THE CARBON FOOTPRINT OF SHEEP FARMING IN WALES

Welsh case study data and comparison with the New Zealand situation

Final report

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EXECUTIVE SUMMARY

1. This project aimed to estimate the carbon footprint for case study farms in Wales and to compare these results with those relating to New Zealand as presented by Saunders *et al.* (2006).

2. A carbon footprint including the greenhouse gases CO_2, N_2O and CH_4 was calculated for two Welsh case study farms using data collected directly from those farms.

3. The analysis was undertaken assuming two different system boundaries. The simplest system boundary for the carbon footprint only considered greenhouse gas emissions (GHG) from direct use of farm inputs (e.g. use of diesel) and those generated during their manufacture (e.g. manufacture of fertilisers).

4. An expanded system boundary included all emissions considered under system boundary 1 plus GHG emissions from soil, livestock and their excreta and carbon exports from the system in the form of animals leaving the farm.

5. When using the narrowest system boundary, case study farm 1 emitted 1,106 kg CO_2 equivalents ha^{-1} $year^{-1}$ (best case = 522, worst case = 1,691). Case study farm 2 emitted 242 kg CO_2 equivalents ha^{-1} $year^{-1}$ (best case = 126, worst case = 359).

6. On case study farm 1 lambs accounted for 65.4% of the total amount of live weight sold, which means that of the total emissions, 1.0 to 3.2 (average 2.1) kg CO_2 equivalents kg^{-1} live weight can be allocated to lambs only. On case study farm 2 lambs accounted for 57.5% of the total amount of live weight sold, which means that of the total emissions, 1.0 to 2.8 (average 1.9) kg CO_2 equivalents kg^{-1} live weight can be allocated to lambs only.

7. When using the expanded system boundary, which included emissions from livestock, fertilisers and manure, case study farm 1 emitted 5,278 kg CO_2 equivalents ha^{-1} $year^{-1}$ (best case = 3,385, worst case = 12,711). Case study farm 2 emitted 4,216 kg CO_2 equivalents ha^{-1} $year^{-1}$ (best case = 1,678, worst case = 11,624).

8. On both farms, direct N_2O emissions from soils and CH_4 from enteric fermentation dominated GHG emissions. This stresses the importance of including these emissions in carbon footprint calculations.

9. A critical review of the Saunders *et al*. (2006) report suggested it was subject to a number of methodological problems and inconsistencies in approach. One major problem with this report was the generalisation made about all UK lamb production, when they had only considered one farm system typical of lowland England. A second issue relates to Saunders *et al*. (2006) only considering emissions of CO_2, and not the emissions of N_2O and CH_4. Given the global warming potential of N_2O and CH_4 this leads to a significant underestimate of the carbon footprint of the systems they consider.

10. In addition to developing a full carbon footprint for the two case study farms (discussed above) the data from these case study farms were also manipulated in a similar manner to that undertaken by Saunders *et al.* (2006). This enabled a

direct comparison of the case study data with those presented by Saunders *et al.* (2006). This comparison suggested that when the methodology adopted by Saunders *et al.* (2006) is used to estimate the carbon footprint of the Welsh farms, their carbon footprint is significantly lower than that presented by Saunders *et al.* (2006) for UK farms. Further, the carbon footprint of one farm is significantly less than that presented by Saunders *et al.* (2006) for New Zealand lamb production, while that of the other farm was greater than the New Zealand footprint. These results cast doubt on Saunders' assertion that it is more carbon efficient to import lamb from New Zealand than to produce and consume it in the UK.

11. These results demonstrate the variation that occurs between farms producing the same product, and as such they severely undermine the generalisability of any claims made about the carbon footprint of a farming enterprise for a whole country or region. Only through collecting data from an adequate number of similar farms within a region can we hope to understand the variation in their carbon footprints.

12. The main message for UK consumers from this work is that it is not necessarily more carbon efficient to buy New Zealand produced lamb in preference to Welsh lamb. Indeed Welsh lamb production may emit fewer greenhouse gas emissions than those reported by Saunders *et al.* (2006) for New Zealand, however this issue cannot be resolved until similar methodologies are applied in both countries to a large number of farms.

Contents

1. Introduction

1.1 Carbon footprinting

A carbon footprint is a measure of the impact of human activities on the climate, expressed in terms of the total amount of greenhouse gases (GHGs) produced. The carbon footprint of a product describes emissions from all stages of its life cycle, from manufacture and processing to packaging, transport, retailing, consumption and waste disposal. All direct, on-site emissions as well as indirect emissions incurred off-site (e.g. during the manufacture of inputs to the production system) should be included in the calculation of a carbon footprint.

Agriculture contributes to global emissions, and emissions of the greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) are of particular concern. In the UK, agriculture accounts for about 7% of total greenhouse gas emissions (Defra 2005). They result from the use of machinery and electricity, the production of fertilisers, pesticides, concentrate feeds and other inputs, but are also released naturally from soils, ruminant animals and their excreta. Processes beyond the farm gate, for lamb production for example the transport of animals to the slaughterhouse and processing, also contribute to the carbon footprint of a product.

In response to ever increasing concerns about climate change many businesses, including the food industry, are faced with significant commercial and political pressure to reduce their impact on the environment. The calculation of carbon footprints, the proposed carbon labelling of products, life cycle analyses (LCA) of products and the debate surrounding food miles are all a reflection of these concerns and the attempts to identify, quantify, reduce and offset this impact.

Despite this widespread interest in estimating the contribution that the manufacture and consumption of many products make to global warming, there remains some debate about the use of the term 'carbon footprint'. For example, Wiedmann & Minx (2007) argue that an indicator measuring all greenhouse gases, not just CO_2, would be better termed a 'climate footprint'. Meanwhile Hammond (2007) proposes to call it 'carbon weight' because it is often expressed in kilograms or tonnes per person or activity. For the purpose of this report, we use the term 'carbon footprint' because it is the most commonly accepted terminology at the moment. We define it as outlined in the first paragraph of this section, and consider emissions of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). These are the GHGs that are most affected by agricultural activity (Robertson & Grace 2004); other GHGs and gases that also contribute to climate change through radiative forcing, such as halocarbons, ozone or carbon monoxide, will not be considered in this report.

Carbon footprints are expressed in units of CO_2 equivalents. This is because different greenhouse gases have different impacts on the atmosphere, with 1 kg of CH_4 being equivalent to 23 kg of CO_2 and 1 kg of N_2O equivalent to 296 kg CO_2 over a 100 year time horizon (IPCC 2001). The conversion of N_2O and CH_4 to CO_2 equivalents is based on their effect on the radiative forcing of the atmosphere relative to the effect of CO_2. This depends, amongst other factors, on their atmospheric lifetime, their current concentration in the atmosphere and their ability to capture infrared radiation. Both CH_4 and N_2O are at much lower concentrations in the atmosphere than CO_2, but because their global warming potentials are 23 and 296 times greater respectively, small changes in these gases can have relatively large effects.

1.2 The Carbon Trust methodology

Several companies and organisations are currently developing and proposing carbon footprint protocols for carbon labelling. These include for example the non-profit organisation Carbonfund.org (http://www.carbonfund.org/site/uploads/Product_Certification_Protocol_-_2007-07.pdf), Tesco (http://www.eci.ox.ac.uk/research/energy/downloads/carbonlabelling_workshop.pdf) and the Carbon Trust. The Carbon Trust has recently developed a draft methodology to enable calculation of the GHG emissions from an individual product across its life cycle (see http://www.carbon-label.co.uk/pdf/methodology_full.pdf), which will be described in more detail in the following section.

The Carbon Trust methodology is intended to enable businesses to quantify emissions associated with their products, enable comparison between different products, allow companies to compete on green credentials and identify the potential for emissions reductions. The introduction of a carbon label on products will then allow consumers to understand which products are carbon intensive and choose products with lower carbon footprints. The methodology tries to balance analytical accuracy with an attempt to make it simple and practical to apply. At present, it is still being developed, but ultimately, the Carbon Trust hopes to advance the methodology to become the agreed UK standard.

The system boundary for the carbon label is defined to include all supply chain steps up to the arrival of the product at the retailers plus disposal, i.e. those steps that the producer can influence. Emissions incurred while in-store (e.g. from heating, lighting or refrigeration) and from the use of a product (e.g. energy used to cook food, refrigerate in the home or power electrical appliances) are not included in the current draft methodology, because the producer has little influence on these emissions and actions by the consumer cannot be accurately measured. Only where products are raw materials for other products will the GHG analysis exclude the disposal stage. The focus is on inputs, outputs and processes that will have a significant impact on the overall footprint of the product. All greenhouse gases are included, and all emissions are converted to CO_2 equivalents. The base unit for calculations is the 'product unit', which defines an item as it would be purchased by the consumer, including its packaging. However, emissions can also be calculated as kg CO_2 equivalents per kg of product.

The current Carbon Trust methodology does not consider changes in the carbon which might be contained in vegetation or soils on farms. Furthermore, it is not entirely clear if GHG emissions from soils and livestock are taken into consideration.

The current Carbon Trust methodology comprises five major steps:

1. Analysis of the internal product data: this involves gathering detailed information on the product, e.g. raw materials required, production activities involved, waste and co-products produced, storage and transportation needs.
2. Building of a supply chain process map: the process map should include every significant process step and raw material and identify all inputs and outputs to be analysed.
3. Definition of boundary conditions and identification of data requirements
4. Collection of primary and secondary data
5. Calculation of emissions by supply chain process steps: emissions can be calculated using both energy and direct emissions data, using emission coefficients to convert into carbon equivalents.

It is interesting to note that if carbon labels were introduced they may serve to confuse the message communicated by other food-related initiatives. For example, if the label showed a product imported from overseas to be less carbon intensive than UK produced food, then this may conflict with policy objectives to encourage consumption of local food. Another possible problem is that improvements in one environmental impact category such as carbon emissions may lead to increased negative impacts from another category, e.g. nitrate leaching, eutrophication, acidification or land use.

To summarise, the carbon label introduced by the Carbon Trust includes:

- the greenhouse gases CO_2, N_2O and CH_4;
- the footprint for the product and its packaging;
- all supply chain steps up to the arrival of the product at the retailers plus disposal;
- inputs, outputs and unit processes directly associated with the product.

The carbon label does <u>not</u> include:

- emissions in the retail store (this may change as the methodology develops);
- emissions during the use of the product;
- indirect emissions, e.g. from workers commuting to a factory or the consumer to the shop and home;
- all emissions from the manufacture and maintenance of capital goods;
- the carbon which might be locked up by the productive and non-productive areas on farms;
- any offsetting of emissions so as to provide information on the actual emissions associated with a product.

1.3 Aim and report outline

The aim of this report is to estimate the carbon footprint for real farms in Wales, and to compare these results with those relating to New Zealand as presented by Saunders *et al.* (2006).

The report is presented in 10 sections:

Section 2 discusses issues relating to data availability and use.

In Section 3, different system boundaries for the calculation of the carbon footprint of lamb farming are defined.

The methods used and assumptions made for the calculations of the carbon footprint for two Welsh farms are explained in Section 4.

Section 5 summarises the results of a recent study (Saunders *et al.* 2006) that calculated the carbon emissions from a model UK lamb farming system and New Zealand produced lamb. It also contains a critique of the methods used and results presented in this study.

The carbon footprints for the two Welsh case study farms using successively more comprehensive system boundaries are presented in Sections 6 and 7.

Section 8 compares the results of Saunders *et al.* (2006) with the results for the two Welsh farms, calculated using the same methods as Saunders *et al.* (2006).

Sections 9 and 10 provide an overall discussion, recommendations and conclusions from this report.

2. Key issues in data availability and understanding

This section discusses the uncertainties surrounding our understanding and knowledge of some of the footprint components. It also notes issues related to the lack of data reported in the scientific literature which were derived from studies in Wales and/or the UK.

2.1 Greenhouse gases and soils

Emissions of CO_2 from soils represent one of the major fluxes in the global carbon cycle (Schlesinger & Andrews 2000). These are mainly due to the respiration of plant roots and soil microbes decomposing soil organic matter and organic compounds exuded from roots. In addition to CO_2, agricultural soils also emit the greenhouse gases CH_4 and N_2O, e.g. from livestock faeces, slurry, manure or fertiliser applications. On a global scale, soil processes contribute about 70% of N_2O emissions and 30% of annual CH_4 emissions to the atmosphere (Mosier 1998).

N_2O is produced naturally in soils by microbes through either nitrification or denitrification. The process of nitrification is the aerobic oxidation of ammonium to nitrate, and denitrification is the anaerobic reduction of nitrate to nitrogen gas. Increases in the availability of nitrogen in the soil usually result in increases in both of these processes, which is why additions of nitrogen to the soil as fertilisers, slurries, manure, etc. have the potential to increase N_2O emissions. In addition to these direct emissions resulting from nitrogen inputs, there are also indirect emissions due to the volatilisation of NH_3 and NO_x, and emissions following the leaching and run-off of nitrogen from managed soils.

CH_4 emissions from grasslands are mainly associated with enteric fermentation and manure. Under anaerobic conditions, soil bacteria produce CH_4, while under aerobic conditions, soils can be a sink for atmospheric CH_4.

There is considerable uncertainty in both our empirical and conceptual understanding of the processes that regulate gaseous emissions from soils (Flechard *et al.* 2007). The amount of GHGs emitted from agricultural soils depends on a variety of biological, chemical and physical variables and is influenced by management practices and local conditions. Thus it is extremely difficult to measure or model these emissions, and this leads to a wide variability of results when comparing different studies.

