MEASURING HOLISTIC CARBON FOOTPRINTS FOR LAMB AND BEEF FARMS IN THE CAMBRIAN MOUNTAINS INITIATIVE.

Rachel Taylor, Anna Jones and Gareth Edwards-Jones

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EXECUTIVE SUMMARY

Introduction

This project was undertaken at the request of farmers in Cambrian Mountain Initiative (CMI) who wished to better understand the greenhouse gas (GHG) emissions that emanate from their farm businesses. The project aimed to provide the farmers with:

a) a comprehensive GHG footprint for each participating farm.

b) a sensitivity analysis that explores how altered management practices may affect the overall carbon footprint of the farm.

c) identification of key areas in the footprint of each farm that offer potential for emissions reduction at a whole-farm level and per kilogramme product.

Twenty-three (23) farmers expressed an interest in having carbon footprints developed for their farms. Only 20 farms are discussed here, as the other 3 farms comprised significant egg production enterprises which are qualitatively different to the beef and lamb production systems which occur on most farms in the group. The results from the egg production systems will be reported separately.

Methods

Bangor University's existing carbon footprint models for estimating the emissions from livestock farms in Wales were further developed to meet the needs of the CMI project. The output of the model is a carbon footprint for each farm, reporting amounts of GHG emissions from each source. Model outputs are expressed as GHG emission per farm, per hectare of land and per unit of product (e.g. kg of lamb liveweight). In addition the footprints include quantitative ranges and qualitative statements relating to the causes of uncertainty.

The models also provide estimates of the amount of carbon (C) sequestered on each farm per annum by soils, woodlands, individual trees and hedgerows.

Farms were visited by a member of the project team between November 2009 and February 2010. Farmers completed a comprehensive questionnaire which asked for details on the structure and function of the farm either for the calendar year 2008 or the tax year 2008/2009.

Three different footprints were calculated. One is compliant with PAS 2050 methodology. A second footprint is termed 'local' and uses some local data rather than IPCC standards - this is further discussed below. A third footprint termed 'PAS plus' considered levels of carbon sequestration on the farm.

IPCC and PAS 2050 require the use of standard, internationally-accepted emissions factors and values in calculating a carbon footprint. Under Tier 1 calculations these values are applicable to large geographic areas and may not reflect emissions at local scale. Tier 2 level data are more locality-specific, but official Tier 2 data do not yet exist for Wales. We used UK-specific values for GHG emissions from organic (peat-derived) soils in upland areas (ECOSSE, 2007) as proxy Tier 2 data. IPCC also recommend that emissions from manure are based on total nitrogen content of the manure. However, in the models used to estimate the footprints of English sheep (Eblex 2009) we believe that 'available nitrogen' in manure and excreta was used rather than 'total N'. So in order to allow some comparison with the Eblex data we also adopted this convention in the 'local' footprint.

Estimation of C sequestration necessitated the use of data on sequestration rates in soils under managed grassland, peatlands, woodlands, isolated trees and hedgerows. It is difficult to get good and consistent measures of C sequestration for these situations, and the scientific literature reports different levels of sequestration. In order to reflect this uncertainty we chose to model a range of sequestration rates. For C sequestration under grassland we took data from Janssens *et al.* (2005) which suggest minimum sequestration rate of 0.04 t C/ha/yr, a maximum rate of 0.44 t C/ha/yr and a mid-range estimate of 0.24 t C/ha/yr.

Carbon sequestered in woodland and isolated trees were estimated from equations provided in IPCC (2006). No biomass or growth estimates are currently available for hedgerows, so we assumed that unmanaged hedges sequestered C at the same rate as short-rotation poplar coppice, including below-ground biomass (Laureysens *et al.* 2003).

Although we have tried to represent the range of sequestration rates possible in each element of the farm, significant uncertainty surrounds these calculations, and the results from this part of the analysis need to be viewed with care.

Two sets of sensitivity analyses were conducted in order to explore the changes in GHG emissions that could arise from implementing management changes on the farms. The first was concerned with understanding changes in farm management, and this considered the impact of four activities: reduce inorganic N use by 5%, reduce stock numbers (for sheep and cattle) by 5%, change manure management to low-emission manure handing systems and utilise anaerobic digestion to treat manures. The second set were concerned with carbon sequestration on the farm and these considered the impacts of three interventions: increase farm woodland area by 5%, increase number of isolated trees by 50 and avoid flailing any hedges in the sample year.

Results

The estimated PAS-compliant footprint per hectare between ranged from 2,103 kg CO_2e /ha/yr to 8,169 CO_2e/ha/yr. The footprints of lamb varied between 7 kg CO_2e /kg and 51 kg CO_2e /kg, and those for beef varied between 8 and 61 kg CO_2e /kg.

In most cases nitrous oxide (N_2O) provided the greatest proportion of the GHGs emitted from the farms, and overall levels of N_2O emissions varied with the amount of 'organic' soils that were on the farm. Some farms on mineral soils have low emissions of N_2O, while others have up to 90 % of their total N_2O emissions arising from organic soils. Emissions of methane are dominated by enteric fermentation from livestock and vary according to the type and numbers of stock on the farm. The emissions related to direct inputs (e.g. fuel, electricity, fertilisers) to the farms were always low.

The use of 'local' data changed the values and patterns of the footprints considerably, particularly for those farms with large areas of organic soils. Footprints per ha ranged from 722 to 6308 CO_2e/ha/yr. Footprints per kg of lamb ranged from 4 to 18 kg CO_2e/kg, and those of beef from 4 to 23 kg CO_2e/kg.

On average farms sequestered about 1 tonne (1025kg) CO_2e/ha/year, or 58 % of their 'local' emissions footprint (25 % of PAS 2050 footprint). Three farms sequestered more than 1400 kg/ha/yr, and the lowest sequestration calculated was 752 kg/ha/yr. Most sequestration was in the form of soil carbon (average 81 %, range 46-100 %). Woodland contributed an average of 7 % of estimated C-sequestration (range 0-33 %). Hedges contributed an average of 5 % of estimated sequestration (range 1- 14 %).

Three farms sequestered more carbon dioxide equivalents per ha than the 'local' footprint suggested they were emitting, and under this scenario they may be considered C-neutral or net C-sinks.

None of the farm management changes modelled reduced farm footprints by more than 5 %, and most reductions were less than this (1-2 %). The modelled carbon sequestration options provided greater levels of change (up to 12 % from adding either 1 ha of woodland or 50 isolated trees per farm).

When viewed as a group the average level of GHG emitted per kg of lamb (PAS 2050-compliant footprint) was 24 kg CO_2e/kg and for beef it was 27 kg CO_2e/kg. Using 'local' data, emissions were 11 kg CO_2e/kg lamb and 13 kg CO_2e/kg for beef. Offsetting current ('local') emissions from the entire group would require converting 950 ha grazing to woodland or adding 87,000 isolated trees. On a per-farm basis, this is an average of 77 ha woodland or 5964 trees. These averages exclude the 'carbon-neutral' farms but are strongly weighted by five farms whose emissions would demand >100 ha woodland each. Six farms could each offset their emissions by planting only 30 ha woodland or 3,500 isolated trees.

Recommendations

As result of undertaking this work we have made several recommendations:

1. Farmers in the Cambrian group should consider recalculating their farm level footprints in 1-2 years in order to verify these results, smooth out any unusual results that arise from using data from the selected calendar year and begin monitoring progress towards GHG reductions on the farms.
2. Farmers in the Cambrian group should begin discussions with other actors in their supply chains in order to seek GHG reductions across the supply chain.
3. Farmers in the Cambrian group should communicate the results of this work in their publicity material.
4. The Welsh Assembly Government (or its agencies) should clarify whether or not grazed organic soils, as occur across Wales, are classified as 'managed' by IPCC.
5. The Welsh Assembly Government (or its agencies) should seek to develop a set of IPCC Tier 2 & 3 data that are available to use when considering the carbon footprints of Welsh farms and food products.
6. Research funders should continue to support work measuring actual levels of carbon sequestration on farms, and in upland ecosystems.
7. Research funders should continue to fund work that seeks to measure and understand N_2O emissions from agricultural land, especially grassland.
8. Research funders should enable researchers in the UK to compare the outputs from models of farm level GHGs by each entering the same data set(s) into their models and then comparing outputs.

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INTRODUCTION

Background to carbon footprinting

There has been much recent interest in estimating the amount of greenhouse gases (GHGs) that are emitted from particular farm systems and food supply chains (e.g. Garnett 2009; Hillier *et al.* 2009; Vergé *et al.* 2009). Although these analyses consider all GHGs, this process is generally referred to as 'carbon accounting' (Carbon Trust 2007). The final summary of the GHGs emitted from the system under analysis is termed a 'carbon footprint'. A carbon footprint can be calculated for any defined system, such as a farm or a food product, either for its entire supply chain up to consumption and waste disposal, or for parts thereof. Carbon footprints are calculated for defined 'functional units' which are the item of production that is being analysed, e.g. a litre of milk of kilogramme of wheat. They are expressed in terms of carbon dioxide equivalents per functional unit (e.g. kg CO_2e per kg of food produced), where the word 'equivalents' indicates that the global warming potentials of the different GHGs have been normalized with respect to that of CO_2.

There are many initiatives around the world seeking to develop methodologies for estimating the carbon footprint of food and agriculture, and at least 16 different methods developed by retailers and countries for product-level footprints (Brenton *et al.* 2009) while several others are being developed specifically for farm-based accounting, e.g. CALM (CLA, undated). Each methodology tends to consider a unique set of variables and system boundaries. However, some of the emerging methodologies are intended to provide a more rigid framework for calculations, specifying rules for data quality and the definition of system boundaries. One problem with the development of different methodologies for measuring carbon footprints is that the final results may not be strictly comparable, thereby potentially causing confusion to consumers and others. In an attempt to avoid this situation The Carbon Trust developed a standard methodology for carbon footprinting of products, termed PAS 2050 (Publicly Available Specification 2050), and this was published in 2008 (BSI 2008). Other stakeholders are developing and implementing similar carbon accounting methodologies around the world which they also hope will become accepted standards (e.g. ISO and WRI). At the time of writing PAS 2050 is the only published standard methodology available and was used in this work.

Carbon footprinting in food and agriculture

Several published studies report the carbon footprints of food items, for examples see Edwards-Jones *et al* (2009a,b); Williams *et al.* (2006), and Basset-Mens & van der Werf (2005). The methods used to calculate these footprints can be classified into one of three types: modelled, aggregated and empirical. Modelled carbon footprints are typically derived from mathematical models of particular agricultural systems and/or supply chains (e.g. Williams *et al.* 2006, Olesen *et al.* 2006, Weiske *et al.* 2006). These models are based more on theoretical considerations of agricultural systems than on actual data collected from farms. For example, Olesen *et al.* (2006) quantified imports of fertilisers and feed as a function of the desired milk production. These system models have not been developed to represent variation between regions and farms in terms of inputs, processes and outputs, and they tend not to take account of spatial or temporal fluctuations in yield due to variation in edaphic and biological factors.

Aggregated approaches for calculating the carbon footprint of food products are based on real farm data collected from a large sample of farms, e.g. national statistical data. An example for this approach is Thomassen *et al.* (2009) where environmental and economic indicators for Dutch dairy farms were calculated using Farm Accountancy Data Network figures for 119 specialised dairy farms. This approach is based on data from real farms and as such will reflect some of the variability between individual businesses. The results of this family of analyses can be statistically representative of a larger geographical area, and allow general conclusions on best practice management or mitigation measures.

The so-called ‘empirical’ method for estimating footprints is a third approach to calculating carbon footprints. Data are collected from one or more farms (and/or or other actors in the supply chain) and these data are used to construct the carbon footprint for that particular, identifiable farm system and/or supply chain. Data are typically collected directly from the farmer or stakeholders via a questionnaire which requests details on inputs and processes that occur on the farm, such as the amount and type of fertiliser applied, electricity and diesel usage, use of plastics, agronomic management, farm product yields and wastes. These data are then manipulated along with relevant emission factors in order to estimate a carbon footprint for that particular farm or food item.

Each of these methods has advantages and disadvantages and they serve different needs. Modelling enables detailed processes to be represented in a clear and understandable manner, and a complete modelling framework offers an efficient and powerful way of repeating and extending the analysis or assessing the impact of changes made in the system. However, one disadvantage of models and the aggregated approach is that they may not represent the diversity and complexity of real agricultural systems. The empirical approach is a more applied approach that is used by businesses to calculate the climate change impact of their products using methodologies such as PAS 2050. In such specific cases, the modelled and aggregated approaches are not relevant, because the analysis needs to be based on a particular farm system or supply chain, and empirical data needs to be collected and analysed specifically from that system.

Uncertainty, subjectivity and variability in carbon footprints

Typically the carbon footprint of a particular product is reported as a single figure, e.g. 2.3 kg CO_2e/kg product. Citing a single precise figure as the output of a carbon footprinting exercise may be misleading as both carbon footprinting and the related technique of Life Cycle Assessment (LCA) have to deal with issues of variability, uncertainty and subjectivity, each of which can reduce the accuracy and precision of the final result.

For example, within an agricultural context, there is tremendous biophysical variability between farms producing the same products, and this can introduce large differences in the carbon footprint of the farm and product. Within Wales, lamb may be produced on an upland farm where there are very few inputs, but there is also low productivity per hectare. Conversely, lamb can also be produced on fertile farms in the lowlands with higher unit productivity but which may also use more inputs such as fertiliser. These farms may have very different carbon footprints per hectare and per kg lamb produced, and it is important that decision-makers understand these differences. Management also varies between farmers; and even neighbouring farms of the same type, e.g. dairy producers, can have different yields and carbon footprints which are partly a function of the personality and skills of the farmer. The weather can also have a large impact on the way a farm is managed. As a result the exact footprint of a farm may vary over time due to the interactions between the climatic environment and the associated management decisions of the farmer. Finally, carbon footprints vary with the underlying soil type. The amount of GHG emitted by soils (principally nitrous oxide (N_2O) with some carbon dioxide (CO_2) and methane (CH_4)) varies with soil type, and also with weather and management. As a result the underlying soil type of a farm can have a large impact on the final footprint for that farm. This sort of variation has not typically been reported in carbon footprints to date, but in the Welsh context Edwards-Jones *et al.* (2009b) suggest that the footprint from farms on organic (peat-derived) soils can be substantially greater than those on mineral soils.

In addition to genuine biophysical variation between farms and years there is also considerable uncertainty inherent in carbon footprints. This uncertainty is related to the limitations of our understanding of ecosystem-level processes, and the choice of emission factors used in the calculations. Emission factors are fundamental to the process of carbon footprinting as they represent the amount of GHG's emitted during specific processes (e.g. methane from ruminants, or GHGs arising from the manufacture of inputs like fertiliser). Emission factors are calculated from the results of fundamental science, and are reported in standard databases such as Ecoinvent (Swiss Centre for Life Cycle Inventories, 2010). However, it is important to note that different databases provide different emission factors which are derived from studies using different system boundaries, data collection techniques, data definition and processing methodologies etc. The choice of emission factor database is a subjective process, while the variation between emission factors for the same process can introduce variability into the process of carbon footprinting.

In addition to the data on emission factors for products held in standard databases, the scientific literature also presents a range of emission factors for many processes e.g. the amount of N_2O released from soils after the application of nitrogen fertiliser. However, scientific understanding of many of these complex processes is limited, partly because their measurement is time-consuming, highly location-specific and may vary greatly with time. The International Panel on Climate Change (IPCC) approach to addressing this problem has been to undertake a meta-analysis of all the available experimental data and to produce standard emission factors. These may be applied worldwide or be relevant to large geographical regions, but can have little relevance to local conditions. IPCC emission factors are presented with their uncertainty ranges (IPCC, 2006), and analysts are free to choose the most appropriate value for their situation.

In addition to variability and uncertainty, carbon footprints also include an element of subjectivity: the analyst is required to represent a real farm in a simplified form, which requires a series of simplifying assumptions to be made. It is important that analysts recognise the subjective nature of their activities.

If carbon footprinting is to be a useful tool for policy and decision makers, the uncertainties surrounding the results of such studies need to be understood, in order to aid the appropriate interpretation of results and avoid misleading conclusions. To date, few studies have tried to report this uncertainty and variability (exceptions include Edwards-Jones *et al.* 2009b, Lloyd & Ries 2008). Similarly, many of the studies reported in the literature have used modelling approaches, rather than using real farm data: which does not allow for an assessment of differences between individual farms (e.g. Williams *et al.* 2006; Weiske *et al.* 2006; Hirschfeld *et al.* 2008).

