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Improving livestock production efficiencies presents a major opportunity to reduce sectorial greenhouse gas emissions

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Abstract

The livestock sector is under considerable pressure to reduce greenhouse gas (GHG) emissions. Repeated measurements of emissions over multiple years will indicate whether the industry is on course to successfully meet emission reduction targets. Furthermore, repeated analyses of individual farm emissions over different timeframes allows for a more representative measure of the carbon footprint (CF) of an agricultural product, as one sampling period can vary substantially from another due to multiple stochastic variables. To explore this, a CF was measured for 15 livestock enterprises that had been assessed three years previously. The aims of the research were to: (1) objectively compare CFs between sampling periods; (2) assess the relationship between enterprise CF and input efficiency; (3) use scenario analyses to determine potential mitigation measures. Overall, no significant difference was detected in beef and lamb enterprise CFs between the two sampling periods. However, when all observations were pooled together, the lowest-emitters were found to have more efficient systems with higher productivity with lower maintenance "overheads", compared with their higher-emitting counterparts. Of significance, scenario analyses revealed that the CF of beef and lamb could be reduced by 15% and 30.5%, respectively, if all enterprises replicated the efficiency levels of the least-emitting producers. Encouraging and implementing efficiency gains therefore offer the livestock industry an achievable method of considerably reducing its contribution to GHG emissions.

Keywords**:** environmental impact; grassland; lifecycle assessment; meat; resource efficiency; sustainable intensification

1. Introduction

Although it provides many positive contributions to society, agriculture is responsible for some negative externalities; one of which is greenhouse gas (GHG) emissions. The contribution of livestock towards such emissions is particularly important as the sector accounts for 14.5% of total global anthropogenic GHG emissions (Gerber et al., 2013). The primary GHGs associated with ruminant production systems are methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). CH_4 emissions are primarily induced through enteric fermentation, excreta, and manure management (McDowell, 2009). N_2O emissions are associated with nitrification and denitrification of soils following nitrogen inputs such as excreta, urine, or inorganic fertiliser (Galloway et al., 2003). Depending on management regimes, CO_2 may be emitted or sequestered from agricultural soils, representing either a source or a sink of emissions (Soussana, et al., 2010). However, there is some disagreement as to the capacity of grasslands to act as a perpetual carbon sink (Smith, 2014).

Considerable attention has therefore been bestowed on the red meat sector's contribution towards climate change. A carbon footprint (CF) provides an estimate of the amount of GHG emissions emitted during part, or all, of the life of a product or service. It is typically expressed in kg CO_2 equivalents (CO_2eq) which includes emissions of CO_2, CH_4, and N_2O (Röös et al., 2014). The CF of both beef and lamb varies substantially, ranging from 9-129 kg CO_2eq per kg meat for beef, and 10-150 kg CO_2eq per kg meat for sheep meat (Nijdam et al., 2012). Differences can be attributed to many factors, such as the type of farming system, location, management practices, the study's system boundary, and the resource use that has been considered (Desjardins et al., 2012; Ripoll-Bosch et al., 2013; Ruviaro et al., 2015). There are two sources of variation in estimating farm-level CFs, namely: variation arising from uncertainties in the primary activity data, including farm management practices, and variation arising from emission factor and model uncertainties (Basset-Mens, et al. 2009). Variation in farm system parameters, coupled with inherent uncertainties associated with emission factors can have implications for reported emissions associated with agricultural production (Crosson et al., 2011). Spatial, temporal and weather can induce uncertainty in emission factors; thereby reducing their robustness (Gibbons et al., 2006). Indeed, the IPCC estimate a global uncertainty of ± 50% for Tier I estimates and ± 20% for Tier II estimates (IPCC, 2006). There may also be interaction between sources of variation; default emission factors may not be representative or applicable, e.g. ruminant fermentation depends on feed (Crosson et al., 2011). Therefore, comparisons of CFs are difficult as models and farm characteristics vary both between and within studies.

Emissions per unit product can vary considerably between farming enterprises (Thoma et al., 2013; Veysset et al., 2010); and many studies have tried to elucidate the main factors explaining CF variability in livestock production. Herrero et al. (2013) identified feed efficiency as a key driver of livestock emissions from detailed, disaggregated global livestock data across nine global regions. The relationship between productivity and GHG emissions has been demonstrated, most notably in the dairy sector. Gerber et al. (2011) found that, on a global scale, emissions per kg of milk declined substantially as animal productivity increases. Nguyen et al. (2013a) also depicts the importance of productivity on dairy emissions at the farm scale. Considering the variability observed within agricultural sectors, it is important to contemplate measures that may reduce emissions most effectively from different enterprises. Nguyen et al. (2013b) investigated the effect of various scenarios in reducing beef enterprise emissions; results suggest that simultaneous application of several compatible farming practices can reduce the climatic impacts of production.

Analysis over different timeframes can serve to elicit where, and how, emissions have changed and are useful in estimating whether industry is meeting environmental targets. Nevertheless, despite their potential value, there has been a distinct lack of studies that temporally assess the CF of individual beef and lamb farm enterprises. Veysset et al. (2014a and 2014b) found no significant differences in the CF of the two sampling years when investigating breed-specific, extensive beef suckler systems in France.

The agricultural sector in Wales is predominated by pasture-based livestock systems. Government targets aspire to reduce overall national emissions by 3% per annum from 2011 onwards (Welsh Government, 2009). Subsequently, the livestock sector has initiated a strategic plan outlining strategies to meet such targets (HCC, 2011). There is a need to capture the CF of beef and lamb over multiple years to determine if the industry is to successfully meet these emission reduction targets. By using the same model, repeated C-footprinting of an enterprise enables comparisons of its environmental performance over time. Such analyses also allow for a more representative measure of the CF of an agricultural product; such is the nature of the sector that one sampling period can vary substantially from another due to multiple stochastic variables (e.g. disease, policy reform, weather).