Plants and soils can also act as sinks for greenhouse gases (that is they serve to 'lock up' or 'sequester' carbon and thereby prevent it from re-entering the atmosphere). Some of the CO_2 that plants sequester during photosynthesis will return to the soil as litter, dead roots and root exudates, thus replenishing soil carbon stocks. Soils can also consume N_2O and CH_4, but the sink strength is significantly affected by factors such as land management, nitrogen fertiliser application and environmental conditions (Powlson *et al.* 1997, Mosier 1998, Castaldi *et al.* 2007, Chapuis-Lardy *et al.* 2007) and may vary between years, seasons and sites with the same land use or fertilisation level (Boeckx & Van Cleemput 2001). This potential sink capacity for greenhouse gases is poorly understood (Edwards-Jones *et al.* submitted) and thus rarely included in calculations of total greenhouse gas emissions from agricultural systems.

All these factors result in a relatively poor understanding of the role that soils play in greenhouse gas budgets, and the variability in sink or source strength with environmental conditions makes accurate predictions difficult. This is one reason why, despite their importance for an assessment of overall greenhouse gas emissions from agricultural systems, emissions from soils are often not accounted for in LCA studies.

2.2 Data availability

As this study did not take actual measurements of gaseous emissions on Welsh farms, we had to rely on values reported in the literature for various components of the carbon footprint. However, Welsh derived data were scarce in the scientific literature, and in the absence of Welsh data, internationally defined default values were used. These tended to surrounded by (large) uncertainty ranges, e.g. direct and indirect N_2O emissions from livestock excreta and soils (especially from drained/managed organic soils), CH_4 oxidation by soils or leaching losses of organic and inorganic carbon. International default values used for e.g. CH_4 emissions from enteric fermentation and nitrogen excretion rates for sheep and cattle might also be improved by taking local measurements. Because different studies give different figures for emissions from direct and indirect inputs, minimum to maximum ranges were used in this report.

3. Definition of system boundaries

Estimates of the carbon footprint of a system will depend on how the system of concern is defined. Systems boundaries may be defined so that they include only certain elements of the food chain, for example those interested in farm level activities may define the system so that it only includes on-farm activities and ignores processing and retail. Alternatively if an analyst were only concerned with the carbon footprint of a retail operation, then they may draw the system boundary to only consider retail and distribution activities.

When considering sheep farming and processing, at least six system boundaries can be defined. These become successively more complex and comprehensive as the system boundary is expanded, as shown below:

On-farm activities:

1. to include emissions from manufacturing, distributing farm inputs and the use of these inputs on the farm (e.g. pesticide production from raw materials, the use of machinery and electricity), but ignoring the flows of greenhouse gases into and out of animals, plants and soils that occur on farm.
2. to include the items in 1 above, plus the greenhouse gas emissions from livestock, their excreta, emissions from soils related to fertiliser use and manure management and the export of meat off the farm (i.e. this system boundary includes N_2O emissions from nitrogen fertiliser application or manure and CH_4 production from livestock).
3. to include the items in 2 above but also consider the flow of greenhouse gases into and out of soils and plants in the productive and non-productive areas of the farm, e.g. woodlands.

On-farm activities, processing, retailing and consumption:

4. to include inputs and processes up to the farm gate plus transport, processing, packaging, retailing, consumption and waste disposal.
5. to include the items in 4 above plus the greenhouse gas emissions from livestock, their excreta, soil and manure management and the carbon exported in meat.
6. to include the items in 5 above but also consider the flow of greenhouse gases into and out of soils and plants in the productive and non-productive areas of the farm, e.g. woodlands.

The methodology proposed by the Carbon Trust (see Section 1.2) is equivalent to a combination of boundaries 1 and 4, including some of the processes beyond the farm gate, but excluding the retailing and consumption stages. It also excludes the carbon exchange between pasture, soil and atmosphere.

Non-productive areas of farms as included in boundaries 3 and 6 may form quite large areas in many agricultural systems, and these and the pastures themselves may have the potential to both release and lock-up carbon. However, the flow of carbon into and out plants and soils remains relatively poorly understood, and for this reason they are ignored in this report. However, in a separate report ‘The carbon footprint of sheep farming in Wales: the potential for a carbon-neutral production system', we explore the potential for plants and soils on-farm to mitigate, or 'off-set', carbon emissions from elsewhere in the farm system. This discussion raises the possibility that in the case of sheep farming, a carbon neutral production system may be developed by balancing the GHG releases from farm inputs to and activities on a sheep farm with non-productive areas such as rough grassland, grass strips, hedgerows and woodlands.

The next section of this report describes the methods used to calculate the carbon footprint for sheep farming. The analysis considers both system boundaries 1 and 2 in the list presented above.

4. Methods

This report will present three examples of carbon footprint calculations for sheep farming, using different system boundaries. Example 1 refers to a report by Saunders *et al.* (2006) and involves a recalculation and critical appraisal of their results for sheep farming in New Zealand and the UK. For detailed information on the methods used, please refer to the original report, available at http://216.194.201.113/blog/Food%20Miles.pdf.

Examples 2 and 3 consider Welsh sheep farming. Farm details and data on energy use and indirect inputs for one particular year were obtained from two HCC development farms. For both of these farms, the carbon footprint using system boundaries 1 and 2 was calculated. One process beyond the farm gate (boundaries 4 and 5) was also considered.

In general, no Welsh data on emissions from inputs were available and UK data were also rare. Therefore, wherever available from the literature, a range of emissions reported was used for the calculations in order to define a minimum, maximum and mid range value of possible emissions. Where emission factors defined by the Intergovernmental Panel on Climate Change (IPCC) were used, the uncertainty range surrounding these defaults was considered in order to reflect uncertainty in their estimation. For the calculations, the minimum, maximum and mid or default value of these ranges were used to represent a best case, worst case and average scenario. The reliability and robustness of the results should be enhanced by this explicit consideration of uncertainty and environmental variability.

The following sections describe the methods used to calculate the carbon footprint for the two Welsh case study farms. Results are presented as CO_2 equivalents per hectare per year and as CO_2 equivalents per kg live weight leaving the farm.

4.1 Carbon footprint: On-farm activities (system boundary 1)

System boundary 1 considers direct emissions from the use of diesel or electricity as well as indirect emissions from the production of farm inputs such as fertilisers and pesticides.

Direct inputs

Using data presented in Tzilivakis *et al.* (2005) for the UK, emissions from the use of diesel were calculated as 2.74 kg CO_2 equivalents per litre diesel. For petrol and electricity, the Defra (2007) figures of 2.315 kg CO_2 per litre petrol and 0.523 kg CO_2 per kWh were used; these figures do not include N_2O and CH_4 emissions.

Indirect inputs

For the calculation of emissions from the manufacture of fertilisers, pesticides and concentrate feed, literature values were collected and, where possible, a range of reported values in CO_2 equivalents used (Appendix 1-5). Emissions were calculated using the minimum, maximum and mid value of that range. Note that some of these figures originate from countries other than the UK, where different transportation distances and energy mixes used may result in different figures. Another potential problem with these data is that the figures from different studies include different processes, e.g. production, packaging, transportation, storage and transfer, with some being more comprehensive than others, and some studies not stating exactly which processes are included. Only figures reported in the literature that included N_2O and CH_4 as well as CO_2 were used.

For fertilisers, GHG emissions were calculated using data per kg of nitrogen, phosphate or potassium, not per kg product, because the data available for the case studies were kg of these elements applied. Data on GHG emissions from phosphate fertiliser production were obtained from the literature as kg CO_2 equivalents per kg P_2O_5; this was corrected for the amount of P only by multiplying by 0.436 based on the molecular weight of the elements. Data on energy use during potassium fertiliser manufacture were obtained from the literature; the only conversion factor from energy use to GHG emissions was found in Saunders *et al.* (2006) (Appendix 3). For sulphur, the only information available in the literature were the figures used by Saunders *et al.* (2006) (energy use: 5 MJ kg^{-1}, emission rate: 0.06 kg CO_2 MJ^{-1}). For both potassium and sulphur fertiliser, the Saunders *et al.* (2006) figures used were originally taken from a New Zealand study and exclude N_2O and CH_4.

For silage film, the range of GHG emissions obtained from the literature for PE and LDPE plastics was 1.3-1.94 kg CO_2 equivalents kg^{-1} plastic (Theunis & Franck 2001, GUA 2004). Silage film for silage clamps was assumed to be used for two years.

The range for concentrate feed covers a variety of feed types, which may not accurately reflect the feed used on the case study farms.

The only figure available for bedding and straw were an energy use of 1.50 MJ kg^{-1} dry matter and an emission rate of 0.058 kg CO_2 MJ^{-1} (Saunders *et al.* 2006); these figures were originally specified for New Zealand and may not reflect UK conditions.

In addition to the calculation of GHG emissions using these ranges, calculations were also made using the same emission factors as Saunders *et al.* (2006) to enable a direct comparison of the results of those authors and the system they described and the two Welsh case studies.

Partitioning emissions between the lamb and beef production systems

Both Welsh case study farms were mixed livestock farms. Emissions associated with cattle were included in the footprint calculation. It would theoretically be possible to estimate the proportion of the emissions relating to sheep only by allocating total emissions from a farm system by the relative proportions of sheep and cattle live weight which leave the farm system. Indeed such an allocation of emission by unit of end product is in line with standard LCA practice (ISO 2006a, b). However, there are some philosophical and practical problems with this approach. On a philosophical this approach goes against the concept of an agricultural 'system', and it is more realistic to consider the whole system as an integrated production unit. Further, given that a farmer may allocate inputs according to expected profitability, is also unclear as to whether it is more appropriate to allocate emissions to the weight of end product (kg GHG/kg meat), or to the value of a unit of end product (GHG/£/kg meat). Undertaking such calculations requires information on the live weight, killing-out percentage and maybe price of all individual stock which leave the farm. These data were available for lamb and beef, but not for any cull ewes and other stock. A second problem relates to the existence of multiple products arising from livestock, e.g. meat, skins and wool. Again it is theoretically possible to allocate emissions to each of the final products by considering the weight of the final unit of sale. Unfortunately though no data were available on this.

A final issue relates to identifying the most appropriate functional unit for analysis. Standard LCA methodology requires emissions be expressed per unit of a defined functional unit (i.e. per kg of meat or litre of milk), however it remains debatable as to what is the most relevant functional unit leaving a farm system. The final product of most traditional livestock farms is live animals. The final product leaving an abattoir is a carcass. For this reason it could be argued that the most appropriate functional unit for farm level analysis is the number and live weight of animals. Only if full data are available for the supply chain up to and including the abattoir would it be logical to undertake analyses which used deadweight as the functional unit. Against this background the primary results of GHG emissions from case study farms are presented as GHGs per hectare. However, in order to provide some indicative figures of the relative importance of the two enterprises the overall carbon footprint of the farm system was also divided by proportion to the live-weight of sheep and beef leaving the farm. This was only realistic for system boundary 1, which considered emissions from direct inputs. A similar partitioning was not undertaken for system boundary 2 as the calculations were complicated by the requirement to partition N_2O emissions from the soil arising from the application of fertiliser and manure, and untangling this complication was beyond the scope of this project.

4.2 Carbon footprint: On-farm activities plus emissions from livestock and nutrient management (system boundary 2)

For a more comprehensive assessment of the global warming impact of sheep farming, GHG emissions from the grazing animals and their excreta as well as from soils following nitrogen additions should be considered. Some emission factors were taken from the Intergovernmental Panel on Climate Change (IPCC) guidelines on national greenhouse gas reporting (IPCC 2006). These emission factors are default values, which may not always accurately reflect local conditions, but they were used in this study for lack of locally validated figures. Emissions were calculated using these default values and their uncertainty range as minimum and maximum values. Emissions from lambs and their excreta were calculated not per year, but for the actual average time that they remain on the farm. Sheep were assumed to stay outside all year round; cattle are housed for 6 months per year on both case study farms. Calves were assumed to remain on the farms for 12 months.

The following paragraphs describe in more detail the different GHG fluxes considered and the methods used to calculate their contribution to the carbon footprint.

CH_4 from enteric fermentation

Using IPCC default emission factors, each adult sheep emits 8 kg CH_4 year^{-1} through enteric fermentation. For lambs less than one year old, an emission factor of 3.2 kg CH_4 year^{-1} was applied as in Baggott *et al.* (2007) for the UK national greenhouse gas inventory. For non-dairy cattle, the IPCC default is 57 kg CH_4 animal^{-1} year^{-1} which applies to adults and calves. For equations, see Appendix 6.

CH_4 from excreta and manure management

Emissions of CH_4 in the field and from stored cattle excreta were calculated using emissions factors presented in Baggott *et al.* (2007) and IPCC equations (Appendix 7). Methane emissions from manure management amount to 0.19 kg CH_4 animal^{-1} year^{-1} for adult sheep and 0.076 kg CH_4 animal^{-1} year^{-1} for lambs less than one year old. For adult beef cattle and cattle less than one year old, these values are 2.74 kg CH_4 animal^{-1} year^{-1} and 2.96 kg CH_4 animal^{-1} year^{-1} respectively.

Direct N_2O emissions from managed soils

An increase in available nitrogen increases nitrification and denitrification rates, resulting in increased N_2O emissions. Human-induced nitrogen additions considered for the calculation of direct N_2O emissions from soil were synthetic nitrogen fertilisers, organic fertilisers and urine and dung deposited on the pasture by the grazing animals. Emissions from the area of managed organic soil were also included. Using IPCC methods, N_2O emissions were calculated according to the equations provided in Appendix 8.

Indirect N_2O emissions from managed soils

In addition to direct N_2O emissions from the soil to which nitrogen is applied, indirect emissions occur through:

1. the volatilisation of nitrogen as NH_3 and oxides of nitrogen (NO_x) and the deposition of these gases and their products NH_4^+ and NO_3^- onto soils and the surfaces of water bodies;
2. the leaching and run-off of nitrogen from synthetic fertilisers, organic fertilisers and excreta of the grazing animals.

Indirect N_2O emissions were calculated using IPCC methods; for the relevant equation, see Appendix 9.