PROJECT AIMS AND OBJECTIVES

This work aimed to develop an holistic and ‘cutting edge’ assessment of 23 farms in the Cambrian Mountains Initiative (CMI). This assessment should help the relevant farmers with their on-farm management and marketing activities. It will also help relevant agencies understand GHG emissions from farms in the region, and this understanding will inform their future work in this area.

Deliverables

There were three main deliverables from this project:

1. A comprehensive GHG footprint for each participating farm holding that takes into account:

- Existing land-use GHG balance, addressing variation in vegetation and soils
- Emissions from agricultural management, including soils, soil management, land use change, livestock and fertiliser and manure management
- Emissions from agricultural and processing equipment operations (fuel and energy use)
- Indirect (Scope 3) emissions from all inputs, including bought-in feeds and fertilisers
- Carbon sequestered in soils and plant biomass

2. A sensitivity analysis for each farm holding that explores how changed management practices may affect the overall carbon footprint of the farm. Relevant management changes include alterations in stock management or density, reducing fertiliser inputs, and changes to manure management systems.

3. Identification of key areas of the footprint of each farm that offer significant potential for emissions reduction at a whole-farm level and per kilogramme product.

The project aimed to analyse 23 farms, however it emerged after data collection that three of these farms had significant poultry enterprises (laying hens) as part of the farm business. Given that poultry production is very different to the production of lamb and beef which constitute the major farming activities of the other 20 farms, it was decided not to include the poultry farms in this report. Rather, a separate report focusing solely on poultry will be produced to accompany this one, which focuses on the production of beef and lamb.

METHODS

The livestock enterprise footprinting model has been developed in Bangor over the last three years and the earliest version of the model is described in Edwards-Jones *et al.* (2009b). This model utilises data collected from specific farms and aims to be PAS 2050 compliant. This base-level model was taken as the baseline for this work but was updated and modified in order to meet the specific requirements of this project. The approach adopted by the Bangor models is summarised in the following sections.

Defining the system boundary

Estimates of the carbon footprint of a system (in this case, a livestock enterprise) depend on how that system is defined. System boundaries may be defined so that they include only certain elements of the food chain. For example, investigators interested in farm-level activities may define the system so that it only includes on-farm activities and ignores processing and retail. Alternatively, the system boundary could be drawn to include the production stage plus other elements of the food chain, such as processing and retailing. The system boundary used in this study includes emissions arising from the manufacture and distribution of farm inputs (c.f. embodied GHGs in the classic approaches to Life Cycle Assessment (LCA), ISO 2006a,b); the use of energy on the farm (fuels and electricity), the GHG emissions from livestock and their excreta, and emissions from soils related to fertiliser use and manure management. The GHGs included are the three most important GHGs emitted from agricultural activities, namely carbon dioxide (CO_2) nitrous oxide (N_2O) and methane (CH_4). Processes beyond the farm gate, such as processing, retailing and consumption are not considered in this version of the model.

A definition of the system boundary therefore includes this economic or systematic boundary; a temporal boundary (one calendar year, stating the start date for each farm) and finally a spatial boundary – the amount of land managed. The actual area of land managed by a particular farm business may change through a business year as the amount of rented land increases and decreases. In addition to land owned or rented by a particular farm business, that business may also have access to common land. In our model we included the area of owned land, plus the area under common-land agreements and land rented for the whole year. Land rented for less than a year was modelled as a proportion of its area: N ha for x/12ths of the year where x is the number of months rented. For example, if 10 ha were rented for 5 months it was modelled as 10 x 5/12 ha added to the farm area.

Non-productive areas of farms (e.g. hedges, marshland, woodland) may represent quite large areas in many agricultural systems, and these and the pastures themselves have the potential to both release and lock up carbon (Castaldi *et al.* 2007; Chapuis-Lardy *et al.* 2007). Although the flow of carbon into and out of plants and soils remains relatively poorly understood, we use data from the literature to estimate the potential range of sequestration / emissions that occur in the soils and woody vegetation on the farms.

Functional units and allocation

We present the GHG emissions (carbon) footprint for the whole farm year, and also use two functional units to present results which can be compared between enterprises: GHG emissions per unit product (e.g. per litre milk at the farm gate) and per hectare of farmland. The former is the functional unit that reaches the consumer, and is the recommended functional unit under PAS 2050 and in most standard LCAs. The latter considers the agricultural enterprise as an integrated production unit, and relates to the aim of assessing and reducing the environmental impacts caused by agricultural production on a given area of land.

Many farm enterprises produce more than one economically significant output; for example dairy farms produce milk but also live dairy stock (calves, barrens etc); sheep enterprises produce lamb, breeding stock, cull stock and wool. Emissions from the farm enterprise are allocated between different outputs using economic allocation based on income from the various stated outputs (this approach is recommended by PAS 2050).

Data sources and data uncertainty

We utilise emission factors for farm inputs and processes that have been gathered from recognised standard databases, e.g. the Intergovernmental Panel on Climate Change (IPCC), Ecoinvent. The diversity of emission factors available in the literature introduces some uncertainty into their application to the Welsh situation. Because of this uncertainty we utilise a minimum, maximum and mid-range value of possible emissions for each process / product in order to represent a best case, worst case and average scenario. When using emission factors defined by IPCC we include the uncertainty range surrounding these default values in order to reflect uncertainty in their estimation.

In addition, we present a second carbon footprint calculated using similar methodology but with two significant changes. Firstly, rather than utilise the IPCC Tier 1 methods of estimating N_2O emissions, we used data obtained from measuring actual emissions from peat and peat-derived soils in the UK (ECOSSE: Scottish Executive Environment and Rural Affairs Department, 2007). Secondly, rather than use ‘total nitrogen’ for estimating the N_2O emissions from manure and excreta (as recommended by IPCC), we calculated these emissions using ‘available nitrogen’. It must be stressed that this second footprint is not perfectly compliant with PAS 2050, and it is only calculated for the purpose of direct comparison with footprints prepared using similar assumptions (e.g. EBLEX 2009).

Data collection

In order to calculate carbon footprints, specific data were collected through interviewing the relevant farmers. Project officers used a carefully developed questionnaire - reflecting our most recent experiences of carbon footprinting of farms and the new carbon-sequestration element of the model - to elicit and record the data that the analysis requires from each participating farmer. In accordance with our previous experience, in most cases it was necessary to discuss completed questionnaires with the project officer who collected the data - in some cases requiring further contact with the farmers - in order to verify certain details / assumptions made as the analysis progressed. The questionnaire was made available in English and Welsh.

Data gaps for specific farms

Where data for a specific item or process were not available for an individual farm, we use national data sources, published UK reference examples or standardised estimates for the missing data. One common example is the fuel used by contractors working on a farm, e.g. performing hedge-flailing or harvesting operations. We estimate fuel use for these operations (where necessary) from a table of machine sizes, working rates and fuel efficiencies provided to us by a large UK-based agricultural machinery manufacturer. Examples are included in the description of the model calculations below. If we have been required to use standardised data to fill data gaps these assumptions are clearly stated in the relevant individual farm report.

Bangor University livestock enterprise carbon-footprint model

Compliance with PAS 2050

Bangor University farm footprints are compliant with the PAS 2050 cradle-to-gate approach. In order to comply with PAS 2050, the footprint includes all emissions resulting from the transformation of raw materials (e.g. from the production of fertiliser); use of energy; manufacturing and service provision i.e. emissions from consumables, operation of premises, transport and storage. The footprints exclude emissions from the production of capital goods (e.g. tractor production). Examples of agricultural emissions to be included in a PAS 2050 footprint given within the guidance include emissions from the application of fertiliser, emissions from direct land use change (from non-agricultural to agricultural land) and CH4 from cattle, all of which are included in our footprints (where relevant).

PAS 2050 guidance gives a number of instructions directly relevant to agricultural footprinting, which we have followed to ensure compliance. These are:

- *"Non CO2 emissions from livestock and soils should be calculated using the highest tier IPCC approach or the highest approach used by [our] country"*. We have used IPCC calculations and emissions factors for emissions such as N_2O released directly from the management of organic soil.
- *"Changes in carbon content of soil other than those arising from direct land use change shall be excluded from the assessment"*. Changes such as sequestration in peatlands have been excluded from the PAS 2050 - compliant footprints.
- *"CO_2 emissions from biogenic (biomass derived) material should be excluded (except those arising from land use change). Non - CO_2 emissions from both fossil and biogenic material carbon sources should be included"*. No emissions in the system boundary (see detail above) fall into these categories.
- *"Where atmospheric CO_2 is taken up by a product which is not a living organism the impact of carbon storage is determined from the weighted average of the biogenic carbon in a product or atmospheric CO_2 taken up and not re-emitted to the atmosphere over the 100 year assessment period"*. No emissions in the system boundary (see detail above) fall into this category.

- *"Biogenic carbon storage shall be included if: the product is not for human or animal consumption; more than 50% of the mass of C of biogenic origin in the product remains removed from the atmosphere for one year or more; AND the material containing the biogenic C is obtained from an input that is the result of human actions OR a recycled or re-used input (i.e. ensures the carbon stored is in addition to that which would have occurred without human intervention). (C storage through forest management activities in a managed forest is not included in the scope of PAS)".* Carbon storage in farm woodland and other woody biomass has not been included in the PAS 2050 - compliant footprint, since we cannot be certain that more than 50 % of the mass of carbon of biogenic origin remains removed from the atmosphere for one year or more.
- *"GHG emissions from direct land use change shall be assessed for any input originating from agricultural activities. This is to be in accordance with IPCC including all direct land use change after 1st January 1990. 5 % of the total emissions from land use change shall be included in each year over the 20 years following the land use change".* Under this definition *"direct land use change"* is the conversion of non-agricultural to agricultural land use, as a consequence of producing an agricultural product (or input to a product) on that land. Where land use on a study farm has changed from non-agricultural to agricultural use (e.g. woodland to grassland or arable) since 1990, it has been included within the footprint calculation.

The footprint results are reported to 2 significant figures and per unit of produce (kg) to ensure compliance. Where a farm produces more than one economic output (e.g. lamb and beef) we use economic allocation of emissions between co - products (as suggested by PAS 2050 guidance).

Direct and indirect inputs

These include emissions arising from the use of energy on the farm (fuels and electricity) on the farm, and those produced during the manufacture and distribution of farm inputs ('embodied energy' in the classic approaches to Life Cycle Assessment (LCA), (ISO 2006a,b). Emissions factors (EF) are taken from the IPCC and ETH EF databases. Agrochemicals include field applications and externally applied pharmaceuticals (dips and parasite treatments) and these are modelled using mean and range EF values from the published scientific literature (*cf.* Edwards-Jones *et al.* 2009b).

Stock data and organic nitrogen

Animal numbers and their emissions categories change as livestock enters, grows and leaves the defined farm boundary throughout the farming year, and the magnitude of the livestock contribution to the farm enterprise carbon footprint consequently varies. We model direct and indirect emissions from livestock on a month-by-month basis so that we can investigate differences in management efficiency (expressed as fattening times) between enterprises.

Many farms house a proportion of their stock for part of the year. Where this occurs we calculate the emissions from, and nutrient content of, manure and bedding materials from housed stock using standard (IPCC) nitrogen-excretion rates based on the farmers' stated manure-handling methods.

Nitrous-oxide emissions

Nitrous oxide is a powerful greenhouse gas and is emitted from several sources on a livestock farm. Each is calculated using standard IPCC methodology as follows:

a) **Direct N_2O from manure management:** Not all the nitrogen entering the manure handling system (from animal excreta and bedding materials) remains in storage: a proportion of it is emitted from the manure directly (as N_2O) and indirectly (as ammonia). We calculate these emissions from total N entering the system using IPCC emissions factors (IPCC, 2006).

b) **Direct N_2O from soils:** Soil microbiota release N_2O in response to nitrogen availability. We calculate the nitrogen applied as mineral fertilisers, applied as organic nitrogen from the muckheap, and deposited directly onto fields (urine and excreta) by grazing stock. Each is multiplied by the specific emission factor (IPCC 2006) for that N source and stock type, and state results including the range of uncertainty given by IPCC.

c) **Direct N_2O from managed organic soils:** Organic, peaty soils are highly biologically active and consequently produce a 'background' amount of N_2O which has been estimated by IPCC. Any areas of managed organic soils will therefore contribute these emissions (per ha) to the farm carbon footprint. We assume that land that is grazed by livestock must by definition be 'managed', although we recognise that this is a debatable point.

d) **Indirect N_2O emissions:** Nitrogen-rich materials such as fertilisers and manure volatilise a small proportion of N (primarily as ammonia) directly to the atmosphere. Some N also reaches the wider environment via nitrogen in leachate and runoff from soil application. Each of these is calculated from the nitrogen applied (see above) using IPCC equations and emission factors.

Once the individual sources of N_2O have been calculated they can be summed and converted to CO_2 equivalents, with their associated ranges of uncertainty.

Methane emissions

Ruminant animals emit methane (CH_4) directly from the gut (enteric fermentation) and indirectly from their excreta. Emissions of CH_4 in the field and from stored cattle and sheep excreta are calculated using IPCC equations and emission factors presented in Baggott *et al.* (2007) and IPCC (2006). These emission factors are specific to animal species, type and age/size categories.

Emissions from liming

Soils produce CO_2 in response to lime application. IPCC (and hence PAS 2050) require us to calculate all the carbonate-carbon content of lime and lime-containing treatments applied to soil and convert it to CO_2 equivalents (with a 50% uncertainty range).

Beyond PAS 2050: carbon sequestration estimates

Detailed information on tree cover, soil, habitat extent and management was collected from farmers as part of the footprint questionnaires, using and annotating farm maps (Ordnance Survey and Tir Gofal habitat maps) as an aid to memory during the interviews. We calculate C-sequestration in metric tonnes of carbon sequestered (added to long-term stocks in woody biomass or soils) per hectare per year (t C/ha/yr) and convert this to an offset against farm GHG emissions, expressed in tonnes CO_2-equivalent (t CO_2e/ha/yr).

The first stage of calculating carbon sequestration is to estimate growth rates for trees of different species on the farm, based on the farm soil types, altitude and climate: for this we use a Forestry Commission yield class tool (Ecological Site Classification; Forestry Commission 2001). We model the carbon sequestered in trees (woodland, plantation, parkland and isolated trees), hedges and soils as these are described for us by the farmer.

Scientific uncertainty is associated with IPCC expansion factors (for calculating total biomass) and published growth rates (particularly for mixed-species woodlands and plantations) and is included in the calculations throughout. Our stated results include these maximum and minimum values which we present in the same way as for the emissions footprint.

Woodland and tree plantations

Carbon sequestered in woodland includes components in the trees (above- and below-ground biomass), deadwood and litter, and soil. We calculate the biomass increment in trees of the stated species or species mix, age and planting density for each woodland parcel, growing at the yield class estimated for those species on the farm (IPCC 2006). Deadwood and litter carbon annual increments are calculated for newly-planted woodlands but considered to be in equilibrium for older woodlands; as is soil carbon (IPCC Tier 1; IPCC 2006). We calculate and subtract the carbon content and associated changes in below-ground biomass for any wood harvested (e.g. firewood) to give a woodland carbon sequestration value for the sample year.

Isolated trees

'Isolated' trees include trees in parkland, emergent trees in hedgerows and any other non-woodland trees. These are modelled individually since free-grown trees grow more rapidly than densely-planted trees. We model isolated broadleaves as oaks (Jobling and Pearce 1977) using IPCC equations for above- and below-ground biomass (IPCC 2006). Similarly, we calculate and subtract the carbon content of any wood or trees harvested in the sample year from the total.

Hedges

No biomass or growth estimates are currently available for hedgerows. We calculate the spatial area (and height) of hedges from farmers' estimates of length and width, and consider hedges flailed to a standard height/width in the sample year to be in equilibrium (in terms of annual carbon increment). Carbon sequestration in hedges not flailed in the sample year is modelled using reference data for an equivalent area of established short-rotation poplar coppice, including below-ground biomass (Laureysens *et al.* 2003). These data suggest a minimum sequestration rate of 2.20 t C/ha/yr, a maximum rate of 11.40 t C/ha/yr and a mid-range estimate of 6.37 t C/ha/yr.

Ungrazed peat wetlands

We estimate the carbon sequestered in ungrazed permanent peat wetlands using values from Watson *et al*. (2000), and exclude these areas from the managed organic soil N_2O emissions calculation. The minimum reference sequestration rate is 0.02 t C/ha/yr, a maximum rate of 0.05 t C/ha/yr and a mid-range estimate of 0.04 t C/ha/yr. Grazed peat grassland is included under permanent grassland (below).