Empirical data were collected for the years 2009/10 and 2012/13 from a set of 15 Welsh beef and/or sheep farmers. Both sampling periods encapsulate unusual weather events that may affect the CF in alternative ways; 2009/10 had a particularly cold winter (Met Office, 2010), whereas 2012/13 experienced an especially cold spring (Slingo, 2013). The aims of the research were (1) to objectively compare CFs between sampling periods; (2) to assess the relationship between enterprise CF and input efficiency; (3) to use scenario analyses to determine potential mitigation measures that may lower emissions. The findings add to the small body of evidence published hitherto on temporal variation in reported farm carbon footprints, and, it is anticipated, will help determine how the industry can reduce emissions and subsequently guide future policy recommendations.

2. Methodology

2.1 The carbon footprint model

The respective global warming potential (GWP) of a GHG is a relative measure of how much heat, relative to CO_2, a GHG traps in the atmosphere. The magnitude of individual gases' emissions are subsequently categorised in terms of their carbon dioxide equivalent (CO_2eq) over a 100-year horizon to compare and report emissions. In this study, the widely adopted GWP values of 25 CO_2eq and 298 CO_2eq have been used for CH_4 and N_2O, respectively (IPCC, 2007).

Empirical farm data were used to estimate the CF of beef and lamb production using an updated model to the one employed by Edwards-Jones et al. (2009); a model which has been recently used to assess the CF of sheep systems in England and Wales (Jones et al., 2014). The model calculates the total emissions associated with bringing 1 kg of beef or lamb to slaughter and includes emissions from direct and indirect inputs associated with production. It also encapsulates emissions from other animals in the herd. If one enterprise can produce the same volume of liveweight to slaughter with fewer breeding stock than another enterprise, then it will have a smaller carbon footprint. This is a consequence of having fewer animals contributing towards GHG emissions to produce the same volume of slaughter liveweight. Animal movements are also monitored on a monthly basis so that accurate assessments can be made on the quantity of animals within a certain cohort. Liveweight gain per month is also considered for growing stock.

2.2 The functional unit and system boundary

The magnitude of a CF of a product is determined by the system boundaries in which it is analysed. For beef and lamb enterprises, most system boundaries are set from 'cradle to farm gate', where all direct and indirect emissions are incorporated into a footprint, from the birth of an animal until such time it leaves the farm for slaughter. Upstream emissions were also considered for the manufacture of fertiliser, concentrate feed production, bedding etc. The final CF is subsequently expressed as a functional unit per kg liveweight (Edwards-Jones et al., 2009).

The 'cradle to farm gate' system which the model encapsulates accounts for emissions from direct and indirect inputs, emissions from on-farm production, emissions attributed towards the movement of stock in and out of the system, and sequestration from on-farm carbon sinks and stores such as trees, grassland, and hedgerows (Fig. 1). However, most studies have traditionally not included soil carbon sequestration in carbon footprinting calculations due to methodological limitations (Brandão et al., 2012). Consequently, the carbon accounting methodology standard developed by The Carbon Trust (PAS 2015) does not include sequestration in its methodology (PAS, 2011). What's more, recent research has questioned grassland's ability to continually sequester CO_2 (Smith, 2014). Hence, the CF in this study is reported without the inclusion of sequestration.

The IPCC recommends that emissions of N_2O from drainage of peat soils be included in emissions allocated to the sector using that land (e.g. agriculture or forestry), and by implication to the products arising from that sector. These continuous emissions are distinct from emissions arising from recent land use change and emissions associated with N input (Van Beek et al., 2010). Thus, 'area of managed peat soil' was included in the model in order to account for drainage-relate peat soil emissions, which have been shown to be significant for Welsh upland livestock production (Edwards-Jones et al., 2009).

2.3 Allocation method

Allocation is required to assign the environmental impacts to the functional unit when a system has more than one saleable product. Different allocation methods include economic allocation, mass allocation, energy allocation, and allocation based on protein content (Nguyen et al., 2012). However, it is recommended that allocation is avoided where possible by dividing the unit process to be allocated into two or more sub-systems and collecting the input and output data associated with each sub-system (Flysjö et al., 2011; Pirlo et al., 2013). The aforementioned method was employed whenever possible to differentiate emissions associated with beef and lamb produced on the same enterprise; thereby empirically assigning emissions to distinct saleable outputs. Where enterprises reared both cattle and sheep, certain aspects of production were subjected to economic allocation as emissions could not be assumed explicitly to one production system over another.

2.4 Data collection

Of the 15 farms sampled, five specialised in lamb, four specialised in beef, and six were mixed enterprises (both beef and sheep); none were organic. During face-to-face interviews, demographic data were collected, and information on important aspects of their farm's production system, such as direct and indirect inputs (e.g. feed, fertiliser, bedding), stock movements (e.g. purchases, births and housing), outputs (number and weight of animals sold), and farm characteristics. Data were provided for 12 months of production, with the sample period commencing in March; stock movement records and other forms of inventory records were used where possible to verify and supplement data collection. Furthermore, farmers' perceptions of their on-farm GHG emissions and wider knowledge of climate change were briefly assessed as these may influence their management factors and hence their farm's CF (Hyland et al., 2016).

2.5 Emission factors

IPCC Tier II methodology was used for assessing emissions of enteric emissions from cattle as this was the procedure for reporting agricultural emissions in the UK GHG inventory at the time of calculation (Webb et al., 2014). All other calculations are based on standard Tier I approaches. Tier I assumptions continue to be used as the default emission factor for enteric fermentation for sheep; however, the UK uses a country-specific emission factor for enteric fermentation for lamb, set at 40% of that for an adult sheep (Webb, 2014). Grass and feed intake was assumed to be ad-lib, and the CF utilises emission factors which are dependent on UK average annual feed composition for sheep and beef cattle (Webb, 2014).