Direct N_2O emissions from manure management

Direct emissions occurring during the storage and treatment of manure before it is applied to land were calculated using IPCC methods (Appendix 10). Emissions generated by excreta in the field are included under *N_2O emissions from managed soils*.

Indirect N_2O emissions from manure management

Indirect emissions resulting from volatile nitrogen losses during manure collection and storage were calculated using IPCC methods (Appendix 11). As the sheep were assumed to stay outside all year round, this calculation was only carried out for the cattle that are housed for 6 months per year on both case study farms.

Carbon content of livestock

The carbon content of sheep and cattle was assumed to be 5.1% of live weight (Byrne *et al.* 2007).

4.3 Carbon footprint: System boundaries 4-5

Data needed to calculate energy use and emissions associated with the slaughter and processing, packaging, retailing, consumption and waste disposal of meat products were not available for this report. This is why the only process beyond the farm gate that could be included in this report is the transport of sheep and cattle to the slaughterhouse or the markets where they are sold. Lambs from the first case study farm go straight to the slaughterhouse, but for cattle and all livestock from the second case study farm, it is not known where the animals go from the market. This means that emissions could only be calculated from the farm to the market.

The distance travelled by livestock to the slaughterhouse or market was obtained from the two Welsh case study farms. All transport was assumed to be by 16 t trucks. Multiplying the total live weight (t) by the distance travelled gives the total tonne kilometres (t*km). GHG emissions from a 16 t truck are 0.316 kg CO_2 equivalents

$(t*km)^{-1}$ (Spielmann *et al.* 2004). The average live weight of lambs sold was obtained from each farm, while for calves, an average weight of 350 kg was assumed. Results are expressed as kg CO_2 equivalents ha^{-1} $year^{-1}$. This figure was then doubled to account for the truck driving back to the farm; although emissions will be lower for an empty truck, this difference was assumed to be negligible.

4.4 Methodological issues

Both Welsh case study farms are mixed livestock farms. We have included emissions associated with cattle because it was not possible to allocate the various inputs accurately to either sheep or cattle production. This is also more realistic because sheep-only systems are very rare in Wales.

There are more potential products from sheep than just meat, e.g. wool. In our footprint calculations, the whole system with all possible products is included, i.e. all emissions from rearing sheep and cattle up to the farm gate are included and expressed on a per hectare basis. This represents the total cost of the system, but results are also presented per kg live weight leaving the farm.

Emissions of greenhouse gases associated with the manufacture and ongoing maintenance of capital goods (e.g. tractors, machinery, buildings) were not included in the analysis. This was primarily due to a lack of data. However, Frischknecht *et al.* (2007) recently evaluated the contribution of capital goods in LCA studies of agricultural products and concluded that with regard to climate change, capital goods have a minor impact and could thus be excluded. The exclusion of capital goods is also in accordance with the methodology proposed by the Carbon Trust.

Note that emissions from the disposal of farm waste (e.g. empty fertiliser bags, pesticide containers, silage wraps, etc.) and disposal of dead livestock are not included. Also not included in the footprint are emissions from the production of medicines such as antibiotics or vaccines, and any emissions resulting from the visits to the farm made by vets and other business advisors. These items were excluded due to the absence of relevant data.

For both case study farms, all replacement livestock was assumed to be reared on the farm. All silage used was taken to have been produced on-farm. Any potential ploughing of the grasslands on the case study farms was not taken into consideration for lack of data.

Case study farm 1 grows 4.9 ha of cereals and 8.1 ha of forage. It was assumed that all straw/bedding used on farm 1 is produced on-farm. Inputs could not be separated into grassland, cereals or forage, so that total farm emissions per hectare were calculated based on total farm hectares, not grassland hectares.

Case study farm 2 sends 150 ewe lambs away over the winter (40 miles). Emissions from sheep and their excreta were calculated as if they remained on the farm all year round, but additional concentrate feed, electricity, diesel, etc. used while the sheep were away are not included in the calculations.

Values presented in tables may not add up to the sum presented as total; this is due to rounding errors.

For some emissions, no range of values is presented due to a lack of data in the literature, and IPCC default factors are not necessarily the mid value of their uncertainty range. This means that for overall totals, the mid value given in the tables may not be the middle of the range calculated.

5. A consideration of the Saunders study on the carbon footprint of New Zealand and UK sheep farming

5.1 Introduction

A recent study by Saunders *et al.* (2006) compared energy usage and CO_2 emissions for lamb produced in the UK to lamb produced in New Zealand (NZ) and exported to the UK. The aim was to determine whether foodmiles are a true indicator of the carbon intensity of products. The calculations were based on system boundary 1 as described above, plus an allowance for emissions associated for post-production shipping of NZ produced lamb to the UK. Results were expressed in terms of energy consumption and CO_2 emissions per tonne carcass. Transport within either country was not included. Saunders *et al.* (2006) applied a co-product discount rate of 0.879 in order to only account for the product meat and exclude by-products such as wool. Disposal of any farm waste is not included. Note also that this study only takes CO_2 emissions into account, excluding emissions of N_2O and CH_4. It is therefore not a complete account of all the greenhouse gas emissions derived from sheep productions systems, and is not compliant with the current recommendations of the Carbon Trust.

The authors based their calculations for UK produced lamb on the following system:

- lowland farm;
- average stocking rate: 11 ewes ha^{-1};
- 1.45 lambs reared per ewe;
- weight of the average lamb carcass: 19.3 kg;
- production of 308 kg of meat ha^{-1};
- 53 kg of concentrates fed to each ewe and 12 kg to each lamb; all of this is assumed to be barley;
- fertiliser application: 87 kg of nitrogen, 8 kg of phosphorus, 17 kg of potassium and 99 kg of lime per hectare;
- pesticides are assumed to be herbicides only at 1.75 kg ha^{-1};
- farm buildings: sheep shed with 1.35 m^2 of pen space per ewe;
- no allowance was made for vehicles, machinery and fences for the UK based system.

5.2 Results as presented

The study concluded that both direct and indirect energy inputs per tonne carcass were considerably lower for New Zealand produced lamb than UK lamb due to the more extensive production system in New Zealand (Table 1). When transport of meat from New Zealand to the UK was included in the calculation, the total production energy and CO_2 emissions per tonne carcass were still about four times lower than for lamb produced in the UK (Table 1). The authors concluded that foodmiles alone are not representative of the emissions associated with the sheep meat.

Table 1. Total energy and carbon dioxide indicators for lamb production in New Zealand (NZ) and the UK as presented in Saunders *et al.* (2006).

	Quantity/ hectare		Energy MJ/tonne carcass		CO_2 emissions kg CO_2/tonne carcass	
	NZ	UK	NZ	UK	NZ	UK
Direct						
Fuel, electricity and oil (l of diesel equivalent)		128		17156		1116.9
Fuel use (l of diesel)	15.5		3565		244.9	
Electricity use (kWh)	13.8		594		11.4	
Direct sub total			**4159**	**17156**	**256.3**	**1116.9**
Indirect						
Nitrogen (kg)	5.7	76	1953	16147	90.1	807.4
Phosphorus (kg)	12.5	7	985	336	59.1	20.2
Potassium (kg)	0.5	15	29	498	1.7	29.9
Sulphur (kg)	12.3		323		19.4	
Lime (kg)	22.3	87	71	170	50.6	122.7
Agri-chemicals (kg ai)	0.6	1.5	338	1549	20.3	92.9
Concentrate (kg of dry matter)		681		7432		457.5
Forage, fodder and bedding (kg grass silage)		271		1319		76.5
Indirect sub total			**3699**	**27451**	**241.2**	**1607.1**
Capital						
Vehicles and machinery (kg)	0.8		273		25.4	
Farm buildings (m^2)	0.1	13.1	198	1251	19.8	125.1
Fences (m)	1.9		194		17.5	
Stock water supply			66		3.0	
Capital sub total			**731**	**1251**	**65.7**	**125.1**
Total production			**8589**	**45858**	**563.2**	**2849.1**
Yield (kg lamb carcass ha^{-1})	**190**	**308**				
Post production						
Shipping NZ to UK (17840 km)			2030		124.9	
Total production energy input/emissions			**10619**	**45858**	**688.1**	**2849.1**

5.3 Problems with the results as presented

Saunders *et al.*'s (2006) study contains several mathematical errors. Table 2 shows the results of this study corrected where possible; however, some results could not be recalculated for lack of transparency in the original data. The data presented in Table 2 includes the co-product discount rate.

Table 2. Total energy and carbon dioxide indicators for lamb production in New Zealand (NZ) and the UK, recalculated after Saunders *et al.* (2006).

	Quantity/ hectare		Energy MJ/tonne carcass		CO_2 emissions kg CO_2/tonne carcass	
	NZ	**UK**	**NZ**	**UK**	**NZ**	**UK**
Direct						
Fuel, electricity and oil (l of diesel equivalent)		128		17147		1116.3
Fuel use (l of diesel)	15.5		3557		244.4	
Electricity use (kWh)	13.8		594		11.6	
Direct sub total			**4151**	**17147**	**255.9**	**1116.3**
Indirect						
Nitrogen (kg)	5.7	76	1950	16139	97.5	806.9
Phosphorus (kg)	12.5	7	987	342	59.2	20.5
Potassium (kg)	0.5	15	26	485	1.6	29.1
Sulphur (kg)	12.3		324		19.4	
Lime (kg)	22.3	87	70	170	50.7	122.1
Agri-chemicals (kg ai)	0.6	1.5	337	1548	20.5	92.9
Concentrate (kg of dry matter)		681		7428		457.3
Forage, fodder and bedding (kg grass silage)		271		1319		76.5
Indirect sub total			**3694**	**27431**	**248.9**	**1605.3**
Capital						
Vehicles and machinery (kg)	0.8		273		25.9	
Farm buildings (m^2)	0.1	13.1	198	1250	18.6	125.0
Fences (m)	1.9		194		17.4	
Stock water supply			66		3.2	
Capital sub total			**731**	**1250**	**65.1**	**125.0**
Total production			**8576**	**45828**	**570.0**	**2846.6**
Yield (kg lamb carcass ha^{-1})	**190**	**308**				
Post production						
Shipping NZ to UK (17840 km)			2030		124.9	
Total production energy input/emissions			**10606**	**45828**	**694.9**	**2846.6**

5.4 Other problems with this study

Other problems with this study include inconsistencies in approach, data reliability, and system boundary definition:

- the farming system chosen as an example of UK production has been criticised for not being representative (Dube 2007, White *et al.* 2007), and does not reflect the more extensive upland lamb rearing system predominant in Wales;
- the authors did not have real-farm data for direct and indirect inputs for the UK and thus calculated emissions based on figures taken from Nix (2004) and Chalmers *et al.* (2001), which decreases the reliability of their results and makes an unfair comparison to the results for NZ that are based on more complete statistics gathered from seven farms;
- this study only looks at emissions from direct, indirect and capital inputs, but does not consider emissions from the animals and their excreta or from the soil;
- the already mentioned lack of inclusion of N_2O and CH_4 in the calculation, i.e. the results do not reflect total greenhouse gas emissions; these GHGs are not related to energy use, but considering that N_2O dominates the global warming potential from agriculture (Williams *et al.* 2006), and that CH_4 contributes significantly too, even small differences in these gases between NZ and UK may lead to significantly changed results;
- because a breakdown of data for fuel, electricity and diesel consumption was not available to these authors, CO_2 emissions from all these inputs were assumed to be equivalent to diesel for the UK calculation;
- the results are presented as emission per tonne carcass; however, transport of animals to the slaughterhouse and processing energy costs are not included, so that the results should better be presented per tonne live weight or per ha;
- it was assumed that all lambs and sheep weigh 55 kg. This seems to be significantly higher than reports for the average carcass weight in NZ (Meat New Zealand 2003). Overestimation of lamb weight will serve to bias any comparison made on emissions of GHG / kg of lamb produced;
- through the application of the co-product discount rate, the results do not reflect the system as a whole;
- it is not stated whether lamb shipped from NZ is refrigerated during the journey; if so, this energy cost is excluded from the calculation;
- the discount rate applied for the NZ system appears to differ slightly between inputs;
- emissions associated with capital inputs are not comparable between NZ and the UK (farm buildings are included for both countries, but vehicles, machinery and fences only for NZ);
- capital inputs included are not comprehensive, especially for the UK where only farm buildings (sheep sheds) are included, or in the case of shipping lamb from NZ to UK, the capital costs of shipping are excluded.

5.5 Summary

In view of the scarcity of studies trying to estimate the GHG budget of sheep farming systems and the growing importance of carbon footprinting for businesses, customer concerns and attempts to identify mitigation opportunities, this study highlighted several useful issues. However, in order to arrive at a more robust conclusion, real farm data are needed rather than secondary data on inputs and farm operations, and other farm types need to be investigated to increase reliability and representativeness. Finally, the other problems listed above need to be addressed in order to develop a more robust set of data.

In the next two chapters, carbon footprint calculations for two Welsh case study farms will be presented, using real-farm data and including all GHGs. These will then be compared to the data on UK farms presented by Saunders *et al.* (2006).

6. Carbon footprints of sheep farming systems: Welsh case study 1

6.1 Description of farm

The first Welsh case study farm is an upland farm classified as SDA (severely disadvantaged area). Its altitude ranges from 230-305 m and a very high percentage of its land can be described as improved and fertile. The lambs are sold from early July until the following January, ranging in age from 4-10 months and on average 6-7 months. For the calculation of emissions from lambs and their excreta, it was assumed that they stay on the farm for 6.5 months. Calves were assumed to stay on the farm for 12 months. All soils on the farm are mineral. All lambs sold were assumed to travel to the slaughterhouse at a distance of 13 miles. All cattle were assumed to be sold at a market 7 miles from the farm. The farm has a Tir Gofal agri-environmental agreement. The farm grows 4.9 ha of cereals and 8.1 ha of forage crops. Table 3 gives a description of the farm and lists annual inputs and outputs.

