamb enterprise resulted in net emissions (kg CO_2e emissions minus sequestration) of 14.0 kg CO_2e/kg of DW lamb. In terms of your beef enterprise, the net emissions (kg CO_2e emissions minus sequestration) was 23.6 kgCO_2e/kg of DW beef.

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In terms of efficiency measures, a well-managed flock or herd will optimise livestock growth rates, reducing their days on farm and the associated GHG emissions. This also necessitates fewer inputs such as feed, and reduces mortalities. Livestock growth rates are a function of many products – the genetic merit of animals, their diet, animal health, and the influence of variables such as the weather, to name a few. Strategies that optimise these would make both economic and environmental sense for Welsh farms.

In terms of sequestration levels, strategically increasing woodland cover on Welsh farms is to be encouraged as it can offer many environmental benefits over and above carbon sequestration, and in many cases, benefits to the economic viability of farm businesses, particularly where farmers can capitalise on schemes to pay for establishment and/or management costs. Ultimately, trees will likely play an important part in helping the Welsh livestock sector move towards net zero GHG emissions. Measures that retain carbon in soil should be implemented, and further research to prove how to enhance sequestration in soils under grassland systems would be very worthwhile. Nevertheless, it is also important to remember that enhanced sequestration should not substitute overall emission reduction, which should be the primary aim to achieving a net zero livestock sector in Wales.

Farm 3

Your carbon footprint

Carbon footprints are presented as 'carbon dioxide equivalents', or CO_2e, which is all of the measured GHGs converted to and expressed as a single GHG equivalent, based on their Global Warming Potential (GWP) values used internationally by the Intergovernmental Panel on Climate Change (IPCC). The GHGs that are included in your footprint, and are converted to CO_2e, are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The gases with the most impact are CH_4, which is largely produced by livestock and released into the atmosphere via enteric fermentation, and N_2O, which occurs mainly from soil, following applications of nitrogen fertiliser and livestock manures, as well as urine and dung deposition by grazing livestock (included in the "Soil Nitrous Oxide – Manure" section of your footprint). Storage of manure also releases both gases manure. These two gases are very potent in terms of their GWP, with the tool employing GWP factors of 25 and 298 for CH_4 and N_2O, respectively (IPCC, 2006). This equates to CH_4 having a GWP that is 25 greater than CO_2, and N_2O having a GWP that is 298 times greater than CO_2, over a 100-year period. Some scientists argue that this artificially inflates the contribution of CH_4 to climate change as the CH_4 breaks down after 12-20 years; however, as explained earlier, we have used the internationally-recognised GWP of 25 for CH_4, to comply with the methods employed by the IPCC. Using recognised methods is important to ensure credibility of results.

As your farm produced more than one output (lamb and beef), emissions from the farm enterprise were allocated between different outputs on an economic basis, as the percentage of total farm income earned from the relevant output. Such use of economic allocation allows common burdens (e.g., from the manufacture and use of fertiliser on mixed farms) to be "shared" on individual farms between lamb and beef deadweight outputs (BSI, 2011). For instance, where you apply fertiliser on land grazed by both cattle and sheep, if 60% of your farm income is from cattle, then 60% of the emissions caused by that fertiliser would be allocated to cattle, and 40% to lamb. Similarly, sequestration values have been "shared" between different enterprises based on economic allocation. It is important to reiterate that the results presented here are based on data provided to us. The accuracy of the results is therefore dependent on the accuracy of the data you provided.

Your lamb carbon footprint

In Figure 1, we present the total CO_2e output per kg of <u>lamb</u> product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 19.3 kg CO_2e/kg of DW lamb (i.e., for every kg of DW of lamb you produced, this resulted in the emissions of 19.3 kg of CO_2e). This was similar to the average of 19.4 kg CO_2e/kg of DW lamb for sheep farms in this project. Your sequestration levels were also average at 5.8 kg CO_2e/kg of DW lamb (where the average was 5.5 kg CO_2e/kg of DW lamb).

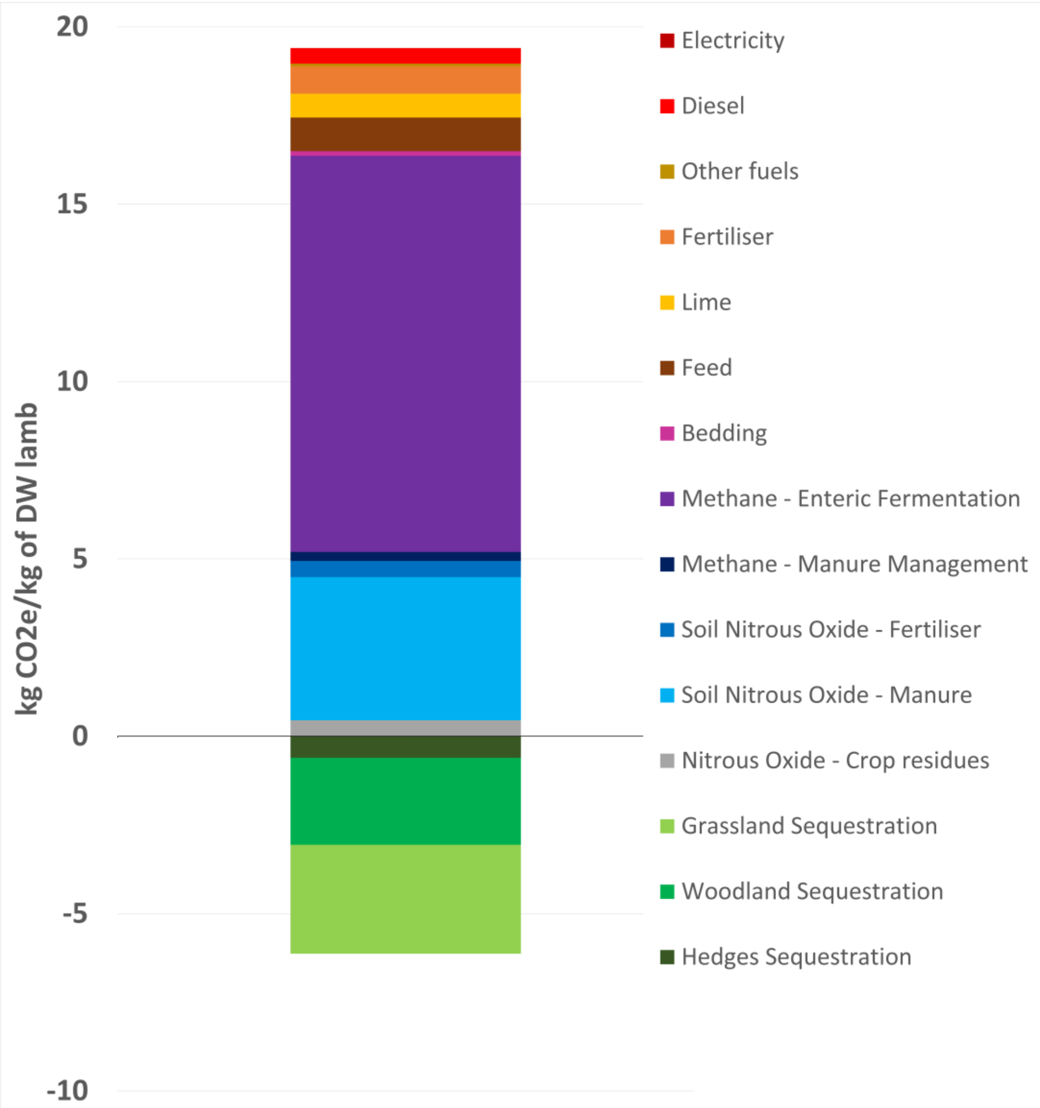


Figure 1: Your lamb carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW lamb.

Both the GHG emissions produced for your lamb footprint and the sequestration occurring on-farm **resulted in net emissions (kg CO_2e emissions minus sequestration) of 13.4 kg CO_2e/kg of DW lamb**. This is displayed as the bar in red in Figure 2, along with the values for all farms.

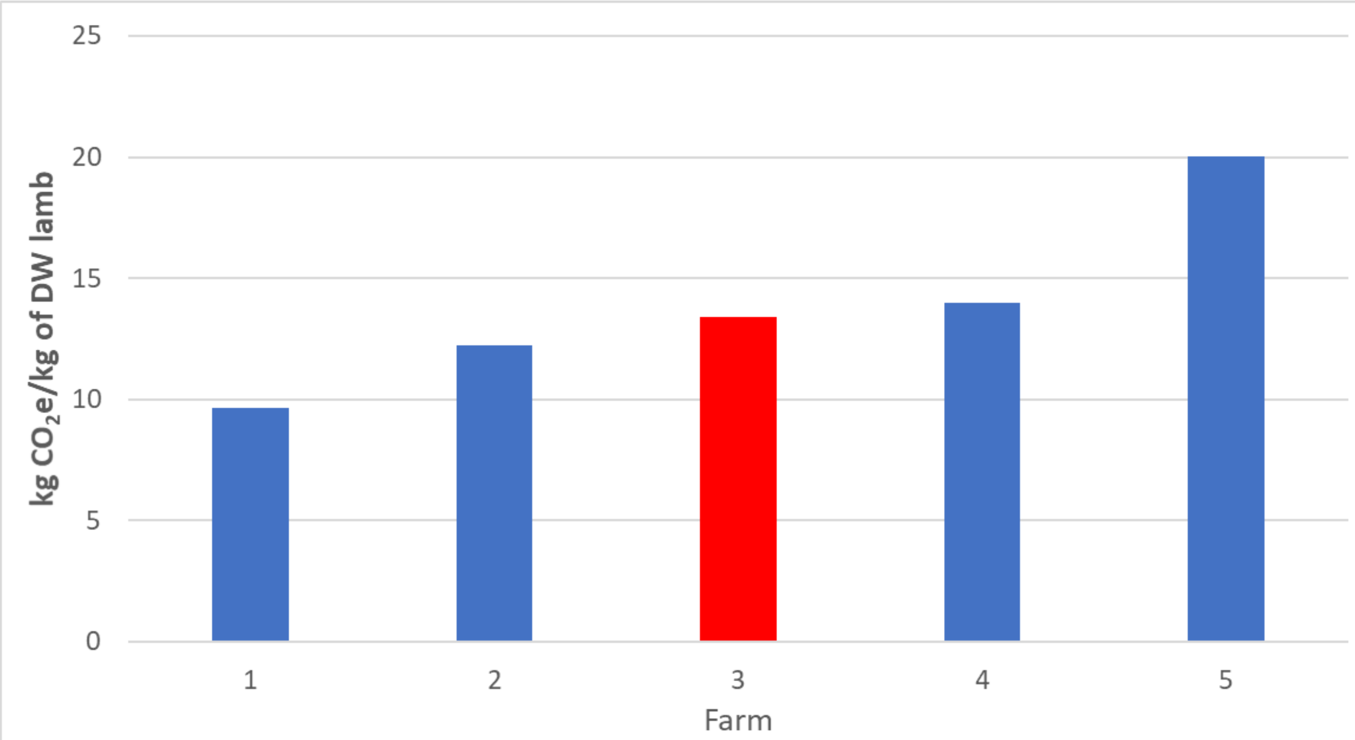


Figure 2: Lamb net emissions in kg CO_2e/ kg of DW lamb of the five sheep farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Your beef carbon footprint

In Figure 3, we present the total CO_2e output per kg of <u>beef</u> product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 19.4 kg CO_2e/kg of DW beef, and below the average of 28.4 kg CO_2e/kg of DW beef for beef farms in this project. Your sequestration levels were below the average for all farms, at 6.1 kg CO_2e/kg of DW beef (where the average was 8.0 kg CO_2e/kg of DW beef).

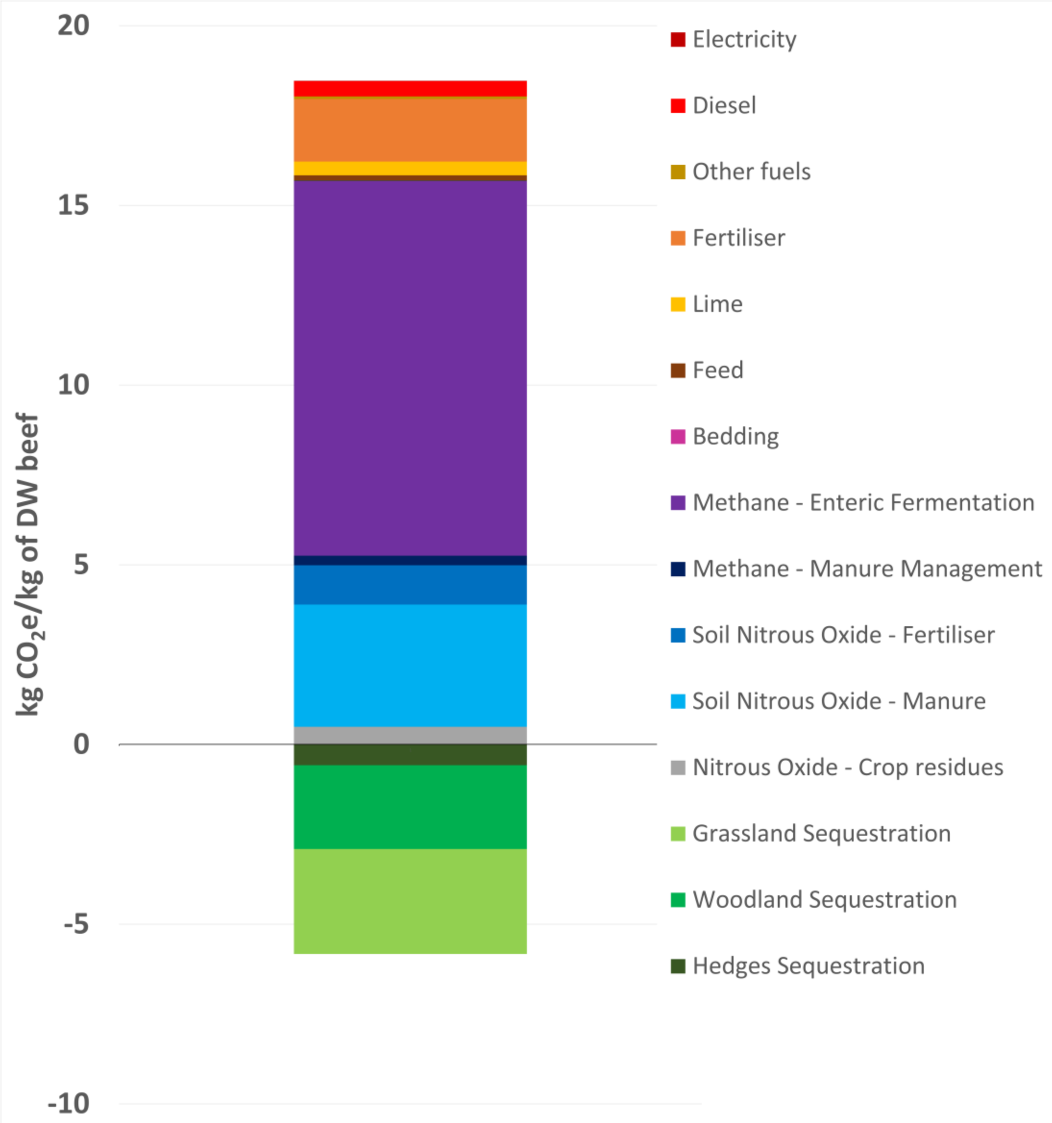


Figure 3: Your beef carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW beef.

In terms of your beef enterprise, **the net emissions (kg CO_2e emissions minus sequestration) was 13.3 kg CO_2e/kg of DW beef**. This is displayed as the bar in red in Figure 4, along with the values for all of farms.