Fertiliser, diesel, agrochemicals, bedding, and compound feeds emission factors were mid-range values from Edwards-Jones et al. (2009) and Jones et al. (2014). Emission factors for non-blended feed crops (straights) were taken from the Scottish Executive Environment (2007). A mean emission factor for of 13.87 kg CO_2 eq/kg lw and 7.62 kg CO_2 eq/kg lw was used for the purchase of live beef stores and lamb bought for finishing, respectively (Edwards-Jones et al., 2009; Taylor et al., 2010; Jones et al., 2014). Mean emissions from UK peat soil were estimated to be 0.25 kg N_2O-N per hectare annually; a deviation from IPCC default emission factors (Scottish Executive Environment, 2007). Other studies have also adopted such an estimate in place of the IPCC default of 8 kg N_2O-N per hectare annually as it is arguably more representative of UK conditions (Taylor et al., 2010; Jones et al., 2014). It should be reiterated that ongoing C sequestration under grasslands is not included in the CFs reported in this study. However, emissions and sequestration associated with land use change between grassland, cropland and forested land use categories are included where those changes were reported to have occurred within the past 20 years (PAS, 2011), and annualised based on a 20-year transition period (IPCC, 2006). A full breakdown of the emission factors used in the model can be seen in Table S1 within the supplementary material.

3. Results

3.1 Farmers' perceptions of on-farm emissions

The CF results calculated for 2009/10 had been previously sent to each farmer ca. 6 months after first being collected. From this, farmers could ascertain how they compared to others in the sample in terms of their CF. Considering their past experiences with carbon footprinting, farmers were asked to depict their perceptions of their on-farm emissions when data were collected again in 2012/13. Farmers who took part in the case study suspected their respective footprint to be small in comparison to similar farming operations. However, the farmers were somewhat unsure as to livestock's contribution towards climate change (Table 1); a discourse that could potentially influence the adoption of adaptation and mitigation measures that address climate change (Hyland et al., 2016). Nevertheless, most deemed themselves capable and willing to lower their respective footprints; but this was dependent on financial viability.

3.2 Temporal comparison of carbon footprints

Differences in the return on investment between Welsh beef and lamb did not vary substantially between the two sampling periods. Industry reports a 1.49 and 1.47 times greater return on investment for lamb in comparison to beef in 2009/10 and 20012/13, respectively. This was based on percentage of total costs covered by enterprise returns. Therefore, economic allocation, when required, was not affected by diverging market forces between beef and lamb production observed during the two sampling periods (HCC, 2015).

The CFs of beef and lamb for each of the respective farming enterprises is represented in Table 2. Furthermore, mean GHG emissions from beef and lamb enterprises from both sampling years is summarised in Table 3; as is the contribution of each parameter to the CF. As one farm experienced a significant merger in 2012/13, it was subsequently omitted from the temporal analysis carried out in this section. A state of equilibrium was observed in the other farms during respective sampling periods. Equilibrium was determined by comparing the number of animals in certain categories (e.g. number of breeding animals and young stock intended for slaughter or replacement) at the beginning and end of the 12-month sampling period. Statistical analyses were restricted to non-parametric tests to determine significant differences between both years. The mean CF for lamb increased in 2012/13; whereas the mean footprint of beef decreased (Table 3); however, Wilcoxon rank test revealed that these changes were not statistically significant. Furthermore, Mann-Whitney tests revealed that there was no significant difference between the CF of beef-only and sheep-only systems and that produced in a mixed system. Therefore, the allocation method did not significantly affect the results.

The type of enterprises assessed in the study, their respective farm labels, and the total slaughter weight produced for the two sampling years are denoted in Table 4. Figure 2 depicts the differences in CFs of beef and lamb of individual farms between the two sampled years. The slaughter rate for lamb, which is referred to in subsequent sections, was calculated by assessing the proportion of lambs potentially available for slaughter (lambs intended for slaughter carried over from previous year + bought store lambs + total lambs born – lambs born kept for replacement) sold for slaughter in the 12 month period. For beef production, the slaughter rate was calculated by assessing what proportion of cattle intended for slaughter were sold for slaughter during both 12-month sampling period.

Although not statistically significant, the mean percentage change in total emissions for lamb was +12% from 2012/13 in comparison to 2009/10. Enterprises L2 and L5 showed the largest increase in emissions between the two sampling years, 52% and 37% respectively; whereas M3 reduced its emissions by the largest proportion, of 39% (Fig. 2). L2 differed little between the two years in terms of total slaughter rate, lambing proficiency, or stocking rates, although 7.5% fewer lambs were brought to slaughter in 2012/13. On this enterprise, the main disparity was the average weight that lambs were brought to slaughter; being 38 kg in 2009/10, and 30 kg in 2012/13. Consequently, the total weight brought to slaughter in 2009/10 was 73% larger than in 2012/13; thereby resulting in a smaller total footprint per kg of liveweight produced. The CF of lamb produced on L5 had also increased as emissions associated with bought in feed were 95% larger in 2012/13 compared 2009/10. In addition, a large proportion of its stock due for slaughter in 2012/13 were still on-farm at the end of the period (18%); conversely, the enterprise had sold all but 2% of its lambs assigned for slaughter by the end of 2009/10. However, this may have been brought about due to the extreme weather of spring 2012/13, the results of which are likely to be augmented on this enterprise due to its high elevation (350 m).

The enterprise which showed the greatest reduction in their lamb CF between the two years was M3 (Fig. 2). Average liveweight of lamb brought to slaughter in 2009/10 was 36 kg, whereas it was 40 kg in 2012/13. It also simultaneously increased its total slaughter rate from

88% to 98%. These gains resulted in an overall reduction of 39% in GHG emissions per kg of liveweight slaughtered.