Grassland and soils under grassland

The measurement of carbon sink or source activity in grassland depends either on measuring the very small and spatially variable changes in soil C stocks over decades (Hungate *et al.* 1996; Conant *et al.* 2001) or alternatively, full C accounting by reliably measuring the very large fluxes of C into and out of the grass and soil system, which are also spatially and temporally variable (Jones and Donelly 2004).

We reviewed the studies on grassland C sequestration in order to identify the range of likely sequestration levels that could occur in Welsh farmed grasslands. During this review we concluded that relatively few of the published studies were applicable to the on-farm situation in Wales. The main reasons for studies being excluded were:

a) the experimental system was not comparable with Welsh grassland (examples included single-species experimental plots, modified atmospheric conditions, modified light and soil environments);
b) the studies assumed very different cropping and management strategies (>4 cuts removed per year, no cutting or grazing at all);
c) the studies had been conducted in ecosystems not found in Wales (e.g. tundra ecosystems where grassland is the climax vegetation, or arid zone grasslands; both of which have much lower natural productivity than UK temperate grassland).

In addition several studies had to be excluded because the system boundary used to measure soil carbon also included C pools in grazing stock, live plant biomass or C exports in cut herbage – which, under IPCC and PAS 2050 calculation methodologies for agricultural land, are considered to be in equilibrium and therefore excluded from farm C accounting.

As a result of conducting this review we identified 5 studies that we felt were relevant to Welsh farmed grassland (Dawson and Smith 2007; Fitter *et al.* 1997; Janssens *et al.* 2005; Soussana *et al.* 2004; Vleeshouwers & Verhagen 2002). Even amongst these studies, differences in sampling, methodology, grassland type and management and study duration all contribute to very high variation in estimated C balance under UK grassland. We found few studies of C sequestration in peat soils under permanent grassland. Drainage affects C-sequestration and GHG fluxes in peat soils, but none of the sample farms had recently-drained (i.e. since 1990) peatlands as described by this literature (DEFRA 2009, Freibauer 2004). Garnett *et al.* (2000) suggest that light grazing has no impact on soil C sequestration in blanket peat habitats. Organic and peat-derived soils are therefore explicitly included in the following summary of study findings.

Average C sequestration across these five studies was 0.45 tonnes/ha/yr; with published values ranging from a net C loss of 2.31 tonnes/ha/yr (C flux measurements over drained organic soils: Soussana *et al.* 2009) to a net C sequestration of 2.9 tonnes/ha/yr (soil C stock in species-poor peaty gley grassland: Fitter *et al.* 1997). However, it should be noted that considerable uncertainty remains around estimates of soil C under grasslands. Some authors consider soil C under grassland to reach equilibrium after 10 years (Janzen *et al.* 1998), while others suggest that soil C sequestration is theoretically unlimited (Six *et al.* 2002). Given the range of published values in the literature, and the unresolved question of soil C saturation over time, we decided to utilise the information on carbon sequestered in soils under permanent grazed grassland, grazed peatland and croplands using the UK figures (mean and range) presented in Janssens *et al.* (2005). These data represent a conservative estimate of soil C sequestration under a management strategy applicable to the Welsh context; with a minimum sequestration rate of 0.04 t C/ha/yr, a maximum rate of 0.44 t C/ha/yr and a mid-range estimate of 0.24 t C/ha/yr. Janssens' mid-range estimate is below that of the five other studies we reviewed, but we believe that given the current state of knowledge on this topic it is prudent to take a conservative approach to estimating sequestration of C into soils.

Using local data in the model

IPCC and PAS 2050 require the use of standard, internationally-accepted emissions factors and values in calculating a carbon footprint. However, these values are applicable to large geographic areas and may not reflect emissions at national scale. We calculate a second footprint for each farm that differs from the Tier 1 PAS 2050 – compliant footprint in using a UK-specific value for emissions from organic (peat-derived) soils measured in Scottish and Welsh upland areas (ECOSSE, 2007) and which is considerably lower than the accepted IPCC values.

This second footprint also follows the methodology used by DEFRA in their carbon-footprinting reports (e.g. EBLEX (2009); Cranfield University animal AgriLCA model (2007)) in calculating emissions from the 'available N' content of manure and excreta, rather than the 'total N' advised by IPCC and required by PAS 2050. 'Available N' is nitrogen that is available for use by plants; and is loosely defined as the soluble nitrogen (in the form of ammonia and nitrates) excreted. It excludes nitrogen contained in bacteria and undigested complex molecules in the faeces. Available N excretion rate is specific to each species and production class of livestock, and represents a proportion (15 to 80 %) of the total nitrogen excreted. Using this lesser proportion of N excretion per animal can reduce the calculated N- and manure-related emissions by as much as 80 %, generating a much smaller footprint per kg or ha.

Sensitivity analysis – modelling changes in farm operations

The Bangor University model builds a detailed picture of each farm's emissions and estimated C-sequestration over a year of farm business. With this level of detail, we can make small changes to the stated farm operations and stocking levels, highlighting a suite of potential options for reducing farm emissions or increasing C-sequestration. For each farm, we compare the footprint of normal annual farm operations to the following simulated changes:

Reducing inorganic N use by 5%

The inorganic N contained in fertilisers imported onto the farm is reduced by 5 %. The model reduces both embodied C-emissions (from fertiliser production) and soil emissions from N application on the land.

Reduce stock numbers (for sheep and cattle) by 5%

Cattle and sheep stock numbers in each age / production category are reduced by 5 % (on a month-by-month basis). The model reduces emissions from stored manure, excreta and enteric fermentation, and soils (in response to the application of manure and deposition of excreta). Use of concentrates, bedding and other consumables are not changed.

Change manure management to low-emission systems

Emissions from manure are reduced by changing the defined manure-handling system to relatively anaerobic storage systems (pit storage for solid manure and anaerobic lagoons rather than open or crusted lagoons for liquids). Direct emissions (N_2O and CH_4) and indirect emissions (NH_4 and NO_x) are reduced, while the N content of stored manure reaching the fields increases (increasing N_2O emissions from soils). No compensatory changes are made to inorganic N use.

Change manure management to anaerobic digestion

No measurements are yet available for on-farm emissions associated with manure processing in anaerobic digesters, or the storage or field application of AD digestates. We model the effect of manure processing through anaerobic digestion by a) reducing emissions from stored manure to zero and b) calculating the carbon content of the methane normally emitted from stored manure and converting this directly to CO_2. Direct emissions (N_2O and CH_4) and indirect emissions (NH_4 and NO_x) from manure disappear altogether, while the N content of stored manure reaching the fields increases (increasing N_2O emissions from soils). No compensatory changes are made to inorganic N use. We note that this is likely to a) underestimate the CO_2 produced by AD since a greater proportion of the C content of manure is converted to methane in an AD unit than in a manure storage system or pile; and b) overestimate the soil response to N in the relatively biologically-inert AD-digestate applied to fields (P. Williams, *pers. comm.* 2010).

Sequestration – increase farm woodland areas by 5%

We model the effect of increasing farm woodland area by adding 1 ha to extant farm woodland area. If more than one woodland type exists, the increase is divided equally between the different types. This 1 ha is removed from the area of mineral soil under grassland. Note that this exercise models *mature woodland* – planting new woodland would sequester lass C per annum over the first approx. 25 years as the trees became established.

Sequestration – increase number of isolated trees by 50

We model the effect of increasing the number of isolated trees by adding 50 individual mature trees to the farm total. This change does not remove any productive farm area as it assumes the trees are planted on field boundaries. Note that this exercise models *mature trees* – planting new trees would sequester lass C per annum over the first approx. 25 years as the trees became established.

Sequestration – no hedges flailed in the sample year

We model the effect of hedge regeneration by assuming that no hedges were flailed during the sampled year. All the hedges on the farm are therefore considered to sequester carbon at an annual rate based on growth rates for coppiced poplar. This is an estimate as no data were available on woody biomass content or growth increments for hedge-managed trees.

RESULTS

Basic patterns in PAS 2050-compliant farm footprints

There is considerable variation in the estimated footprint per hectare between the farms (Table 1). Farm 2 had the lowest footprint with 2,103 kg CO_2e /ha/yr while farm 8 had the greatest level of emissions with 8,169 kg CO_2e/ha/yr. There was a similar level of variation in the outputs per unit product with Farm 16 having the lowest footprint per kg of lamb (7 kg CO_2e /kg) and Farm 12 the greatest with a footprint of 51 kg CO_2e /kg. The footprint per kg liveweight of beef was greater than that of lamb in nearly every case and varied between a low of 8 and a high of 61 kg CO_2e /kg. The footprint of wool tended to be quite low at between 1 and 7 kg CO_2e /kg, but it did exceed 9 kg CO_2e /kg on three farms.

Table 1. PAS 2050-compliant Tier 1 carbon footprints for each farm, expressed as footprint (kg CO_2e) per ha, and per kg product e.g. (liveweight) beef, per kg (liveweight) lamb and kg of wool.

FARM	Carbon footprint, kg CO_2e			
	ha	kg lamb	kg beef	kg wool
1	4,479	14	27	1
2	2,103	38	23	3
3	3,277	19	24	5
4	3,786	10	23	2
5	3,127	23	32	2
6	6,800	16	-	5
7	6,485	38	30	1
8	8,169	13	20	1
9	4,411	28	42	7
10	3,167	24	-	7
11	4,162	18	16	4
12	3,877	51	61	13
13	4,514	37	50	3
14	4,185	44	-	9
15	3,667	10	9	1
16	5,703	7	8	1
17	4,954	27	25	4
18	3,892	27	-	9
19	4,005	20	21	2
20	4,963	14	-	3

Nitrous oxide (N_2O) provided the greatest proportion of the GHGs emitted from the farms in all but five cases. In these cases the emissions from methane were slightly greater than those of nitrous oxide (Table 2). The total emissions relating to inputs represented relatively small proportions (average 11 %) of the overall farm emissions in nearly all cases. The nitrous oxide emissions from soil management are related to the amount of nitrogen applied to the land in the form of inorganic fertiliser and manure. The emissions from organic soils are related to the nature of the soil and the extent of these soil types on the farm. This will be discussed in detail later, but as can be seen from Table 2 some farms have no emissions in this category (e.g. farms 4 & 15) while others have up to 90 % of their total nitrous oxide emissions arising from organic soils (farm 12). Emissions of methane are dominated by enteric fermentation from livestock and they tend to vary according to the type and numbers of stock the farms carry. Their proportional importance also depends on the soil type, for example farm 15 is on mineral soils and has no nitrous oxide emissions from ‘organic soils’, and in this case methane represents 68 % of farm emissions. However, on farm 14, where there are substantial emissions of nitrous oxide from both organic soils and manure handling, methane only represents 9 % of the total emissions.

Table 2. Sources of emissions in the farm footprints. Emissions shown are from energy use, fuel and transport, agrochemicals (fertilisers and pesticides), soil management (primarily the application of organic and inorganic nitrogen), direct emissions from organic soils, manure handling systems and direct emissions from stock (methane from enteric fermentation and excreta). Numbers are expressed as percentages. NB the percentage values of fuels, transport, electricity and agrochemicals are shown here as examples. There are also other inputs to the farm and hence these values do not sum to the Total value for inputs.

FARM	Footprint per ha (kg CO_2e)	Percentage contribution to the farm C-footprint								
		All inputs	*(fuel and transport)*	*(electricity)*	*(agrochemicals)*	N_2O			methane	lime
						soil management	organic soil	manure handling		
1	4479	12	*2*	*0.1*	*0.01*	17	42	1.4	28	0.1
2	2103	3	*0.7*	*0.0*	*0.01*	10	71	0	16	0.3
3	3277	9	*3*	*0.5*	*0.01*	20	28	2	41	0
4	3786	10	*3*	*0.3*	*0.01*	37	-	1	51	0.6
5	3127	19	*4*	*0.1*	*0.04*	10	22	0.7	46	3
6	6800	25	*2*	*0.1*	*0.00*	11	1.0	1	61	0.1
7	6485	10	*2*	*0.1*	*0.02*	15	46	1	27	1
8	8169	15	*2*	*0.1*	*0.02*	29	6.8	2	47	1
9	4411	6	*2*	*0.0*	*0.01*	13	63	0.1	18	0.1
10	3167	3	*0.6*	*0.0*	*0.00*	12	65	0.1	19	-
11	4162	12	*1*	*0.3*	*0.01*	20	36	1	29	2
12	3877	4	*1*	*0.1*	*0.00*	8	72	1	16	0.2
13	4514	3	*0.7*	*0.0*	*0.00*	12	62	1	23	0.0
14	4185	4	*0.8*	*0.0*	*0.00*	8	76	2	10	0.5
15	3667	15	*5*	*0.1*	*0.02*	13	-	0.5	68	3
16	5703	23	*3*	*0.9*	*0.00*	12	43	2	19	2
17	4954	11	*1*	*0.1*	*0.01*	15	48	1	25	0.8
18	3892	9	*2*	*0.1*	*0.05*	19	45	1	26	-
19	4005	14	*2*	*0.1*	*0.00*	17	30	1	37	-
20	4963	16	*2*	*0.0*	*0.02*	26	20	0	33	4

Understanding variation

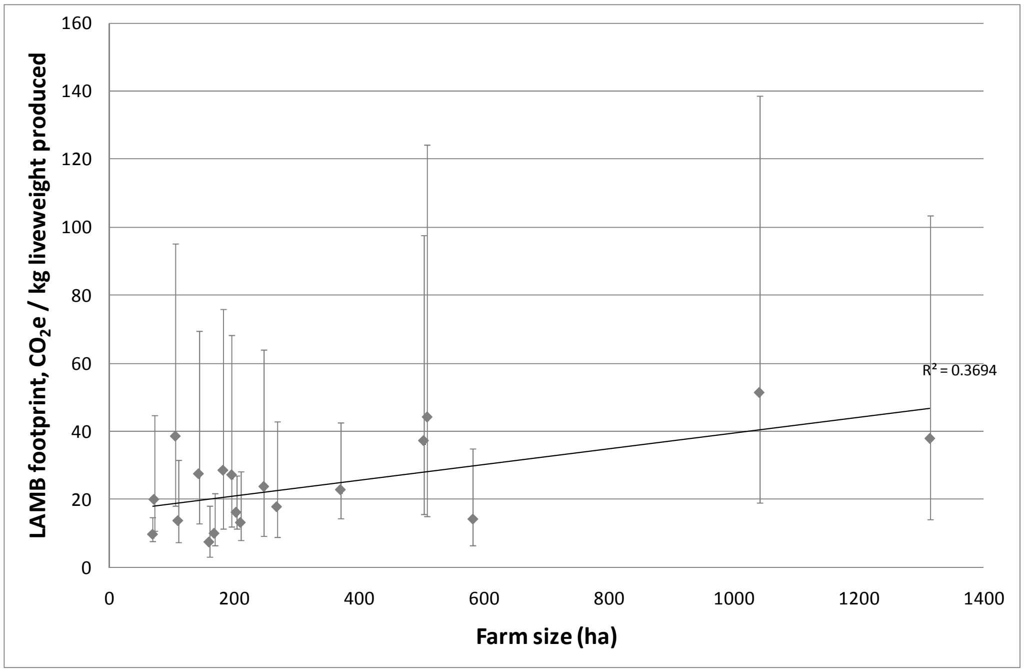

Figure 1. Carbon footprint of lamb (kg CO2$_e$ /kg liveweight) against farm size (ha). Error bars show maximum and minimum values taking into account the full range of scientific uncertainty in GHG emissions estimates.