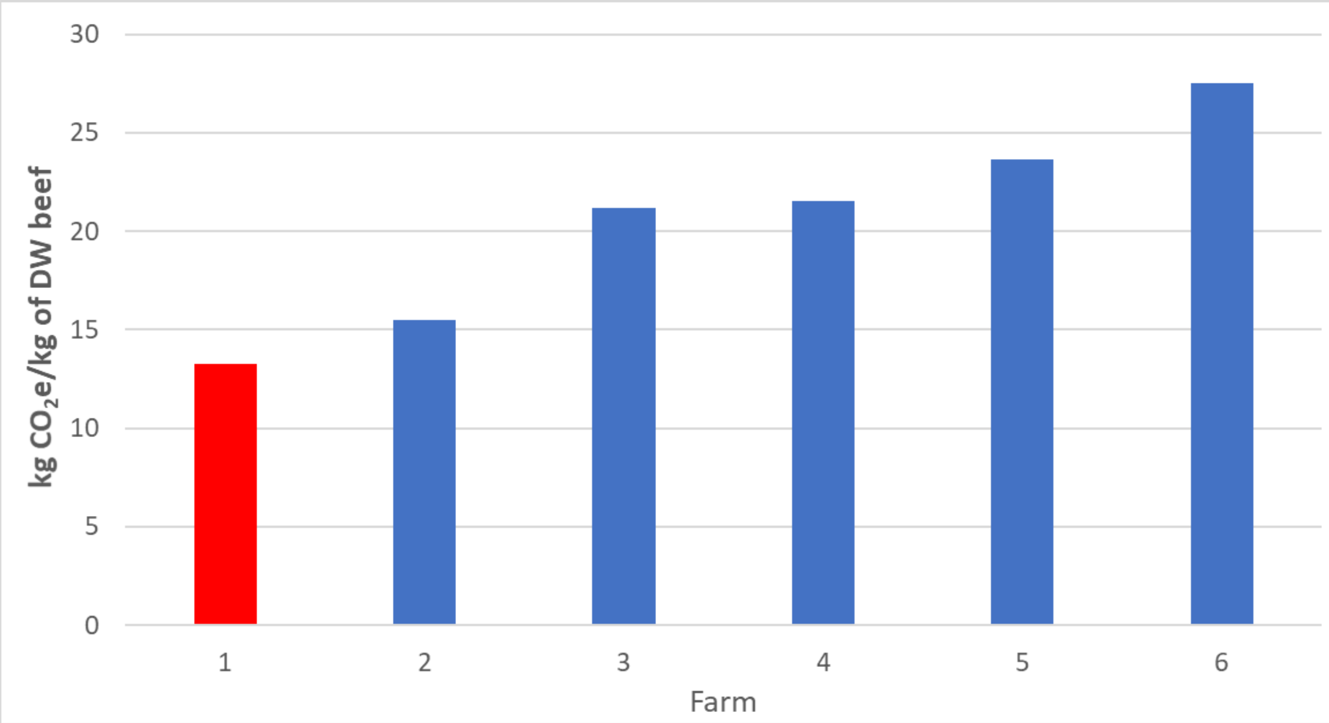


Figure 4: Beef net emissions in kg CO_2e/ kg of DW beef of the six beef farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Reducing your product's carbon footprint

Improving efficiency

Measures intended to reduce your product's carbon footprint may also lead to an improvement in livestock performance, and potentially, an increase in the farm's profitability. Some of the measures may be farm-specific, and may not be as effective or applicable to your farm as others. An example of this could be the cost, effort and impracticality associated with cultivating and reseeding hill pasture as opposed to lowland, where the economic and environmental costs may be greater than the potential returns. Due to this, prioritisation should be given to those measures deemed both effective and practical for your farm. Potential measures for improving efficiency are as follows:

- One of the most effective strategies are related to *optimising the diet of animals*, which can potentially reduce concentrate feed requirements, lower feed costs, and increase growth rates, meaning days to finishing are reduced (therefore less CH_4 is emitted over the lifetime of the animal)
- *Genetic improvement* will aid to reduce days to slaughter and improve growth rates, resulting in less emissions associated during the animal's lifetime. This measure may also lead to increased DW produced without an increase in feed requirements

- *Increasing the lamb/calf rearing percentage*, leading to greater kg produced per ewe/cow, and therefore a reduction in the emissions associated with the ewe/cow
- *Reducing the calving interval* in suckler cow systems. An extended calving interval means that the GHG burden of unproductive adult cows has to be borne by other animals. Given the high body mass of adult cows, they can account for a significant proportion of emissions associated with feed use and enteric fermentation. A protracted calving period may also lead to further inefficiencies at later stages of production, such as issues around optimal feeding for animals at different growth stages
- *Lambing as ewe lambs* where practical and feasible as well as *reducing heifer age when first put in calf*, leading to greater output (kg produced) at a younger age (otherwise 'unproductive'), and therefore a reduction in GHGs associated with the ewe lamb/heifer at this period of its life (and consequently, its lifetime)
- *Reducing the burden of disease* (e.g., reducing losses through abortions, lameness, pneumonia) or parasites (e.g. gastrointestinal worms) can have very significant impacts on livestock performance, value, and reduce GHG emissions per kg produced
- *Improving the way that manure/slurry is stored and applied* (e.g., avoiding spreading during winter) can decrease emissions and simultaneously reduce the need for bought-in fertiliser as better use is made of the nutrients within the product
- *Improving grassland management*, thereby reducing the need for bought-in concentrates and improving growth rates
- *Using legumes* (plants that increase nitrogen in soils naturally, such as clover) can provide a valuable source of high quality, home-grown fodder, and reduce the need for bought-in fertiliser
- When re-seeding, *grasses of a high water-soluble carbohydrate* (WSC) concentration ("high-sugar grasses") have been shown to reduce N_2O emissions from pasture systems through reduced excretion of nitrogen in animals feeding on such grasses compared to conventional grass
- *Introduction of a forage crop within a grass rotation or arable crop* can reduce the burden of pests and weeds, thereby saving on the use of herbicides and pesticides and their associated emissions (although the use of these agro-chemicals was deemed too low to be included in this audit).

Enhancing sequestration

Carbon sequestration in both soils and vegetation (trees and hedges) provides a valuable opportunity to off-set GHG emissions produced on-farm. We estimate that sequestration offset roughly 38% of your farm's total footprint. Grassland makes up a significant percentage of the sequestration on your farm. This is to be expected, as a large proportion of your land is managed as grassland. However, sequestration of carbon in woodland was also responsible for offsetting 13% of your farm's footprint.

We estimated your soil's sequestration, based on the current science. There is much discussion about the potential for off-setting livestock-derived GHG emissions through the sequestration of carbon in grassland systems that dominate Wales. However, whether agricultural soils are a carbon sink (sequestering carbon) or source (release carbon) depends on a number of wide-ranging variables, including climate, soil type, land use/management, water availability and, most importantly, the actual organic matter content of the soil (Freibauer et al., 2004). Accurately estimating sequestration, without field sampling to measure actual change in soil carbon, is difficult. Firstly, changes in soil carbon tend to occur slowly (over many years), therefore determining sequestration rates is challenging (whereas in contrast, calculating the GHG emissions associated with farm inputs is comparatively much easier). Secondly, soil carbon (and the potential for sequestration) is very dependent on soil type, with sequestration potential in lighter, mineral soils being many times greater than in organic-rich soils, as the rate of sequestration slows with time (Ostle et al., 2009). The heterogeneous nature of soils in Wales, with many farms with varying areas of more than one soil type, of different bulk densities, adds to this complexity. Thirdly, management of those soils will have a notable impact on the rate of carbon sequestration or loss, and in some cases, though less so in pasture systems, management may be subject to frequent change (differences in cropping cycles, inputs, etc.). Fourthly, even where soil data exists, variation in sampling protocols to measure changes in soil carbon can have very notable impacts on results; for instance, sampling at different depths, and due to within-field variability of soils, etc. (Dawson and Smith, 2007). Collectively, these factors mean that there is therefore a high dependence on assumptions and estimations when predicting the sequestration potential of grassland systems. Such challenges at least partly explain why estimates of the sequestration values of soils on farms notably vary between different carbon assessment tools (Taft et al., 2018), and should always be interpreted with caution. The capacity to make significant further gains in sequestration may be limited in soils under permanent grasslands as many are likely to be at a state of carbon equilibrium (where emissions and sequestration are balanced) (CIEL, 2020). Some advocate that rotational grazing can increase soil carbon; however, currently, there is not enough robust science to determine this. Where a rotational grazing approach is practised, this was not accounted for within this audit, as estimating sequestration rates in soils managed in this way is very difficult without detailed soil sampling, as previously mentioned.

The potential and rate of sequestration in woodland and hedges will vary with factors such as species planted, rotation length of woodland, the frequency of flailing and laying hedges, soil types, and climate (Ostle et al., 2009). However, a recent study concluded that the New Zealand beef and lamb sectors were close to achieving carbon neutrality due to the relatively high woodland cover on such farms (mean of 15%) accounting for considerable sequestration to off-set emissions (Beef and Lamb New Zealand, 2020). This emphasises the important role that trees can play in sequestering carbon on farms. Measures that protect, and indeed enhance soil carbon, are to be encouraged, as are opportunities for better management of existing trees and hedges, alongside the strategic planting of trees on Welsh livestock farms. Potential measures to enhance sequestration levels include:

- *Leaving hedges to grow taller and wider* could offer a simple and cost-neutral way to increase sequestration rates on farm, as well as delivering enhanced shelter for both livestock and wildlife
- *Establishing additional hedges and trees in suitable locations*, e.g. along fence lines, on unproductive land could make important contributions in reducing whole farm footprints once trees reach the phase where sequestration rates are high. As well as sequestering carbon above-ground and in soil, trees and hedges planted appropriately can also improve the efficiency of production by reducing losses and energy losses through improving shelter provision
- Tillage prior to re-seeding is likely to give rise to carbon losses from soils, as some of the accumulated carbon will be lost as it is respired by soil bacteria. From a carbon perspective, it is better to *reduce the frequency of re-seeding* (and the primary focus should be on managing older leys well, so that they remain productive and reduce the need to re-seed). However, the rate of sequestration is likely to be increased following re-seeding due to higher yield from a new ley, thus recovering some of the carbon lost, until the soil again reaches equilibrium. In the event of re-seeding, minimum tillage approaches such as direct drilling or scarification of seeds is preferred to reduce soil losses of carbon and the risk of soil erosion
- *Incorporation of multi-species swards* on-farm that typically have a deeper-rooting growth structure than ryegrass-only swards. Such deep-rooting species can deliver 'deep sequestration' of carbon in soils, given that soil carbon is concentrated in the plant root zone (Thorup-Kristensen et al., 2020)

- *Permanent pastures generally also have deeper-rooting systems* than annual crops as plant species grow a larger rooting network over time, thus will accumulate deeper layers of carbon sequestration in soils (Thorup-Kristensen et al., 2020)
- *Implementing a precise rotational grazing system* that is carefully managed. Compared to set-stocked systems, rotational systems allow 'rest' periods for grass to recover post-grazing, which can enhance overall grass yields if grazing occurs at the optimal grass growth stage (Dawson and Smith, 2007). In turn, this should also increase root growth and therefore carbon inputs to soil. However, further research is greatly needed to validate this, as the scientific evidence currently does not exist. It is also important to note that where ground conditions are not suitable, rotational grazing can lead to soil compaction and run-off, which would ultimately negatively affect soil sequestration levels. Further, where such systems lead to an increase in livestock numbers, there is a need to consider how the resulting greater emissions of CH_4 may outweigh any positive effects associated with increased soil carbon storage. Whilst this may reduce the emissions intensity of <u>their products</u>, it clearly has the opposite effect in terms of <u>total farm</u> emissions, which would not help Welsh agriculture reach its ambition of being net zero emissions.

Conclusions and recommendations

Estimating the net emissions associated with the production of lamb and beef on Welsh farms through carbon footprinting is a valuable exercise to help farmers consider how their management impacts their farm's carbon balance. As well as potentially reducing the costs of production, farmers that are able to demonstrate their environmental credentials may be better placed to market their produce more positively to consumers in the future. It should also be noted that future private and public funding schemes may reward good practise. There has never been a greater need to improve our understanding of how farm GHG emissions can be reduced and/or off-set through sequestration.

The results of your carbon audit presented here are an estimation based on the data that you provided. To reiterate, the findings of this audit is expressed as GHG emission per unit of DW product (kg CO_2e/kg of lamb or beef DW), and is not the farm's total emissions. Your lamb enterprise resulted in net emissions (kg CO_2e emissions minus sequestration) of 13.4 kg CO_2e/kg of DW lamb. In terms of your beef enterprise, the net emissions (kg CO_2e emissions minus sequestration) was 13.3 kgCO_2e/kg of DW beef.

Welsh agriculture has an ambition to be net zero in terms of GHG emissions, meaning it sequesters at least as much carbon as it emits. The net emissions (kg CO_2e emissions minus sequestration) was positive on all farms that participated in the study, i.e., no farm sequestered more carbon than the GHGs their activities emitted. Whilst there were a few exceptions, sequestration generally made only a modest difference to overall net emissions, off-setting equal to 30% of GHG emissions across all production systems. Although our sample size was small in this study, these results indicate that Welsh farms therefore have a considerable challenge to deliver the net zero ambition. There is scope for every farm that participated in this study to implement measures to reduce their product's carbon footprint. **To achieve this, farms will need to both i) reduce emissions, and ii) enhance sequestration.**

In terms of efficiency measures, a well-managed flock or herd will optimise livestock growth rates, reducing their days on farm and the associated GHG emissions. This also necessitates fewer inputs such as feed, and reduces mortalities. Livestock growth rates are a function of many products – the genetic merit of animals, their diet, animal health, and the influence of variables such as the weather, to name a few. Strategies that optimise these would make both economic and environmental sense for Welsh farms.

In terms of sequestration levels, strategically increasing woodland cover on Welsh farms is to be encouraged as it can offer many environmental benefits over and above carbon sequestration, and in many cases, benefits to the economic viability of farm businesses, particularly where farmers can capitalise on schemes to pay for establishment and/or management costs. Ultimately, trees will likely play an important part in helping the Welsh livestock sector move towards net zero GHG emissions. Measures that retain carbon in soil should be implemented, and further research to prove how to enhance sequestration in soils under grassland systems would be very worthwhile. Nevertheless, it is also important to remember that enhanced sequestration should not substitute overall emission reduction, which should be the primary aim to achieving a net zero livestock sector in Wales.

Farm 4

Your carbon footprint

Carbon footprints are presented as 'carbon dioxide equivalents', or CO_2e, which is all of the measured GHGs converted to and expressed as a single GHG equivalent, based on their Global Warming Potential (GWP) values used internationally by the Intergovernmental Panel on Climate Change (IPCC). The GHGs that are included in your footprint, and are converted to CO_2e, are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The gases with the most impact are CH_4, which is largely produced by livestock and released into the atmosphere via enteric fermentation, and N_2O, which occurs mainly from soil, following applications of nitrogen fertiliser and livestock manures, as well as urine and dung deposition by grazing livestock (included in the "Soil Nitrous Oxide – Manure" section of your footprint). Storage of manure also releases both gases manure. These two gases are very potent in terms of their GWP, with the tool employing GWP factors of 25 and 298 for CH_4 and N_2O, respectively (IPCC, 2006). This equates to CH_4 having a GWP that is 25 greater than CO_2, and N_2O having a GWP that is 298 times greater than CO_2, over a 100-year period. Some scientists argue that this artificially inflates the contribution of CH_4 to climate change as the CH_4 breaks down after 12-20 years; however, as explained earlier, we have used the internationally-recognised GWP of 25 for CH_4, to comply with the methods employed by the IPCC. Using recognised methods is important to ensure credibility of results.

As your farm produced more than one output (beef and dairy), emissions from the farm enterprise were allocated between different outputs on an economic basis, as the percentage of total farm income earned from the relevant output. Such use of economic allocation allows common burdens (e.g., from the manufacture and use of fertiliser on mixed farms) to be "shared" on individual farms between lamb and beef deadweight outputs (BSI, 2011). For instance, where you apply fertiliser on land grazed by both beef cattle and dairy cattle, if 60% of your farm income is from beef cattle, then 60% of the emissions caused by that fertiliser would be allocated to beef cattle, and 40% to dairy cattle. Similarly, sequestration values have been "shared" between different enterprises based on economic allocation. It is important to reiterate that the results presented here are based on data provided to us. The accuracy of the results is therefore dependent on the accuracy of the data you provided.