As a whole, there was a mean -13% divergence in the mean CF for beef between the two periods, although this was not statistically significant. Enterprise B2 depicted the greatest inflation in emissions, its footprint rising by 30%; whereas B3 and M6 substantially reduced theirs (Fig. 2).

B2 did not vary to any great degree in terms of total slaughter rate, or the weight of animals brought to slaughter, while the stocking rate only expanded marginally. Direct N_2O emissions associated with manure management and storage increased by 38% as cattle were housed for two months longer in 2012/13 because of the poor spring weather. CH_4 emissions from manure also ascended by 20%; a result of a slight augmentation in herd size. B2 brought 2.82 tonnes of additional concentrate feed on-farm in 2012/13 due to the extended housing period brought about by the poor spring weather; thereby raising emissions from bought concentrates by 93% per kg of liveweight. Most of this additional feed was the same concentrate type as the previous sample year, while 0.3 t was mineral licks, which were not used in 2009/10. Furthermore, a 21% increase in the amount of N applied between both years led to a rise in emissions associated with inorganic fertiliser. Consequently, emissions related to indirect and direct fertiliser use were raised by 75% and 46%, respectively.

Conversely, enterprises B3 and M6 both reduced their footprint by 40% and 30%, respectively. Diesel use decreased substantially on both farms. More importantly, both reduced livestock time to slaughter thereby increasing their slaughter rate in 2012/13; thereby reducing associated CH_4 and N_2O emissions diminished accordingly.

3.3 Emission sources

As no significant difference were observed between both sampled years, both datasets were aggregated together. Aggregate data series refers to a set of values, each of which is averaged across respondents. The CF was averaged over the two years and each model variable was assessed to determine its overall contribution towards the overall footprint (Fig 3). For both beef and lamb, the dominant source of emissions was CH_4 from enteric fermentation which constituted 46% and 43% of their respective CF. N_2O from manure and excreta followed as the next most prevalent contributor of emissions for lamb production, with 18% of its CF generated from such sources. Its larger value for lamb can be ascribed to the longer time period in which lambs were out to pasture. Beef had similar contributions from N_2O from manure and excreta (10%) and CH_4 from excreta (11%). Larger CH_4 emissions from beef excreta compared to that of lamb is a result of the longer housing period of cattle. Other emissions sources were considerably smaller for both.

The contribution of CH_4 and N_2O emissions towards the total footprint of beef and lamb is depicted in Figure 4. Enteric fermentation was by far responsible for the greatest proportion of emissions, followed by CH_4 arising from excreta. The greatest proportion of N_2O was from run-off/leaching (Fig. 4).

3.4 Variability

The aggregated datasets revealed a wide range of variation in emissions for both beef and lamb (Fig. 5). The mean CF of lamb was 15.13 kg CO_2eq/ kg lw, and 16.33 kg CO_2eq/ kg lw for beef. Total emissions ranged between 12.89–19.69 kg CO_2eq/kg lw for beef and between 9.89–21.14 kg CO_2eq/kg lw for lamb; a 34.5% and 53.3% variance between the highest and lowest-emitters of beef and lamb, respectively.

3.5 Comparison of largest and smallest carbon footprints

It is useful to compare emissions between large and small footprints to highlight where differences transpire (Veysset et al., 2014 ab). For this purpose, data were pooled and direct comparisons between the smallest 25% (CF-) and largest 25% (CF+) of footprints (Table 5). Considering lambs firstly, the numbers of breeding stock, lambing percentage, and number of animals slaughtered were similar for large and small CFs. Nevertheless, larger footprints were associated with farms taking longer to get lambs to slaughter; thereby increasing CH_4 emissions associated with enteric fermentation and N_2O emissions from urine deposition. Larger CFs also entailed greater concentrate use to fatten lambs when grass becomes less plentiful later in the growing season; though this was not associated with higher levels of liveweight of kg of lambs produced (Table 5). Likewise, the largest beef CFs had almost twice the stocking rate of growing stock (0.82 vs 0.49 heads of growing stock per hectare). This may have had a negative impact on animal growth rates. Consequently, a large beef CF was influenced by enterprises slower in getting stock to slaughter (56% of animals to slaughter, compared to 96% for a small CF); resulting in greater N_2O and CH_4 emissions per kg of liveweight produced. Generally, beef CFs were larger on farms at higher elevations while utilising the same levels of inputs as enterprises operating at lower elevations. The study found that enterprises who had larger beef footprints had similar production levels as enterprises who had lower emissions. However, these farms required a larger number of growing animals to reach parity in liveweight brought to slaughter, which raised emissions per liveweight produced.

3.6 Scenario analyses

Scenario analyses were carried out to explore how changes in management practices may alter the CF of beef and lamb per kg of liveweight produced for each of the 42 observations. Mitigation measures should aim to reduce emissions without simultaneously increasing any other externalities (Picasso et al., 2014). A recent study found that farmers consider the adoption of legumes as being the most practical measure they could adopt to reduce their CF (Jones et al., 2013). Concentrate feed use and fertiliser demands could be reduced without compromising the farm's carrying capacity of stock by incorporating legumes such as red and white clover into grass leys (Phelan et al., 2015). On average, a good grass-clover sward can give annual dry matter yields equivalent to yield from grass applied typical N application rates (Defra, 2010). Although clearly not an option on all farms (e.g. due to the wrong soil type), the adoption of clover could reduce both fertiliser and concentrate demand without compromising production efficiency gains as dry matter yield is comparable to fertilised swards while the crude protein content is higher (reducing concentrate feed requirements). It is reasonable to assume that the scenarios investigated can be therefore considered separately without having to consider upstream emissions. Another mitigation measure deemed practical by farmers is increasing young stock growth rates for early finishing (Jones et al., 2013); this would allow for improved slaughter rates. The management alterations that were examined therefore include: reduce concentrate feed by 50% and 80% (C < 25%; C < 50%), reduce fertiliser applied by 50% and 80% (F < 50%; F < 80%), and for the quicker finishing times for young stock, i.e. for all enterprises to match the slaughter rates of the least emitting enterprises observed in the previous section (> Prod efficiency). Manure management systems that could lower emissions are of particular relevance to beef enterprises.