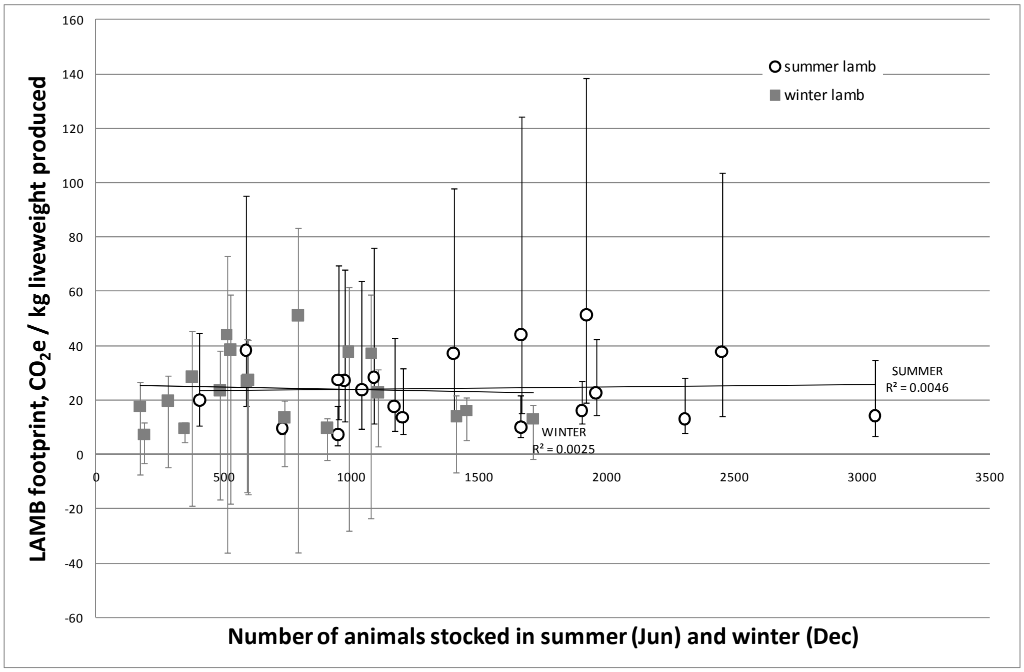

Figure 2. Carbon footprint of lamb (kg $CO2_e$ /kg liveweight) against stock numbers in summer (circles) and winter (squares). Error bars show maximum and minimum values taking into account the full range of scientific uncertainty in GHG emissions estimates.

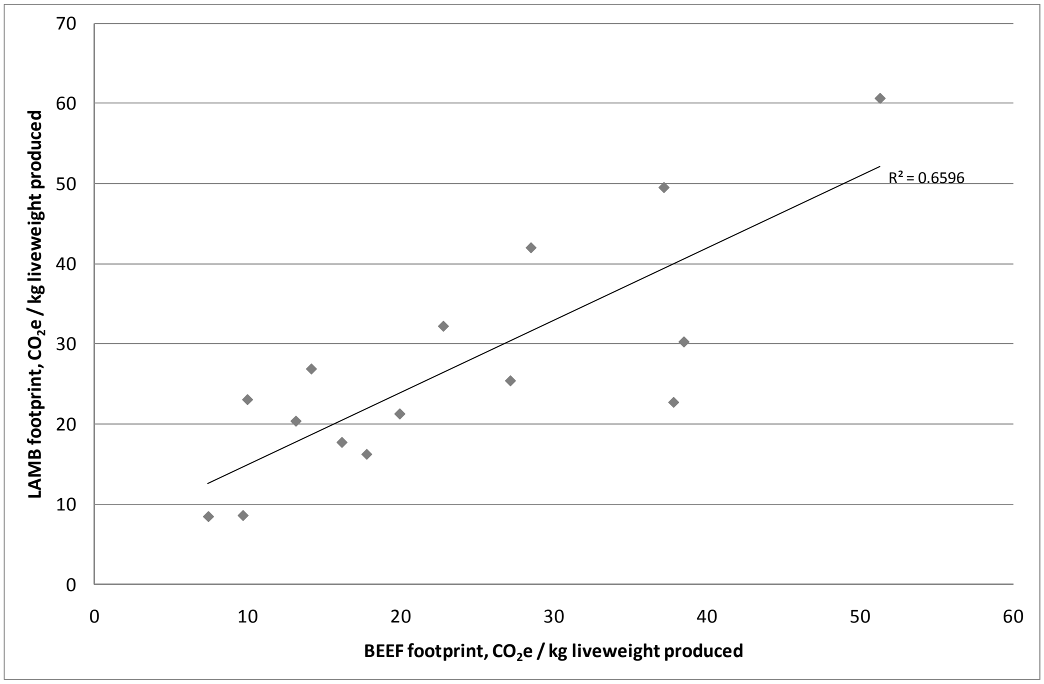

Figure 3. Carbon footprint of lamb (kg $CO2_e$ /kg liveweight) against carbon footprint of beef (kg $CO2_e$ /kg liveweight) from the same farm. Error bars omitted for clarity.

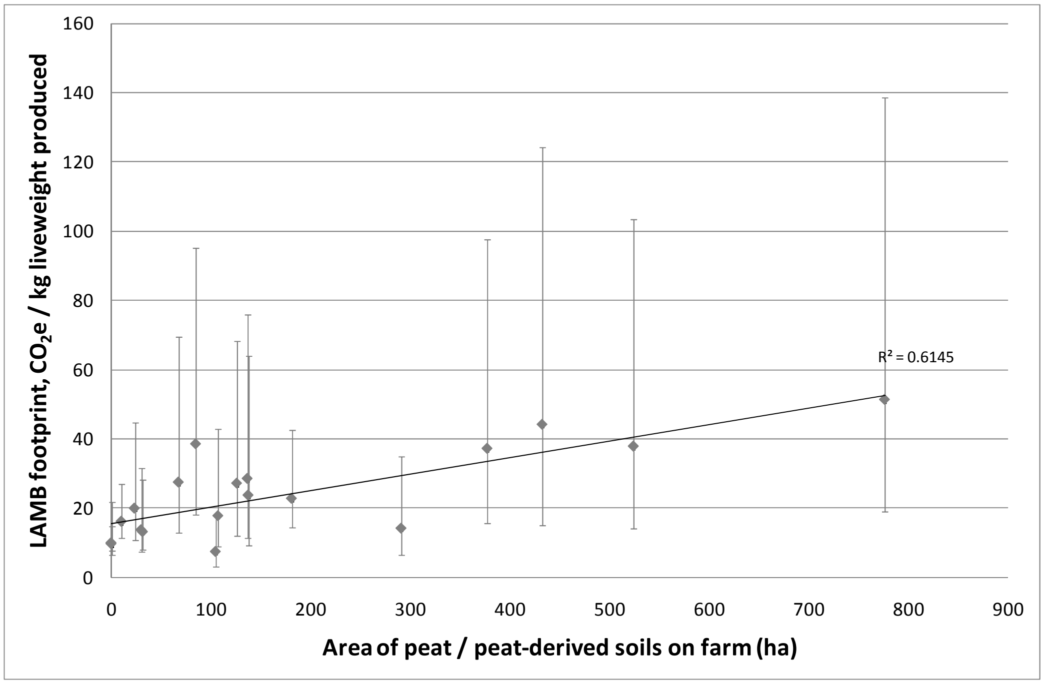

Figure 4. Carbon footprint of lamb (kg $CO2_e$ /kg liveweight) against the area of the farm on organic soils. Error bars show maximum and minimum values taking into account the full range of scientific uncertainty in GHG emissions estimates.

Understanding variation

The size of the carbon footprint of lamb leaving the farm tended to increase with the size of the farm (Figure 1). However, the footprint of lamb was not related to stock numbers either in summer or winter (Figure 2). Those farms which tended to have large carbon footprints per kg of lamb also tend to have large footprints per kg of beef produced (Figure 3). These observations can be partially explained by the relationship shown in Figure 4, which demonstrates that the footprint of lamb increases as the area of the farm on organic (peat-derived) soils increases ($r^2 = 0.61$). This relationship also explains much of what was reported in Tables 1-3 above. In essence the emissions of nitrous oxide from organic soils dominate the overall level of emissions from these farms. The greater the area of the farm, the more chance it has of including organic soils, most of which are in the uplands. Similarly, if the farm has organic soils, then the emissions are large for both sheep and beef.

Footprints using local data on nitrous oxide emissions, and available nitrogen.

Carbon footprints per hectare calculated using available N and local soil emissions data are considerably smaller, being on average 48 % of the PAS 2050-compliant footprints (Table 3). Farms without extensive organic soil show smaller differences in footprint per ha (e.g. Farm 6; 7 % reduction) while those with extensive grazed peatland had much larger differences, e.g. Farm 14 footprint decreased by 79 %. Farm 2 still had the lowest footprint with 722 kg CO_2e /ha/yr while farm 6 had the greatest level of emissions with 6308 CO_2e/ha/yr. There was a similar level of variation in the outputs per unit product with Farm 16 having the lowest footprint per kg of lamb (4 kg CO_2e /kg) and Farm 7 had the greatest with a footprint of 18 kg CO_2e /kg. The footprint per kg liveweight of beef was greater than that of lamb in nearly every case and varied between a low of 4 and a high of 23 kg CO_2e /kg. The footprint of wool remains quite low: for most farms at or near 1 kg CO_2e /kg, but it did reach 4 kg CO_2e /kg on two farms.

As a result of the lower ‘local’ emissions factor used for organic soils and a smaller N contribution from manure in these footprints, the relative importance of nitrous oxide (N_2O) in the farm footprints has declined. Methane provided the greatest proportion (average 58 %) of the GHGs emitted from the farms in all cases (Table 4). Emissions of methane are dominated by enteric fermentation from livestock and they tend to vary according to the type and numbers of stock the farms carry. Emissions from nitrous oxide (N_2O) in these footprints average 15 % of the farm footprint, primarily from soil management (in response to the application of mineral N and manure). Their proportional importance depends on stock numbers and the relative contributions from inputs such as concentrates and fertilisers. The total emissions relating to farm inputs represented a relatively larger proportion (average 20 %) of the overall farm emissions. The reduced importance of organic soils in these farm footprints meant that the relationship previously identified between organic soils (and farm size) was no longer significant ($R^2 = 0.02$, graph not shown).

Table 3 – Overall ‘local’ carbon footprints for each farm, expressed as footprint (kg CO_2e) per ha, and per kg product e.g. (liveweight) beef, per kg (liveweight) lamb, per litre milk (where relevant) etc. The three farms in bold type have higher C-sequestration estimates than their local-data emissions footprints.

FARM	Carbon footprint, kg CO_2e			
	ha	kg lamb	kg beef	kg wool
1	2,196	7	13	1
2	**722**	**13**	**8**	**1**
3	1,927	11	14	3
4	2,846	7	17	2
5	2,270	17	23	1
6	6,308	15	-	4
7	2,981	18	14	1
8	9,203	10	15	1
9	1,375	9	13	2
10	**912**	**7**	**-**	**2**
11	2,214	9	9	2
12	1,001	13	16	3
13	1,461	12	16	1
14	**890**	**9**	**-**	**2**
15	3,311	9	8	1
16	2,876	4	4	1
17	2,163	12	11	2
18	1,740	12	-	4
19	2,389	12	13	1
20	3,165	9	-	2

Table 4 – Breakdown of the key elements of the ‘local’ farm footprint (per ha) – emissions from energy use, fuel and transport, soil management (primarily the application of organic and inorganic nitrogen), direct emissions from organic soils, manure handling systems and direct emissions from stock (methane from enteric fermentation and excreta). Numbers are expressed as percentages.

FARM	Footprint per ha (kg CO_2e)	Percentage contribution to the farm C-footprint								
		All inputs	*(fuel and transport)*	*(electricity)*	*(agrochemicals inc. fertilisers)*	N_2O			methane	lime
						soil management	organic soil	manure handling		
1	2196	24	*4*	*0.1*	*7*	15	3	1	58	0.2
2	722	7	*2*	*0.1*	*3*	37	6	0	48	1
3	1927	15	*5*	*0.9*	*4*	13	1	1.3	69	0
4	2846	13	*4*	*0.4*	*6*	18	-	0	68	0.8
5	2270	26	*5*	*0.2*	*14*	6	0.9	0.2	63	5
6	6308	27	*3*	*0.1*	*11*	6	0.0	1	66	0.1
7	2981	21	*5*	*0.2*	*8*	14	3	1	59	2
8	9203	13	*1*	*0.1*	*7*	11	1	1	42	1
9	1375	19	*6*	*0.1*	*7*	17	6	0.1	57	0.3
10	912	12	*2*	*0.0*	*2*	15	7	0.1	66	-
11	2214	22	*3*	*0.5*	*11*	16	2	1	55	3
12	1001	16	*5*	*0.3*	*7*	13	9	1	61	0.6
13	1461	9	*2*	*0.1*	*5*	13	6	1	71	0.1
14	890	18	*4*	*0.1*	*14*	19	11	2.5	47	2
15	3311	17	*6*	*0.1*	*5*	4	-	0.1	76	3
16	2876	46	*5*	*1.7*	*10*	10	3	1	37	4
17	2163	24	*2*	*0.2*	*8*	13	3	1	57	2
18	1740	21	*4*	*0.2*	*8*	18	3	1	57	-
19	2389	24	*4*	*0.1*	*6*	12	2	0.3	62	-
20	3165	26	*3*	*0.0*	*13*	16	1	0.1	51	6

Carbon sequestration

Levels of carbon sequestration vary substantially between the farms, although more than half the farms fall in the range of 800-900 kg CO$_2$e/ha/yr (Table 5). Some farms had engaged in tree felling during the sample year and this had a negative impact on overall sequestration in that time period. The majority of modelled sequestration occurred in soils under (permanent) grassland. However, there is considerable uncertainty surrounding the level of sequestration that does occur on grassland soils. This uncertainty relates to the level of sequestration that occurs on grasslands of different types and ages. For example, as soil carbon tends to be lost from arable rotations, then soil carbon will tend to increase under grassland established on land previously utilised for arable crops. However, at some point equilibrium may be reached and very little soil sequestration then occurs; indeed it may even become zero. The time taken to reach this equilibrium is unknown for most grasslands. The mid-range value used to estimate the values presented in Table 3 was 0.24 tC/ha/yr, while the minimum value reported by Janssens *et al.* (2005) was 0.04 tC/ha/yr, which is 6 times lower than the mid-range value. If the grassland soils on the case study farms are sequestering carbon at rates towards the lower end of the range, then on-farm sequestration will be many times lower than reported in Table 5.

Table 5. Estimated annual carbon sequestration (tCO$_e$/yr) in different elements of the farm ecosystem. Negative figures indicate a loss of carbon from that source, e.g. through felling of trees. NB These data are based on the mid range of values for sequestration in each element. The actual level of sequestration may vary substantially from the estimates provided by these ‘mid values’.

FARM	Sequestration per ha (kg CO$_2$e)	Percentage of C-sequestration by habitat			
		woodland (net)	isolated trees	hedges	grassland (soils)
1	910	5	10	1	84
2	945	13	13	0	74
3	1119	25	3	0	73
4	1194	5	18	6	72
5	979	9	2	2	87
6	1202	7	12	9	73
7	745	*-14*	-	-	100
8	888	*-2*	-1	11	91
9	929	*-2*	6	1	95
10	1457	32	18	4	46
11	752	17	7	-	76
12	880	0	1	1	98
13	869	1	2	1	96
14	933	1	6	-	92
15	959	7	1	6	86
16	1474	20	12	9	58
17	989	2	3	2	93
18	823	6	9	-	84
19	1025	-	-1	14	87
20	1522	13	33	1	53

There is less uncertainty surrounding the level of carbon sequestration in trees of known species and age. However, it was felt too onerous a task to ask farmers to record the species and size (e.g. diameter at breast height) for every tree on their farm. For this reason the calculations for carbon sequestration for woodlands and individual trees on farms are subject to an unknown level of uncertainty. However, it is unlikely that this would result in overwhelming systematic bias as some trees will be smaller or younger than the average assumed in the model and some will be larger or older. Regardless of these uncertainties it is apparent that those farms that tend to have the highest levels of overall sequestration also tend to have high sequestration in woodlands and isolated trees. This emphasises the important role that trees can play in sequestering carbon on farms. The only slight uncertainty about using trees in this way relates to the final use of the timber. Obviously felling and burning of wood for fuel will release the carbon back into the atmosphere, whereas if timber were utilised in construction most of the carbon would remain locked up in the timber. However, if timber burned for fuel is substituting for fossil fuel use, this will still make a positive impact on reducing GHG emissions from a global perspective.

Carbon balance and carbon offset

Under PAS 2050 guidelines, biogenic carbon stored in vegetation and soils cannot be assumed to "remain[s] removed from the atmosphere for one year or more following production of the product" or to be stored in the product (as in timber used in construction) for a defined proportion of the 100-year CO_2e measuring period. However, our estimation of the C-sequestration in trees and soils on farms allows a novel comparison between carbon footprint (per ha) and carbon sequestration, although this cannot be considered to constitute C-offset. Since this comparison is outside the defined boundaries of PAS 2050 we present the comparison for both PAS 2050 and 'local' footprints, but discuss only the 'local' data.

Farms in the Cambrians sequestered an average of 1 tonne (1025kg) CO_2e /ha / year, or 58 % of their 'local' emissions footprint (25 % of PAS 2050-compliant emissions). Three farms sequestered more than 1400kg/ha/yr, and the lowest sequestration calculated was Farm 11 (752 kg/ha/yr) (Table 5). Most of this sequestration was in the form of soil carbon (average 81 %); reaching 100% in a farm with no isolated trees and some wood harvesting reported (Farm 7) and as little as 46 % on a farm with relatively extensive woodland and large numbers of isolated trees (Farm 10). Woodland contributed an average of 7 % of estimated C-sequestration, varying between 33 % (Farm 20) and zero or net C-emission of 14 % on farms where harvesting operations took place during the sample year. Hedges contributed an average of 5 % of estimated sequestration, in a range from 14 % (Farm 19: few trees and no woodland) to < 1 % (three farms with few hedges or all hedges flailed in the sample year).