Your beef carbon footprint

In Figure 1, we present the total CO_2e output per kg of <u>beef</u> product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 22.7 kg CO_2e/kg of DW beef (i.e., for every kg of DW of beef you produced, this resulted in the emissions of 22.7 kg of CO_2e), and below the average of 28.4 kg CO_2e/kg of DW beef for beef farms in this project. Your sequestration levels were lower than the average at 1.2 kg CO_2e/kg of DW beef (where the average was 8.0 kg CO_2e/kg of DW beef).

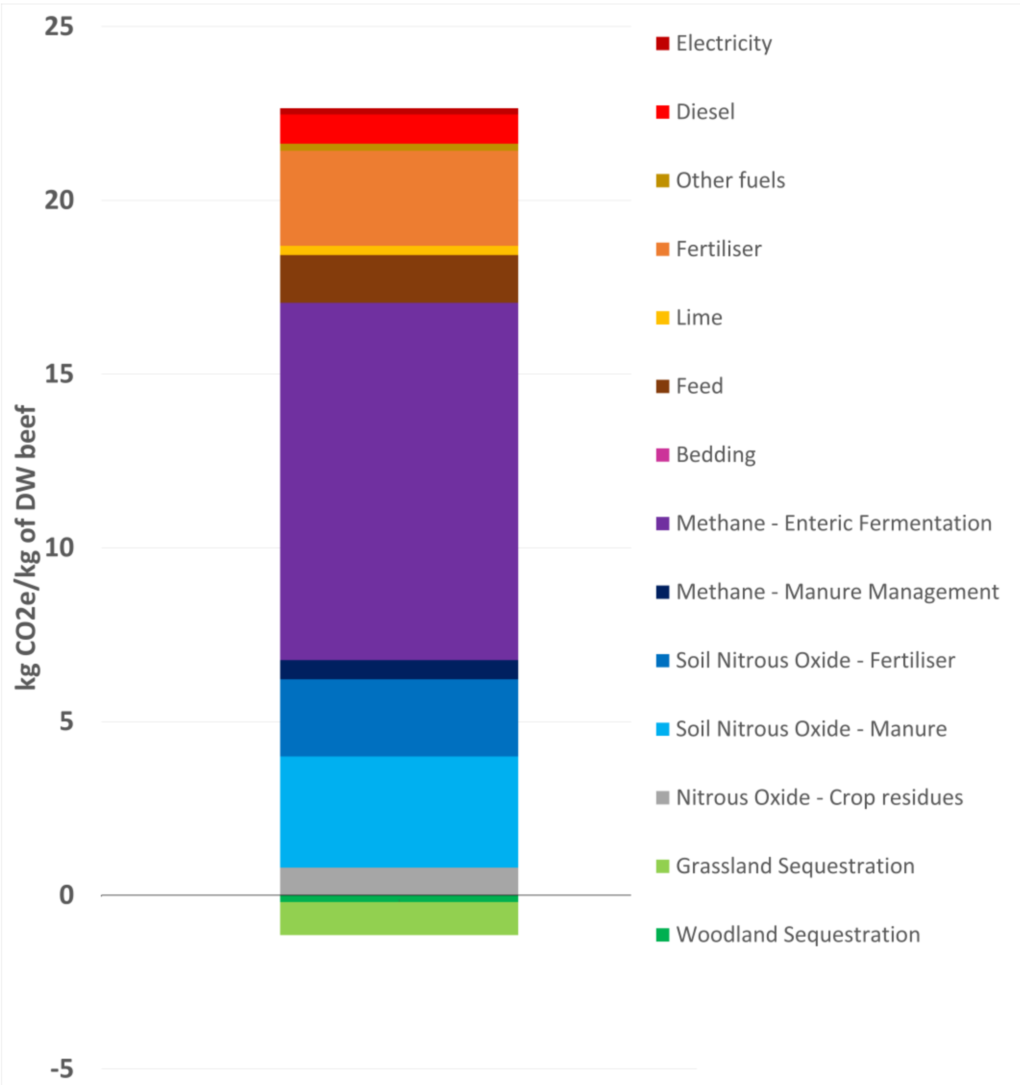


Figure 1: Your beef carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW beef.

In terms of your beef enterprise, **the net emissions (kg CO_2e emissions minus sequestration) was 21.6 kg CO_2e/kg of DW beef**. This is displayed as the bar in red in Figure 2, along with the values for all of farms.

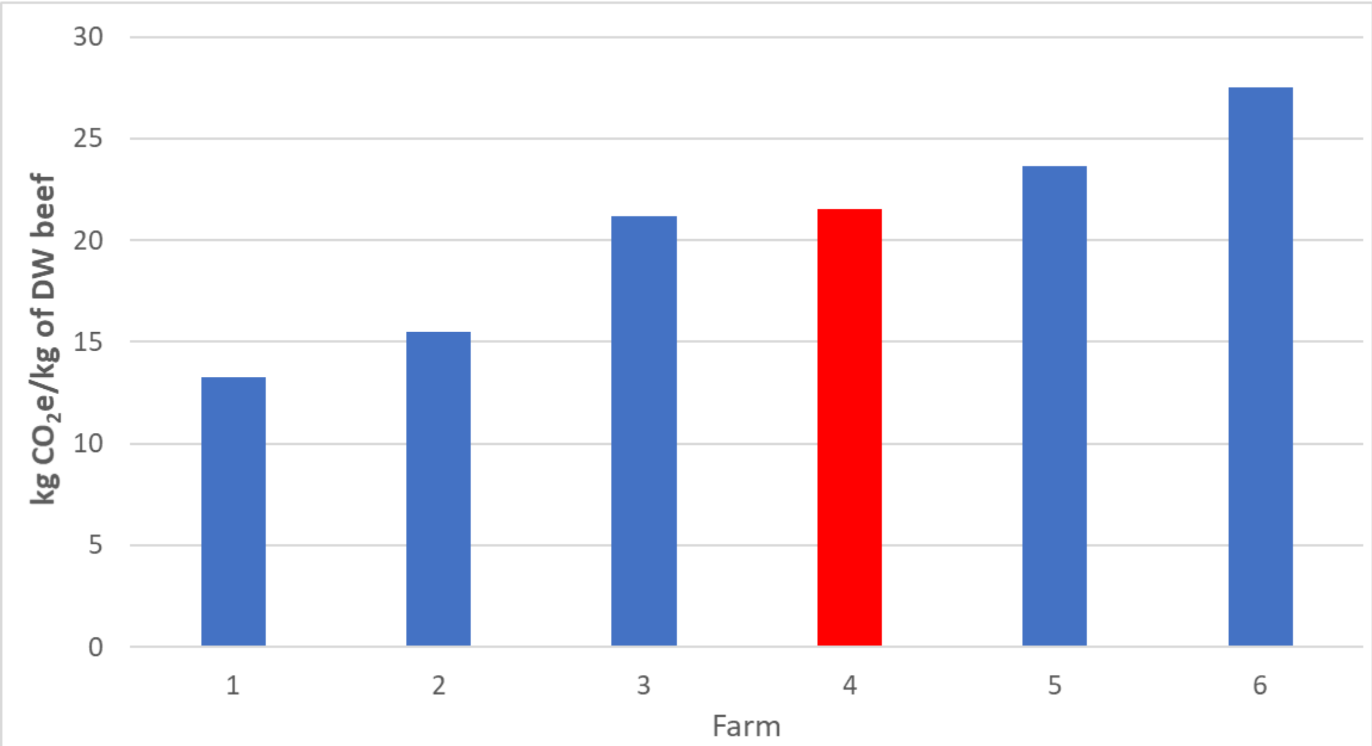


Figure 2: Beef net emissions in kg CO_2e/ kg of DW beef of the six beef farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Your dairy footprint

In Figure 3, we present the total CO_2e output per kg of dairy product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 1.0 kg CO_2e/kg FPC milk which is just below the national average of 1.3 kg CO_2e/kg FPC milk from all dairy farms audited using AgRE Calc (Farm Management Handbook, 2021). Your sequestration levels were roughly 0.1 kg CO_2e/kg FPC milk.

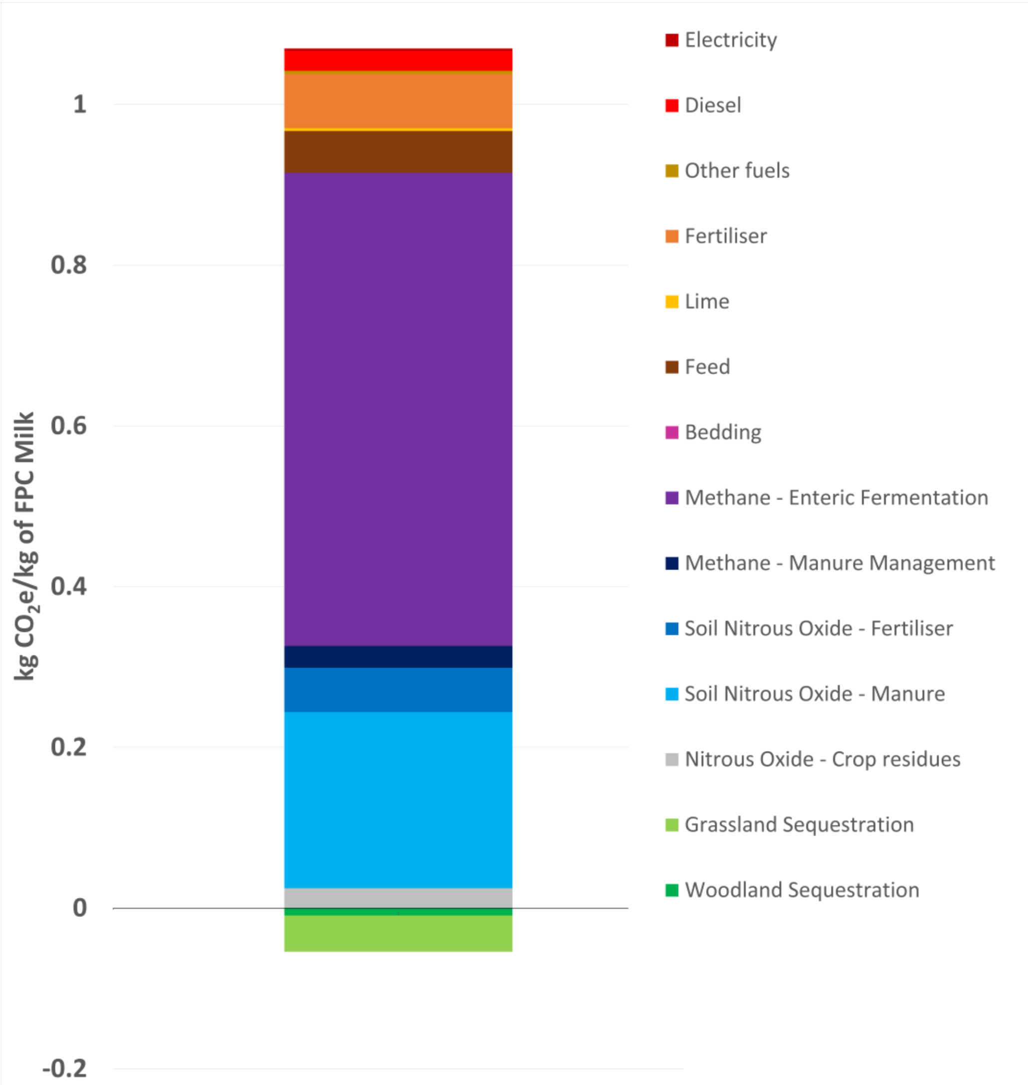


Figure 3: Your dairy carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of FPC milk and negative values demonstrating farm sequestration/kg of FPC milk.

Both the GHG emissions produced for your milk footprint and the sequestration occurring on-farm **resulted in net emissions (kg CO_2e emissions minus sequestration) of 0.9 kg CO_2e/kg FPC milk.**

Reducing your product's carbon footprint

Improving efficiency

Measures intended to reduce your product's carbon footprint may also lead to an improvement in livestock performance, and potentially, an increase in the farm's profitability. Some of the measures may be farm-specific, and may not be as effective or applicable to your farm as others. An example of this could be the cost, effort and impracticality associated with cultivating and reseeding hill pasture as opposed to lowland, where the economic and environmental costs may be greater than the potential returns. Due to this, prioritisation should be given to those measures deemed both effective and practical for your farm. Potential measures for improving efficiency are as follows:

- One of the most effective strategies are related to *optimising the diet of animals*, which can potentially reduce concentrate feed requirements, lower feed costs, and increase growth rates, meaning days to finishing are reduced (therefore less CH_4 is emitted over the lifetime of the animal)
- *Genetic improvement* could aid to reduce days to slaughter and improve growth rates, resulting in less emissions associated during the animal's lifetime. This measure may also lead to increased DW or milkproduced without an increase in feed requirements
- *Increasing the calf rearing percentage*, leading to greater kg produced per cow, and therefore a reduction in the emissions associated with the cow
- *Reducing the calving interval* of cows. An extended calving interval means that the GHG burden of unproductive adult cows has to be borne by other animals. Given the high body mass of adult cows, they can account for a significant proportion of emissions associated with feed use and enteric fermentation. A protracted calving period may also lead to further inefficiencies at later stages of production, such as issues around optimal feeding for animals at different growth stages
- *Reducing heifer age when first put in calf*, leading to greater output (kg produced) at a younger age (otherwise 'unproductive'), and therefore a reduction in GHGs associated with the heifer at this period of its life (and consequently, its lifetime)
- *Reducing the burden of disease* (e.g., reducing losses through abortions, lameness, pneumonia) or parasites (e.g. gastrointestinal worms) can have very significant impacts on livestock performance, value, and reduce GHG emissions per kg produced
- *Improving the way that manure/slurry is stored and applied* (e.g., avoiding spreading during winter) can decrease emissions and simultaneously reduce the need for bought-in fertiliser as better use is made of the nutrients within the product

- *Improving grassland management*, thereby reducing the need for bought-in concentrates and improving growth rates
- *Using legumes* (plants that increase nitrogen in soils naturally, such as clover) can provide a valuable source of high quality, home-grown fodder, and reduce the need for bought-in fertiliser
- When re-seeding, *grasses of a high water-soluble carbohydrate* (WSC) concentration ("high-sugar grasses") have been shown to reduce N_2O emissions from pasture systems through reduced excretion of nitrogen in animals feeding on such grasses compared to conventional grass
- *Introduction of a forage crop within a grass rotation or arable crop* can reduce the burden of pests and weeds, thereby saving on the use of herbicides and pesticides and their associated emissions (although the use of these agro-chemicals was deemed too low to be included in this audit).

Enhancing sequestration

Carbon sequestration in both soils and vegetation (trees and hedges) provides a valuable opportunity to off-set GHG emissions produced on-farm. We estimate that sequestration offset roughly 5% of your farm's total footprint. Grassland makes up a significant percentage of the sequestration on your farm. This is to be expected, as a large proportion of your land is managed as grassland.