Consequently, the adoption of low-emission manure management systems (e.g. covering of farmyard manure stores) was also considered (MM) (Fig. 6).

The most effective method for enterprises to decrease their CF was through increasing production efficiency (Fig. 6). This can be defined as the efficiency at which an enterprise utilises its inputs (fertiliser, concentrate feed, bedding, etc.) to get animals to slaughter. In such a scenario, emissions reduced by 15% and 30.5% for beef and lamb, respectively. For beef production, this was followed by changing manure handing systems to lower-emitting techniques (↓7.5%), reducing fertiliser by 80% (↓6.8%), feed concentrate use by 80% (↓5.0%), fertilisers by 50% (↓4.3%), and feed concentrate use by 50% (↓3.1%). Subsequent to adopting the practices of the least-emitting producers, the most effective scenarios of lowering emissions for lamb was reducing feed concentrate use by 80% (↓6.7%), fertiliser use by 80% (↓5%), feed concentrate by 50% (↓4.1%), fertiliser use by 50% (↓3.1%), and changing manure management practices to lower-emitting systems (↓1.8%).

4. Discussion

Wales has features that characterise the challenges countries have in reducing GHG emissions from pastoral-based systems. Its topography varies considerably, encapsulating an array of challenges and environments faced globally by farmers in the sector. Whilst only fifteen farms were part of this study, they nevertheless capture the breadth of farming systems and challenges and the results are therefore of relevance to other livestock systems. Continued measures of CFs are also useful to inform future studies (Ruviaro et al., 2015). Further, this study is one of few that have revisited livestock enterprises to determine whether their CF has changed with time, and the underlying drivers of any change. While most of the farmers deemed themselves capable and willing to reduce their respective C-footprints, the cost of implementing mitigation measures was often seen as a barrier to implementation (Table 1). Some farmers were somewhat unsure as to livestock’s contribution to climate change; a discourse that could potentially influence the adoption of adaptation measures. Much of adaptation is reactive and triggered by past or current events, but it can also be anticipatory and based on assessments of climate change (Adger et al., 2005).

Both sampling periods experienced abnormal weather patterns, and temporal analyses revealed that there were no significant differences in the mean CF for beef and lamb when comparing the two sampling years. The winter of 2009/10 was the coldest since 1978/79, with significant snowfall between December and February (Met Office, 2015). In 2012, the summer, autumn and winter were much wetter than normal (Met Office, 2015). This may explain the 12% rise in the mean lamb CF in 2012/13. Smaller liveweights cause greater emissions associated with producing 1 kg of liveweight for slaughter as total emissions are spread over a lighter animal when all other aspects of production stay the same. The difficult weather conditions of 2012/13 also affected the number of cattle brought to slaughter. UK producers were faced with rationing their herd in the face of high input costs and concerns over forage availability and quality. Furthermore, the horsemeat scandal of 2013 assured demand for UK beef was high, with many UK farmers taking advantage of the strong market conditions (Defra, 2014). This may explain the increase in total slaughtered beef liveweight sold in 2012/13; a factor which contributed to reducing the mean beef CF by 13%.

Famers’ perceptions of the necessity to implement measures which address climate change differ (Hyland et al., 2016). Nonetheless, whether motivation to adopt is dictated by environmental or productivist tendencies, there are many measures which farmers could adopt to reduce their CF which would appeal to both discourses. Some enterprises had notably reduced their respective footprints by increasing production efficiencies compared to 2009/10. As production systems become more efficacious, emissions are spread over increased units of production. When both sample periods were amalgamated, it was observed that both high- and low-emitting enterprises produced the same volume of liveweight with no significant differences in input levels. There were no defining differences in the breeds of sheep and cattle on farms; however, the least-emitting farms showed better animal performance and animal productivity by requiring a lower carrying population to produce 1 kg of liveweight for slaughter.

Previous research has shown that more intensive systems can have a lower environmental impact per kg product than extensive operations (FAO, 2010). However, in this study, there were comparable stocking rates for the largest and smallest CFs. Conversely, it was higher productivity, which effectively ‘diluted’ emissions from stock maintenance on footprints with the lowest emissions. Scenario analysis found that if all enterprises adopted the production practices of the enterprises with the smallest CFs, emissions for beef and lamb would be reduced by 15% and 30.5%, respectively. Such reductions far surpassed the other scenarios investigated, i.e. reduction in fertiliser use, reduction in concentrate feed, and the adoption of lower emitting manure management systems. The results imply that there is substantial potential to reduce GHG emissions from the livestock sector if widespread uptake of efficiency measures were adopted. Such measures include improving the genetic potential (e.g. use of Estimated and Genomic Breeding Values) and optimising nutritional needs of the animals, better utilisation of pasture, improving soil and nutrient management, and reducing losses due to disease. For instance, inclusion of clover in grassland systems improve animal performance and concurrently ‘fix’ atmospheric N, thereby offers an opportunity to displace reliance on synthetic fertilisers (Phelan et al., 2015). Implementing such measures would bring about economic benefits to the sector and therefore represent 'win–win' options, which should appeal to producers and policy-makers alike (Hyland et al. 2016).

It is widely reported that if farming enterprises adopted the efficiencies of the least emitting producers that a large reduction in sectoral emissions can be achieved (Audsley and Wilkinson, 2014; Gerber et al., 2013). The technical abatement potential can vary considerably between farms (MacLeod et al., 2010). Potential barriers to uptake include a low awareness and/or a low willingness to adopt certain measures (resulting from particular social or demographic profiles within their beef sectors) coupled with perceptions that the adoption of some mitigation measures as not economically viable (MacLeod et al., 2015). Conversely, economic benefits often occur because of improved efficiency (higher yield and/or less resource used) and therefore make business sense. The aggregated effects from improved efficiencies on markets and resources may therefore entice farmers to adopt appropriate mitigation measures.