Three farms (Farms 2, 10 and 14) sequestered more carbon per ha than their farm emissions footprint per ha, and may be considered C-neutral or net C-sinks with respect to their 'local' footprint (Figure 5).

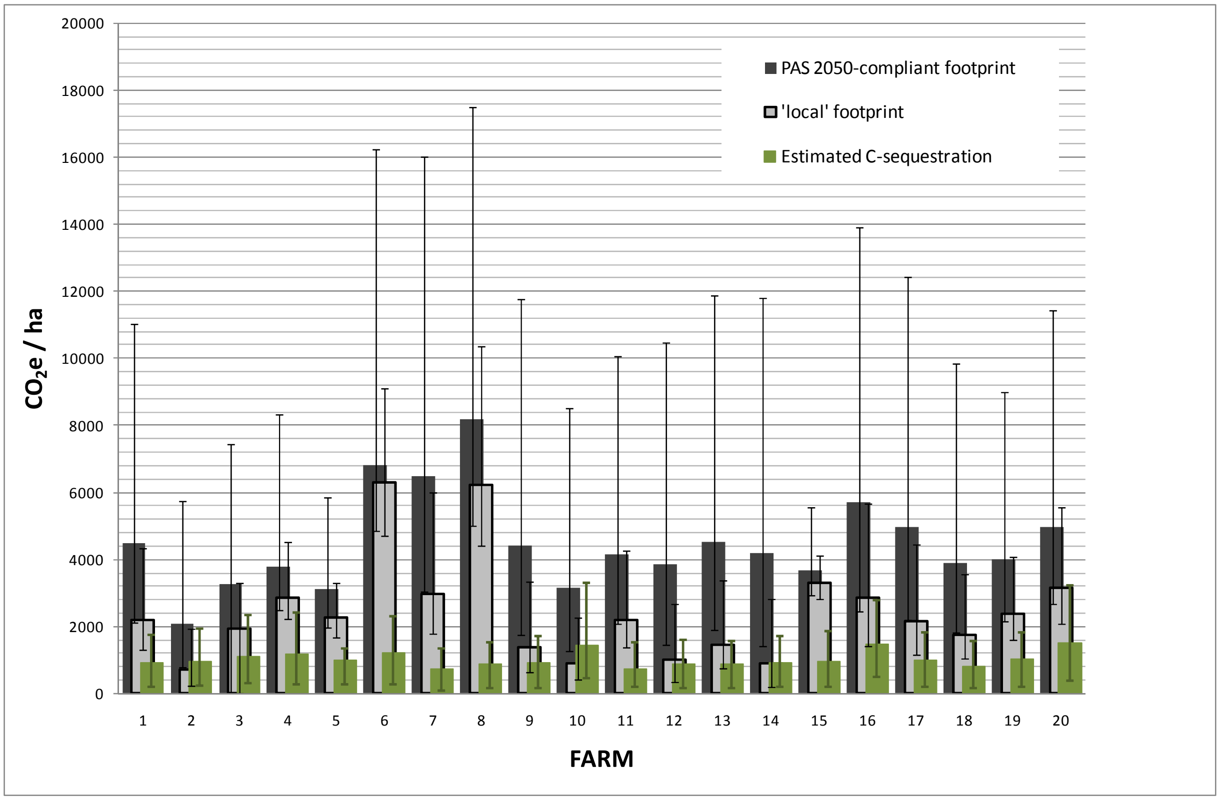

Figure 5. Footprint per ha (PAS 2050 Tier 1 and local-data) compared with estimated C-sequestration (potential C-offset). Error bars show maximum and minimum values taking into account the full range of scientific uncertainty in GHG emissions and sequestration estimates.

Modelling the potential for management change

A detailed breakdown of the impacts of some possible management changes that might be considered likely to reduce GHG emissions on a livestock farm is shown in Table 6, and a summary of the overall results across 20 CMI farms is shown in Table 7. The biggest decrease in GHG emissions was consistently obtained from reducing stock numbers, with the greatest decrease (4.6 %) being modelled on farm 4 (Table 7). While all of the other modelled changes resulted in reductions in GHG emissions, these tended to be less than 1 % of the PAS 2050-compliant footprint (Table 7). Given that the modelled changes were all relatively small in magnitude, then perhaps their relatively small impact could have been predicted. However, these results clearly indicate that emissions are unlikely to be significantly reduced by easily implemented management options.

The management options that sought to increase C sequestration rates on farm showed greater impacts, but overall they also tended to be relatively small in magnitude (Table 8, Table 9). The percentage increases in on-farm sequestration arising from the modelled options tended to vary with the structure of the farm.

Table 6 – Breakdown of the key elements of the farm footprint (per ha) of a single farm (Farm 2) for different management scenarios, highlighting the sensitivity of the farm C-footprint to changes in N-fertiliser use, stock numbers and manure management systems. Numbers are expressed as percentages.

	Scenario considered	Footprint per ha (kg CO_2e)	% change	Percentage contribution to the farm C-footprint									
									N_2O				
				All inputs	*(fuel and transport)*	*(electricity)*	*(feed)*	*(agrochemicals)*	soil management	organic soil	manure handling	methane	lime
From PAS 2050-compliant footprint													
	Current management	2103		2.5	*0.72*	*0.04*	*0.78*	*0.89*	9.8	70.6	0.3	16.4	0.34
1	Reduce inorganic N by 5%	2103	0.0	2.5	*0.72*	*0.04*	*0.78*	*0.88*	9.8	70.6	0.3	16.4	0.34
2	Reduce stock by 5% (sheep and cattle)	2074	-1.4	2.5	*0.73*	*0.04*	*0.79*	*0.91*	9.5	71.6	0.3	15.7	0.35
3	Manage manure anaerobically	2095	-0.4	2.5	*0.73*	*0.04*	*0.78*	*0.90*	9.7	70.9	0.1	16.4	0.34
4	All manure to AD	2096	-0.4	2.5	*0.73*	*0.04*	*0.78*	*0.90*	10.1	70.9		16.2	0.34
From 'local' footprint													
	Current management	722	*(-66%)*	7.3	*2.11*	*0.12*	*2.27*	*2.60*	37.2	6.4	0.4	47.7	1.00
1	Reduce inorganic N by 5%	720	-0.3	7.3	*2.11*	*0.12*	*2.27*	*2.55*	37.0	6.4	0.4	47.8	1.00
2	Reduce stock by 5% (sheep and cattle)	691	-4.3	7.6	*2.20*	*0.12*	*2.37*	*2.72*	37.0	6.7	0.4	47.2	1.04
3	Manage manure anaerobically	714	-1.2	7.4	*2.13*	*0.12*	*2.29*	*2.63*	36.7	6.5	0.2	48.3	1.01
4	All manure to AD unit	722	0.0	7.3	*2.11*	*0.12*	*2.27*	*2.60*	38.2	6.4		47.1	1.00

Table 7. Summary of the results of management-change modelling (from Tier 1 PAS 2050 footprint) for 20 farms and four different management scenarios; changes in N-fertiliser use, stock numbers and manure management systems. Numbers are expressed as percentages.

FARM	PAS 2050 emissions / ha	% reduction in PAS 2050 emissions footprint for each management change			
		5% reduced N fertiliser	5% reduced stock (sheep and cattle)	Anaerobic manure storage (pit/lagoon)	Manures all through AD unit
1	4,479	-0.3	-2.4	-1.0	-1.1
2	2,103	0.0	-1.4	-0.4	-0.4
3	3,281	-0.2	-3.0	-1.5	-2.8
4	3,786	-0.3	-4.6	-0.4	-0.9
5	3,127	-0.3	-2.3	-0.3	-1.1
6	6,800	-0.6	-3.5	-0.8	-1.7
7	6,485	-0.2	-2.2	-0.7	-0.8
8	8,169	-0.6	-3.6	-1.7	-1.9
9	4,411	-0.2	-1.7	0.0	0.0
10	3,167	-0.1	-1.7	0.0	0.0
11	4,162	-0.3	-2.7	-1.3	-0.9
12	3,877	-0.2	-1.2	-0.5	-0.6
13	4,514	-0.1	-1.7	-0.6	-0.7
14	4,185	-0.2	-1.0	-0.9	-1.1
15	3,667	0.0	-4.3	-0.1	-1.1
16	5,703	-0.2	-1.9	-0.6	-1.3
17	4,954	-0.2	-2.0	-0.7	-0.8
18	3,892	-0.3	-2.3	-0.8	-1.0
19	4,005	-0.3	-2.6	-0.1	-0.7
20	3,281	-0.2	-3.0	-1.5	-2.8

For those farms that had small amounts of woodland, the addition of an extra hectare of woodland had a positive impact on sequestration which offered reasonably high percentage increases (e.g. farm 15 in Table 9). However, on farms with greater levels of existing woodland the addition of an extra hectare still increased overall levels of sequestration, but only provided a small percentage increase over existing levels (e.g. Table 8; farm 14 in Table 9).

Table 8. Breakdown of the key elements of C-sequestration estimates (per ha) for Farm 2 under different management scenarios, highlighting the sensitivity of the farm C-footprint to changes in woodland area, numbers of isolated trees and hedge management. Numbers are expressed as percentages.

Scenario considered		Sequestration per hectare (kg CO_2e)	*% change*	woodland	isolated trees	hedges	grassland (soils)
Current estimated sequestration per year		945		115	120	3	678
1	Woodland area increased by 1ha	950	*0.6*	121	120	3	677
2	Isolated trees increased by 50	948	*0.3*	115	122	3	678
3	No hedges flailed	960	*1.6*	115	120	18	678

Table 9. Summary of the results of management-change modelling from current estimated C-sequestration baselines across the 20 farms under three different management scenarios, highlighting the possible scale of potential C-sequestration with increased woodland area, numbers of isolated trees and altered hedge-cutting regime. Numbers are expressed as percentages. Farms in bold type sequester more $C0_2$e than their emissions per ha.

FARM	(local) emissions / ha	estimated sequestration / ha	% change in carbon sequestration for each management change					
			1ha woodland added		add 50 isolated trees		No hedges flailed	
			%	Seq.	%	Seq.	%	Seq.
1	2,196	910	1.1	920	0.7	916	3.3	940
2	**722**	**945**	0.6	**950**	0.3	**948**	1.6	**960**
3	1,933	1,156	1.2	1,169	0.4	1,160	2.9	1,189
4	2,846	1,194	2.6	1,225	1.8	1,215	2.2	1,221
5	2,270	979	2.1	999	0.9	988	9.5	1,072
6	6,308	1,202	3.0	1,237	1.4	1,219	11.1	1,335
7	2,981	745	1.0	753	4.2	777	3.2	770
8	6,210	888	4.4	928	1.8	904	51.6	1,346
9	1,375	929	0.5	933	2.0	947	12.0	1,040
10	**912**	**1,457**	1.8	**1,484**	1.0	**1,471**	8.3	**1,578**
11	2,214	752	2.7	772	1.7	765	2.3	769
12	1,000	880	0.5	885	0.4	883	2.6	903
13	1,461	869	1.6	883	0.8	875	5.9	920
14	**890**	**933**	0.4	**937**	0.7	**939**	0.0	**933**
15	3,311	959	11.8	1,072	5.0	1,007	32.9	1,274
16	2,876	1,474	3.9	1,532	1.4	1,495	1.0	1,489
17	2,163	989	4.1	1,029	1.7	1,006	0.9	998
18	1,740	823	4.8	862	2.3	842	7.4	884
19	2,389	1,025	8.1	1,109	3.7	1,064	1.4	1,040
20	1,933	1,156	1.2	1,169	0.4	1,160	2.9	1,189

A similar pattern was seen from adding 50 more isolated trees. While the increase in absolute levels of sequestration would be similar across all farms (some small variation due to differences in soil type and potential tree growth rates on different farms), the percentage increase in sequestration varied from a low of 0.3 to 5 % (Table 9). However, the addition of isolated trees is a relatively attractive option to farmers as these trees could be planted on existing field boundaries, which would not reduce the area of land available for production. A large number of trees in field boundaries may affect light intensities and water availability on field margins, which may reduce grass/crop productivity; but they could also offer shelter to stock and act as wind-breaks.

Carbon balance across the Cambrian Mountains producer group

Net carbon balance on farms may be manipulated either by decreasing farm emissions or by increasing C-sequestration (in this study, in trees and soils). Growth rates for trees and woodland vary with farms' soil types and locations, so a single isolated tree sequesters an average of only 0.32 kg CO_2e / yr with a range across the farms of 0.05 to 0.96 kg CO_2e / yr. Across the Cambrians farms in this study, carbon sequestration in one ha mature woodland is equivalent to approximately 92 isolated trees. Offsetting all the 'local' emissions from the entire sample of 20 farms would require converting 1200 ha grazing land to woodland or adding 100,000 isolated trees. On a per-farm basis, this is an average of 77 ha woodland or 6,000 trees: but coordinating tree planting across the group to take advantage of the best growing conditions might reduce this to 250 ha woodland or 30,000 trees.

The averages are also strongly weighted by five farms whose emissions would demand >100 ha woodland each. Seven farms could each offset their emissions by planting only 30 ha woodland or 3,500 isolated trees on their own land.

Table 10 summarises the average GHG emissions footprint(s) and estimated carbon sequestration (potential C-offset) across the producer group and the different management interventions modelled.

Table 10. Summary of the results of management-change modelling for footprint reduction and C-sequestration baselines across the 20 farms.

Footprint	**Emissions / sequestration (kg CO_2e)**			**% change in emissions footprint or sequestration for each management change**			
	per ha	Per kg lamb	Per kg beef	5% reduced N fertiliser	5% reduced stock (sheep and cattle)	Anaerobic manure storage (pit/lagoon)	Manures all through AD unit
PAS 2050	4402	24	27	-0.24	-2.46	-0.70	-1.09
Local	2386	11	13	-0.52	-3.74	-0.65	-1.40
Sequestration				Add 1 Ha woodland	Add 50 isolated trees	No hedges flailed	
	1013	6	6	2.86	-3.41	8.16	

DISCUSSION

Model validation and uncertainty

All mathematical models are simplified representations of reality. Normally when working with models it is possible to run experiments in order to test the accuracy and predictive power of the model. For example, imagine a model concerned with predicting the impact of fertiliser on wheat growth. Here the modeller may run a series of experiments where different wheat varieties were subjected to different levels of light, water and fertiliser and these data would be used to develop the mathematical relationships in the model. Once developed, the model would be used to predict yields from different quantities of light, water and fertiliser, and in order to test the accuracy of the model a series of experiments could be run in order to specifically test the model predictions. This latter process is commonly termed model validation.

It is difficult to apply these processes to the development of models concerned with predicting the GHG emissions of farm systems. This is for two main reasons. Firstly, it is not possible to run 'farm level experiments' in order to collect data which may help develop the model. Secondly, it is not possible with current technology to measure directly the amount of GHGs emitted from a farm over a year, or indeed any time scale. The absence of data to both build and validate the model, means that users need to treat the model outputs with caution.

When building the model used here we tried to ensure its processes and internal validity (i.e. does it accurately perform the mathematical relations do what we want) by getting an experienced modeller from outside the Bangor group to check the model workings. However, the possibility remains that there are mathematical and/or process errors remaining in the final version of the model used in this work. We will only be able to discover any such errors through a process of constant use and review of the model, and by comparing its outputs with those from other models. In order to hasten this process we recommend that modellers in the UK should seek to compare the outputs from models of GHGs by each entering the same data set(s) into their models and then comparing outputs.

There are two other areas of uncertainty in the modelling process. One of these relates to the way on-farm GHG emissions are calculated, and this is discussed in the following paragraphs. A second relates to the quality of the empirical data on GHG sequestration and emissions from different parts of the ecosystem. The uncertainty surrounding carbon sequestration rates in grassland soils was discussed earlier in the report. Similarly, the data on sequestration of carbon into hedgerows is the subject of particular uncertainty. This arises from three main sources. Firstly, there are no data on sequestration in hedges, and in the absence of these data we assumed hedges sequestered carbon at the same rate as short rotation coppice. This assumption may lead to incorrect estimates of carbon sequestration. Secondly, we had no data on the actual biomass contained in a 1 m length of hedge, and again the assumptions adopted here could be incorrect. Finally, the farmers' estimates of hedge length may be inaccurate.