Table 3. Description of Welsh case study farm 1.

Farm details	
Total area of farm (ha)	129.5
Number of ewes	800
Number of lambs sold per year	747
Average live weight of lambs sold (kg)	39
Number of cattle	49
Number of calves	44
Distance to slaughterhouse (lambs) (miles)	13
Distance to market (calves) (miles)	7
Energy use	
Diesel use (including diesel used by contractors) (l $year^{-1}$)	5986
Petrol use (l $year^{-1}$)	415
Electricity use (kWh $year^{-1}$)	7400
Fertiliser	
Nitrogen (kg N $year^{-1}$)	12559
Phosphorus (kg P $year^{-1}$)	3649
Potassium (kg K $year^{-1}$)	3697
Sulphur (kg $year^{-1}$)	168
Organic nitrogen (kg N $year^{-1}$)	970.6
Pesticides	
Herbicide (l $year^{-1}$)	5
Insecticide (l $year^{-1}$)	5
Feed	
Concentrate (kg dry matter $year^{-1}$)	71170.8
Silage used (t $year^{-1}$)	1063
Other feed (kg $year^{-1}$)	3424
Straw or other bedding (t $year^{-1}$)	33.5

6.2 Results: System boundary 1

Table 4 presents the results on GHG emissions from direct and indirect inputs. Total GHG emissions range from 522 to 1691 kg CO_2 equivalents ha^{-1} $year^{-1}$. Emissions are dominated by nitrogen fertiliser, followed by concentrate feed and diesel use. The lowest emissions are associated with silage wrap, pesticides and sulphur. When estimated per kg live weight beef and lamb leaving the farm, emissions ranged from 1.5 kg CO_2 equivalents kg^{-1} live weight (minimum value) to 4.9 kg CO_2 equivalents kg^{-1} live weight (maximum value). The average value was 3.2 kg CO_2 equivalents kg^{-1} live weight. Lambs account for 65.4% of the total amount of live weight sold, which means that of the total emissions, 1.0 to 3.2 (average 2.1) kg CO_2 equivalents kg^{-1} live weight can be allocated to lambs only.

Table 4. GHG emissions in kg CO_2 equivalents ha^{-1} $year^{-1}$ on a Welsh upland mixed sheep/cattle farm, calculated using a range of values reported in the literature. The minimum, maximum and mid value of these ranges were used to represent a best case, worst case and average scenario.

	min.	max.	mid.
Direct			
Diesel	126.6	126.6	126.6
Petrol [a]	7.4	7.4	7.4
Electricity [a]	29.9	29.9	29.9
Total direct	**163.9**	**163.9**	**163.9**
Indirect			
Fertiliser – N	290.0	927.1	608.6
Fertiliser – P	-5.2	13.3	4.1
Fertiliser – K [a]	8.6	20.6	14.6
Fertiliser – sulphur [a]	0.39	0.39	0.39
Pesticides	0.14	1.44	0.79
Concentrates	62.2	561.6	311.9
Silage wrap	1.7	2.5	2.1
Total indirect	**357.8**	**1526.9**	**942.5**
TOTAL	**521.7**	**1690.8**	**1106.4**

[a] due to a lack of data on total GHG emissions, this is CO_2 only

6.3 Results: System boundary 2

In addition to direct and indirect inputs, GHG emissions from the grazing animals, their excreta and soils are listed in Table 5. Total emissions range from 3.4 to 12.7 t CO_2 equivalents ha^{-1} $year^{-1}$. Emissions are dominated by CH_4 from enteric fermentation, followed by direct N_2O emissions from soils. This highlights the importance of these GHGs for agricultural systems and for the results of carbon footprint studies. Emissions per kg of live weight leaving the farm range from 9.8 to 37.0 kg CO_2 equivalents kg^{-1}, with a median value of 15.3 kg CO_2 equivalents kg^{-1}.

Figure 1 summarises the relative importance of emissions from direct and indirect inputs, direct and indirect N_2O emissions and CH_4 emissions, once again illustrating how total emissions are dominated by CH_4 and N_2O.

Table 5. GHG emissions in kg CO_2 equivalents ha^{-1} $year^{-1}$ on a Welsh upland mixed sheep/cattle farm, calculated using a range of values reported in the literature. The minimum, maximum and mid value of these ranges were used to represent a best case, worst case and average scenario.

		min.	**max.**	**mid.**
Total direct (see Table 4)		163.9	163.9	163.9
Total indirect (see Table 4)		357.8	1526.9	942.5
Meat – lambs		42.1	42.1	42.1
Meat – calves		22.1	22.1	22.1
Direct N_2O from managed soils	from synthetic fertiliser	135.3	1353.3	451.1
	from organic fertiliser	10.5	104.6	34.9
	from excreta – sheep	162.5	1625.2	541.7
	from excreta – cattle	62.3	533.8	177.8
	total	**370.6**	**3616.8**	**1205.6**
Direct N_2O from manure management	cattle	15.0	55.6	27.8
	calves	9.0	33.3	16.7
	total	**24.0**	**89.0**	**44.5**
Indirect N_2O from managed soils	from atmospheric deposition of volatilised nitrogen	9.4	2340.5	178.2
	from leaching/runoff	5.6	2233.3	251.2
	total	**14.9**	**4573.8**	**429.5**
Indirect N_2O from manure management	cattle	1.1	180.9	25.0
	calves	0.7	108.3	15.0
	total	**1.8**	**289.1**	**40.0**
CH_4 from enteric fermentation	sheep	1366.6	1366.6	1366.6
	cattle	941.5	941.5	941.5
	total	**2308.1**	**2308.1**	**2308.1**
CH_4 from excreta	sheep	32.5	32.5	32.5
	cattle	47.0	47.0	47.0
	total	**79.5**	**79.5**	**79.5**
TOTAL EMISSIONS		**3384.9**	**12711.4**	**5277.6**

6.4 Results: System boundaries 4-5

Total emissions from transporting lambs to the slaughterhouse are 1.5 kg CO_2 equivalents ha^{-1} $year^{-1}$. Emissions from cattle travelling to the market are 0.2 kg CO_2 equivalents ha^{-1} $year^{-1}$. Adding the same amount for the return journey back to the farm results in a total of 3.4 kg CO_2 equivalents ha^{-1} $year^{-1}$.

This figure is relatively minor compared to emissions from other processes and adding this figure to the results for system boundaries 1 and 2 as presented above does not change results significantly.

However, if data were available for slaughter, processing, packaging and distribution, the overall carbon footprint of the product might change significantly.

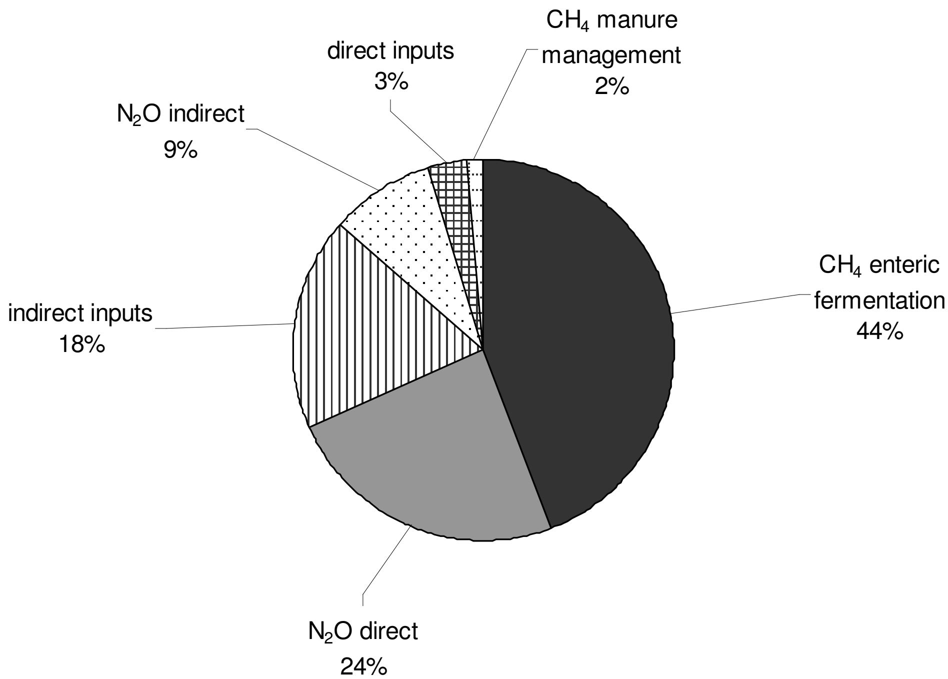

Figure 1. Relative contribution to total GHG emissions on case study farm 1 of direct and indirect inputs, direct and indirect N_2O emissions from soil and manure management and CH_4 emissions through enteric fermentation and from manure management.

7. Carbon footprints of sheep farming systems: Welsh case study 2

7.1 Description of farm

The second Welsh case study farm is a hill farm with very little lowland. The lambs are marketed from late June until November with a high percentage going late summer to November. The average age is 5-6 months. About 75% of soils (215 ha) are organic. In terms of inputs and number of livestock, this farm is more extensive than the first case study farm (Tables 6 and 3). All lambs and cattle sold were assumed to be transported to two local markets. For the cattle, no exact breakdown of how many cattle go to which market was available, so it was assumed that half goes to each. Some bulls are taken to the market in Carlisle at a distance of 200 miles, but because no exact numbers were available, this was excluded from the calculation. The farm has a Tir Gofal agri-environmental agreement. Results were calculated per hectare per year based on the total area of the farm excluding the on-farm woodland.

Table 6. Description of Welsh case study farm 2.

Farm details	
Total area of farm (ha)	286.5
Area of woodland on farm (ha)	3.2
Number of ewes	480
Number of lambs sold per year	410
Average live weight of lambs sold (kg)	30
Number of cattle	51
Number of calves	26
Distance to market 1 (251 lambs, 13 calves) (miles)	38
Distance to market 2 (159 lambs, 13 calves) (miles)	15
Energy use	
Diesel use (including diesel used by contractors) (l $year^{-1}$)	5048
Electricity use (kWh $year^{-1}$)	1441
Fertiliser	
Nitrogen (kg N $year^{-1}$)	4458
Phosphorus (kg P $year^{-1}$)	1708
Potassium (kg K $year^{-1}$)	924
Organic nitrogen (kg N $year^{-1}$)	851
Pesticides	
Herbicide (l $year^{-1}$)	23
Insecticide (l $year^{-1}$)	20
Feed	
Concentrate (kg dry matter $year^{-1}$)	39104
Silage used (t $year^{-1}$)	100
Other feed (kg $year^{-1}$)	1960
Straw or other bedding (t $year^{-1}$)	37
Hay purchased (t $year^{-1}$)	3.2

7.2 Results: System boundary 1

Table 7 presents the results on GHG emissions from direct and indirect inputs. Total GHG emissions range from 126 to 359 kg CO_2 equivalents ha^{-1} $year^{-1}$. As in case study 1, nitrogen fertiliser, concentrate feed and diesel use dominate emissions. The lowest emissions are associated with potassium fertiliser, phosphate fertiliser and pesticides. When considered on a live weight basis, emissions range from 1.7 to 4.8 (average 3.2) kg CO_2 equivalents kg^{-1} live weight. Lambs account for 57.5% of the total amount of live weight sold, which means that of the total emissions, 1.0 to 2.8 (average 1.9) kg CO_2 equivalents kg^{-1} live weight can be allocated to lambs only.

Table 7. GHG emissions in kg CO_2 equivalents ha^{-1} $year^{-1}$ on a Welsh upland mixed sheep/cattle farm, calculated using a range of values reported in the literature. The minimum, maximum and mid value of these ranges were used to represent a best case, worst case and average scenario.

	min.	max.	mid.
Direct			
Diesel	48.3	48.3	48.3
Electricity [a]	2.6	2.6	2.6
Total direct	**50.9**	**50.9**	**50.9**
Indirect			
Fertiliser – N	46.5	148.7	97.6
Fertiliser – P	-1.1	2.8	0.9
Fertiliser – K [a]	1.0	2.3	1.6
Pesticides	0.1	1.0	0.6
Concentrates	15.5	139.7	77.6
Bedding [a]	11.6	11.6	11.6
Silage wrap	1.0	1.5	1.3
Total indirect	**74.6**	**307.7**	**191.2**
TOTAL	**125.5**	**358.6**	**242.1**

[a] for lack of data on total GHG emissions, this is CO_2 only

7.3 Results: System boundary 2

GHG emissions from the grazing animals, their excreta and soils are listed in Table 8. Adding these to the emissions from direct and indirect inputs, total emissions range from 1.7 to 11.6 t CO_2 equivalents ha^{-1} $year^{-1}$. Emissions are dominated by direct N_2O emissions from soils, especially from organic soils, followed by CH_4 from enteric fermentation. Emissions per kg live weight leaving the farm range from 22.5 to 155.6 kg CO_2 equivalents (average: 56.4 kg CO_2 equivalents).

Figure 2 summarises the relative importance of emissions from direct and indirect inputs, direct and indirect N_2O emissions and CH_4 emissions, illustrating how total emissions are dominated by N_2O and CH_4.