All farms were located in designated 'Less Favoured Areas' and were constrained by similar variables (e.g. climate and soil types). The empirical data collected for this study showed no overall significant changes in the CF between the two sampling years, though we acknowledge that this might be different with a larger sample size or over a longer period. Another limiting factor of the study was the simplified method used to compute GHG emissions based on mostly Tier I methodologies which only partially capture the effects of different management practices, and which may therefore miss some of the temporal variation in emissions associated with changing management. Nevertheless, footprinting a comparatively small number of farms at multiple time points can offer an appropriate metric to determine efficiency changes within, and among, producers. Even factors not explicitly reflect in Tier 1 methods, such as feed (grass) digestibility, are often partially reflected in Tier 1 footprints via altered input to production ratios.

Many studies have previously elicited the source of variation in emission intensities generated from livestock enterprises using IPCC guidelines. Herrero et al. (2013) also denoted feed efficiency as a key driver of productivity, resource use, and GHG intensity, with notable differences between production systems. The inverse relationship between productivity and GHG emissions has already been elicited by Gerber et al. (2001) and Nguyen et al. (2013a) in dairy production. Previous research that has used a similar GHG accounting approach as used in this study have also corroborated farm variability and management practices to be an influencing factor in the GHG intensity of production (Nguyen et al., 2013b; Thoma et al., 2013). For instance, Veysset et al. (2010) deduced that GHG emissions were primarily determined by the proportion of cows in the total herd, according to the farming system deployed, i.e. calf-to-weanling *vs.* calf-to-beef. Although this current study is somewhat limited by its small sample size, the time lapse between sampling years, and GHG computation methods, it nevertheless adds to the current literature by highlighting the temporal variability in GHG emissions arising from the same farming enterprises. This study is also novel in that it assesses emissions from mixed livestock farming systems, as well as those who concentrate explicitly on rearing beef or sheep.

The farmers who took part in this study believed that reducing emissions from their respective farms to be of little value. However, most expressed an interest in reducing their farm CF. Considering the study focus, respondents may have answered in a manner that was deemed favourable when questioned about potentially reducing their own emissions. Conversely, farmers may indeed be aware of the economic advantages that may be forthcoming with many mitigation strategies and were genuinely interested in reducing emissions. Farm resource endowments, capital structure, regional landscape constraints, and financial leverage are critical factors which determine the potential of farms to adopt new practices (Kanellopoulos et al., 2014). Farmers' interests in particular mitigation strategies, and their potential to adopt them, may depend on their existing endowments of resources as well as other attributes (FAO, 2013). The specific characteristics of individual farmers (e.g. wealth levels, age, farm endowment, land type, management system, and the genetic profile of their livestock) may limit their ability to adopt measures that address climate change. It is therefore important that policies and incentives consider the inequality of opportunity and outcomes amongst farmers.

5. Conclusions

The red meat sector is a significant contributor to anthropogenic GHG emissions. To lower emissions, it is recommended that a broad array of mitigation measures are adopted. However, the results elicited from the two sampling periods reiterates that there is considerable potential to reduce sectorial emissions (15% and 30.5% for beef and lamb, respectively) if producers were to adhere to the practices and approaches adopted by low-emitting enterprises.

Acknowledgements

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6. Supplementary material

Table S1 Activity data and emission factors used to estimate the primary emissions of methane and nitrous oxide

GHG source	Activity data used for calculation	Reference	Emission factor	References
CH_4				
Enteric fermentation (sheep > 1 year)	Monthly stock numbers	Farm stock diary	1/12 × 8 kg/head/yr	IPCC (2006)
Enteric fermentation (lambs < 1 year)	Monthly stock numbers	Farm stock diary	1/12 × 3.2 kg/head/yr	Webb et al. (2014)
Excreta and managed manure (sheep > 1 year)	Monthly stock numbers	Farm stock diary	1/12 × 0.48 kg/head/yr	Webb et al. (2014)
Excreta and managed manure (sheep <1 year	Monthly stock numbers	Farm stock diary	1/12 × 0.129 kg/head/yr	Webb et al. (2014)
Enteric fermentation (cattle > 1 year)	Monthly stock numbers	Farm stock diary	1/12 × 50.5 kg/head/yr (cows > 1 year) 1/12 × 48 kg/head/yr (heifer, all others > 1 year))	Webb et al. (2014)
Enteric fermentation (cattle < 1 year)	Monthly stock numbers	Farm stock diary	1/12 × 32.8 kg/head/yr (calves < 1 year)	Webb et al. (2014)
Excreta and managed manure (cattle > 1 year)	Monthly stock numbers	Farm stock diary	1/12 × 13 kg/head/yr	Webb et al. (2014)
Excreta and managed manure (cattle < 1 year)	Monthly stock numbers	Farm stock diary	1/12 × 11 kg/head/yr	Webb et al. (2014)
N_2O (direct)				
N additions to soil:				
Mineral fertiliser	N applied in fertiliser	Farm records	0.01 kg N_2O-N/kg N	IPCC (2006)
Manure	Monthly stock numbers housed and liveweights	Farm records	0.01 kg N_2O-N/kg N	IPCC (2006)