It should also be noted that the impact of not flailing hedges depends very much on what the farmer did in the case study year. If he flailed his hedges in the case study year then the model will assume all his hedges to be in equilibrium – i.e. that the carbon sequestered in woody material in stems and roots is balanced by carbon losses from decomposition of the cut stems and some root dieback after cutting. If he did not flail his hedges in the case study year the model will assume that all his hedges sequestered carbon in growing stems and expanded root systems. (Most farmers flailed a stated percentage of their hedges in the study year, and this percentage has been modelled as remaining in equilibrium, while the remainder sequestered a small amount of carbon). Finally, it is debatable whether or not it is appropriate to consider hedge flailing within a farm-level model. If a farmer did not flail his hedges in one year, then he would sequester an increment of carbon in that year, and this would be more than if he had flailed them. However, if at some point in the future he does flail the hedges then it is likely that the carbon sequestered in the cut wood over the previous years will be lost. It is hard to state this definitively as the level of carbon loss will depend on how the farmer treats the cuttings; but if they are left to decompose naturally then a large proportion of the sequestered carbon will be emitted to the atmosphere (some may also be taken into the soil). The impact of flailing hedges was studied here mainly because this issue had regularly been raised by farmers in previous studies and meetings; many farmers felt that it was unfair that carbon sequestration in trees and hedges could not be counted in their favour when conducting carbon footprints. However, as the results show, while hedges do lock up some carbon, the levels sequestered are low compared to levels of emissions, and further the carbon in hedges would need to be locked up over the long term in order to have any meaningful impact on overall GHG balances on the farm.

A fourth and final issue relates to the accuracy of the data provided by farmers. If farmers provided inaccurate data on their farm businesses then this will be reflected in the final outcome of the model. There is no direct way to check for such occurrences. We do not believe that there was any evidence that farmers would have systematically biased their responses to the survey, however there is the possibility that random errors occurred. One way to deal with such occurrences is to collect similar data at different times in the future, for example annually or bi-annually; and start to develop long-term data on the different components of their carbon footprints. These data might then be used to identify any random errors introduced in a given year.

Organic soils and IPCC methods

Many of the farms analysed in this study had large areas of ‘organic soils’ (i.e. soils with high levels of organic matter). According to the current IPCC methods ‘managed organic soils’ are responsible for emitting considerable amounts of N_2O. These emissions are purely a function of the biological activity of these soils and are not related to any inputs of fertiliser or manure. They do not occur on mineral soils. This is a particular problem for Welsh farmers as much of the soil in Wales is classified as ‘organic’.

The importance of applying IPCC methods to Welsh farms is apparent from the large difference in the levels of emissions of N_2O that are obtained by following the IPCC methods compared with using empirical measurements of N_2O from organic soils in Wales (the ECOSSE data). Given these differences it is important that the relevant issues are clarified and agreed with IPCC and other relevant bodies. As a result we recommend that the Welsh Assembly Government (or its agencies) clarify whether or not grazed organic soils, as occur across Wales, are classified as ‘managed’ by IPCC.

If Welsh grazed soils are defined as ‘managed’, and therefore their N_2O emissions need to be included in any footprints, then it is necessary to understand the level of N_2O that should be included in calculations. Currently the IPCC method suggests a method that can be used to calculate the relevant levels of N_2O emissions from soils, fertilisers and manure (a so-called Tier 1 method). As seen from the model results there is a large difference in N_2O emissions when IPCC methods are used, compared with the measured levels of N_2O emission. Unfortunately, the local measured data are not yet eligible to be used in the IPCC method. This is because IPCC has three Tiers of calculation. Tier 1 is a series of equations that are to be used in the absence of verified data on specific emissions. Tier 1 methods are defined in order to be applicable in any region across the globe. This inevitably reduces their applicability to any one location. Tier 2 and 3 methodology tries to get around this issue by enabling the use of local verified data instead of the Tier 1 methods. The ECOSSE data are analogous to Tier 2 data, but are not yet formally recognised as such. This is a major problem for Welsh farmers, and it is a major recommendation of this work that Wales should seek to develop a set of Tier 2 data that are available to use when considering the carbon footprints of Welsh farms and food products.

Sources of emission and farmer responses

It is clear from the results that the majority of GHG emissions from farms in the Cambrian Initiative are derived from soils (N_2O) or ruminant livestock (CH_4). The emissions derived from the construction and use of inputs is relatively low, and varies between 2 and 25 % of total PAS 2050-compliant farm-level emissions. Much of this variation is related to the nature of soils on the farm. Typically on those farms with large areas of organic soils the direct inputs comprise a small percentage of total emissions, but they comprise a greater proportion on farms with few organic soils. These results are in line with the results of other studies (e.g. Edwards-Jones et al. 2009b, Williams et al. 2006) which suggest that direct inputs to extensive beef and lamb systems are low in relative and absolute terms. At one level this is good news for livestock farmers as their direct farming activities are having a minimal impact on the climate. However, at another level this pattern of emissions is worrying for farmers as it is extremely difficult for them to actively reduce the total levels of emissions from their farm systems. This issue is highlighted by the results of the modelled changes to the farm systems (Table 7). These data suggest that none of the mitigation options modelled reduced overall emissions by more than 5 %. Stock reduction was the most effective mitigation option modelled, but clearly any such reduction would have financial impacts for farmers, and therefore may not be universally welcomed by them. The mitigation options modelled here are only a small set of possible mitigation options, and further work is needed to more fully explore the impacts of possible mitigation activities on GHG emissions, farm structures and farm finances.

While these results suggest limited potential for farmers to reduce emissions by making small changes to their businesses, they also highlight the need for continued research in areas related to methane emissions, e.g. stock breeding, stock management and /or technological interventions for reduced methane production. There is also a need for further research work on a range of issues relating to N_2O emission from soils and manure.

It is interesting to note that while there may be relatively little potential for sheep and beef farmers to easily reduce GHG emissions by changing their management practices, previous studies on the lamb supply chain have suggested that the footprint of cooked lamb can be reduced by up to 32 % by the adoption of known technologies related to renewable electricity, biofuels, anaerobic digestion, waste reduction and packaging (Taylor *et al.* 2009). This is important as PAS 2050 product-level footprints are comprised of emissions from across the supply chain. So if Welsh farmers want to reduce the footprint of food products bought by consumers then they need to work with other stakeholders in the supply chain in order to bring about real reductions in GHGs / kg product. In the short term, such a supply chain approach is more likely to offer potential for GHG reductions than is a strategy which is focused solely at the farm level. We recommend that the Cambrian Producer Group discuss these issues with processors and retailers in order to explore the possibility of reducing GHGs from across their supply chains.

Sequestration options on farms

The model results suggest that many of the farms are sequestering significant amounts of carbon in their soils and woody vegetation. Indeed in some situations some farms may be sequestering more than they are emitting. The greatest level of sequestration is occurring in soils (typically 46 % to 100 % of all on-farm sequestration). As noted earlier in this report there is relatively little empirical data available on carbon sequestration on soils under grazed grassland, and further the existing data suggest a range of possible sequestration rates. As a result the estimates of carbon sequestration presented here could actually range from zero (no sequestration occurring) to double the estimates presented here.

The sequestration rates of trees are better studied than those of grassland soils, however significant uncertainties remain in estimating sequestration on farms. This uncertainty relates to the level of information on tree species and size provided by farmers. In order to make the survey as practical as possible, only basic information on woodland and trees were requested from farmers. As a result sequestration rates for each farm are not as precise as would be possible if more accurate data on tree size and species were obtained. We do not expect these assumptions to introduce any systematic bias into the model calculations, although we do recognise that more precise estimates would be possible if better information were available. While we may have expected woodland to sequester carbon, the model results suggest that isolated trees around the farm can also sequester significant amounts of carbon.

Planting more woodlands and isolated trees both offer potential to sequester more carbon on the farms. An extra 1ha of woodland on the farms in the study could increase annual sequestration rates by up to 12%, while planting 50 isolated trees could increase sequestration rates by up to 5%. The model also suggests that a change in hedge cutting regimes could also offer some carbon sequestration, but these estimates are based on quite uncertain input data.

The results of the model support other work that suggests that trees offer real potential for on-farm sequestration (if planted in appropriate places and managed correctly). However, it is important not to underestimate the level of tree planting that would be needed to offset the emissions from agricultural activities. For example, across this sample of Cambrians farms, on average each farm would need to plant 6,000 isolated trees or 77 ha woodland to offset emissions from the whole producer group. However, offset requirements vary considerably between farms, and part of this discussion should consider the appropriate scale for plantings, i.e. should each individual farms aim to be ‘carbon neutral’ or should sequestration strategies be enacted at larger spatial scales (e.g. catchments, counties, regions)? Variation in tree growth rates between farms (as a result of differing soil types and elevation) highlights the potential benefits of cooperative planning: the sum total of individual farms’ offset requirements across the group is equivalent to 94,987 isolated trees or 1,232 ha woodland. If tree planting were coordinated across the group to take advantage of farms with the best growing conditions, the Group’s carbon offset might be reduced to 250 ha woodland or 30,000 trees. We recommend that WAG (and its agencies) discuss potential for further woodland plantings with relevant farming organisations.

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APPENDIX I: ANONYMISED FARM REPORT

Farm Carbon Footprint:

4479 kg CO_2e per hectare

What is a carbon footprint?

A carbon footprint summarises the greenhouse gases (GHGs) emitted from a defined system, and is a crucial starting point for any business to begin to understand and manage its emissions. For each of the 23 farms participating in the Cambrian Mountains carbon footprinting exercise this individual farm report is the first stage in your carbon management process.

What is included in my farm carbon footprint?

The farm questionnaire completed by you was designed to provide sufficient detail on farm inputs and processes to enable us to calculate emissions of the three most significant GHGs from agricultural activities i.e. carbon dioxide (**CO_2**), nitrous oxide (**N_2O**) and methane (**CH_4**). Within this report all emissions are expressed in terms of carbon dioxide equivalents (CO_2e). Converting emissions to carbon dioxide equivalents is a way of taking account of the different impacts these three gases have on the atmosphere. Please see the glossary for a more detailed discussion of this issue.

In your farm carbon footprint we have included all emissions arising from the manufacture and transport of farm inputs such as fertilisers and bedding; emissions from all processes on farm such as energy use, emissions from livestock, from manure management and soils. Emissions arising once produce has left your farm (e.g. meat processing, retailing and consumption) are not included. In addition to this standard “cradle to gate” footprint we have estimated carbon sequestered by vegetation and soils on farm (see glossary). Stemming from this we have calculated how much of the farm’s emissions are offset by sequestration in vegetation and soils to produce a farm balance emissions figure.

Emissions from the disposal of dead livestock, the production of antibiotics and vaccines and emissions from clover in the grass sward have not been included in the footprint given the lack of emissions data available in the literature relating to these components of the farm system.

How was my farm carbon footprint calculated and is it accurate?

The data you provided in your farm questionnaire was coupled with standard equations, emissions data and sequestration estimates for each vegetation type to produce a model which calculates the CO_2e emissions of each farm input and process, and the carbon sequestered by each vegetation type.

In your results section you will find two footprints for your farm. The first was calculated using internationally accepted emissions values (IPCC) and is PAS 2050 compliant (see glossary). You should use this footprint if asked to provide PAS 2050 compliant data or if comparing with other PAS 2050 footprints. All figures quoted within this report are from your PAS 2050 footprint unless otherwise stated.

Because the emissions values used in the calculation of a PAS 2050 footprint are standard international values they may not be representative of the Welsh situation, and may in fact over estimate the “true” carbon footprint of Welsh farms. To account for this, we have produced a second footprint which uses locally derived data where available. Whilst this footprint is likely to provide a more accurate representation of your farm emissions it is not PAS 2050 compliant. If you are comparing the figures for your farm to those published by EBLEX then you should use this second footprint to ensure a fairer comparison.

Carbon flows through soils and vegetation are poorly understood and because of this our understanding of the sequestration potential of vegetation and soils is limited. We have estimated your carbon sequestration as carefully as possible in line with current scientific understanding, but there is considerable uncertainty in these calculations and the real values may vary quite a lot from the average figures we quote here.

You will find the full range of values for your carbon footprint and carbon sequestration in Appendix 1. These figures allow for the range of scientific uncertainty in international standard values. For clarity, in the main body of the report we have presented only the middle (‘mid’) values which we believe represent the ‘best-estimate values’.

For your farm footprint we have made some additional assumptions where information was incomplete. These assumptions / exclusions are unlikely to make any noticeable difference to the farm footprint values. They were as follows:

- Livestock sent away to tack were transported in a 26-tonne rigid-wheelbase lorry.
- The power outputs and fuel tank capacities of tractors used by contractors were estimated as following: 355 hp forage harvester, 95hp tractor with mower, 120 hp tractors with trailers, 120 hp tractor with hedge flail, 95 hp tractor with slurry pump.
- Feed and concentrates were delivered in a >17 tonne rigid-wheelbase lorry.
- Diesel use for the transport of 1816 kg of wool by a haulier was excluded (no journey distance given).
- The remaining wool was transported in a 7.5 to 17 tonne rigid-wheelbase lorry.
- For woodland sequestration calculations, where species composition was described as ‘mixed’ we assumed 50% conifer and 50% broadleaf average values.

What are the results?

For the sample year 1st October 2008 to 30th September 2009, your whole-farm emissions were estimated to have been:

2,606,295 kg CO_2e

(within a possible range of 1,229,508 to 6,422,625 kg CO_2e)

Table 1 gives a summary breakdown of your farm's GHG emissions. Emissions data in kg CO_2e are given per kg of produce for your sample year (1st October 2008 to 30th September 2009). Emissions per unit of produce are the standard units used and this is what is typically communicated to consumers. Emissions have been allocated to farm enterprises based upon their economic contribution to your farm business, according to the prices you provided in your farm questionnaire. In the sample year, lamb sales accounted for 48.4% of your farm income and therefore 48.4 % of your farm emissions have been allocated to this enterprise; similarly 2.6% to live sheep sales, 45.8% to beef, 3.1% to live cattle sales and 0.2% to wool production.

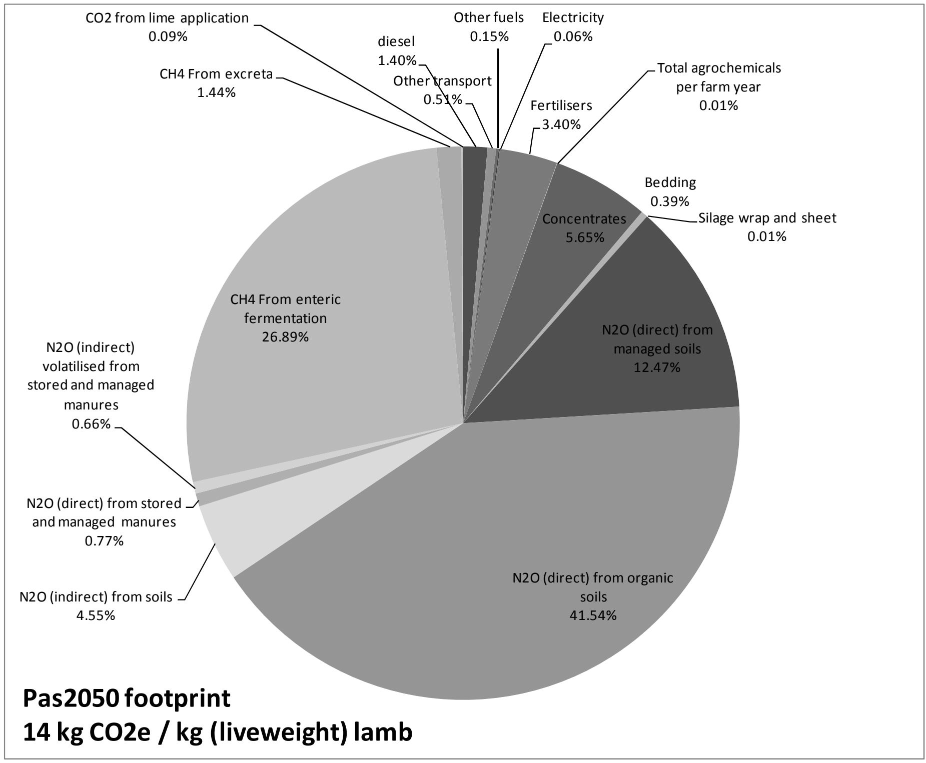
Of your farm produce, beef has the largest carbon footprint per kg sold, followed by lamb. Figures 1 and 2 give a percentage breakdown of the carbon footprint per kg of product. Figure 1 uses international emissions data and is PAS2050 compliant. Figure 2 uses local data where available and is likely to provide a truer representation of your farm emissions; this is not PAS 2050 compliant but should be used for comparison with Eblex carbon footprints.