Table 8. GHG emissions in kg CO_2 equivalents ha^{-1} $year^{-1}$ on a Welsh upland mixed sheep/cattle farm, calculated using a range of values reported in the literature. The minimum, maximum and mid value of these ranges were used to represent a best case, worst case and average scenario.

		min.	**max.**	**mid.**
Total direct (see Table 7)		50.9	50.9	50.9
Total indirect (see Table 7)		74.6	307.7	191.2
Meat – lambs		8.0	8.0	8.0
Meat – calves		5.9	5.9	5.9
Direct N_2O emissions	from synthetic fertiliser	21.6	217.1	72.4
	from organic fertiliser	4.1	41.4	13.8
	from organic soils	697.8	8373.4	2791.1
	from excreta – sheep	42.1	420.6	140.2
	from excreta – cattle	24.6	210.4	70.1
	total	**790.2**	**9263.0**	**3087.7**
Direct N_2O from manure management	cattle	7.1	26.2	13.1
	calves	2.4	8.9	4.4
	total	**9.5**	**35.1**	**17.5**
Indirect N_2O from managed soils	from atmospheric deposition of volatilised nitrogen	2.3	581.3	45.1
	from leaching/runoff	1.3	523.0	58.8
	total	**3.6**	**1104.3**	**103.9**
Indirect N_2O from manure management	cattle	0.5	85.1	11.8
	calves	0.2	28.9	4.0
	total	**0.7**	**114.0**	**15.8**
CH_4 from enteric fermentation	sheep	356.5	356.5	356.5
	cattle	352.3	352.3	352.3
	total	**708.9**	**708.9**	**708.9**
CH_4 from excreta	sheep	8.5	8.5	8.5
	cattle	17.4	17.4	17.4
	total	**25.9**	**25.9**	**25.9**
TOTAL EMISSIONS		**1678.1**	**11623.6**	**4215.6**

7.4 Results: System boundaries 4-5

Total emissions from transporting lambs and cattle to the markets are 0.64 and 0.43 kg CO_2 equivalents ha^{-1} $year^{-1}$ respectively. Adding the same amount for the return journey back to the farm results in a total of 2.14 kg CO_2 equivalents ha^{-1} $year^{-1}$.

This figure is very small compared to emissions from other processes and adding this figure to the results for system boundaries 1 and 2 as presented above does not change results significantly.

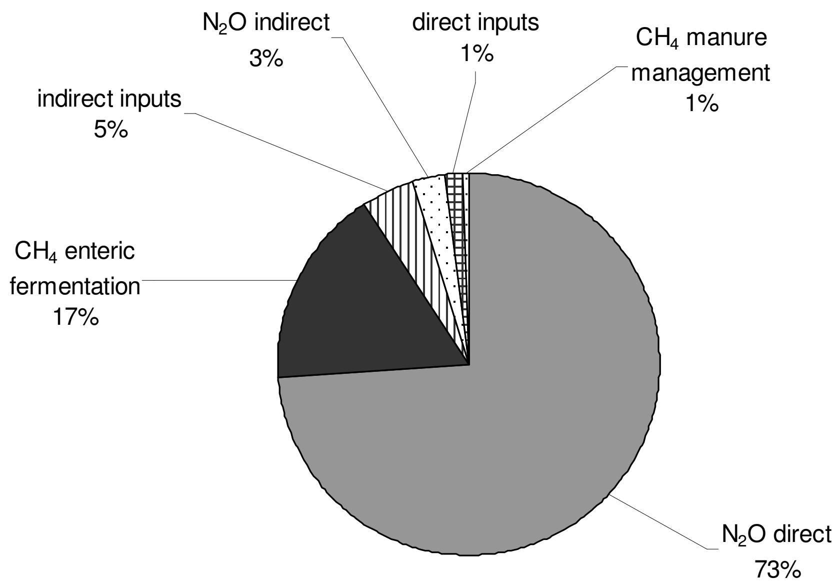

Figure 2. Relative contribution to total GHG emissions on case study farm 2 of direct and indirect inputs, direct and indirect N_2O emissions from soil and manure management and CH_4 emissions through enteric fermentation and from manure management.

8. Comparison of Saunders *et al.*'s (2006) UK results with the two Welsh case study farms

Saunders *et al.* (2006) originally expressed their results as energy per tonne carcass and kg CO_2 per tonne carcass. Table 9 presents Saunders *et al.*'s (2006) data for NZ and UK, recalculated per ha and excluding the co-product discount rate applied by those authors in order to represent the whole system. Also presented in Table 9 are the results of a calculation using the same reasoning, emission factors and equations as Saunders *et al.* (2006) for direct and indirect inputs on the two Welsh case study farms. Capital inputs were not considered for lack of data in Saunders *et al.* (2006) for the UK. Results for the Welsh case study farms are presented for the whole system (i.e. including lambs and beef cattle) and separately for lambs and cattle by allocating emissions based on the amount of live weight sold for each livestock type.

Table 9. CO_2 emissions using system boundary 1 (see Section 3). New Zealand (NZ) and UK results are recalculated after Saunders *et al.* (2006) per hectare, excluding capital inputs and not applying a co-product discount rate. For the Welsh case study farm calculations, the same reasoning, emission factors and equations as in Saunders *et al.* (2006) were used.

	CO_2 emissions kg CO_2/ha			
	Saunders *et al.*: NZ	**Saunders *et al.*: UK**	**Wales: case study 1**	**Wales: case study 2**
Direct				
Fuel, electricity and oil		391.1		
Fuel use	99.7		131.4[a]	47.3
Electricity use	4.7		29.9	2.6
Direct sub total	**104.4**	**391.1**	**161.3** [b]	**49.9** [b]
Indirect				
Nitrogen	40.0	282.8	315.2	50.6
Phosphorus	24.1	7.2	25.4	5.4
Potassium	0.7	10.2	17.1	1.9
Sulphur	7.9		0.4	
Lime	20.7	42.8		
Agri-chemicals	7.8	32.6	1.4	2.8
Concentrate		160.2	119.2	29.7
Forage, fodder and bedding		26.8		11.2
Indirect sub total	**101.2**	**562.6**	**478.7**	**101.6**
Total production	**205.6**	**953.7**	**640.0**	**151.5**
Post production				
Shipping NZ to UK (17840 km)	52.7			
TOTAL SYSTEM EMISSIONS			**640.0**	**151.5**
EMISSIONS ALLOCATED TO LAMBS	**258.3**	**953.7**	**418.6**	**87.1**
EMISSIONS ALLOCATED TO BEEF CATTLE			**221.4**	**64.4**

[a] includes diesel and petrol
[b] this figure is not directly comparable to Saunders *et al.*'s figure

Saunders *et al.*'s (2006) figure for the UK is greatest and almost four times more than for NZ. The two Welsh case studies, however, both have lower emissions than the UK system presented by Saunders *et al.* (2006). Emissions from the second Welsh case study farm are even lower by almost a factor of three than the NZ system. These figures counter the conclusion reached by Saunders *et al.* (2006) that emissions from lamb imported from NZ are lower than emissions from UK produced lamb.

9. Discussion

9.1 Carbon footprint estimate

Case study farm 2 is more extensive than farm 1, with lower inputs, fewer livestock and a greater farm area. This is reflected in the carbon footprint results for system boundary 1: the greater amount of nitrogen fertiliser, concentrates, diesel, electricity and other inputs on farm 1 results in a carbon footprint of on average about 4.5 times greater than on farm 2. However, looking at the GHG balance in system boundary 2, the results for both case study farms are very similar for the worst and average case scenario; only the best case scenario has a significantly lower carbon footprint on farm 2. This is because of the great contribution of N_2O emissions from managed organic soils on case study farm 2, which has 75% of organic soils, whereas farm 1 has no organic soils at all. The emissions from these soils cancel out the lower emissions from all other sources as compared to farm 1. The two case studies illustrated how N_2O and CH_4 emissions dominate the GHG balance. This shows how footprint calculations that do not take these emissions into account will greatly underestimate the carbon footprint.

9.2 Comparison with Saunders *et al.* (2006)

Using real-farm data increased the reliability of the estimate of the carbon footprint compared to the study of Saunders *et al.* (2006) who had to rely entirely on secondary data sources. The farm type chosen for Saunders *et al.*'s estimate was a UK lowland farm, which is not representative of the dominant farming types in Wales. Applying the same reasoning, emissions factors and methods as these authors to the Welsh data, the results contest Saunders *et al.*'s conclusion that it is more environmentally friendly for UK consumers to consume New Zealand rather than buying Welsh lamb. Total emissions from case study 1 were still greater than for New Zealand, but the estimate for Welsh case study 2 was significantly lower than for lamb imported from New Zealand. Considering all the problems associated with the methodology used by Saunders *et al.* (2006) as described in Chapter 5.4, these results should however be interpreted with caution.

9.3 Limitations

This study only presents data for two Welsh farms, representing only two Welsh farming systems. In order to develop a more robust and general picture of the carbon footprint of Welsh sheep farming, a greater number of farms and farms types would need to be investigated. For example, the footprint of an intensive lowland farm is likely to differ considerably from the very extensive upland farm in case study 2. Another factor to be considered when interpreting results is that both case study farms are HCC demonstration farms, which means they demonstrate and promote the principles of business development, environmental safeguarding and market focus. They implement management changes and new technologies designed to improve gross margins as well as sustainability. In addition, both farms have a Tir Gofal agri-environment agreement, which involves setting maximum stocking rates on semi-natural habitats. Non-members may stock those habitats more heavily and be more intensive on agriculturally improved land. This means that the case study farms may implement best practice and environmentally friendly practices which may not be universally practiced on Welsh sheep farms. For this reason, the results may not be entirely representative of the average Welsh production system.

For the footprint to apply to lamb production only, it would be necessary to analyse data from sheep only farms. The fact that most Welsh farms are mixed sheep and cattle farms presents a problem for the footprint calculation per kg of product, as inputs are hard to allocate to either sheep or cattle production.

Clearly, it would also have been desirable to be able to include more processes beyond the farm gate in the footprint calculation. This was not possible because of a lack of exact information on where livestock go after live sales at the markets, and the lack of data on energy use during any of the processes further along the food chain. If capital goods, e.g. farm buildings and machinery, were included in the calculation alongside processing and retailing activities, then the overall system would become a greater source of GHGs.

The real-farm data used represent one particular year. Obviously, farm practices and inputs used may vary between years according to climatic conditions and extreme events.

Flechard *et al.* (2007) point out that climate-sensitive emission factors for N_2O should be developed in order to improve emissions estimates based on current IPCC default values.

9.4 On-farm sinks

This analysis has ignored the flows of carbon and GHGs into and out of plants and soils on farms. These items were omitted from the analysis due to the uncertainty that surrounds their quantification. However, a full system analysis of GHGs in agricultural systems would consider these stock and flows; such analysis was beyond the scope of this particular project.

9.5 Recommendations and next steps

1. If the UK and New Zealand really want to compare the carbon footprint of relevant production systems, then the only sensible way to do this is for a team from both countries to agree a standard data set and analytical methodology. If this were agreed then an adequate comparison could be achieved.

2. Rather than expend energy in comparing the relative merits of producing sheep in the UK and New Zealand, the sheep producers of both of these countries may like to consider the carbon footprint of sheep compared to other meat production systems such as pork, chicken and farmed fish. If sheep meat could be shown to have a smaller carbon footprint per unit meat (or protein) than these other production systems, then this may enable promotion of the entire sheep meat market at the expense of other meat production systems.

3. When any future analysis of the carbon footprints of farm processes are conducted it is essential that sufficient farms are sampled in order to both represent the variation in environment / farm system but also the variation between farms utilising similar systems. For example, recent work by Milà i Canals *et al.* (2007) shows that the variation in environmental burdens between

farms in the same country can be as large as that between countries. Data presented in this current study were obtained from only two farms. This is clearly insufficient to enable any generalisations about Welsh production overall, but it does demonstrate the variation in the carbon footprints of lamb production systems. Given the absence of previous studies of this type it is impossible to predict the sample size needed to obtain adequate representation of the entire sector in Wales. However, data from at least 5-10 farms per sheep system are probably the minimum sample sizes needed to enable generalisations.

4. The results of this work, and other studies, only consider a small part of the complete food system. There is an urgent need for studies that cover the complete food system from production to waste disposal. These studies also need to consider the emissions to and from natural parts of the ecosystem such as plants, soils and freshwaters. Only by taking such widescale analysis can we obtain a thorough understanding of the impacts of food production systems.

10. Conclusions

In this report, a carbon footprint including the greenhouse gases CO_2, N_2O and CH_4 was calculated for two Welsh case study farms, using minimum, maximum and average figures for the different components of the footprint obtained from the literature. These figures were used to calculate a best case, worst case and average scenario.

On both farms, direct N_2O emissions from soils and CH_4 from enteric fermentation dominated GHG emissions, which stresses the importance of including these emissions in carbon footprint calculations. Of the indirect and direct inputs, nitrogen fertilisers, concentrate feeds and diesel use represent the greatest GHG costs. The more extensively managed farm has a slightly lower carbon footprint per ha than the more intensively managed farm; however, per kg live weight, the more extensive farm has a greater carbon footprint due to its lower output.

The carbon footprint of both UK case study farms was significantly lower than that presented by Saunders *et al.* (2006) for UK farms. The carbon footprint of one farm was significantly less than that calculated by Saunders *et al.* (2006) for New Zealand lamb production, while that of the other farm was greater than the New Zealand footprint. These results demonstrate the variation that occurs between farms producing the same product, and as such they severely undermine the generalisability of any claims made about the carbon footprint of a farming enterprise for a whole country or region. Only through collecting data from an adequate number of similar farms within a region can we hope to understand the variation in their carbon footprints.

The main message for consumers from this work is that it is possible to buy Welsh lamb that is produced from farms which have fewer greenhouse gas emissions than those reported by Saunders *et al.* (2006) for New Zealand. However, not all Welsh lamb currently has a lower carbon footprint than New Zealand lamb. If consumers wish to purchase lamb from farms with low carbon footprints then, in the absence of a relevant labelling scheme, they may wish to purchase lamb from extensive upland and hill farms in preference to lowland lamb produced in more intensive systems.

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Appendix

Appendix 1. Greenhouse gas emission factors for mean nitrogen fertiliser, ammonium nitrate fertiliser (AN) and calcium ammonium nitrate fertiliser (CAN) reported in the literature. The minimum, maximum and mid range value were used in the carbon footprint calculations to represent the whole range of emissions estimates in the literature as a best case, worst case and average scenario.