	N excretion rate Fraction of N lost in manure management	IPCC (2006) IPCC (2006)		
Crop residues	Crop yield and fraction of residues removed N content of above and below ground residues	Farm records IPCC (2006)	0.01 kg N_2O-N/kg N	IPCC (2006)
Drained or managed peat soil	Area of managed peat soil	Farm records	0.25 kg N_2O-N/ha	Scottish Executive (2007)
Excreta deposited on pasture	Monthly stock numbers grazing and liveweights N excretion rate	Farm records IPCC (2006)	0.01 kg N_2O-N/kg N	IPCC (2006)
Managed manure	Monthly stock numbers housed and liveweights N excretion rate	Farm records IPCC (2006)	0.005 kg N_2O-N/kg N excreted (solid storage) 0.01 kg N_2O-N/kg N excreted (deep bedding, liquid slurry with crust cover)	IPCC (2006)

N_2O (indirect)

N volatilised from soil and re-deposited	N applied in fertiliser, manure and excreta Fraction of applied synthetic and organic N volatilised	Farm records IPCC (2006)	0.01 kg N_2O-N/kg N/kg NH_3-N + NO_X-N volatilised	IPCC (2006)
N leaching and runoff from managed soil	N applied in fertiliser, manure, excreta and crop residues Fraction of applied N lost through leaching and runoff	Farm records IPCC (2006)	0.0075 kg N_2O-N/kg N leaching and runoff	IPCC (2006)
Managed manure	Monthly stock numbers housed and liveweights	Farm records		IPCC (2006)

	N excretion rate Fraction of N volatilised in manure management	IPCC (2006)	0.01 kg N_2O-N/kg N/kg NH_3-N + NO_X-N volatilised	

7. References

Adger, N.W., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. *Glob. Environ. Chang.* 15, 77–86.

Audsley, E., Wilkinson, M., 2014. What is the potential for reducing national greenhouse gas emissions from crop and livestock production systems? *J. Clean. Prod.* 73, 263–268.

Basset-Mens, C., Kelliher, F. M., Ledgard, S., Cox, N., 2009. Uncertainty of global warming potential for milk production on a New Zealand farm and implications for decision making. *Int. J. Life Cycle Ass.* 14 (7), 630-638.

Brandão, M., Levasseur, A., Kirschbaum, M.U.F., Weidema, B.P., Cowie, A.L., Jørgensen, S.V., Hauschild, M.Z., Pennington, D.W., Chomkhamsri, K., 2012. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *Int. J. Life Cycle Assess.* 18, 230–240.

Chadwick, D. R., 2005. Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. *Atmos. Environ.* 39 (4), 787-799.

Crosson, P., Shalloo, L., O'Brien, D., Lanigan, G.J., Foley, P.A., Boland, T.M., Kenny, D.A., 2011. A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. S*pec. Issue Greenh. Gases Anim. Agric. - Find. a Balanc. between Food Emiss.* 166-167, 29–45.

Defra, 2010. Fertiliser manual RB209. London: Department for Environment, Food & Rural Affairs.

Defra, 2014. *Total factor productivity of the UK agricultural industry 2013 – 1st estimate*. London: Department for Environment, Food & Rural Affairs.

Desjardins, R. L., Worth, D. E., Vergé, X. P., Maxime, D., Dyer, J., Cerkowniak, D. (2012). Carbon footprint of beef cattle. *Sustainability 4* (12), 3279-3301.

Edwards-Jones, G., Plassmann, K., Harris, I., 2009. Carbon footprinting of lamb and beef production systems: Insights from an empirical analysis of farms in Wales, UK. *J. Agr. Sci.* 147(6), 707.

FAO, 2013. National planning for GHG mitigation in agriculture: A guidance document. Rome: Food and Agricultural organization of the United Nations.

FAO, 2010. Greenhouse gas emissions from the dairy sector. Rome: A Life Cycle Assessment.

FAO. 2010. *Definition of sustainable diets. international scientific symposium: Biodiversity and sustainable diets*. Rome: Food and Agriculture Organization of the United Nations.

Flysjö, A., Cederberg, C., Henriksson, M., Ledgard, S., 2011. How does co-product handling affect the carbon footprint of milk? case study of milk production in new zealand and sweden. *Int. J. Life Cycle Ass.* 16 (5), 420-430.

Galloway, J. N., Aber, J. D., Erisman, J. W., Seitzinger, S. P., Howarth, R. W., Cowling, E. B., et al., 2003. The nitrogen cascade. *Bioscience* 53(4), 341-356.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijk,am, J., Falcucci, A. Tempio, G., 2013. *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities.* Rome: Food and Agriculture Organization of the United Nations (FAO).

Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas emissions intensity in dairy systems. Livest. Sci. 139, 100–108.

Gibbons, J.M., Ramsden, S.J., Blake, A., 2006. Modelling uncertainty in greenhouse gas emissions from UK agriculture at the farm level. Agric. Ecosyst. Environ. 112, 347–355.

HCC, 2015. Cost of Production [WWW Document]. doi:http://hccmpw.org.uk/publications/farming_industry_development/cost_of_production/

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl. Acad. Sci. U. S. A.* 110, 20888–93.

Hyland. J.J., Barnes, A., Parkhill, K., Jones, D.L., Williams, A.P., 2016. Farmers' perceptions of climate change: Identifying types. *Agr. Hum. Values.* 33, 323-339.

IPCC, 2006. *Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Inventories Programme. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T.,Tanabe, K. (Eds). Insitude for Global environmental strategies, Hayama, Japan.

IPCC, 2007. *Climate change 2007: The Physical Science Basis. Contribution of Working Groups* I *to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, United Kingdom and New York.

Jones, A., Jones, D., Edwards-Jones, G., Cross, P., 2013. Informing decision making in agricultural greenhouse gas mitigation policy: A Best–Worst scaling survey of expert and farmer opinion in the sheep industry. *Environ. Sci. Policy.* 29, 46-56.

Jones, A., Jones, D., Cross, P., 2014. The carbon footprint of lamb: Sources of variation and opportunities for mitigation. *Agr. Syst.* 123, 97-107.