We estimate your soil's sequestration, based on the current science. There is much discussion about the potential for off-setting livestock-derived GHG emissions through the sequestration of carbon in grassland systems that dominate Wales. However, whether agricultural soils are a carbon sink (sequestering carbon) or source (release carbon) depends on a number of wide-ranging variables, including climate, soil type, land use/management, water availability and, most importantly, the actual organic matter content of the soil (Freibauer et al., 2004). Accurately estimating sequestration, without field sampling to measure actual change in soil carbon, is difficult. Firstly, changes in soil carbon tend to occur slowly (over many years), therefore determining sequestration rates is challenging (whereas in contrast, calculating the GHG emissions associated with farm inputs is comparatively much easier). Secondly, soil carbon (and the potential for sequestration) is very dependent on soil type, with sequestration potential in lighter, mineral soils being many times greater than in organic-rich soils, as the rate of sequestration slows with time (Ostle et al., 2009). The heterogeneous nature of soils in Wales, with many farms with varying areas of more than one soil type, of different bulk densities, adds to this complexity. Thirdly, management of those soils will have a notable impact on the rate of carbon sequestration or loss, and in some cases, though less so in pasture systems, management may be subject to frequent change (differences in cropping cycles, inputs, etc.). Fourthly, even where soil data exists, variation in sampling protocols to measure changes in soil carbon can have very notable impacts on results; for instance, sampling at different depths, and due to within-field variability of soils, etc. (Dawson and Smith, 2007). Collectively, these factors mean that there is therefore a high dependence on assumptions and estimations when predicting the sequestration potential of grassland systems. Such challenges at least partly explain why estimates of the sequestration values of soils on farms notably vary between different carbon assessment tools (Taft et al., 2018), and should always be interpreted with caution. The capacity to make significant further gains in sequestration may be limited in soils under permanent grasslands as many are likely to be at a state of carbon equilibrium (where emissions and sequestration are balanced) (CIEL, 2020). Some advocate that rotational grazing can increase soil carbon; however, currently, there is not enough robust science to determine this. Where a rotational grazing approach is practised, this was not accounted for within this audit, as estimating sequestration rates in soils managed in this way is very difficult without detailed soil sampling, as previously mentioned.

The potential and rate of sequestration in woodland and hedges will vary with factors such as species planted, rotation length of woodland, the frequency of flailing and laying hedges, soil types, and climate (Ostle et al., 2009). However, a recent study concluded that the New Zealand beef and lamb sectors were close to achieving carbon neutrality due to the relatively high woodland cover on such farms (mean of 15%) accounting for considerable sequestration to off-set emissions (Beef and Lamb New Zealand, 2020). This emphasises the important role that trees can play in sequestering carbon on farms. Measures that protect, and indeed enhance soil carbon, are to be encouraged, as are opportunities for better management of existing trees and hedges, alongside the strategic planting of trees on Welsh livestock farms. Potential measures to enhance sequestration levels include:

- *Leaving hedges to grow taller and wider* could offer a simple and cost-neutral way to increase sequestration rates on farm, as well as delivering enhanced shelter for both livestock and wildlife
- *Establishing additional hedges and trees in suitable locations*, e.g. along fence lines, on unproductive land could make important contributions in reducing whole farm footprints once trees reach the phase where sequestration rates are high. As well as sequestering carbon above-ground and in soil, trees and hedges planted appropriately can also improve the efficiency of production by reducing losses and energy losses through improving shelter provision

- Tillage prior to re-seeding is likely to give rise to carbon losses from soils, as some of the accumulated carbon will be lost as it is respired by soil bacteris. From a carbon perspective, it is better to *reduce the frequency of re-seeding* (and the primary focus should be on managing older leys well, so that they remain productive and reduce the need to re-seed). However, the rate of sequestration is likely to be increased following re-seeding due to higher yield from a new ley, thus recovering some of the carbon lost, until the soil again reaches equilibrium. In the event of re-seeding, minimum tillage approaches such as direct drilling or scarification of seeds is preferred to reduce soil losses of carbon and the risk of soil erosion
- *Incorporation of multi-species swards* on-farm that typically have a deeper-rooting growth structure than ryegrass-only swards. Such deep-rooting species can deliver 'deep sequestration' of carbon in soils, given that soil carbon is concentrated in the plant root zone (Thorup-Kristensen et al., 2020)
- *Permanent pastures generally also have deeper-rooting systems* than annual crops as plant species grow a larger rooting network over time, thus will accumulate deeper layers of carbon sequestration in soils (Thorup-Kristensen et al., 2020)
- *Implementing a precise rotational grazing system* that is carefully managed. Compared to set-stocked systems, rotational systems allow 'rest' periods for grass to recover post-grazing, which can enhance overall grass yields if grazing occurs at the optimal grass growth stage (Dawson and Smith, 2007). In turn, this should also increase root growth and therefore carbon inputs to soil. However, further research is greatly needed to validate this, as the scientific evidence currently does not exist. It is also important to note that where ground conditions are not suitable, rotational grazing can lead to soil compaction and run-off, which would ultimately negatively affect soil sequestration levels. Further, where such systems lead to an increase in livestock numbers, there is a need to consider how the resulting greater emissions of CH_4 may outweigh any positive effects associated with increased soil carbon storage. Whilst this may reduce the emissions intensity of <u>their products</u>, it clearly has the opposite effect in terms of <u>total farm</u> emissions, which would not help Welsh agriculture reach its ambition of being net zero emissions.

Conclusions and recommendations

Estimating the net emissions associated with the production of lamb and beef on Welsh farms through carbon footprinting is a valuable exercise to help farmers consider how their management impacts their farm's carbon balance. As well as potentially reducing the costs of production, farmers that are able to demonstrate their environmental credentials may be better placed to market their produce more positively to consumers in the future. It should also be noted that future private and public funding schemes may reward good practise. There has never been a greater need to improve our understanding of how farm GHG emissions can be reduced and/or off-set through sequestration.

The results of your carbon audit presented here are an estimation based on the data that you provided. To reiterate, the findings of this audit is expressed as GHG emission per unit of DW product (kg CO_2e/kg of beef DW) and per unit of milk (kg CO_2e/kg FPC milk), and is not the farm's total emissions. Your beef enterprise resulted in net emissions (kg CO_2e emissions minus sequestration) of 21.6 kg CO_2e/kg of DW beef. In terms of your dairy enterprise, the net emissions (kg CO_2e emissions minus sequestration) were 0.9 kg CO_2e/kg of FPC milk.

Welsh agriculture has an ambition to be net zero in terms of GHG emissions, meaning it sequesters at least as much carbon as it emits. The net emissions (kg CO_2e emissions minus sequestration) was positive on all farms that participated in the study, i.e., no farm sequestered more carbon than the GHGs their activities emitted. Whilst there were a few exceptions, sequestration generally made only a modest difference to overall net emissions, off-setting equal to 30% of GHG emissions across all production systems. Although our sample size was small in this study, these results indicate that Welsh farms therefore have a considerable challenge to deliver the net zero ambition. There is scope for every farm that participated in this study to implement measures to reduce their product's carbon footprint. **To achieve this, farms will need to both i) reduce emissions, and ii) enhance sequestration.**

In terms of efficiency measures, a well-managed flock or herd will optimise livestock growth rates, reducing their days on farm and the associated GHG emissions. This also necessitates fewer inputs such as feed, and reduces mortalities. Livestock growth rates are a function of many products – the genetic merit of animals, their diet, animal health, and the influence of variables such as the weather, to name a few. Strategies that optimise these would make both economic and environmental sense for Welsh farms.

In terms of sequestration levels, strategically increasing woodland cover on Welsh farms is to be encouraged as it can offer many environmental benefits over and above carbon sequestration, and in many cases, benefits to the economic viability of farm businesses, particularly where farmers can capitalise on schemes to pay for establishment and/or management costs. Ultimately, trees will likely play an important part in helping the Welsh livestock sector move towards net zero GHG emissions. Measures that retain carbon in soil should be implemented, and further research to prove how to enhance sequestration in soils under grassland systems would be very worthwhile. Nevertheless, it is also important to remember that enhanced sequestration should not substitute overall emission reduction, which should be the primary aim to achieving a net zero livestock sector in Wales.

Farm 5

Your carbon footprint

Carbon footprints are presented as 'carbon dioxide equivalents', or CO_2e, which is all of the measured GHGs converted to and expressed as a single GHG equivalent, based on their Global Warming Potential (GWP) values used internationally by the Intergovernmental Panel on Climate Change (IPCC). The GHGs that are included in your footprint, and are converted to CO_2e, are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The gases with the most impact are CH_4, which is largely produced by livestock and released into the atmosphere via enteric fermentation, and N_2O, which occurs mainly from soil, following applications of nitrogen fertiliser and livestock manures, as well as urine and dung deposition by grazing livestock (included in the "Soil Nitrous Oxide – Manure" section of your footprint). Storage of manure also releases both gases manure. These two gases are very potent in terms of their GWP, with the tool employing GWP factors of 25 and 298 for CH_4 and N_2O, respectively (IPCC, 2006). This equates to CH_4 having a GWP that is 25 greater than CO_2, and N_2O having a GWP that is 298 times greater than CO_2, over a 100-year period. Some scientists argue that this artificially inflates the contribution of CH_4 to climate change as the CH_4 breaks down after 12-20 years; however, as explained earlier, we have used the internationally-recognised GWP of 25 for CH_4, to comply with the methods employed by the IPCC. Using recognised methods is important to ensure credibility of results.

As your farm produced more than one output (lamb and beef), emissions from the farm enterprise were allocated between different outputs on an economic basis, as the percentage of total farm income earned from the relevant output. Such use of economic allocation allows common burdens (e.g., from the manufacture and use of fertiliser on mixed farms) to be "shared" on individual farms between lamb and beef deadweight outputs (BSI, 2011). For instance, where you apply fertiliser on land grazed by both cattle and sheep, if 60% of your farm income is from cattle, then 60% of the emissions caused by that fertiliser would be allocated to cattle, and 40% to lamb. Similarly, sequestration values have been "shared" between different enterprises based on economic allocation. It is important to reiterate that the results presented here are based on data provided to us. The accuracy of the results is therefore dependent on the accuracy of the data you provided.

Your lamb carbon footprint

In Figure 1, we present the total CO_2e output per kg of lamb product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 24.6 kg CO_2e/kg of DW lamb (i.e., for every kg of DW of lamb you produced, this resulted in the emissions of 24.6 kg of CO_2e). This was above the average of 19.4 kg CO_2e/kg of DW lamb for sheep farms in this project. Your sequestration levels were slightly below average at 4.6 kg CO_2e/kg of DW lamb (where the average was 5.5 kg CO_2e/kg of DW lamb).

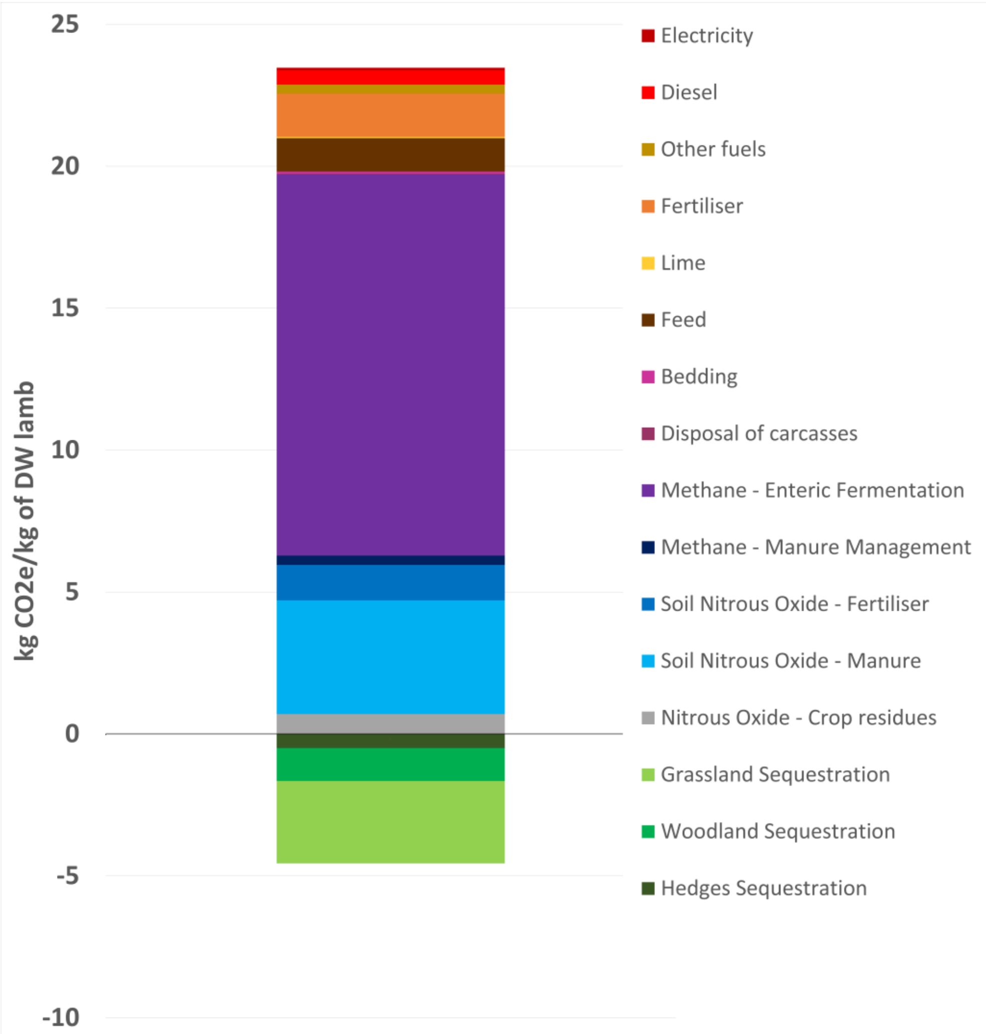


Figure 1: Your lamb carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW lamb.

Both the GHG emissions produced for your lamb footprint and the sequestration occurring on-farm **resulted in net emissions (kg CO_2e emissions minus sequestration) of 20.0 kg CO_2e/kg of DW lamb**. This is displayed as the bar in red in Figure 2, along with the values for all farms.

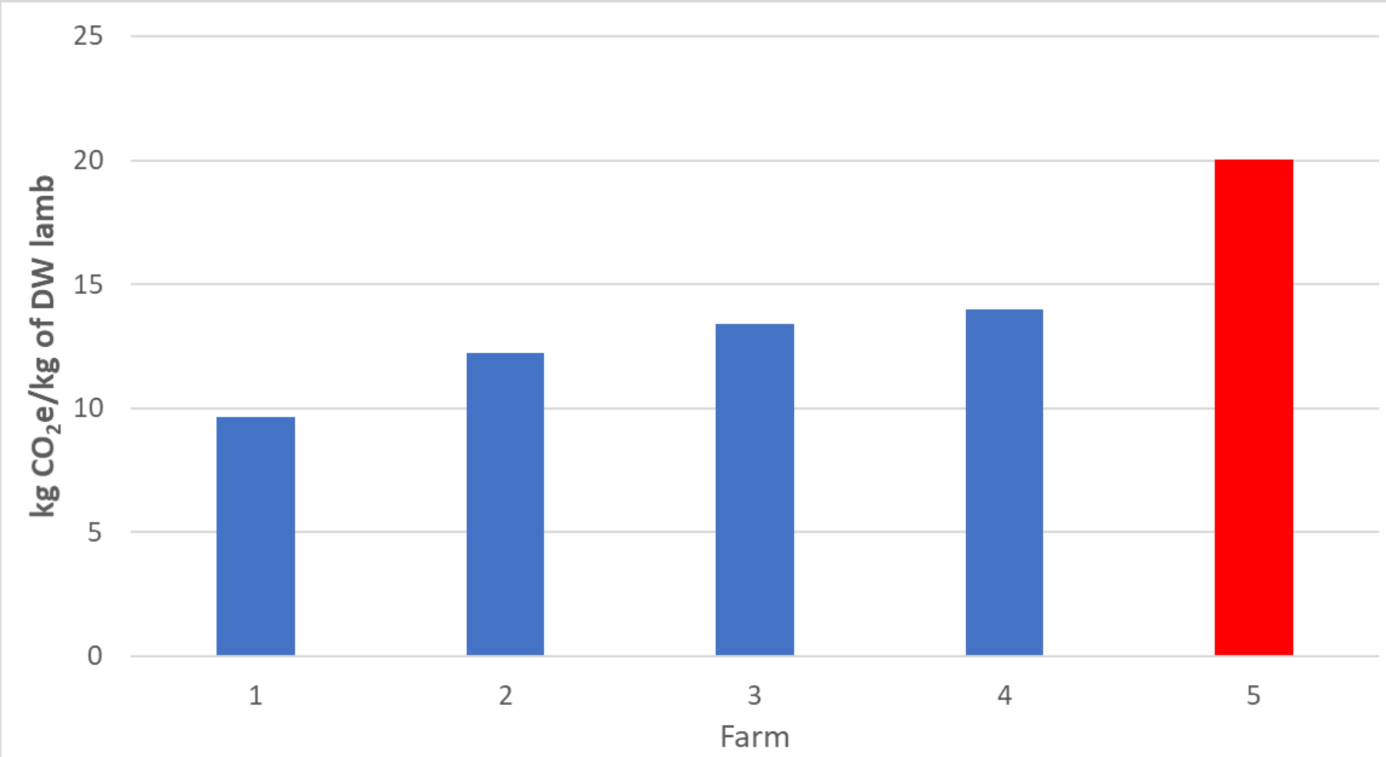


Figure 2: Lamb net emissions in kg CO_2e/ kg of DW lamb of the five sheep farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Your beef carbon footprint

In Figure 3, we present the total CO_2e output per kg of beef product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 26.3 kg CO_2e/kg of DW beef, and just below the average of 28.4 kg CO_2e/kg of DW beef for beef farms in this project. Your sequestration levels were lower than the average for all farms, at 5.1 kg CO_2e/kg of DW beef (where the average was 8.0 kg CO_2e/kg of DW beef).