Product	**Country**	**Composition**	**kg CO_2 equ kg^{-1} N**	**Reference**
N fertiliser	Germany		5.47	1
Mean N fertiliser	Germany	28.6% N	7.62	2
Mean N fertiliser	Germany	27.7% N	5.34	2
Mean N fertiliser	Germany	27.7% N	5.64	2
AN	Western European average	N:P:K 35:0:0	7.03	2
AN	European average	N:P:K 33.5:0:0	6.81	2
AN	Europe modern technology	N:P:K 33.5:0:0	2.99	2
AN	Netherlands	N:P:K 33.5:0:0	7.11	2
AN	UK	N:P:K 33.5:0:0	6.54	2
AN	Europe	N:P:K 33.5:0:0	6.73	2
CAN	Sweden	N:P:K 27.6:0:0	8.47	2
CAN	Sweden	N:P:K 27.6:0:0	9.56	2
CAN	Sweden	N:P:K 27.2:0:0	9.56	2
CAN	Europe average	N:P:K 26.5:0:0	7.48	2
CAN	Europe average	N:P:K 26.5:0:0	6.87	2
CAN	Europe modern technology	N:P:K 26.5:0:0	3.02	2
CAN	Netherlands	N:P:K 27.9:0:0	6.81	2
Range			**2.99-9.56**	

1 Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M.A., Munch, J.C. & Beese, F. (2002). Integrated evaluation of greenhouse gas emissions (CO_2, CH_4, N_2O) from two farming systems in southern Germany. *Agriculture, Ecosystems and Environment* **91**, 175-189.

2 Wood, S. & Cowie, A. (2004). *A review of greenhouse gas emission factors for fertiliser production.* IEA Bioenergy Task 38.

Appendix 2. Greenhouse gas emissions from the production of phosphate fertilisers reported in the literature. Source: Wood & Cowie (2004). The minimum, maximum and mid range value were used in the carbon footprint calculations to represent the whole range of emissions estimates in the literature as a best case, worst case and average scenario.

Fertiliser type	Country	Composition (N:P:K:S)	kg CO_2 equ kg^{-1} P_2O_5
Mean P fertiliser	Germany	0:32.2:0:0	0.82
Mean P fertiliser	Germany	0:38.8:0:0	0.46
Mean P fertiliser	Germany	0:35.5:0:0	0.70
SSP	Europe average	0:21:0:23	1.05
SSP	Europe average	0:21:0:23	0.10
SSP	Europe modern technology	0:21:0:23	-0.24
TSP	Europe average	0:48:0:0	1.08
TSP	Europe average	0:48:0:0	0.35
TSP	Europe modern technology	0:48:0:0	-0.42
Range			**-0.42 to 1.08**

Appendix 3. Greenhouse gas emissions from the production of potassium fertiliser reported in the literature. The conversion of MJ kg^{-1} K as obtained from the literature to CO_2 emissions was based on a conversion factor of 0.06 kg CO_2 MJ^{-1} taken from Saunders *et al.* (2006). Note that this conversion factor does not include N_2O and CH_4 emissions. The minimum, maximum and mid range value were used in the carbon footprint calculations to represent the whole range of emissions estimates in the literature as a best case, worst case and average scenario.

	MJ kg^{-1}	**kg CO_2 kg^{-1} K**	**Reference**
	10	0.60	1
	7.0	0.42	2
	5-12	0.3-0.72	3
	7.0	0.42	4
	7.8	0.47	5
Range		**0.3-0.72**	

1 Saunders, C., Barber, A. & Taylor, G. (2006). *Food miles – Comparative energy/emissions performance of New Zealand's agriculture industry.* AERU Research Report No. 285.

2 Tzilivakis, J., Warner, D.J., May, M., Lewis, K.A. & Jaggard, K. (2005). An assessment of the energy inputs and greenhouse gas emissions in sugar beet *(Beta vulgaris)* production in the UK. *Agricultural Systems* **85**, 101-119.

3 Carlsson-Kanyama, A. & Faist, M. (2000). *Energy use in the food sector: A data survey.* Swedish Environmental Protection Agency, AFR Report 291, Stockholm.

4 Dalgaard, T., Halberg, N. & Porter, J.R. (2001). A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture, Ecosystems and Environment* **87**, 51-65.

5 Nemecek, T., Heil, A., Huguenin, O., Meier, S., Erzinger, S., Blaser, S., Dux, D. & Zimmermann, A. (2004). *Life Cycle Inventories of Agricultural Production Systems.* Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf (Switzerland).

Appendix 4. Greenhouse gas emissions from the production of pesticides reported in the literature. The conversion of MJ kg^{-1} active ingredient (ai) as obtained from the literature to CO_2 equivalents was based on a conversion factor of 0.0589 kg CO_2 equivalents MJ^{-1}. This conversion factor was calculated using UK data presented in Tzilivakis *et al.* (2005). The minimum, maximum and mid range value were used in the carbon footprint calculations to represent the whole range of emissions estimates in the literature as a best case, worst case and average scenario.

Product		**MJ kg^{-1} ai**	**kg CO_2 equ kg^{-1} ai**	**Reference**
general herbicide		310	18.3	1
herbicides	min.	80	4.7	2
herbicides	max.	460	27.1	2
insecticide		315	18.6	1
insecticide	min.	58	3.4	2
insecticide	max.	580	34.2	2
fungicide		210	12.4	1
fungicide	min.	61	3.6	2
fungicide	max.	397	23.4	2
pesticide	min.	118	7.0	3
pesticide	max.	400	23.6	3
pesticide	average	226.9	13.4	4
Range			**3.4-34.2**	

1 Saunders, C., Barber, A. & Taylor, G. (2006). *Food miles – Comparative energy/emissions performance of New Zealand's agriculture industry.* AERU Research Report No. 285.

2 Dalgaard, T., Halberg, N. & Porter, J.R. (2001). A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. *Agriculture, Ecosystems and Environment* **87**, 51-65.

3 Carlsson-Kanyama, A. & Faist, M. (2000). *Energy use in the food sector: A data survey.* Swedish Environmental Protection Agency, AFR Report 291, Stockholm.

4 Nemecek, T., Heil, A., Huguenin, O., Meier, S., Erzinger, S., Blaser, S., Dux, D. & Zimmermann, A. (2004). *Life Cycle Inventories of Agricultural Production Systems.* Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf (Switzerland).

Appendix 5. Greenhouse gas emissions from the production of concentrate feed reported in the literature. The minimum, maximum and mid range value were used in the carbon footprint calculations to represent the whole range of emissions estimates in the literature as a best case, worst case and average scenario.

Product	Country	kg CO_2 equ t^{-1} product	Reference
processed feed: wheat-feed (N-org)	UK	128	1
processed feed: wheat-feed (org)	UK	108	1
processed feed: maize gluten free	UK	338	1
processed feed: soya meal (no hulls)	UK	944	1
processed feed: soya meal (with hulls)	UK	853	1
processed feed: rape meal	UK	550	1
production of barley	UK	726	1
production of barley	UK	710	1
feed supplement, composition 1	Ireland	975	2
feed supplement, composition 2	Ireland	808	2
feed supplement, composition 3	Ireland	416	2
feed supplement, composition 4	Ireland	780	2
Range		**108-975**	

1 Williams, A.G., Audsley, E. & Sandars, D.L. (2006). *Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities.* Main Report. Defra Research Project IS0205. Bedford: Cranfield University and Defra.

2 Casey, J.W. & Holden, N.M. (2006). Quantification of greenhouse gas emissions from sucker-beef production in Ireland. *Agricultural Systems* **90**, 79-98.

Appendix 6. Equations used for the calculation of CH_4 emissions from enteric fermentation (after IPCC 2006)

$CH_{4\ ent\ ferm} = (EF_{sheep} * N_{sheep}) + (EF_{cattle} * N_{cattle})$

where:

$CH_{4\ ent\ ferm}$ = methane emissions from enteric fermentation, kg CH_4 year^{-1}

EF_{sheep} = emission factor for sheep; 8 kg CH_4 animal^{-1} year^{-1} for adult sheep, 3.2 kg CH_4 animal^{-1} year^{-1} for lambs less than one year old

N_{sheep} = number of animals

EF_{cattle} = emission factor for cattle; 57 kg CH_4 animal^{-1} year^{-1} for non-dairy cattle, including calves

N_{cattle} = number of animals

Using these equations, total on-farm emissions per year were calculated, which were then divided by the number of hectares to give emissions per hectare per year.

Appendix 7. Equations used for the calculation of CH_4 emissions from excreta (after IPCC 2006)

$CH_{4\ excreta} = (EF_{sheep} * N_{sheep}) + (EF_{cattle} * N_{cattle})$

where:

$CH_{4\ excreta}$ = methane emissions from manure, kg CH_4 year^{-1}

EF_{sheep} = emission factor for sheep; 0.19 kg CH_4 animal^{-1} year^{-1} for adult sheep, 0.076 kg CH_4 animal^{-1} year^{-1} for lambs less than one year old

N_{sheep} = number of animals

EF_{cattle} = emission factor for cattle; 2.74 kg CH_4 animal^{-1} year^{-1} for adult beef cattle and 2.96 for calves (Baggott *et al.* 2007)

N_{cattle} = number of animals

Appendix 8. Equations used for the calculation of direct N_2O emissions from managed soils (after IPCC 2006)

$N_2O\text{-}N_{Direct} = N_2O\text{-}N_{N\ inputs} + N_2O\text{-}N_{OS} + N_2O\text{-}N_{PRP}$

where:

$N_2O\text{-}N_{N\ inputs} = (F_{SN} + F_{ON}) * EF_1$

$N_2O\text{-}N_{OS} = F_{OS,\ temperate\ grassland} * EF_{2\ temperate\ grassland}$

$N_2O\text{-}N_{PRP} = (F_{PRP,\ sheep} * EF_{3\ sheep}) + (F_{PRP,\ cattle} * EF_{3\ cattle})$

and:

$N_2O\text{-}N_{Direct}$ = annual direct N_2O-N emissions from managed soils, kg N_2O-N year^{-1}

$N_2O\text{-}N_{N\ inputs}$ = annual direct N_2O-N emissions from nitrogen inputs to managed soils, kg N_2O-N $year^{-1}$

$N_2O\text{-}N_{OS}$ = annual direct N_2O-N emissions from managed organic soils, kg N_2O-N $year^{-1}$

$N_2O\text{-}N_{PRP}$ = annual direct N_2O-N emissions from urine and dung inputs to grazed soils, kg N_2O-N $year^{-1}$

F_{SN} = annual amount of synthetic fertiliser nitrogen applied, kg N $year^{-1}$

F_{ON} = annual amount of animal manure applied, kg N $year^{-1}$

$F_{OS,\ temperate\ grassland}$ = annual area of managed/drained organic soils, ha

F_{PRP} = annual amount of urine and dung nitrogen deposited by grazing animals on pasture, range and paddock, kg N $year^{-1}$

EF_1 = emission factor for N_2O emissions from N inputs; default value: 0.01 kg N_2O-N kg^{-1} N, uncertainty range: 0.003-0.03 kg N_2O-N kg^{-1} N

EF_2 = emission factor for N_2O emissions from drained/managed organic soils; default value: 8 kg N_2O-N ha^{-1}, uncertainty range: 2-24 kg N_2O-N ha^{-1}

EF_3 = emission factor for N_2O emissions from urine and dung deposited by grazing animals; default value for sheep: 0.01 kg N_2O-N kg^{-1} N, uncertainty range: 0.003-0.03 kg N_2O-N kg^{-1} N; default value for cattle: 0.02 kg N_2O-N kg^{-1} N, uncertainty range: 0.007-0.06 kg N_2O-N kg^{-1} N

F_{PRP} was calculated as:

$$F_{PRP} = (N_{sheep} * N_{ex\ sheep} * MS_{sheep}) + (N_{cattle} * N_{ex\ cattle} * MS_{cattle})$$

where:

N = number of animals

N_{ex} = annual average nitrogen excretion per head, kg N $animal^{-1}$ $year^{-1}$

MS = fraction of total annual nitrogen excretion that is deposited on the pasture

For sheep, MS was set to one, assuming that they are outside all year round. For cattle, MS was set to 0.5, assuming they spend half of each year inside. For sheep, it was assumed that N_{ex} of a lamb is half that of an adult ewe.

N_{ex} was calculated as:

$$N_{ex} = (N_{rate\ sheep} * TAM_{sheep} /1000 * 365) + (N_{rate\ cattle} * TAM_{cattle} /1000 * 365)$$

where:

$N_{rate\ sheep}$ = default excretion rate for sheep in Western Europe, 0.85 kg N (1000 kg animal mass)$^{-1}$ day^{-1}

TAM_{sheep} = typical animal mass, IPCC default: 48.5 kg $animal^{-1}$

$N_{rate\ cattle}$ = default excretion rate for non-dairy cattle in Western Europe, 0.33 kg N (1000 kg animal mass)$^{-1}$ day^{-1}

TAM_{cattle} = typical animal mass, 525 kg $animal^{-1}$ for mature non-dairy cattle, 350 kg $animal^{-1}$ for calves at slaughter (IPCC default for Western Europe is 420 kg)

N_{ex} was calculated separately for cattle and calves, based on different TAM values. For the calculation of F_{PRP}, N_{ex} of lambs was assumed to be half of N_{ex} of adult ewes.