Table 1. Your farm’s carbon footprint in kg CO$_2$e per kg of produce

CARBON FOOTPRINT	**kg CO2e per kg sold**		
Direct inputs	lamb	beef	Wool
diesel	0.20	0.38	0.02
Other transport	0.07	0.14	0.01
Other fuels	0.02	0.04	0.00
Electricity	0.01	0.02	0.00
TOTAL	**0.30**	**0.57**	**0.03**
Indirect inputs			
fertiliser - N per farm year	0.46	0.87	0.04
fertiliser - P per farm year	0.00	0.00	0.00
fertiliser - K per farm year	0.00	0.01	0.00
fertiliser -sulphur per farm year	0.00	0.00	0.00
fertiliser - lime per farm year	0.02	0.04	0.00
Total agrochemicals per farm year	0.00	0.00	0.00
Concentrates	0.80	1.52	0.07
Bedding	0.05	0.10	0.00
Silage, wrap and sheet	0.00	0.00	0.00
TOTAL	**1.34**	**2.54**	**0.12**
TOTAL EMISSIONS FROM FARM INPUTS	*1.64*	*3.11*	*0.14*
CO2e from N2O			
Direct N2O from managed soils			
Inorganic N fertilisers	0.34	0.64	0.03
Sheep manure/excreta	1.13	2.15	0.10
Cattle manure/excreta	0.29	0.56	0.03
Direct N2O from organic soils	5.87	11.16	0.51
Indirect N2O from soils			
N2O from atm dep of volatilised N	0.27	0.51	0.02
N2O from leaching / runoff	0.37	0.71	0.03
Direct N2O from stored and managed manure			
Sheep	0.05	0.09	0.00
Cattle	0.06	0.11	0.01
Indirect N2O (volatilisation) from stored manure			
Sheep	0.04	0.08	0.00
Cattle	0.05	0.09	0.00
TOTAL	**8.48**	**16.11**	**0.73**
CO2e from CH4			
From enteric fermentation			
Sheep	2.24	4.26	0.19
Dairy cattle	0.00	0.00	0.00
Beef cattle (B)	1.56	2.97	0.13
From excreta			
Sheep	0.05	0.10	0.00
Dairy cattle	0.00	0.00	0.00
Beef cattle (B)	0.15	0.29	0.01
TOTAL	**4.01**	**7.61**	**0.35**
CO2 from lime application	0.01	0.03	0.00
TOTAL FARM FOOTPRINT	**14.14**	**26.86**	**1.22**

These emissions data include all farm inputs and processes and are compliant with PAS 2050

Figures 1 and 2. The percentage contributions of farm inputs and processes to your carbon footprint in the sample year 1st October 2008 to 30th September 2009.



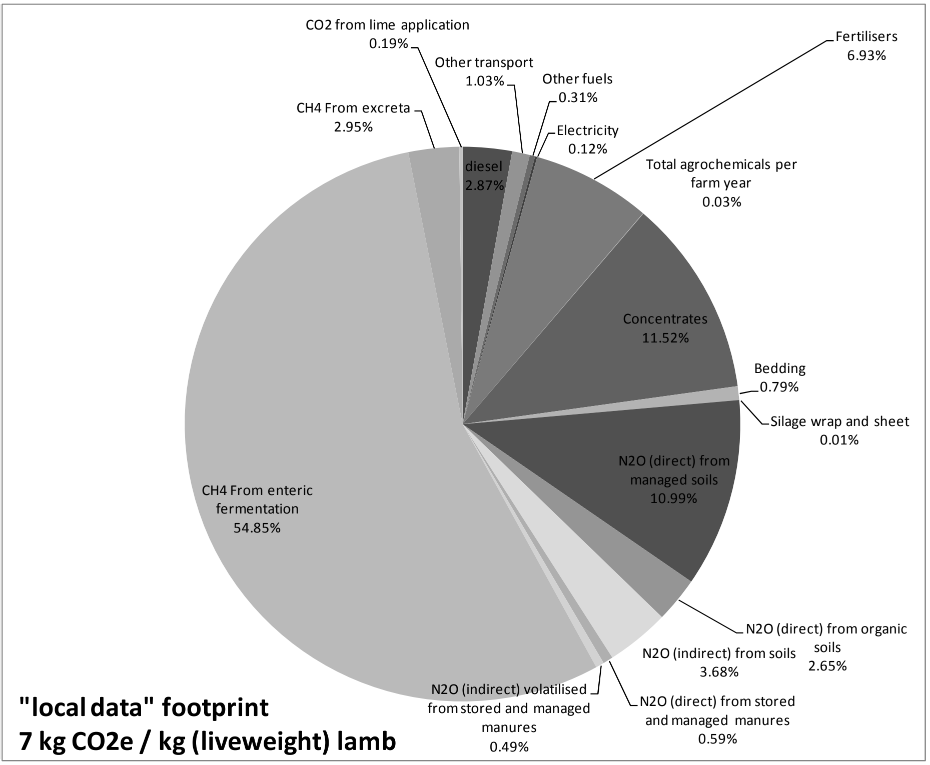


Figure 1. PAS 2050 compliant footprint calculated using internationally accepted emissions values.

Figure 2. Non PAS 2050 compliant footprint calculated using local emissions values, where available.

The footprint glossary at the rear of the report gives an explanation of each emissions category.

For every kg of lamb produced 14 kg CO_2e were emitted in the sample year.

In the second (non PAS 2050 compliant) footprint, emissions per kg of lamb produced have decreased from 14 kg CO_2e to 7 kg CO_2e. This is likely to be a more accurate representation of your farm emissions and clearly highlights enteric fermentation and the use of concentrates as focal points for emission reduction efforts.

How do my results compare to others in the Cambrian Mountains?

To put your results in context, figure 3 shows the PAS 2050 footprint, the local emissions data footprint and the sequestration results for all of the farms that particpated in this footprinting process in kg CO_2e per kg of lamb sold. Your farm is number x.

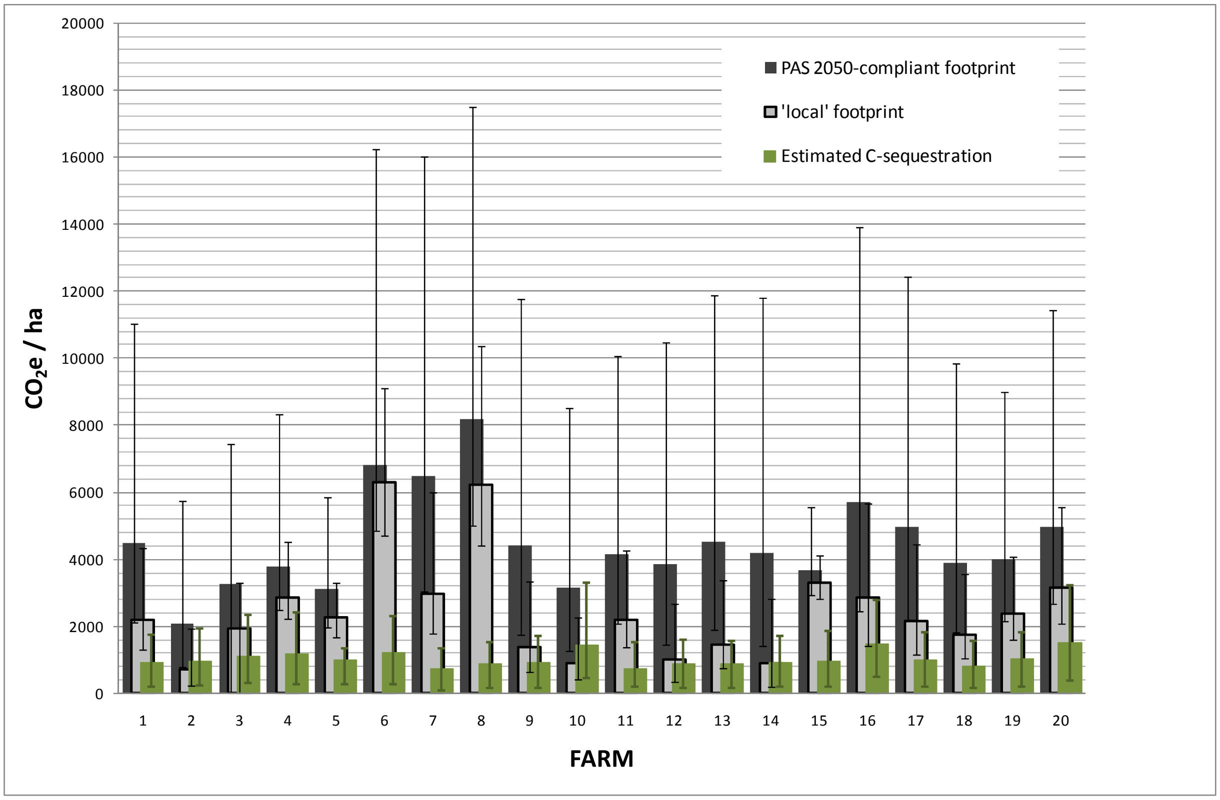


Figure 3. Footprint per ha (PAS 2050 and local-data) and estimated C-sequestration (potential C-offset) for all farms in the Cambrian Mountains Initiative. Error bars show maximum and minimum values taking into account the full range of scientific uncertainty in GHG emissions and sequestration estimates.

What can I do to reduce farm emissions?

Within our carbon footprint model it was possible to explore the impact some potential management changes could have on your farm emissions, these are recorded in the table below. There are many more potential opportunities for reducing emissions which we have not modelled. Some options such as replacing concentrates with home-grown feeds cannot be modelled at present due to the complexity of their knock-on effects, for example we would have to make assumptions on the area of grassland ploughed, the resulting change in animal productivity and its effect on how long animals spend on the farm.

Management change	Category of emissions affected	Farm footprint (kg CO_2e / ha)		% change in farm carbon footprint
		Before	After	
Reduce mineral N fertiliser applied by 5%	N_2O emissions from soils	4479	4465	-0.3%
	Agrochemicals			
Reduce numbers of sheep and cattle by 5% (each)	N_2O emissions from soils	4479	4370	-2.4%
	N_2O emissions from manure and excreta			
	CH4 emissions from enteric fermentation and manure			
Manage manure anaerobically (lagoon and pit storage)	N_2O emissions from soils	4479	4436	-1%
	N_2O emissions from manure			
	CH4 emissions from manure			
All manure handled in AD system	N_2O emissions from soils	4479	4431	-1.1%
	N_2O emissions from manure			
	CH4 emissions from manure			

What about sequestration in farm vegetation?

For the sample year 1st October 2008 to 30th September 2009, whole farm sequestration was estimated to have been:

529, 483 kg CO_2e

(within a possible range of 118,094 to 1,014,166 kg CO_2e)

Deducting the amount sequestered from the amount emitted in the sample year gives an estimated “farm

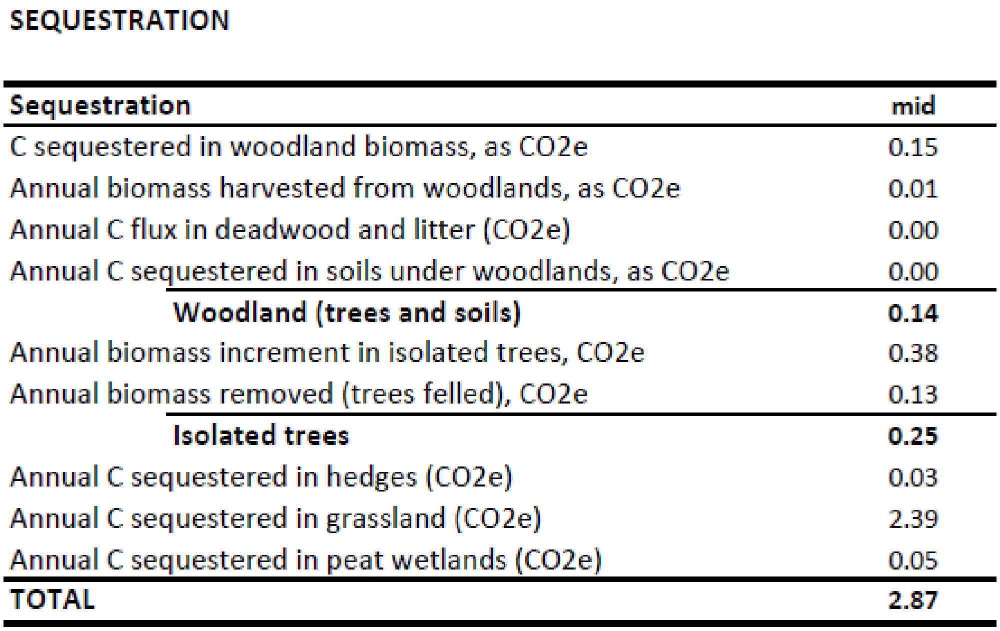
2,076,813 kg CO_2e

(within a possible range of 1,111,413 to 5,408,459 kg CO_2e)

balance” emissions figure of:

Table 2 gives a breakdown of sequestration on your farm. Again, emissions data are given in kg CO_2e per kg of lamb produced. Values relate to the carbon sequestered in biomass and the underlying soil for each vegetation type on your farm within the sample year. For every kg of lamb produced 3 kg CO_2e were sequestered in the sample year.

Table 2. Breakdown of carbon sequestration in farm vegetation and soils within the sample year

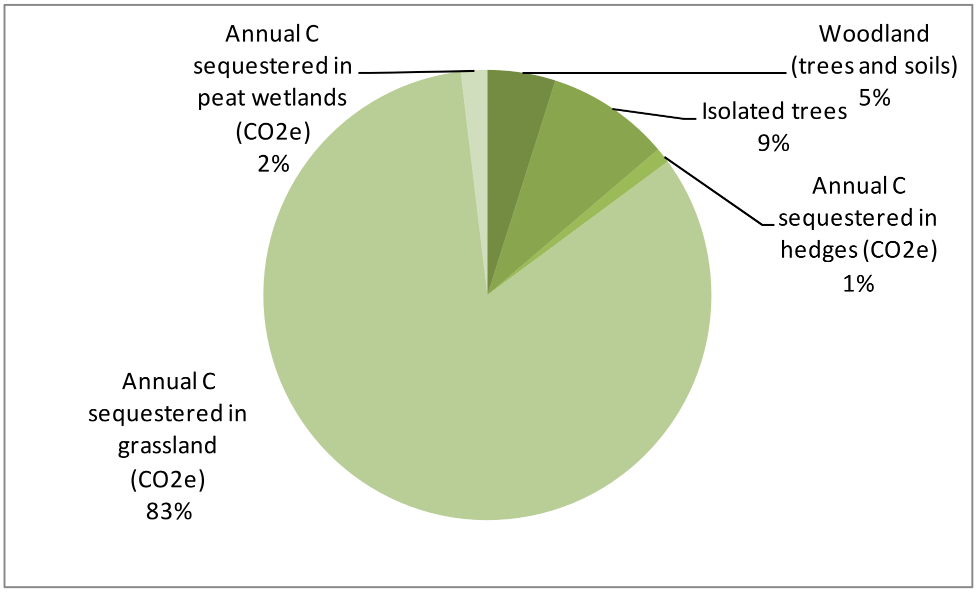


SEQUESTRATION

Sequestration	**mid**
C sequestered in woodland biomass, as CO2e	0.15
Annual biomass harvested from woodlands, as CO2e	0.01
Annual C flux in deadwood and litter (CO2e)	0.00
Annual C sequestered in soils under woodlands, as CO2e	0.00
Woodland (trees and soils)	**0.14**
Annual biomass increment in isolated trees, CO2e	0.38
Annual biomass removed (trees felled), CO2e	0.13
Isolated trees	**0.25**
Annual C sequestered in hedges (CO2e)	0.03
Annual C sequestered in grassland (CO2e)	2.39
Annual C sequestered in peat wetlands (CO2e)	0.05
TOTAL	**2.87**

This method of estimating sequestration as part of farm carbon accounting has been developed by Bangor University; these data are not included in PAS

Figure 4. The percentage contributions of farm vegetation (and underlying soil) to carbon sequestration in the sample year 1st October 2008 to 30th September 2009.



Given its extent, grassland is the predominant carbon sink on your farm. To maintain this sink conversion to arable land and overgrazing should be avoided. Despite covering just 1% of the area of the farm, woodland sequestered 5% of the total carbon sequestered on farm in the sample year.

What can I do to increase sequestration on farm?