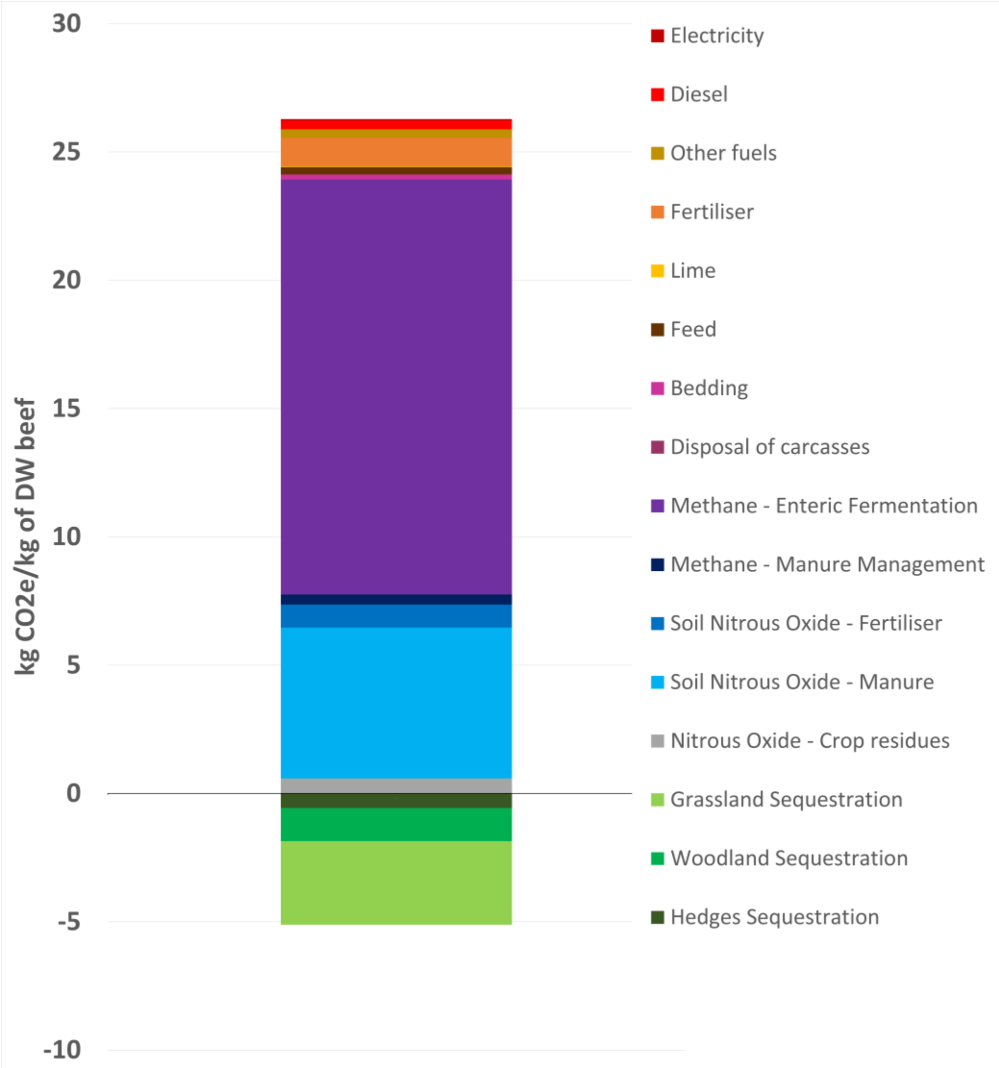


Figure 3: Your beef carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW beef.

In terms of your beef enterprise, **the net emissions (kg CO_2e emissions minus sequestration) was 21.2 kg CO_2e/kg of DW beef**. This is displayed as the bar in red in Figure 4, along with the values for all of farms.

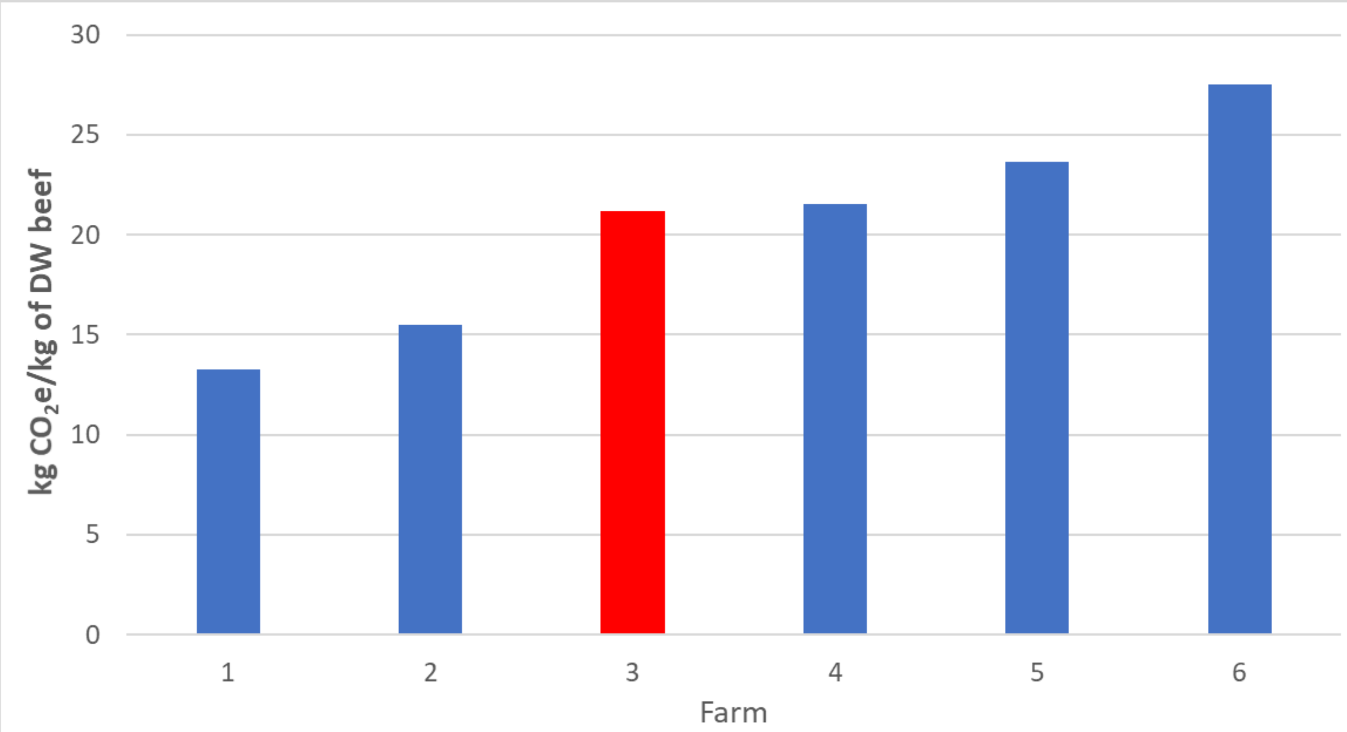


Figure 4: Beef net emissions in kg CO_2e/ kg of DW beef of the six beef farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Reducing your product's carbon footprint

Improving efficiency

Measures intended to reduce your product's carbon footprint may also lead to an improvement in livestock performance, and potentially, an increase in the farm's profitability. Some of the measures may be farm-specific, and may not be as effective or applicable to your farm as others. An example of this could be the cost, effort and impracticality associated with cultivating and reseeding hill pasture as opposed to lowland, where the economic and environmental costs may be greater than the potential returns. Due to this, prioritisation should be given to those measures deemed both effective and practical for your farm. Potential measures for improving efficiency are as follows:

- One of the most effective strategies are related to *optimising the diet of animals*, which can potentially reduce concentrate feed requirements, lower feed costs, and increase growth rates, meaning days to finishing are reduced (therefore less CH_4 is emitted over the lifetime of the animal)
- *Genetic improvement* will aid to reduce days to slaughter and improve growth rates, resulting in less emissions associated during the animal's lifetime. This measure may also lead to increased DW produced without an increase in feed requirements

- *Increasing the lamb/calf rearing percentage*, leading to greater kg produced per ewe/cow, and therefore a reduction in the emissions associated with the ewe/cow
- *Reducing the calving interval* in suckler cow systems. An extended calving interval means that the GHG burden of unproductive adult cows has to be borne by other animals. Given the high body mass of adult cows, they can account for a significant proportion of emissions associated with feed use and enteric fermentation. A protracted calving period may also lead to further inefficiencies at later stages of production, such as issues around optimal feeding for animals at different growth stages
- *Lambing as ewe lambs* where practical and feasible as well as *reducing heifer age when first put in calf*, leading to greater output (kg produced) at a younger age (otherwise 'unproductive'), and therefore a reduction in GHGs associated with the ewe lamb/heifer at this period of its life (and consequently, its lifetime)
- *Reducing the burden of disease* (e.g., reducing losses through abortions, lameness, pneumonia) or parasites (e.g. gastrointestinal worms) can have very significant impacts on livestock performance, value, and reduce GHG emissions per kg produced
- *Improving the way that manure/slurry is stored and applied* (e.g., avoiding spreading during winter) can decrease emissions and simultaneously reduce the need for bought-in fertiliser as better use is made of the nutrients within the product
- *Improving grassland management*, thereby reducing the need for bought-in concentrates and improving growth rates
- *Using legumes* (plants that increase nitrogen in soils naturally, such as clover) can provide a valuable source of high quality, home-grown fodder, and reduce the need for bought-in fertiliser
- When re-seeding, *grasses of a high water-soluble carbohydrate* (WSC) concentration ("high-sugar grasses") have been shown to reduce N_2O emissions from pasture systems through reduced excretion of nitrogen in animals feeding on such grasses compared to conventional grass
- *Introduction of a forage crop within a grass rotation or arable crop* can reduce the burden of pests and weeds, thereby saving on the use of herbicides and pesticides and their associated emissions (although the use of these agro-chemicals was deemed too low to be included in this audit).

Enhancing sequestration

Carbon sequestration in both soils and vegetation (trees and hedges) provides a valuable opportunity to off-set GHG emissions produced on-farm. We estimate that sequestration offset roughly 19% of your farm's total footprint. Grassland makes up a significant percentage of the sequestration on your farm. This is to be expected, as a large proportion of your land is managed as grassland.

We estimated your soil's sequestration, based on the current science. There is much discussion about the potential for off-setting livestock-derived GHG emissions through the sequestration of carbon in grassland systems that dominate Wales. However, whether agricultural soils are a carbon sink (sequestering carbon) or source (release carbon) depends on a number of wide-ranging variables, including climate, soil type, land use/management, water availability and, most importantly, the actual organic matter content of the soil (Freibauer et al., 2004). Accurately estimating sequestration, without field sampling to measure actual change in soil carbon, is difficult. Firstly, changes in soil carbon tend to occur slowly (over many years), therefore determining sequestration rates is challenging (whereas in contrast, calculating the GHG emissions associated with farm inputs is comparatively much easier). Secondly, soil carbon (and the potential for sequestration) is very dependent on soil type, with sequestration potential in lighter, mineral soils being many times greater than in organic-rich soils, as the rate of sequestration slows with time (Ostle et al., 2009). The heterogeneous nature of soils in Wales, with many farms with varying areas of more than one soil type, of different bulk densities, adds to this complexity. Thirdly, management of those soils will have a notable impact on the rate of carbon sequestration or loss, and in some cases, though less so in pasture systems, management may be subject to frequent change (differences in cropping cycles, inputs, etc.). Fourthly, even where soil data exists, variation in sampling protocols to measure changes in soil carbon can have very notable impacts on results; for instance, sampling at different depths, and due to within-field variability of soils, etc. (Dawson and Smith, 2007). Collectively, these factors mean that there is therefore a high dependence on assumptions and estimations when predicting the sequestration potential of grassland systems. Such challenges at least partly explain why estimates of the sequestration values of soils on farms notably vary between different carbon assessment tools (Taft et al., 2018), and should always be interpreted with caution. The capacity to make significant further gains in sequestration may be limited in soils under permanent grasslands as many are likely to be at a state of carbon equilibrium (where emissions and sequestration are balanced) (CIEL, 2020). Some advocate that rotational grazing can increase soil carbon; however, currently, there is not enough robust science to determine this. Where a rotational grazing approach is practised, this was not accounted for within this audit, as estimating sequestration rates in soils managed in this way is very difficult without detailed soil sampling, as previously mentioned.

The potential and rate of sequestration in woodland and hedges will vary with factors such as species planted, rotation length of woodland, the frequency of flailing and laying hedges, soil types, and climate (Ostle et al., 2009). However, a recent study concluded that the New Zealand beef and lamb sectors were close to achieving carbon neutrality due to the relatively high woodland cover on such farms (mean of 15%) accounting for considerable sequestration to off-set emissions (Beef and Lamb New Zealand, 2020). This emphasises the important role that trees can play in sequestering carbon on farms. Measures that protect, and indeed enhance soil carbon, are to be encouraged, as are opportunities for better management of existing trees and hedges, alongside the strategic planting of trees on Welsh livestock farms. Potential measures to enhance sequestration levels include:

- *Leaving hedges to grow taller and wider* could offer a simple and cost-neutral way to increase sequestration rates on farm, as well as delivering enhanced shelter for both livestock and wildlife
- *Establishing additional hedges and trees in suitable locations*, e.g. along fence lines, on unproductive land could make important contributions in reducing whole farm footprints once trees reach the phase where sequestration rates are high. As well as sequestering carbon above-ground and in soil, trees and hedges planted appropriately can also improve the efficiency of production by reducing losses and energy losses through improving shelter provision
- Tillage prior to re-seeding is likely to give rise to carbon losses from soils, as some of the accumulated carbon will be lost as it is respired by soil bacteria. From a carbon perspective, it is better to *reduce the frequency of re-seeding* (and the primary focus should be on managing older leys well, so that they remain productive and reduce the need to re-seed). However, the rate of sequestration is likely to be increased following re-seeding due to higher yield from a new ley, thus recovering some of the carbon lost, until the soil again reaches equilibrium. In the event of re-seeding, minimum tillage approaches such as direct drilling or scarification of seeds is preferred to reduce soil losses of carbon and the risk of soil erosion
- *Incorporation of multi-species swards* on-farm that typically have a deeper-rooting growth structure than ryegrass-only swards. Such deep-rooting species can deliver 'deep sequestration' of carbon in soils, given that soil carbon is concentrated in the plant root zone (Thorup-Kristensen et al., 2020)
- *Permanent pastures generally also have deeper-rooting systems* than annual crops as plant species grow a larger rooting network over time, thus will accumulate deeper layers of carbon sequestration in soils (Thorup-Kristensen et al., 2020)

- *Implementing a precise rotational grazing system* that is carefully managed. Compared to set-stocked systems, rotational systems allow 'rest' periods for grass to recover post-grazing, which can enhance overall grass yields if grazing occurs at the optimal grass growth stage (Dawson and Smith, 2007). In turn, this should also increase root growth and therefore carbon inputs to soil. However, further research is greatly needed to validate this, as the scientific evidence currently does not exist. It is also important to note that where ground conditions are not suitable, rotational grazing can lead to soil compaction and run-off, which would ultimately negatively affect soil sequestration levels. Further, where such systems lead to an increase in livestock numbers, there is a need to consider how the resulting greater emissions of CH_4 may outweigh any positive effects associated with increased soil carbon storage. Whilst this may reduce the emissions intensity of <u>their products</u>, it clearly has the opposite effect in terms of <u>total farm</u> emissions, which would not help Welsh agriculture reach its ambition of being net zero emissions.