Using these equations, total on-farm emissions per year were calculated, which were then divided by the number of hectares to give emissions per hectare per year. To convert N_2O-N emissions to N_2O emissions, the following equation was applied:

$N_2O = N_2O\text{-}N * 44/28$

Appendix 9. Equations used for the calculation of indirect N_2O emissions from managed soils (after IPCC 2006)

1. N_2O from atmospheric deposition of nitrogen volatilised from managed soils

$N_2O\text{-}N_{ATD} = (F_{SN} * Frac_{gasf}) + ((F_{ON} + F_{PRP}) * Frac_{gasm}) * EF_4$

where:

$N_2O\text{-}N_{ATD}$ = annual amount of N_2O-N produced from atmospheric deposition of nitrogen volatilised from managed soils, kg N_2O-N year^{-1}

F_{SN} = annual amount of synthetic fertiliser nitrogen applied, kg N year^{-1}

$Frac_{gasf}$ = fraction of synthetic fertiliser nitrogen that volatilises as NH_3 and NO_x; default value: 0.10 (kg NH_3-N + NO_x-N) (kg N applied)$^{-1}$, uncertainty range: 0.03-0.3 (kg NH_3-N + NO_x-N) (kg N applied)$^{-1}$

F_{ON} = annual amount of animal manure applied, kg N year^{-1}

F_{PRP} = annual amount of urine and dung nitrogen deposited by grazing animals on pasture, range and paddock, kg N year^{-1}

$Frac_{gasm}$ = fraction of applied organic nitrogen fertiliser materials and of urine and dung nitrogen deposited by grazing animals that volatilises as NH_3 and NO_x; default value: 0.20 (kg NH_3-N + NO_x-N) (kg N applied or deposited)$^{-1}$, uncertainty range: 0.05-0.5 (kg NH_3-N + NO_x-N) (kg N applied or deposited)$^{-1}$

EF_4 = emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces; default value: 0.010 kg N_2O-N (kg NH_3-N + NO_x-N volatilised) $^{-1}$; uncertainty range: 0.002-0.05 kg N_2O-N (kg NH_3-N + NO_x-N volatilised) $^{-1}$

Using these equations, total on-farm emissions per year were calculated, which was then divided by the number of hectares to give emissions per hectare per year. To convert N_2O-N emissions to N_2O emissions, the following equation was applied:

$N_2O = N_2O\text{-}N * 44/28$

2. N_2O from atmospheric deposition of nitrogen volatilised from managed soils

$N_2O\text{-}N_L = (F_{SN} + F_{ON} + F_{PRP}) * Frac_{leach} * EF_5$

where:

$N_2O\text{-}N_L$ = annual amount of N_2O-N produced from leaching and runoff of nitrogen additions to managed soils, kg N_2O-N year^{-1}

F_{SN} = annual amount of synthetic fertiliser nitrogen applied, kg N $year^{-1}$

F_{ON} = annual amount of animal manure applied, kg N $year^{-1}$

F_{PRP} = annual amount of urine and dung nitrogen deposited by grazing animals on pasture, range and paddock, kg N $year^{-1}$

$Frac_{leach}$ = fraction of all nitrogen added to/mineralised from managed soils that is lost through leaching and runoff; default value: 0.30 kg N (kg N additions or deposition by grazing animals)$^{-1}$; uncertainty range: 0.1-0.8 kg N (kg N additions or deposition by grazing animals)$^{-1}$

EF_5 = emission factor for N_2O emissions from nitrogen leaching and runoff; default value: 0.0075 kg N_2O-N (kg N leaching/runoff)$^{-1}$; uncertainty range: 0.0005-0.025 kg N_2O-N (kg N leaching/runoff)$^{-1}$

Using these equations, total on-farm emissions per year were calculated, which was then divided by the number of hectares to give emissions per hectare per year. To convert N_2O-N emissions to N_2O emissions, the following equation was applied:

$N_2O = N_2O\text{-}N * 44/28$

Appendix 10. Equations used for the calculation of direct N_2O emissions from manure management (after IPCC 2006)

$N_2O\text{-}N_{D(mm)} = (N_{cattle} * N_{ex\ cattle} * MS_{cattle}) * EF_3$

where:

$N_2O\text{-}N_{D(mm)}$ = direct N_2O emissions from manure management, kg N_2O $year^{-1}$

N = number of animals

N_{ex} = annual average nitrogen excretion per head, kg N $animal^{-1}$ $year^{-1}$

MS = fraction of total annual nitrogen excretion that is deposited on the pasture (= 0.5, assuming that cattle are outside for half of each year)

EF_3 = emission factor for direct N_2O emissions from manure management (solid storage); default value: 0.005 kg N_2O-N (kg N excreted)$^{-1}$; uncertainty range: 0.0027-0.01 kg N_2O-N (kg N excreted)$^{-1}$

Using these equations, total on-farm emissions per year were calculated, which was then divided by the number of hectares to give emissions per hectare per year. To convert N_2O-N emissions to N_2O emissions, the following equation was applied:

$N_2O = N_2O\text{-}N * 44/28$

Appendix 11. Equations used for the calculation of indirect N_2O emissions from manure management (after IPCC 2006)

$N_2O\text{-}N_{ID(mm)} = N_{volatilisation} * EF_4$

where:

$N_2O\text{-}N_{ID(mm)}$ = indirect N_2O emissions due to volatilisation of nitrogen from manure management, kg N_2O year^{-1}

EF_4 = emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces; default value: 0.01 kg N_2O-N (kg NH_3-N + NO_x-N volatilised)$^{-1}$; uncertainty range: 0.002-0.05 kg N_2O-N (kg NH_3-N + NO_x-N volatilised)$^{-1}$

and:

$N_{volatilisation} = (N_{cattle} * N_{ex\ cattle} * MS_{cattle}) * Frac_{gasMS}/100$

$N_{volatilisation}$ = amount of manure nitrogen that is lost due to volatilisation of NH_3 and NO_x, kg N year^{-1}

N = number of animals

N_{ex} = annual average nitrogen excretion per head, kg N animal^{-1} year^{-1}

MS = fraction of total annual nitrogen excretion that is deposited on the pasture (= 0.5, assuming that cattle are outside for half of each year)

$Frac_{gasMS}$ = percent of managed manure nitrogen that volatilises as NH_3 and NO_x; default value for non-dairy cattle: 45%, uncertainty range: 10-65%

Using these equations, total on-farm emissions per year were calculated, which was then divided by the number of hectares to give emissions per hectare per year. To convert N_2O-N emissions to N_2O emissions, the following equation was applied:

$N_2O = N_2O\text{-}N * 44/28$

Appendix 12. Comments from peer reviewer

1. General

1.1 Scope

The review was carried out after completion of the project's final report, and is based only on that report. The reviewer has had no access to other project material nor has he been involved in the execution of the project at any stage. It is accepted that resource constraints and practical difficulties often prevent researchers collecting all the data they would wish to, or exploring all methodological issues of interest. The extent to which considerations of this sort not explicitly mentioned in the report's text have influenced the work carried out is unknown. Some overall comments and key points are made in the next section of this short report. Some of these are dealt with at greater length in section 2, which also contains further comments of a more detailed nature.

1.2 Overall comments

Bangor University's report represents a further valuable contribution to our understanding of the level of greenhouse gas emissions associated with livestock farming and therefore of the greenhouse gases notionally embedded in the products of livestock farms. Naturally, inclusion of a larger number of farms would have been desirable. The area-based approach to assessing enterprise-level impacts of farming has merit, but in this reviewer's opinion needs further development before it can be applied in a fashion that allows comparison; other current work to calculate a carbon-footprint for lamb seen by this reviewer uses GHG per flock at an intermediate stage of the calculation. The presentation of results in terms of ranges of possible values is particularly welcome, giving some indication of the level of uncertainty currently associated with calculations of this kind.

The report draws attention to the influence of modellers' choices about system boundaries and of decisions made (or forced) about data selection on the results of carbon footprint calculations, for example in its consideration of the comparative study of New Zealand and UK lamb carried out by Saunders *et al*. It is therefore unfortunate that the authors fail to explore or explain the influences of *their* choices on the results of this study, although the report clearly states that some choices have been made by them, or forced on them for want of data. The inclusion of maximum-minimum ranges for certain emissions in the inventory is not a substitute for this.

Despite this, and some other shortcomings in the report to which attention is drawn below, almost all of the conclusions as set out in the main report seem sound. It is unfortunate that in abbreviating these conclusions for the executive summary, important caveats attached to the final conclusion (which concerns messages for consumers) have been dropped. This reviewer's opinion is that the body of the report does not support this final conclusion as set out in the Executive Summary. It is certainly possible to conclude from the report that it MAY BE "possible to buy Welsh lamb that is produced from farms which have fewer greenhouse gas emissions than those reported by Saunders *et al* (2006) for New Zealand" but to state that it IS possible seems unjustified on the basis of a comparison of what the researchers themselves find (in Section 9.1) to be only a small component of the whole carbon footprint of livestock farming - especially in the light of the uncertainties and gaps noted by the researchers and recognized uncertainties about the difference between impacts arising from similar agricultural activities carried out in different geographical locations.

Certainly the report makes a strong case for further work to understand the extent to which all the aspects considered in this study vary from farm to farm or region to region. Such work would be a valuable complement to the UK-level LCA carried out at Cranfield University (Williams *et al* 2006) which provides information about the impacts arising from a synthetic "UK national average" production. In this context it is perhaps worth noting that the Swiss Agroscope Reckenholz-Tänikon Research Station (ART) has in hand a Life Cycle Assessment study of agricultural products which involves capturing data over several years from some two hundred farms in Switzerland.

2. Detailed Comments

2.1 Functional Unit & Allocation

2.1.1 Area/enterprise level analysis

The proposition that the impacts of a farming enterprise might initially be measured and reported on an area basis has much merit. Given that one obvious feature of agriculture is that it takes up land (a "resource") to produce food (and to provide other services such as land management), the "environmental intensity" of that land use is a sensible focus of study. But livestock farms often use crops grown elsewhere as animal feed, so care is needed when creating and interpreting per hectare values for impacts. A small farm that uses a large proportion of bought-in feed would presumably be found to have high impacts per hectare in a footprinting or LCA exercise that included the production of inputs (as it should). But it might be a mistake to read into such an outcome that the use of the farm's own land was environmentally-intensive, since the bought-in feeds might enable the farm's own land to be used at a lower intensity level. In the cases considered here, the two case study farms use rather different quantities of concentrate feed, the smaller (Farm 1) using more than the larger. One interpretation of this is that Farm 1 "outsources" more of the land demand associated with producing its products than does Farm 2. The magnitude of any adjustment to the results of the footprint calculations that would follow from incorporating this "off-site production area" is unknown, but deserves some consideration in any future exercise of this sort. The wintering of stock off the farm (as in Farm 2 here) potentially further complicates this area-based analysis.

2.1.2 Product-level analysis

The product-related Functional Unit in this study is essentially one kg liveweight mixed beef and lamb. The authors' argument in favour of using such a mixed functional unit rather than treating beef and lamb separately is understood; the challenge of assigning burdens to one of several products of an indivisible unit process is by no means unique to agriculture, and none of the available mechanisms for tackling it is entirely satisfactory.

The solution proposed here of using an expanded functional unit seems, however, to be inappropriate for taking the farm-level analysis further to the product level. Essentially, the functional unit for Farm 1 is 1kg liveweight comprising 64.5% lamb, 35.5% beef, while that for Farm 2 is 1kg liveweight comprising 57.5% lamb, 42.5% beef. Seen as the weighted average of production of the relative enterprises, and thus as the basis for enterprise-level greenhouse gas accounting, these are hard to fault. Yet in applying this functional unit in the product-level analysis, the researchers appear to be making the implicit assumption that the utility, or function, delivered to society is the same in each of the two cases – i.e that beef liveweight and lamb liveweight are substitutable one for the other. It isn't at all clear to this reviewer that this assumption is justifiable.

When allocation of the aggregated burdens associated with the functional unit between its two components is undertaken in this study, the allocation is essentially done on a mass basis (in each kg of functional unit emerging from Farm 1, 645g is lamb - therefore 64.5% of the impacts associated with the functional unit are allocated to lamb). Allocation on a mass basis in LCA is disfavoured now, and some workers (Guinée *et al* (2002) have recently suggested that there is no justification for adopting this approach except as a proxy for economic allocation. In this study there is no reason to believe that the quantities of most of the agricultural inputs used is at all driven by the relative masses of beef and lamb in the farms' outputs, and the relationships between enteric emissions or emissions to air from excreta from the two types of animal (shown in Table 5) provide adequate reason for questioning mass allocation as an approach that could usefully be applied for systems boundaries more extensive that system boundary 1. Accepting the authors' arguments that other approaches are equally flawed, some exploration of the effect on the study's results of applying different allocation methods would have been preferable to a somewhat arbitrary choice by the researchers of one method alone.

The "discount rate" applied by Saunders *et al* of course serves the purpose of economic allocation. The criticism of Saunders *et al* for failing to represent the whole system as a result of applying this seems to this reviewer to be somewhat overdone; the argument that if wool has value to society then some of the impacts of farming sheep should be allocated to it has some validity and is (as noted above) accepted as one reasonable approach to the challenge mentioned at the beginning of this section.

The desirability of an agreed approach among those applying carbon footprinting or LCA techniques to farming activities (whether sheep farming or other farming) is clear. As other industrial sectors have found, no individual party is well-served in the long run by a dialogue based on claims and counter-claims that draw on the results of applying different modeling approaches to different systems.

2.2 System boundaries

The report notes that a variety of system boundaries can be used in studies of this type, and that one or more greenhouse gases can be included. The subsequent analysis of the effects of boundary choice on results is a useful aspect of the report; the high significance of non-CO_2 substances in total greenhouse gas emissions from agricultural systems has been widely noted elsewhere. The current draft (Draft 2) of the standard for "carbon" footprinting being developed by the British Standards Institute, DEFRA and the Carbon Trust recommends their inclusion in carbon footprint calculations for the products of such systems.