Management change	Farm sequestration (kgCO2e / ha) Before	After	% change in farm sequestration
Planting 1 ha more woodland (on mineral soil)	910	920	+1.1%
Planting 50 more freestanding trees	910	916	+0.7%
Stop flailing hedges	910	940	+3.3%

Where can I go for advice on reducing emissions?

Farming Connect's Climate Change Development Programme has been developed to provide information to the farming and forestry industries on reducing greenhouse gas emissions and adapting to the effects of climate change. Please contact 01248 383689 for further information or to find out what events are being held.

Glossary

CO_2e - Carbon dioxide equivalents	Methane (CH_4) and nitrous oxide (N_2O) have 21 times and 310 times the global warming potential of CO_2 respectively. CO_2 equivalents are a unit of measurement of greenhouse gas (GHG) emissions, where the global warming potential of each GHG has been normalised relevant to that of CO_2.
IPCC - Intergovernmental Panel on Climate Change	The leading scientific body for the assessment of climate change which reviews and asses scientific literature to provide rigorous and balanced scientific information.
Pas 2050 - Publicly Available Standard 2050	A method of measuring the embodied GHG emissions of goods and services developed by the British Standards Institution.
Sequestration	The uptake and long term storage of atmospheric carbon for example in soils and vegetation.

Footprint Glossary

Agrochemical - emissions arising from the manufacture and application of pesticides and sheep dips.

Bedding - emissions arising from the manufacture, delivery and disposal of the straw you buy in.

Concentrates - emissions arising from the processing and delivery of feed and mineral supplements.

CH_4 from enteric fermentation - emissions released directly from your sheep and beef cattle.

CH_4 from excreta - emissions from the excreta of your sheep and beef cattle as they are deposited in the field.

$C0_2$ from lime application – emissions from the manufacture, transport and application of lime.

Diesel – emissions from the manufacture, transport and combustion of diesel by the farm business.

Electricity – emissions from the generation, transmission and use of electricity by the farm business.

Fertilisers – emissions from the manufacture, transport and application of fertilisers.

N_2O (direct) from managed soils - emissions arising in response to the application of fertilisers and manure/excreta to managed soils.

N_2O (direct) from organic soils - emissions resulting from the management of high carbon (peat) soils.

N_2O (direct) from stored and managed manures - direct emissions from sheep and cattle manure within your storage and management systems.

N_2O (indirect) from soils - the loss of nitrous oxides from soil through leaching and runoff.

N_2O (indirect) volatilised from stored and managed manures – these emissions are the result of the evaporation of nitrous oxides from sheep and cattle manure within your storage and management systems.

Other fuels - emissions from the manufacture, transport and use of other fuels (e.g. petrol) by the farm business.

Other transport - emissions arising from the use of diesel for all journeys where the diesel was not included in your farm total e.g. the haulage of livestock away to tack. Please see earlier transport assumptions which were used to calculate diesel consumption.

Silage wrap and sheeting - emissions arising from the manufacture of *s*ilage sheeting used on farm.

Appendix I

FARM CARBON FOOTPRINT RESULTS		Per farm year			Per ha (farm excl. woodland)			Per ha total farm			Per unit production based on economic allocation								
		1st October '08 to 30th September '09			574.9			581.9			lamb (liveweight) sold			beef (liveweight) sold			wool sold		
Direct inputs																			
		min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
diesel				36,617.5			63.7			62.9			0.2			0.4			0.0
Other transport				13,171.9			22.9			22.6			0.1			0.1			0.0
Other fuels				3,935.5			6.8			6.8			0.0			0.0			0.0
Electricity				1,594.1			2.8			2.7			0.0			0.0			0.0
TOTAL				55,318.9			96.2			95.1			0.3			0.6			0.0
Indirect inputs																			
		min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
fertiliser - N per farm year		40,024.1	127,970.2	83,997.2	69.6	222.6	146.1	68.8	219.9	144.3	0.2	0.7	0.5	0.4	1.3	0.9	0.0	0.1	0.0
fertiliser - P per farm year		-74.7	329.1	127.2	-0.1	0.6	0.2	-0.1	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
fertiliser - K per farm year		397.8	954.7	676.3	0.7	1.7	1.2	0.7	1.6	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
fertiliser -sulphur per farm year				214.2			0.4			0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
fertiliser - lime per farm year		810.0	6,210.0	3,510.0	1.4	10.8	6.1	1.4	10.7	6.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Total agrochemicals per farm year		66.2	661.8	364.0	0.1	1.2	0.6	0.1	1.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Concentrates		25,164.0	269,348.0	147,256.0	43.8	468.5	256.1	43.2	462.8	253.0	0.1	1.5	0.8	0.3	2.8	1.5	0.0	0.1	0.1
Bedding				10,116.3			17.6			17.4	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0
Silage, wrap and sheet		117.5	171.4	144.5	0.2	0.3	0.3	0.2	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL		76,835.4	415,975.6	246,405.5	133.6	723.5	428.6	132.0	714.8	423.4	0.4	2.3	1.3	0.8	4.3	2.5	0.0	0.2	0.1
TOTAL EMISSIONS FROM FARM INPUTS		min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
		132,154.3	471,294.6	301,724.5	229.9	819.7	524.8	227.1	809.9	518.5	0.7	2.6	1.6	1.4	4.9	3.1	0.1	0.2	0.1
CO$_2$e from N$_2$O																			
		min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
Direct N2O from managed soils	Inorganic N fertilisers	18,679.2	186,792.1	62,264.0	32.5	324.9	108.3	32.1	321.0	107.0	0.1	1.0	0.3	0.2	1.9	0.6	0.0	0.1	0.0
	Sheep manure/excreta	61,118.6	640,950.5	208,238.5	106.3	1,114.8	362.2	105.0	1,101.4	357.8	0.3	3.5	1.1	0.6	6.6	2.1	0.0	0.3	0.1
	Cattle manure/excreta	17,602.8	180,719.1	54,375.5	30.6	314.3	94.6	30.2	310.5	93.4	0.1	1.0	0.3	0.2	1.9	0.6	0.0	0.1	0.0
Direct N2O from organic soils		270,686.4	3,248,296.8	1,082,745.6	470.8	5,649.7	1,883.2	465.1	5,581.7	1,860.6	1.5	17.6	5.9	2.8	33.5	11.2	0.1	1.5	0.5
Indirect N2O from soils	N2O from atm dep of volatilised N	2,379.2	682,018.6	49,815.8	4.1	1,186.2	86.6	4.1	1,172.0	85.6	0.0	3.7	0.3	0.0	7.0	0.5	0.0	0.3	0.0
	N2O from leaching / runoff	11,932.8	79,098.1	68,651.2	20.8	137.6	119.4	20.5	135.9	118.0	0.1	0.4	0.4	0.1	0.8	0.7	0.0	0.0	0.0
Direct N2O from stored and managed manure	Sheep	4,870.5	18,038.8	9,019.4	8.5	31.4	15.7	8.4	31.0	15.5	0.0	0.1	0.0	0.1	0.2	0.1	0.0	0.0	0.0
	Cattle	5,688.4	22,284.5	11,142.3	9.9	38.8	19.4	9.8	38.3	19.1	0.0	0.1	0.1	0.1	0.2	0.1	0.0	0.0	0.0
Indirect N2O (volatilisation) from	Sheep	360.8	58,626.2	8,117.5	0.6	102.0	14.1	0.6	100.7	13.9	0.0	0.3	0.0	0.0	0.6	0.1	0.0	0.0	0.0
	Cattle	609.9	56,001.9	9,206.9	1.1	97.4	16.0	1.0	96.2	15.8	0.0	0.3	0.0	0.0	0.6	0.1	0.0	0.0	0.0
TOTAL		393,928.7	5,172,766.5	1,563,576.6	685.2	8,997.0	2,719.5	676.9	8,888.8	2,686.8	2.1	28.1	8.5	4.1	53.3	16.1	0.2	2.4	0.7
CO$_2$e from CH$_4$																			
		min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
From enteric fermentation	Sheep			413,118.6			718.5			709.9			2.2			4.3	0.0	0.0	0.2
	Dairy cattle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Beef cattle (B)	260,775.9	314,733.9	287,754.9	453.6	547.4	500.5	448.1	540.8	494.5	1.4	1.7	1.6	2.7	3.2	3.0	0.1	0.1	0.1
From excreta	Sheep			9,811.6			17.1			16.9			0.1			0.1	0.0	0.0	0.0
	Dairy cattle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Beef cattle (B)	17,342.2	38,325.8	27,834.0	30.2	66.7	48.4	29.8	65.9	47.8	0.1	0.2	0.2	0.2	0.4	0.3	0.0	0.0	0.0
TOTAL		701,048.3	775,990.0	738,519.1	1,219.3	1,349.7	1,284.5	1,204.7	1,333.4	1,269.1	3.8	4.2	4.0	7.2	8.0	7.6	0.3	0.4	0.3
CO$_2$e from lime application																			
		min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
CO2 from lime application		2,376.2	2,574.2	2,475.2	4.1	4.5	4.3	4.1	4.4	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL FARM FOOTPRINT		min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
		1,229,507.5	6,422,625.3	2,606,295.4	2,138.5	11,170.9	4,533.1	2,112.8	11,036.5	4,478.6	6.7	34.8	14.1	12.7	66.2	26.9	0.6	3.0	1.2

FARM CARBON FOOTPRINT RESULTS

Direct inputs

	Per farm year			Per ha (farm excl. woodland)			Per ha total farm			Per unit production based on economic allocation								
	1st October '08 to 30th September '09			574.9			581.9			lamb (liveweight) sold			beef (liveweight) sold			wool sold		
Farm outputs / exports																		
	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
Lamb meat			16,700.6			29.0			28.7			0.1			0.2	0.0	0.0	0.0
Live sheep			2,047.8			3.6			3.5			0.0			0.0	0.0	0.0	0.0
Beef (stores to slaughter)			8,303.6			14.4			14.3			0.0			0.1	0.0	0.0	0.0
Live beef cattle sold			617.2			1.1			1.1			0.0			0.0	0.0	0.0	0.0
Live dairy cattle sold			0.0			0.0			0.0			0.0			0.0	0.0	0.0	0.0
Milk produced			0.0			0.0			0.0			0.0			0.0	0.0	0.0	0.0
Wool sold			6,079.9			10.6			10.4			0.0			0.1	0.0	0.0	0.0
Timber sold			0.0			0.0			0.0			0.0			0.0	0.0	0.0	0.0
Crops sold (inc. energy, silage)			0.0			0.0			0.0			0.0			0.0	0.0	0.0	0.0
Total drainage export	63,249.4	400,579.7	231,914.6	110.0	696.7	403.4	108.7	688.3	398.5	0.3	2.2	1.3	0.7	4.1	2.4	0.0	0.2	0.1
TOTAL	**96,998.5**	**434,328.7**	**265,663.6**	**168.7**	**755.4**	**462.1**	**166.7**	**746.3**	**456.5**	**0.5**	**2.4**	**1.4**	**1.0**	**4.5**	**2.7**	**0.0**	**0.2**	**0.1**
Farm C sequestration, as CO_2e																		
Woodland	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid	min	max	mid
C sequestered in woodland biomass, as CO2e	12,111.4	74,761.4	27,604.3	21.1	130.0	48.0	20.8	128.5	47.4	0.1	0.4	0.1	0.1	0.8	0.3	0.0	0.0	0.0
Annual biomass harvested from woodlands, as CO2e	540.7	4,956.2	1,708.7	0.9	8.6	3.0	0.9	8.5	2.9	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Annual C flux in deadwood and litter (CO2e)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Annual C sequestered in soils under woodlands, as CO2e	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11,570.7	69,805.2	25,895.6	20.1	121.4	45.0	19.9	120.0	44.5	0.1	0.4	0.1	0.1	0.7	0.3	0.0	0.0	0.0
Isolated trees							0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Annual biomass increment in isolated trees, CO2e	30,741.7	194,220.9	70,449.3	53.5	337.8	122.5	52.8	333.7	121.1	0.2	1.1	0.4	0.3	2.0	0.7	0.0	0.1	0.0
Annual biomass removed (trees felled), CO2e	10,290.3	77,839.6	23,494.2	17.9	135.4	40.9	17.7	133.8	40.4	0.1	0.4	0.1	0.1	0.8	0.2	0.0	0.0	0.0
	20,451.4	116,381.3	46,955.1	35.6	202.4	81.7	35.1	200.0	80.7	0.1	0.6	0.3	0.2	1.2	0.5	0.0	0.1	0.0
Annual C sequestered in hedges (CO2e)	2,016.9	10,451.0	5,839.7	3.5	18.2	10.2	3.5	18.0	10.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0
Annual C sequestered in grassland (CO2e)	78,314.2	803,176.3	440,745.3	136.2	1,397.0	766.6	134.6	1,380.2	757.4	0.4	4.4	2.4	0.8	8.3	4.5	0.0	0.4	0.2
Annual C sequestered in peat wetlands (CO2e)	5,741.1	14,352.6	10,046.8	10.0	25.0	17.5	9.9	24.7	17.3	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
TOTAL	**118,094.2**	**1,014,166.4**	**529,482.5**	**205.4**	**1,763.9**	**920.9**	**202.9**	**1,742.7**	**909.9**	**0.6**	**5.5**	**2.9**	**1.2**	**10.5**	**5.5**	**0.1**	**0.5**	**0.2**
FARM BALANCE *(total footprint minus sequestration)*	1,111,413.3	5,408,459.0	2,076,812.9	1,933.1	9,407.0	3,612.2	1,909.8	9,293.8	3,568.8	6.0	29.3	11.3	11.5	55.7	21.4	0.5	2.5	1.0

APPENDIX II: NOTES ON PAS 2050 COMPLIANCE

Bangor University farm footprints are compliant with the PAS 2050 cradle-to-gate approach. In order to comply with PAS 2050, the footprint **includes** all emissions resulting from the transformation of raw materials (e.g. from the production of fertiliser); use of energy; manufacturing and service provision i.e. emissions from consumables, operation of premises, transport and storage. The footprints **exclude** emissions from the production of capital goods (e.g. tractor production).

Examples of agricultural emissions to be included in a PAS 2050 footprint given within the guidance include emissions from the application of fertiliser, emissions from direct land use change (from non-agricultural to agricultural land) and CH_4 from cattle, all of which are included in our footprints (where relevant).

PAS 2050 guidance gives a number of instructions directly relevant to agricultural footprinting, which we have followed to ensure compliance. These are:

- “Non CO_2 emissions from livestock and soils should be calculated using the highest tier IPCC approach or the highest approach used by [our] country”. We have used IPCC calculations and emissions factors for emissions such as N_2O released directly from the management of organic soil.

- “Changes in carbon content of soil other than those arising from direct land use change shall be excluded from the assessment”. Changes such as sequestration in peatlands have been excluded from the PAS 2050-compliant footprints.

- “CO_2 emissions from biogenic (biomass derived) material should be excluded (except those arising from land use change). Non CO_2 emissions from both fossil and biogenic material carbon sources should be included”. No emissions within the footprinted system boundaries fall within these categories.

- “Where atmospheric CO_2 is taken up by a product which is not a living organism the impact of carbon storage is determined from the weighted average of the biogenic carbon in a product or atmospheric CO_2 taken up and not re-emitted to the atmosphere over the 100 year assessment period”. No emissions within the footprinted system boundary fall within this category.

- “Biogenic carbon storage shall be included if: the product is not for human or animal consumption; more than 50% of the mass of C of biogenic origin in the product remains removed from the atmosphere for one year or more; AND the material containing the biogenic C is obtained from an input that is the result of human actions OR a recycled or re-used input (i.e. ensures the carbon stored is addition to that which would have occurred without human intervention). (C storage through forest management activities in a managed forest is not included in the scope of PAS)”. Carbon storage within farm woodland and other woody biomass has not been included in the PAS 2050-compliant footprint since it cannot be shown that more than 50% of the mass of carbon of biogenic origin remains removed from the atmosphere for one year or more.

- “GHG emissions from direct land use change shall be assessed for any input originating from agricultural activities. This is to be in accordance with IPCC including all direct land use change after 1st Jan 1990. 5% of the total emissions from land use change shall be included in each year over the 20 years following the land use change”. In this definition “”direct land use change” is the conversion of non-agricultural to agricultural land use as a consequence of producing an agricultural product or input to a product on that land. Where land use on a study farm has changed from non-agricultural to agricultural use since 1990, this has been included within the footprint (e.g. woodland to grassland or arable).

The footprint data is reported to 2 significant figures and per unit of produce (kg) to ensure compliance. Where a farm produces more than one economic output (e.g. lamb and beef) we use economic allocation of emissions between co-products (as suggested by PAS 2050 guidance).