<u>**Conclusions and recommendations**</u>

Estimating the net emissions associated with the production of lamb and beef on Welsh farms through carbon footprinting is a valuable exercise to help farmers consider how their management impacts their farm's carbon balance. As well as potentially reducing the costs of production, farmers that are able to demonstrate their environmental credentials may be better placed to market their produce more positively to consumers in the future. It should also be noted that future private and public funding schemes may reward good practise. There has never been a greater need to improve our understanding of how farm GHG emissions can be reduced and/or off-set through sequestration.

The results of your carbon audit presented here are an estimation based on the data that you provided. To reiterate, the findings of this audit is expressed as GHG emission per unit of DW product (kg CO_2e/kg of lamb or beef DW), and is not the farm's total emissions. Your lamb enterprise resulted in net emissions (kg CO_2e emissions minus sequestration) of 20.0 kg CO_2e/kg of DW lamb. In terms of your beef enterprise, the net emissions (kg CO_2e emissions minus sequestration) was 21.2 kgCO_2e/kg of DW beef.

Welsh agriculture has an ambition to be net zero in terms of GHG emissions, meaning it sequesters at least as much carbon as it emits. The net emissions (kg CO_2e emissions minus sequestration) was positive on all farms that participated in the study, i.e., no farm sequestered more carbon than the GHGs their activities emitted. Whilst there were a few exceptions, sequestration generally made only a modest difference to overall net emissions, off-setting equal to 30% of GHG emissions across all production systems. Although our sample size was small in this study, these results indicate that Welsh farms therefore have a considerable challenge to deliver the net zero ambition. There is scope for every farm that participated in this study to implement measures to reduce their product's carbon footprint. **To achieve this, farms will need to both i) reduce emissions, and ii) enhance sequestration.**

In terms of efficiency measures, a well-managed flock or herd will optimise livestock growth rates, reducing their days on farm and the associated GHG emissions. This also necessitates fewer inputs such as feed, and reduces mortalities. Livestock growth rates are a function of many products – the genetic merit of animals, their diet, animal health, and the influence of variables such as the weather, to name a few. Strategies that optimise these would make both economic and environmental sense for Welsh farms.

In terms of sequestration levels, strategically increasing woodland cover on Welsh farms is to be encouraged as it can offer many environmental benefits over and above carbon sequestration, and in many cases, benefits to the economic viability of farm businesses, particularly where farmers can capitalise on schemes to pay for establishment and/or management costs. Ultimately, trees will likely play an important part in helping the Welsh livestock sector move towards net zero GHG emissions. Measures that retain carbon in soil should be implemented, and further research to prove how to enhance sequestration in soils under grassland systems would be very worthwhile. Nevertheless, it is also important to remember that enhanced sequestration should not substitute overall emission reduction, which should be the primary aim to achieving a net zero livestock sector in Wales.

Farm 6

Your lamb carbon footprint

In Figure 1, we present the total CO_2e output per kg of lamb product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 14.7 kg CO_2e/kg of DW lamb (i.e., for every kg of DW of lamb you produced, this resulted in the emissions of 14.7 kg of CO_2e). This was below the average of 19.4 kg CO_2e/kg of DW lamb for sheep farms in this project. Your sequestration levels were 5.0 kg CO_2e/kg of DW lamb (where the average was 5.5 kg CO_2e/kg of DW lamb).

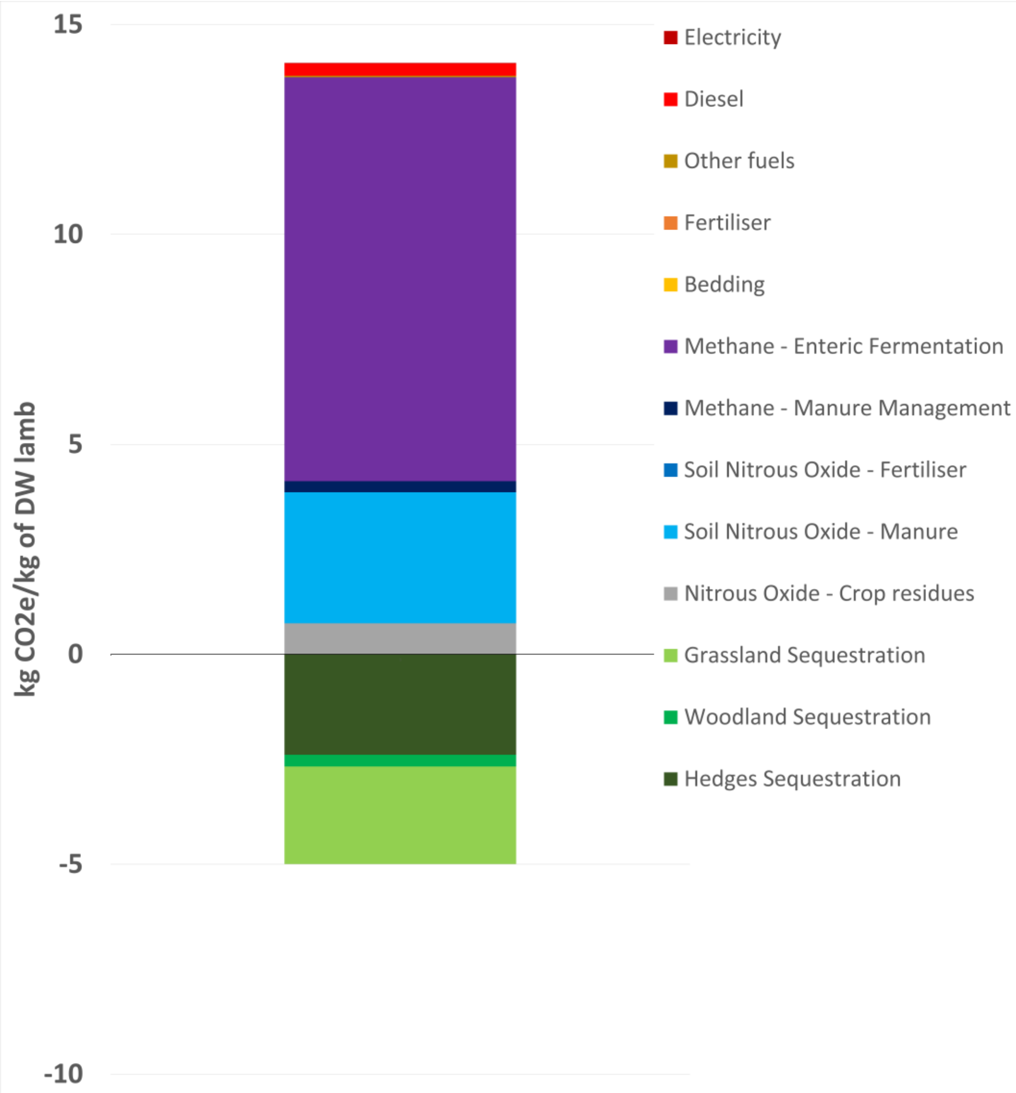


Figure 1: Your lamb carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW lamb.

Both the GHG emissions produced for your lamb footprint and the sequestration occurring on-farm **resulted in net emissions (kg CO_2e emissions minus sequestration) of 9.7 kg CO_2e/kg of DW lamb**. This is displayed as the bar in red in Figure 2, along with the values for all farms.

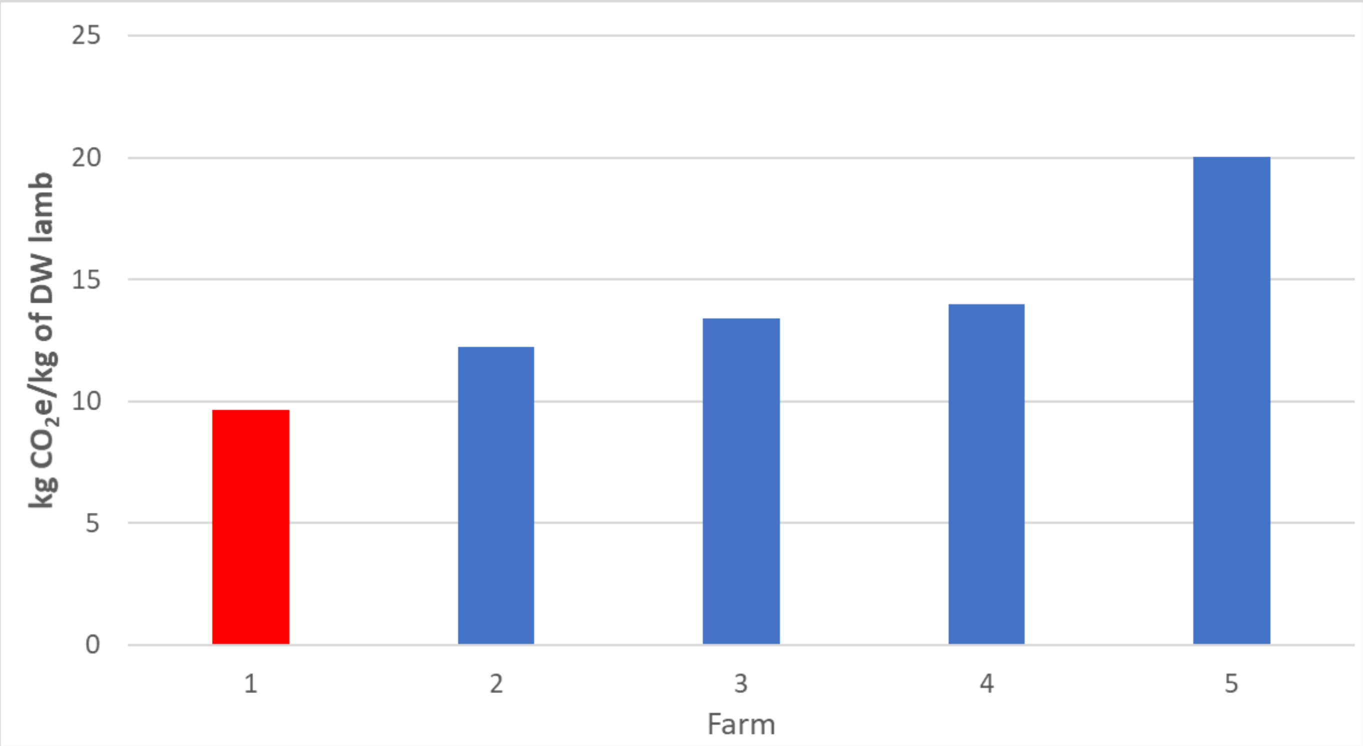


Figure 2: Lamb net emissions of the five sheep farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Your beef carbon footprint

In Figure 3, we present the total CO_2e output per kg of <u>beef</u> product on your farm for a year. A breakdown of the farm's carbon sequestration is also presented. Your total GHG emissions equated to 24.0 kg CO_2e/kg of DW beef, and below the average of 28.4 kg CO_2e/kg of DW beef for beef farms in this project. Your sequestration levels were higher than the average for all farms, at 8.5 kg CO_2e/kg of DW beef (where the average was 8.0 kg CO_2e/kg of DW beef).

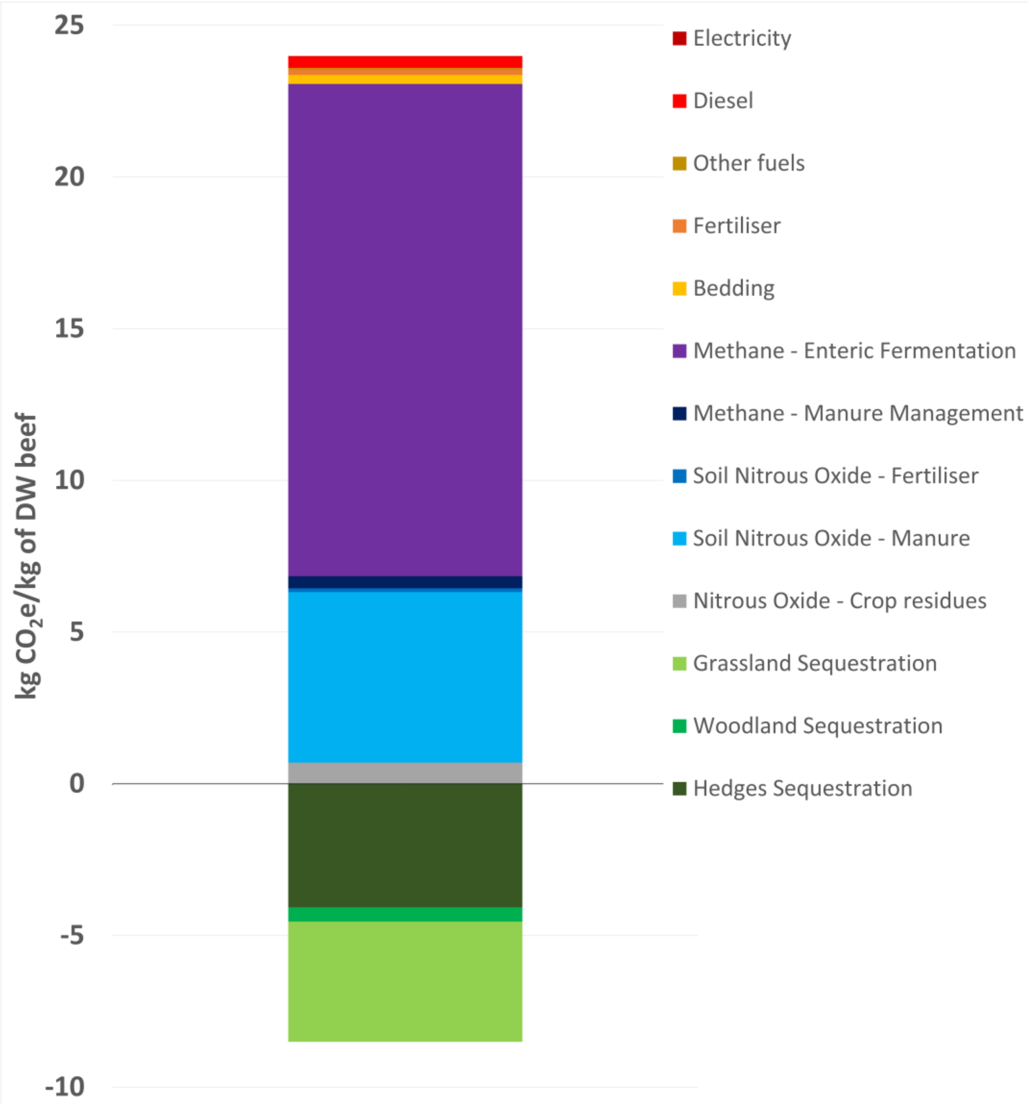


Figure 3: Your beef carbon footprint with positive values demonstrating emissions in kg CO_2e/kg of DW lamb and negative values demonstrating farm sequestration/kg of DW beef.

In terms of your beef enterprise, **the net emissions (kg CO_2e emissions minus sequestration) was 15.5 kg CO_2e/kg of DW beef**. This is displayed as the bar in red in Figure 4, along with the values for all of farms.