Ideally, selection of the system boundaries in studies which cover parts of the life cycle of products rather than their entirety, as this one does, would take heed of the use to which the results are to be put[1]. For example, inclusion of the carbon content of the meat would be justified were the results to be used in a situation where account was to be taken of the ultimate fate of this carbon after consumption and digestion by people: i.e. where emissions associated with the "operation" of the human body and with treatment of human excreta in sewage were to be considered. However, those

[1] Hence the flexibility permitted in ISO 14040 & ISO 14044, which accept that appropriate system boundaries depend to a significant extent on the goal and scope of the study.

calculating carbon footprints up to the farm- or factory-gate seldom have knowledge of or control over the use to which calculated values will be put: this reinforces the argument made by the researchers for some form of agreement about methodology.

Capital equipment has been excluded, and the researchers note Frishcknecht *et al*'s recent work in support of this decision. Others have found that capital equipment can make a significant contribution to the environmental burdens associated with some agricultural systems: the effect is most marked when primary energy data is considered. For instance Foster *et al* (2007), using Cranfield University's LCA model, found that capital equipment accounts for around 9% of the primary energy used in the production of milk. Capital equipment requirements on sheep farms are less than on dairy farms (no requirement for milking equipment), so this omission might have a small influence on the outcomes of the calculations using system boundary 1, which are largely driven by energy inputs to the system. Furthermore, once non-CO_2 GHGs are included its effect on the results of the footprint calculations is likely to be negligible.

2.3 Data

Most of the data used for the emissions "embedded" in indirect inputs are reasonable, and the authors have drawn on well-recognised sources for the most part. Other values for many of the inputs used are available, but it seems that their use would be unlikely to affect the results to a very large extent. For example the current version of Plastics Europe's Life Cycle Inventory data gives a value for the carbon footprint of LDPE film (in this case, as a global Warming Potential over a 100-year timescale, GWP_{100}) as 2.4kg CO_2e/kg film, whereas the researchers here have used a range of 1.3 – 1.94 kg CO_2e/kg. It is worth noting that assigning a value for the GHG emissions embedded in straw also involves allocation of burdens between a primary product (grain) and a by-product (the straw), and so there is perhaps more choice of available values for this than for some of the other inputs listed.

The reviewer is insufficiently expert in the practical details of sheep-farming to comment on the representativeness of the data collected from the case study farms beyond the comments included by the report's authors.

2.4 Results

The results presented using system boundary 1 provide an interesting indication of the difference between inputs used on different farms producing similar products and the range of environmental impact associated with those inputs.

The presentation of results in terms of ranges of possible values is valuable. It seems likely that if more detailed data were collected, and a longer time period considered, additional uncertainties would be revealed. For example it seems unlikely that liveweight output would be constant from year to year, even if the quantities of inputs stayed the same. Methane emissions are also, presumably, subject to some variation, and are known to vary somewhat with diet.
The method used, and the approach to allocation employed, prevent any comparison of the results of this study with the calculation of greenhouse gas impacts associated with sheepmeat production made by Williams *et al* (2006). The authors note that data limitations prohibited the use of a functional unit based on deadweight or meat produced, which would have facilitated such comparisons.

The report itself includes, by design, comparison with the carbon-footprinting study of lamb conducted by Saunders *et al*. The authors note a number of deficiencies in that study and the data it has used. They also note a number of deficiencies in the data available to them – mostly data gaps. One weakness of the report is that it fails to discuss the significance of these gaps, and their potential influence on the results, or explore the results that would be obtained were they filled with figures drawn from, for instance, national or industry-wide statistics. The potential low relevance of such figures to the local situation being studied can be acknowledged – as it has for some other non-Welsh data used - but some such effort seems particularly important in a report that criticises the data selection of workers elsewhere.

Given the assumptions needed to enable the comparison with Saunders *et al* to be made, it would seem unwise to draw very strong conclusions from it. This reviewer can only agree that making such comparisons is not the best use of research effort.

In Williams *et al* (2006), where economic allocation is applied, some 15% of the impact of the "sheepmeat" system is associated with the mutton produced from ewes. Culled ewes have been excluded from this study (partly for want of data), which may mean that the results obtained are higher than they would be had they been included. The treatment, in this study, of the farms involved as disconnected from the lowland farming system is a major difference from both Williams *et al* and other studies. It appears to be justified by the descriptions of the farms provided and by the functional unit used: the effect of this different focus on the results of the calculations seems likely to be quite strong, since other studies have identified strong interactions between upland and lowland sheep farms.

2.5 Recommendations and Conclusions

This reviewer also agrees with the recommendations made in Section 9.5. While the call for studies of wider systems is supported, some consideration must be given to their purpose when designing studies. While very extended system boundaries can in some instances be justified on the basis of the need to increase knowledge and understanding, many LCA or carbon footprint studies are undertaken for decision support. In the latter cases, system boundaries need to take into account the points in the system at which change can take place, and the points at which emissions change as a result. The conclusions in the main report also seem reasonable ones to draw. In the light of comments made in the second paragraph of Section 10 of the report, little weight can be placed on the outcome of the comparison between these Welsh case studies and the analysis carried out by Saunders *et al* in terms of comparing the greenhouse gas emissions associated with production of lamb in two distinct geographic locations.

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Appendix 13. Authors' response to the reviewer's comments

1. General

1.2 Overall comments

The area-based approach to assessing enterprise-level impacts of farming has merit, but in this reviewer's opinion needs further development before it can be applied in a fashion that allows comparison; other current work to calculate a carbon-footprint for lamb seen by this reviewer uses GHG per flock at an intermediate stage of the calculation. The presentation of results in terms of ranges of possible values is particularly welcome, giving some indication of the level of uncertainty currently associated with calculations of this kind.

The report draws attention to the influence of modellers' choices about system boundaries and of decisions made (or forced) about data selection on the results of carbon footprint calculations, for example in its consideration of the comparative study of New Zealand and UK lamb carried out by Saunders et al. It is therefore unfortunate that the authors fail to explore or explain the influences of their choices on the results of this study, although the report clearly states that some choices have been made by them, or forced on them for want of data. The inclusion of maximum-minimum ranges for certain emissions in the inventory is not a substitute for this.

In section 3, we have described and discussed several possibilities for drawing the system boundary in order to highlight the importance of system boundaries on the results of carbon footprinting studies (the same applies to Life Cycle Assessments). We explain that we did not include the exchange of GHGs between pasture, soil and atmosphere because these remain relatively poorly understood. The results are presented separately for each system boundary that we could assess, which allows the reader to examine the importance of system boundaries and how the results change depending on which processes are included. We believe that this goes further than any other study we are aware of – most studies just describe in more or less detail what their chosen boundary was and present the results for this boundary only. The presentation of results per flock poses the same difficulties as per unit liveweight, i.e. how to sensibly allocate between sheep and beef.

Data selection is also an important issue, and we have explained the difficulties in section 2.2. Our criticism of the Saunders *et al*. report is not a criticism of the emission factors they used – we fully appreciate that they had to make choices just as we had to. However, these authors used an extremely narrow system boundary which did not even include methane and nitrous oxides – which they did not discuss when coming to their conclusion that NZ lamb is less GHG intensive then UK lamb. We also had to use standard emission factors for our own calculations, but contrary to Saunders *et al*., we used real farm data rather than farm management handbook data (which led to them having to make more assumptions).

It is certainly possible to conclude from the report that it MAY BE "possible to buy Welsh lamb that is produced from farms which have fewer greenhouse gas emissions than those reported by Saunders et al (2006) for New Zealand" but to state that it IS possible seems unjustified.

We will amend the wording in the executive summary to better reflect some of these uncertainties.

2. Detailed comments

2.1.1 Area/enterprise level analysis

…The magnitude of any adjustment to the results of the footprint calculations that would follow from incorporating this "off-site production area" is unknown, but deserves some consideration in any future exercise of this sort.

This is a very good point. If we were only concerned about greenhouse gas emissions for a functional unit the standard LCA method would take account of this through consideration of so-called 'embedded' emissions. However, this process is not so appropriate when expressing emissions per hectare. This concept is thus similar to the idea of 'ecological footprints' which considers virtual hectares. While this is a valid point unfortunately we are not aware of any methodological approaches used by other LCA researchers to address it. We agree that it would be very valuable to explore this in more detail and draft a methodology that enabled inclusion of the effect of *"off-site production area"*.

The wintering of stock off the farm (as in Farm 2 here) potentially further complicates this area-based analysis.

This is a similar issue to that noted above and we agree it is a problem. We do highlight several complications arising from this wintering off farm but not how it may complicate the area based assessment. However, because additional inputs associated with the wintering away are thought to be very minor (the sheep winter on land that is used for cattle during the rest of the year which would otherwise be left empty, so that no additional inputs such as fertilisers need to be allocated to the sheep) we believe to have captured most of the emissions. Note that our calculations do include the emissions from the animals and their excreta over this winter period are included even though they are not on the 'home farm'.

2.1.2 Product-level analysis

…Yet in applying this functional unit in the product-level analysis, the researchers appear to be making the implicit assumption that the utility, or function, delivered to society is the same in each of the two cases – i.e. that beef liveweight and lamb liveweight are substitutable one for the other. It isn't at all clear to this reviewer that this assumption is justifiable.

This is a fair point. While both lamb and beef are red meat – they are probably not perfectly substitutable to consumers, and in an ideal situation there would have been sufficient precise data to estimate the mass and value of the different products. However, it should be noted that the analysis is not taken to the product level as the system boundary does not include slaughtering and processing. In this situation it is interesting to consider the concept of the functional unit. The sale of live animals off a farm is most certainly not a functional unit from society's point of view, but they may be from a farmer's point of view, i.e. they are both animals that were reared for sale.

…Accepting the authors' arguments that other approaches are equally flawed, some exploration of the effect on the study's results of applying different allocation methods would have been preferable to a somewhat arbitrary choice by the researchers of one method alone.

This is a fair statement, but unfortunately this was a small piece of work conducted over 3 months to a relatively small budget, and it was not possible to explore all the relevant issues.

The "discount rate" applied by Saunders et al. of course serves the purpose of economic allocation. The criticism of Saunders et al. for failing to represent the whole system as a result of applying this seems to this reviewer to be somewhat overdone; the argument that if wool has value to society then some of the impacts of farming sheep should be allocated to it has some validity and is (as noted above) accepted as one reasonable approach to the challenge mentioned at the beginning of this section.

The discount rate does have some value as a concept. However, it is unclear to us what the relevant discount rates should be. There are several products which can be derived from sheep and cattle in addition to wool and meat, e.g. skins. There were insufficient data available to us to identify the value or mass of all of the products resulting from sheep and beef, and this sort of analysis could only be done with the full cooperation of the slaughterhouses and different members of the relevant supply chains. As such it lay beyond the scope of this current study.

2.3 Data

Most of the data used for the emissions "embedded" in indirect inputs are reasonable, and the authors have drawn on well-recognised sources for the most part. Other values for many of the inputs used are available, but it seems that their use would be unlikely to affect the results to a very large extent. For example the current version of Plastics Europe's Life Cycle Inventory data gives a value for the carbon footprint of LDPE film (in this case, as a global Warming Potential over a 100-year timescale, GWP_{100}) as 2.4 kg CO_2e/kg film, whereas the researchers here have used a range of 1.3 – 1.94 kg CO_2e/kg.

We will add this figure for LDPE to our database for future use. In the current study, the contribution from LDPE to overall GHG emissions is very minor, so that overall results would not change were this figure to be used. We appreciate that other values for many of the inputs used may be available but believe that most of them should fall within the range indicated. As we only had limited time to collect these ranges, it is impossible to claim or expect these ranges to include every single figure available in the literature.

2.4 Results

It seems likely that if more detailed data were collected, and a longer time period considered, additional uncertainties would be revealed. For example it seems unlikely that liveweight output would be constant from year to year, even if the quantities of inputs stayed the same. Methane emissions are also, presumably, subject to some variation, and are known to vary somewhat with diet.

As stated in the report, it would have been desirable to have data covering several years. Obviously, farm practices and inputs used may vary between years according to climatic conditions and extreme events. We would add that liveweight output and emissions related to the animals may also change from year to year. All of these are complexities that need to be explored in future studies.

The method used, and the approach to allocation employed, prevent any comparison of the results of this study with the calculation of greenhouse gas impacts associated with sheepmeat production made by Williams et al (2006). The authors note that data limitations prohibited the use of a functional unit based on deadweight or meat produced, which would have facilitated such comparisons.

We explain in the report why we felt that we should not express the results per unit deadweight or meat produced. This would be misleading as it implies that emissions beyond the farm gate (slaughterhouse, processing, packaging, ….) were included.

The report itself includes, by design, comparison with the carbon-footprinting study of lamb conducted by Saunders et al. The authors note a number of deficiencies in that study and the data it has used. They also note a number of deficiencies in the data available to them – mostly data gaps. One weakness of the report is that it fails to discuss the significance of these gaps, and their potential influence on the results, or explore the results that would be obtained were they filled with figures drawn from, for instance, national or industry-wide statistics. The potential low relevance of such figures to the local situation being studied can be acknowledged – as it has for some other non-Welsh data used - but some such effort seems particularly important in a report that criticises the data selection of workers elsewhere.

There are many data gaps in this type of work. As science progresses so these may be filled. However, we doubt that for many of the data gaps listed there would be national or industry statistics freely available. An exploration of the relevance of these gaps would have been desirable, but impossible due to the difficulties of obtaining the data in the time available. While we are fully aware of these gaps we also felt that the most honest approach we could adopt was to list these gaps and problems so that readers may draw their own conclusions about their importance. This seems preferable to assuming that our calculations were based on perfect data on every single input.

Also our main criticism of the Saunders *et al.* study is not about the use of standard figures which may or may not accurately reflect the local situation. Any such study will have to draw on standard figures like that. The problem as we see it is that Saunders *et al*. used standard national data for all farm inputs, rather than real farm data. One might argue that this is more representative because it balances out any regional and year to year differences in inputs used; however, there are several different sheep farming systems in the UK. Saunders *et al*. chose one of these and declared the results representative of the whole UK situation. In addition, they used real farm data for the New Zealand calculations, so we doubt that these authors believe the use of standard data to be preferable.