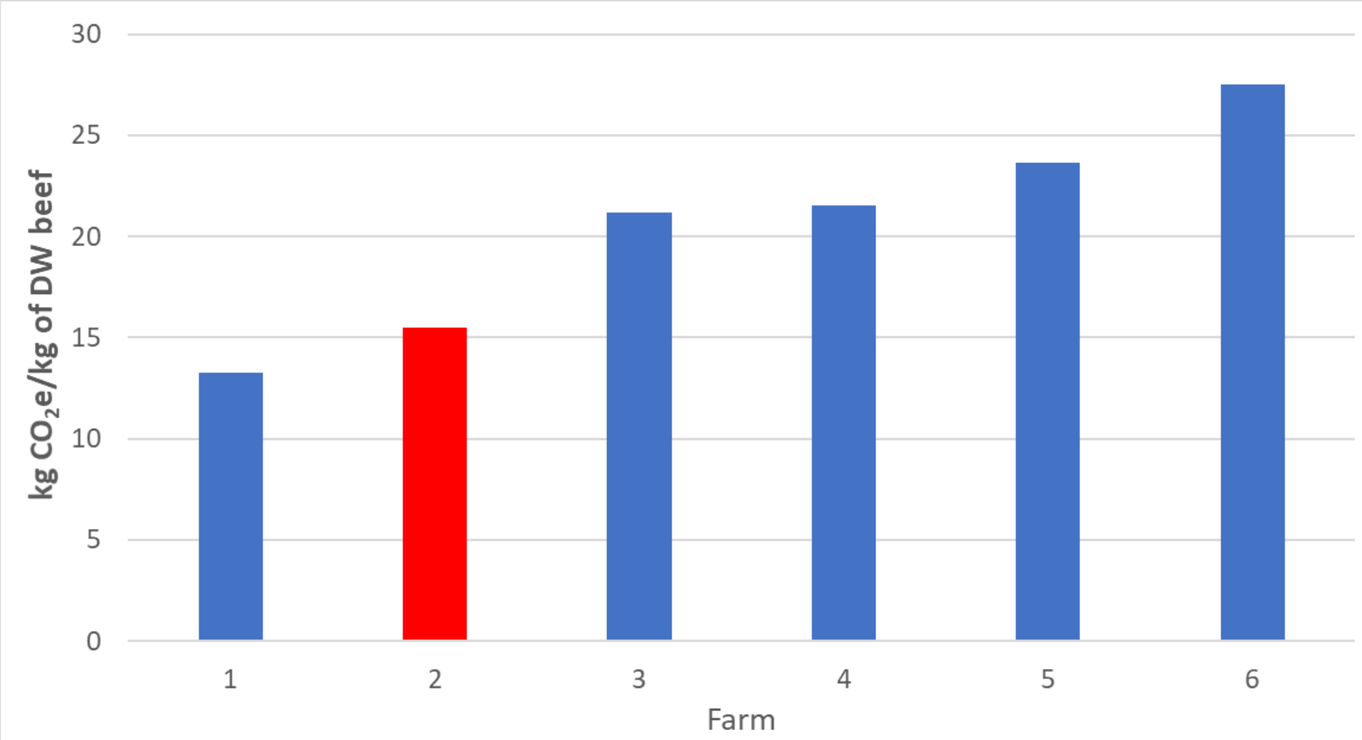


Figure 4: Beef net emissions in kg CO_2e/ kg of DW beef of the six beef farms in chronological order from smallest to greatest. Your farm is highlighted in red.

Reducing your product's carbon footprint

Improving efficiency

Measures intended to reduce your product's carbon footprint may also lead to an improvement in livestock performance, and potentially, an increase in the farm's profitability. Some of the measures may be farm-specific, and may not be as effective or applicable to your farm as others. An example of this could be the cost, effort and impracticality associated with cultivating and reseeding hill pasture as opposed to lowland, where the economic and environmental costs may be greater than the potential returns. Due to this, prioritisation should be given to those measures deemed both effective and practical for your farm. Potential measures for improving efficiency are as follows:

- One of the most effective strategies are related to *optimising the diet of animals*, which can potentially reduce concentrate feed requirements, lower feed costs, and increase growth rates, meaning days to finishing are reduced (therefore less CH_4 is emitted over the lifetime of the animal)
- *Genetic improvement* will aid to reduce days to slaughter and improve growth rates, resulting in less emissions associated during the animal's lifetime. This measure may also lead to increased DW produced without an increase in feed requirements

- *Increasing the lamb/calf rearing percentage*, leading to greater kg produced per ewe/cow, and therefore a reduction in the emissions associated with the ewe/cow
- *Reducing the calving interval* in suckler cow systems. An extended calving interval means that the GHG burden of unproductive adult cows has to be borne by other animals. Given the high body mass of adult cows, they can account for a significant proportion of emissions associated with feed use and enteric fermentation. A protracted calving period may also lead to further inefficiencies at later stages of production, such as issues around optimal feeding for animals at different growth stages
- *Lambing as ewe lambs* where practical and feasible as well as *reducing heifer age when first put in calf*, leading to greater output (kg produced) at a younger age (otherwise 'unproductive'), and therefore a reduction in GHGs associated with the ewe lamb/heifer at this period of its life (and consequently, its lifetime)
- *Reducing the burden of disease* (e.g., reducing losses through abortions, lameness, pneumonia) or parasites (e.g. gastrointestinal worms) can have very significant impacts on livestock performance, value, and reduce GHG emissions per kg produced
- *Improving the way that manure/slurry is stored and applied* (e.g., avoiding spreading during winter) can decrease emissions and simultaneously reduce the need for bought-in fertiliser as better use is made of the nutrients within the product
- *Improving grassland management*, thereby reducing the need for bought-in concentrates and improving growth rates
- *Using legumes* (plants that increase nitrogen in soils naturally, such as clover) can provide a valuable source of high quality, home-grown fodder, and reduce the need for bought-in fertiliser
- When re-seeding, *grasses of a high water-soluble carbohydrate* (WSC) concentration ("high-sugar grasses") have been shown to reduce N_2O emissions from pasture systems through reduced excretion of nitrogen in animals feeding on such grasses compared to conventional grass
- *Introduction of a forage crop within a grass rotation or arable crop* can reduce the burden of pests and weeds, thereby saving on the use of herbicides and pesticides and their associated emissions (although the use of these agro-chemicals was deemed too low to be included in this audit).

Enhancing sequestration

Carbon sequestration in both soils and vegetation (trees and hedges) provides a valuable opportunity to off-set GHG emissions produced on-farm. We estimate that sequestration offset roughly 35% of your farm's total footprint. Grassland makes up a significant percentage of the sequestration on your farm. This is to be expected, as a large proportion of your land is managed as grassland.

We estimated your soil's sequestration, based on the current science. There is much discussion about the potential for off-setting livestock-derived GHG emissions through the sequestration of carbon in grassland systems that dominate Wales. However, whether agricultural soils are a carbon sink (sequestering carbon) or source (release carbon) depends on a number of wide-ranging variables, including climate, soil type, land use/management, water availability and, most importantly, the actual organic matter content of the soil (Freibauer et al., 2004). Accurately estimating sequestration, without field sampling to measure actual change in soil carbon, is difficult. Firstly, changes in soil carbon tend to occur slowly (over many years), therefore determining sequestration rates is challenging (whereas in contrast, calculating the GHG emissions associated with farm inputs is comparatively much easier). Secondly, soil carbon (and the potential for sequestration) is very dependent on soil type, with sequestration potential in lighter, mineral soils being many times greater than in organic-rich soils, as the rate of sequestration slows with time (Ostle et al., 2009). The heterogeneous nature of soils in Wales, with many farms with varying areas of more than one soil type, of different bulk densities, adds to this complexity. Thirdly, management of those soils will have a notable impact on the rate of carbon sequestration or loss, and in some cases, though less so in pasture systems, management may be subject to frequent change (differences in cropping cycles, inputs, etc.). Fourthly, even where soil data exists, variation in sampling protocols to measure changes in soil carbon can have very notable impacts on results; for instance, sampling at different depths, and due to within-field variability of soils, etc. (Dawson and Smith, 2007). Collectively, these factors mean that there is therefore a high dependence on assumptions and estimations when predicting the sequestration potential of grassland systems. Such challenges at least partly explain why estimates of the sequestration values of soils on farms notably vary between different carbon assessment tools (Taft et al., 2018), and should always be interpreted with caution. The capacity to make significant further gains in sequestration may be limited in soils under permanent grasslands as many are likely to be at a state of carbon equilibrium (where emissions and sequestration are balanced) (CIEL, 2020). Some advocate that rotational grazing can increase soil carbon; however, currently, there is not enough robust science to determine this. Where a rotational grazing approach is practised, this was not accounted for within this audit, as estimating sequestration rates in soils managed in this way is very difficult without detailed soil sampling, as previously mentioned.

The potential and rate of sequestration in woodland and hedges will vary with factors such as species planted, rotation length of woodland, the frequency of flailing and laying hedges, soil types, and climate (Ostle et al., 2009). However, a recent study concluded that the New Zealand beef and lamb sectors were close to achieving carbon neutrality due to the relatively high woodland cover on such farms (mean of 15%) accounting for considerable sequestration to off-set emissions (Beef and Lamb New Zealand, 2020). This emphasises the important role that trees can play in sequestering carbon on farms. Measures that protect, and indeed enhance soil carbon, are to be encouraged, as are opportunities for better management of existing trees and hedges, alongside the strategic planting of trees on Welsh livestock farms. Potential measures to enhance sequestration levels include:

- *Leaving hedges to grow taller and wider* could offer a simple and cost-neutral way to increase sequestration rates on farm, as well as delivering enhanced shelter for both livestock and wildlife
- *Establishing additional hedges and trees in suitable locations*, e.g. along fence lines, on unproductive land could make important contributions in reducing whole farm footprints once trees reach the phase where sequestration rates are high. As well as sequestering carbon above-ground and in soil, trees and hedges planted appropriately can also improve the efficiency of production by reducing losses and energy losses through improving shelter provision
- Tillage prior to re-seeding is likely to give rise to carbon losses from soils, as some of the accumulated carbon will be lost as it is respired by soil bacteria. From a carbon perspective, it is better to *reduce the frequency of re-seeding* (and the primary focus should be on managing older leys well, so that they remain productive and reduce the need to re-seed). However, the rate of sequestration is likely to be increased following re-seeding due to higher yield from a new ley, thus recovering some of the carbon lost, until the soil again reaches equilibrium. In the event of re-seeding, minimum tillage approaches such as direct drilling or scarification of seeds is preferred to reduce soil losses of carbon and the risk of soil erosion
- *Incorporation of multi-species swards* on-farm that typically have a deeper-rooting growth structure than ryegrass-only swards. Such deep-rooting species can deliver ‘deep sequestration’ of carbon in soils, given that soil carbon is concentrated in the plant root zone (Thorup-Kristensen et al., 2020)
- *Permanent pastures generally also have deeper-rooting systems* than annual crops as plant species grow a larger rooting network over time, thus will accumulate deeper layers of carbon sequestration in soils (Thorup-Kristensen et al., 2020)

- *Implementing a precise rotational grazing system* that is carefully managed. Compared to set-stocked systems, rotational systems allow 'rest' periods for grass to recover post-grazing, which can enhance overall grass yields if grazing occurs at the optimal grass growth stage (Dawson and Smith, 2007). In turn, this should also increase root growth and therefore carbon inputs to soil. However, further research is greatly needed to validate this, as the scientific evidence currently does not exist. It is also important to note that where ground conditions are not suitable, rotational grazing can lead to soil compaction and run-off, which would ultimately negatively affect soil sequestration levels. Further, where such systems lead to an increase in livestock numbers, there is a need to consider how the resulting greater emissions of CH_4 may outweigh any positive effects associated with increased soil carbon storage. Whilst this may reduce the emissions intensity of <u>their products</u>, it clearly has the opposite effect in terms of <u>total farm</u> emissions, which would not help Welsh agriculture reach its ambition of being net zero emissions.

<u>Conclusions and recommendations</u>

Estimating the net emissions associated with the production of lamb and beef on Welsh farms through carbon footprinting is a valuable exercise to help farmers consider how their management impacts their farm's carbon balance. As well as potentially reducing the costs of production, farmers that are able to demonstrate their environmental credentials may be better placed to market their produce more positively to consumers in the future. It should also be noted that future private and public funding schemes may reward good practise. There has never been a greater need to improve our understanding of how farm GHG emissions can be reduced and/or off-set through sequestration.

The results of your carbon audit presented here are an estimation based on the data that you provided. To reiterate, the findings of this audit is expressed as GHG emission per unit of DW product (kg CO_2e/kg of lamb or beef DW), and is not the farm's total emissions. Your lamb enterprise resulted in net emissions (kg CO_2e emissions minus sequestration) of 9.7 kg CO_2e/kg of DW lamb. In terms of your beef enterprise, the net emissions (kg CO_2e emissions minus sequestration) was 15.5 kgCO_2e/kg of DW beef.

Welsh agriculture has an ambition to be net zero in terms of GHG emissions, meaning it sequesters at least as much carbon as it emits. The net emissions (kg CO_2e emissions minus sequestration) was positive on all farms that participated in the study, i.e., no farm sequestered more carbon than the GHGs their activities emitted. Whilst there were a few exceptions, sequestration generally made only a modest difference to overall net emissions, off-setting equal to 30% of GHG emissions across all production systems. Although our sample size was small in this study, these results indicate that Welsh farms therefore have a considerable challenge to deliver the net zero ambition. There is scope for every farm that participated in this study to implement measures to reduce their product's carbon footprint. **To achieve this, farms will need to both i) reduce emissions, and ii) enhance sequestration.**

In terms of efficiency measures, a well-managed flock or herd will optimise livestock growth rates, reducing their days on farm and the associated GHG emissions. This also necessitates fewer inputs such as feed, and reduces mortalities. Livestock growth rates are a function of many products – the genetic merit of animals, their diet, animal health, and the influence of variables such as the weather, to name a few. Strategies that optimise these would make both economic and environmental sense for Welsh farms.

In terms of sequestration levels, strategically increasing woodland cover on Welsh farms is to be encouraged as it can offer many environmental benefits over and above carbon sequestration, and in many cases, benefits to the economic viability of farm businesses, particularly where farmers can capitalise on schemes to pay for establishment and/or management costs. Ultimately, trees will likely play an important part in helping the Welsh livestock sector move towards net zero GHG emissions. Measures that retain carbon in soil should be implemented, and further research to prove how to enhance sequestration in soils under grassland systems would be very worthwhile. Nevertheless, it is also important to remember that enhanced sequestration should not substitute overall emission reduction, which should be the primary aim to achieving a net zero livestock sector in Wales.

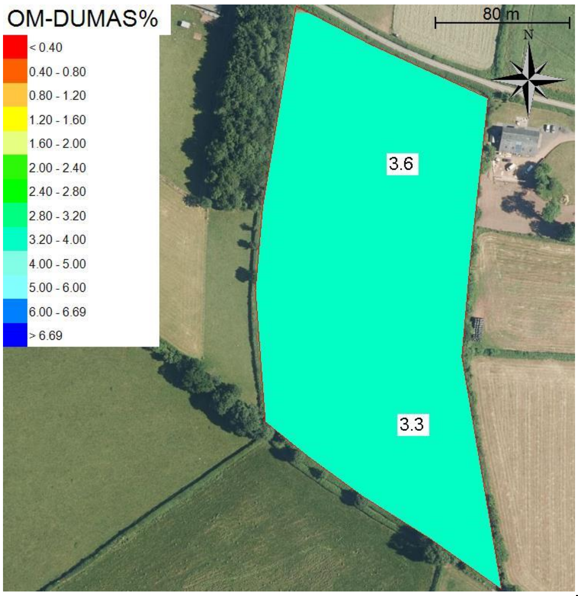
Appendix 2

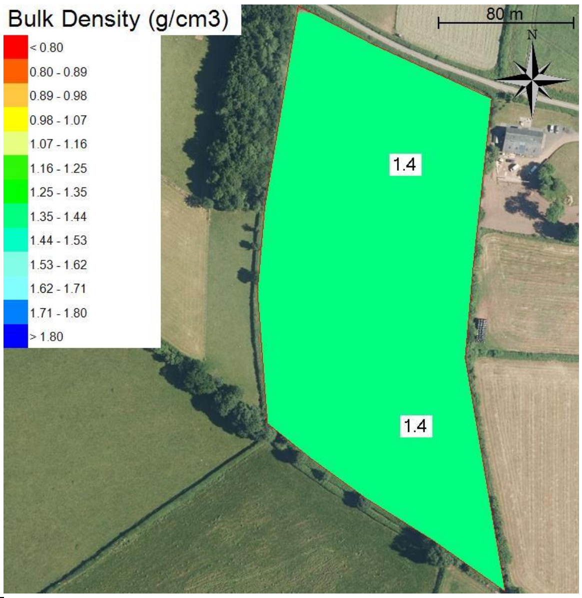
Example outputs for farmer soils report

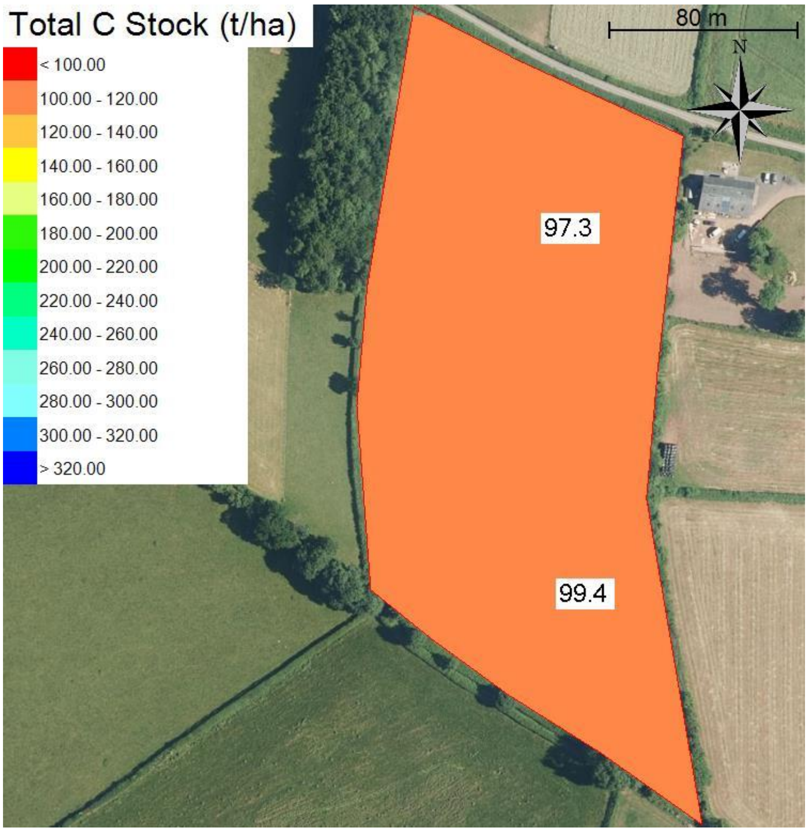
The information below provides the key outputs for the soils analysis undertaken as part of the is project. Each field tested and analysed has a robust and reliable organic matter baseline from which future measurement can be done as all sampling points are GPS located. Nutrient analysis was also done as part of the soil sampling programme.

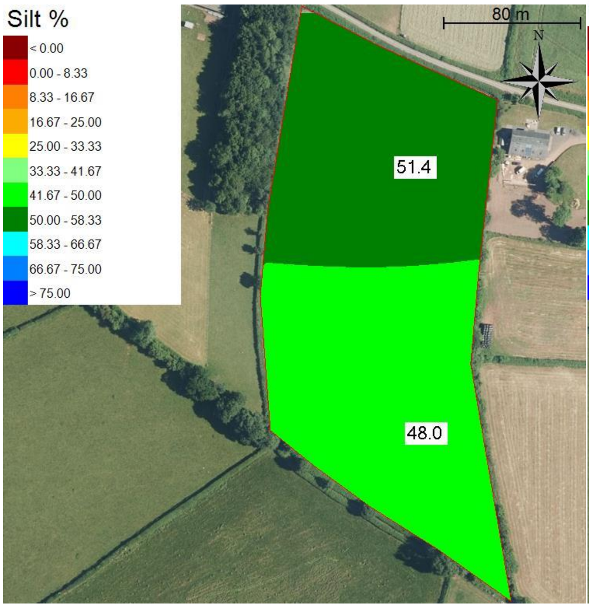
Job 1 **1_Maes_Bach** Field area: 3.39 ha

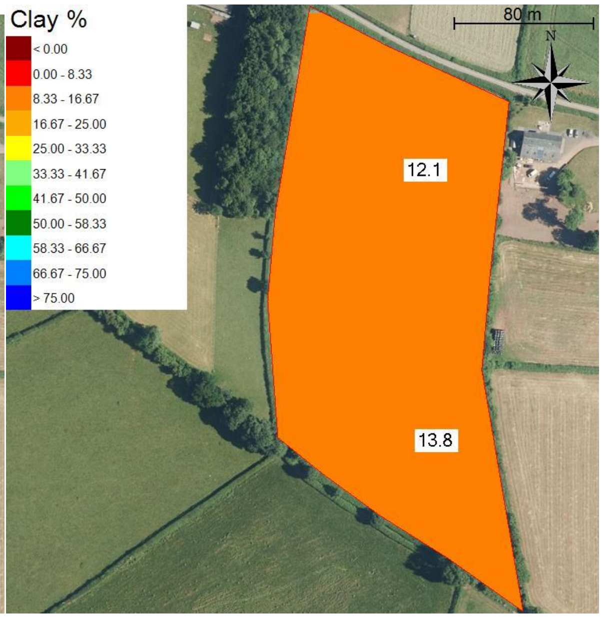
Soil Nutrients	mg/L or pH Val		
Sampled on: 14/12/2021	Min	Max	Average
P Index Map	1.20	1.30	1.25
K Index Map	0.80	0.90	0.85
Mg Index Map	3.20	3.40	3.30
pH	6.00	6.00	6.00
OM-DUMAS%	3.30	3.60	3.45
CEC (Meq/100g)	7.20	9.10	8.15
Ca	1036.00	1149.00	1092.50
B	0.75	0.81	0.78
Cu	4.00	4.60	4.30
S	2.00	2.00	2.00
Fe	614.00	658.00	636.00
Mn	121.00	126.00	123.50
Mo	0.02	0.02	0.02
Na	27.00	32.00	29.50
Zn	3.20	3.50	3.35
Silt %	48.02	51.41	49.72
Clay %	12.13	13.84	12.98
Sand %	36.46	38.14	37.30
Bulk Density (g/cm3)	1.41	1.44	1.43
Organic C %	1.90	2.10	2.00
Total C %	2.30	2.30	2.30
C:N Ratio	9.99	10.36	10.17
N%	0.19	0.20	0.19
Organic C Stock (t/ha)	82.08	88.83	85.46
Total C Stock (t/ha)	97.29	99.36	98.33

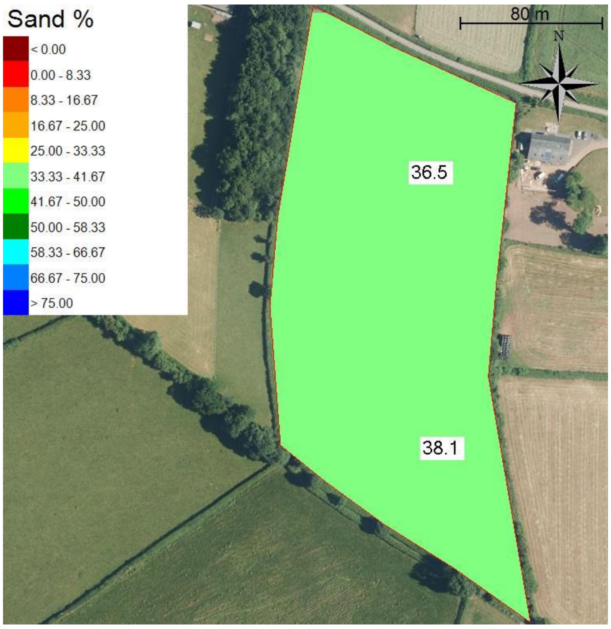

OM-DUMAS%
< 0.40
0.40 - 0.80
0.80 - 1.20
1.20 - 1.60
1.60 - 2.00
2.00 - 2.40
2.40 - 2.80
2.80 - 3.20
3.20 - 4.00
4.00 - 5.00
5.00 - 6.00
6.00 - 6.69
> 6.69
80 m
N
3.6
3.3


Bulk Density (g/cm3)
< 0.80
0.80 - 0.89
0.89 - 0.98
0.98 - 1.07
1.07 - 1.16
1.16 - 1.25
1.25 - 1.35
1.35 - 1.44
1.44 - 1.53
1.53 - 1.62
1.62 - 1.71
1.71 - 1.80
> 1.80
80 m
N
1.4
1.4


Total C Stock (t/ha)
< 100.00
100.00 - 120.00
120.00 - 140.00
140.00 - 160.00
160.00 - 180.00
180.00 - 200.00
200.00 - 220.00
220.00 - 240.00
240.00 - 260.00
260.00 - 280.00
280.00 - 300.00
300.00 - 320.00
> 320.00
80 m
N
97.3
99.4







Appendix 3 Soil Sampling and Analysis methodology

Understanding the levels of variability in the physical aspects of the soil is critical to allow increased accuracy and precision of sample measurements. Our methodology would propose utilising soil conductivity data to target sample collection locations to areas of consistent variation in order to provide better management decisions related directly to these variables, reducing sampling volume and cost whilst allowing for more targeted management. We would initially propose to cover a proportionate area from each of the 6 farm holdings involved in the project and tailor this to find the best delivery program to fit within the budget allocation.

Step 1: Electromagnetic Conductivity Scanning Survey
Non-invasive electromagnetic (EM) scanning service collects high-density data at multiple depths through the soil profile (Figure 1 &2). We use this data to then infer the degree of variability in the

physical/textural characteristics of the soil within the field. This data provides valuable insights to inform other management decisions and precision agriculture operations such as variable rate seed applications.
The soil conductivity assessment can be used alongside other complimentary datasets in addition to the knowledge of the farmer/land manager as part of the ‘ground truthing’ process. Using the EM data layer, areas of indicative variability are targeted for physical soil analysis. This approach can reduce the overall quantity of samples (when compared to a typical ‘grid sampling’ approach) and locate them in the optimum positions. This approach then allows for a wider suite of analytical services to be carried out on each sample and therefore delivering a much more detailed understanding of the physical, chemical, and biological properties of the soil.

Analytical services typically carried out on an agricultural soil tend to focus mainly on the chemical component such as key indicators and macronutrients (P,K,Mg,pH). However, it is less commonplace to understand how these are affected by the physical components of the soil. Validation of these soil types or ‘zones’ can be valuable when profiling a landscape as differing textures can have different characteristics in all aspects from nutrient/organic holding capacities down through to water retention and biological activity.

Figure 1: Kubota RTV vehicle with GPS auto steer guidance and EM Conductivity sensor.

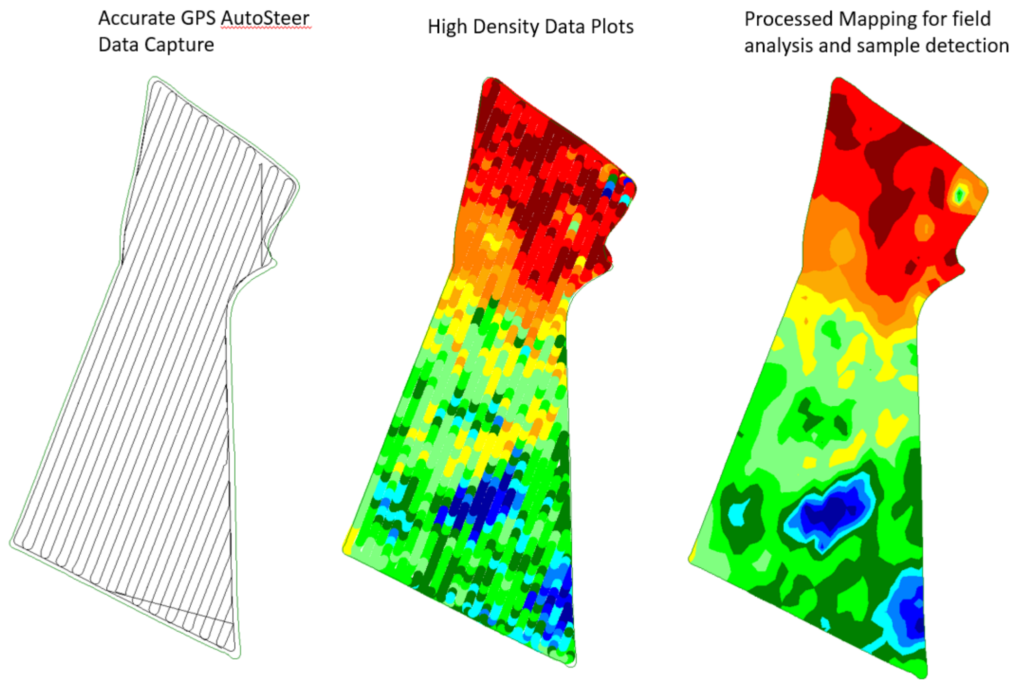


Figure 2: Example dataset of an EM conductivity survey carried out across a field. Accurate and spatially dense data collection provides a high-resolution assessment of variability with the soils physical characteristics, ideal locating areas of interest for targeted soil analysis.

Step 2: Soil Sampling

Targeted sampling: Dividing the field into areas with similar soil properties to determine carbon stocks within field 'zones' as this can reduce uncertainty and aid management.

- Each sample was be comprised of 16 individual soil cores at the desired depth to form the representative sample for that location.
- Soil samples are extracted using a hydraulic powered automatic soil auger which ensures every sample is consistently taken to the required standard.
- Soil sample extraction process is GPS controlled offering the highest levels of consistency, traceability and repeatability which is essential for both benchmarking and change detection in all aspects of soil testing. (Figure 3.)

Figure 3: Hydraulic powered soil sampling auger mounted on Kubota RTV coupled with GPS tracking, bespoke recording software and automated label printing for maximum accuracy, traceability, and efficiency. Testing results are then viewable via access to a digital platform.

Sample Depth:

For measurement of carbon, a minimum of 30cm is required. Intergovernmental Panel on Climate Change (IPCC) guidelines require minimum of 30 cm and if deeper samples are taken, these should be sampled separately. Typically, between 40 - 50% of SOC (to 1m) is found in the top 30cm, meaning there is a considerable C stock lower in the profile. Larger changes in carbon stock occur in the upper layer but longer-term stabilization of SOC occurs in deeper soil layers and is likely to develop over longer periods.

Step 3: Sample Analysis

Soil analysis was tested for Soil Carbon metrics as well as basic nutrient analysis including :

• Basic Nutrient:

o P, K, Mg, pH

• Soil Texture

• Bulk Density

• Soil Carbon Assessment Suite

o Total N

o Organic Carbon

o Organic Matter %

o C:N Ratio

o Total Carbon
o Total Carbon Stock

Analysis has been done using the dry combustion method (DUMAS%) as recommended by the IPCC and FAO (Food and Agriculture Organization of the United Nations) and carried out at an accredited laboratory for agricultural soil testing (Lancrop Laboratories). Results will be presented as total soil carbon and soil organic carbon (SOC). It is important that both are recorded to provide a baseline for the total carbon stock and the element that is more heavily influenced by farming activity which is the organic component.

Dry combustion (DUMAS) has been selected over other methods of carbon calculation as the variability is lower and it can distinguish between carbonate rock carbon and soil carbon. This method is recommended by the FAO Guidelines for soil carbon assessment.

Another key component to assessing carbon stock and stock change is understanding the bulk density of a soil. Bulk density is a critical metric, especially where soil type variability may be present.

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