Kanellopoulos, A., Reidsma, P., Wolf, J., van Ittersum, M.K., 2014. Assessing climate change and associated socio-economic scenarios for arable farming in the Netherlands: An application of benchmarking and bio-economic farm modelling. *Eur. J. Agron.* 52, 69–80.

MacLeod, M., Eory, V., Gruère, G., Lankoski, J., 2015. Cost-Effectiveness of Greenhouse Gas Mitigation Measures for Agriculture. Paris: OECD.

MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., 2010. Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. *Agric. Syst.* 103, 198–209.

Met Office (2015) Climate summaries. http://www.metoffice.gov.uk/climate/uk/summaries. Accessed Aug 24, 2015.

McDowell, R. W. (Ed.)., 2009. *Environmental impacts of pasture-based farming.* CABI Publishing.

Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: a review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy.* 37, 760-770.

Nguyen, T.T.H., Doreau, M., Corson, M.S., Eugène, M., Delaby, L., Chesneau, G., Gallard, Y., van der Werf, H.M.G., 2013a. Effect of dairy production system, breed and co-product handling methods on environmental impacts at farm level. *J. Environ. Manage.* 120, 127–37.

Nguyen, T.T.H., Doreau, M., Eugène, M., Corson, M.S., Garcia-Launay, F., Chesneau, G., van der Werf, H.M.G., 2013b. Effect of farming practices for greenhouse gas mitigation and subsequent alternative land use on environmental impacts of beef cattle production systems. *Animal* 7, 860–9.

Nguyen, T. T. H., van der Werf, H. M. G., Eugène, M., Veysset, P., Devun, J., Chesneau, G., et al., 2012. Effects of type of ration and allocation methods on the environmental impacts of beef-production systems. *Livest. Sci.* 145, 239-251.

PAS, B., 2011. 2050: 2011 specification for the assessment of the life cycle greenhouse gas emissions of goods and services. *British Standards Institution.*

Phelan, P., Moloney, A., McGeough, E., Humphreys, J., Bertilsson, J., O'Riordan, E., et al., 2015. Forage legumes for grazing and conserving in ruminant production systems. Cr. Rev. Plant Sci. 34, 281-326.

Picasso, V.D., Modernel, P.D., Becoña, G. Salvo, L., Gutiérrez. L, Astigarraga, L., 2014. Sustainability of meat production beyond carbon footprint: a synthesis of case studies from studies from grazing systems in Uruguay. *Meat Sci.* 98, 346-354.

Pirlo, G., Terzano, G., Pacelli, C., Abeni, F., Carè, S., 2013. Carbon footprint of milk produced at Italian buffalo farms. *Livest. Sci*. 161, 176-184.

Ripoll-Bosch, R., de Boer, I.J.M., Bernués, A., Vellinga, T.V., 2013. Accounting for multi-functionality in the carbon footprint of lamb: A comparison of three contrasting Mediterranean systems. *Agr. Syst.* 116, 60-68.

Röös, E., Sundberg, C., Hansson, P.-A., 2014. Assessment of Carbon Footprint in Different Industrial Sectors, Volume 1, EcoProduction. Springer Singapore, Singapore.

Ruviaro C.F., de Léis, C.M., Lampert, V.N., Otávio, J., Barcellos, J., Dewes, H., 2015. Carbon footprint in different production systems on a southern Brazilian farm: a case study. *J. Clean Prod.* 96, 435-443.

Scottish Executive Environment, 2007. *ECOSSE estimating carbon in organic soils sequestration and emissions*. Edinburgh: Scottish Executive.

Smith, P., 2012. Delivering food security without increasing pressure on land. *Global Food Security.* 2(1), 18-23.

Smith, P., 2014. Do grasslands act as a perpetual sink for carbon? *Global Change Biology.* 20(9), 2708-2711.

Slingo, J., 2013. Why was the start to spring 2013 so cold? Met Office. http://www.metoffice.gov.uk/media/pdf/i/2/March2013.pdf. Accessed 12 Feb 2015.

Soussana, J., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Anim. 4(3), 334-350.

Taylor, R., Jones, A., Edwards-Jones, G., 2010. *Measuring holistic carbon footprints for lamb and beef farms in the cambrian mountains initiative*. Swansea: Countryside Council for Wales.

Thoma, G., Popp, J., Nutter, D., Shonnard, D., Ulrich, R., Matlock, M., Kim, D.S., Neiderman, Z., Kemper, N., East, C., Adom, F., 2013. Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. *Int. Dairy J.* 31, S3–S14.

van Beek, C.L., Pleijter, M., Kuikman, P.J., 2010. Nitrous oxide emissions from fertilized and unfertilized grasslands on peat soil. Nutr. Cycl. Agroecosystems 89, 453–461.

Veysset, P., Lherm, M., Bébin, D., Roulenc, M., 2014a. Mixed crop–livestock farming systems: A sustainable way to produce beef? Commercial farms results, questions and perspectives. *Anim.* 8 (08), 1218-1228.

Veysset, P., Lherm, M., Bébin, D., Roulenc, M., Benoit, M., 2014b. Variability in greenhouse gas emissions, fossil energy consumption and farm economics in suckler beef production in 59 French farms. *Agri. Ecosyst. Environ.* 188, 180-191.

Veysset, P., Lherm, M., Bébin, D., 2010. Energy consumption, greenhouse gas emissions and economic performance assessments in French Charolais suckler cattle farms: Model-based analysis and forecasts. *Agric. Syst.* 103, 41–50.

Webb, N., Broomfield, M., Brown, P., Buys, G., Cardenas, L., Murrells, T., Pang, Y., Passant, N., Thistlewaite, G., Watterson, J., 2014. UK Greenhouse Gas Inventory, 1990 to 2012: Annual Report for Submission under the Framework Convention on Climate Change. London: Department of Energy and Climate Change.

Figure 1 Schematic representation of the system boundary within which the carbon footprint was assessed

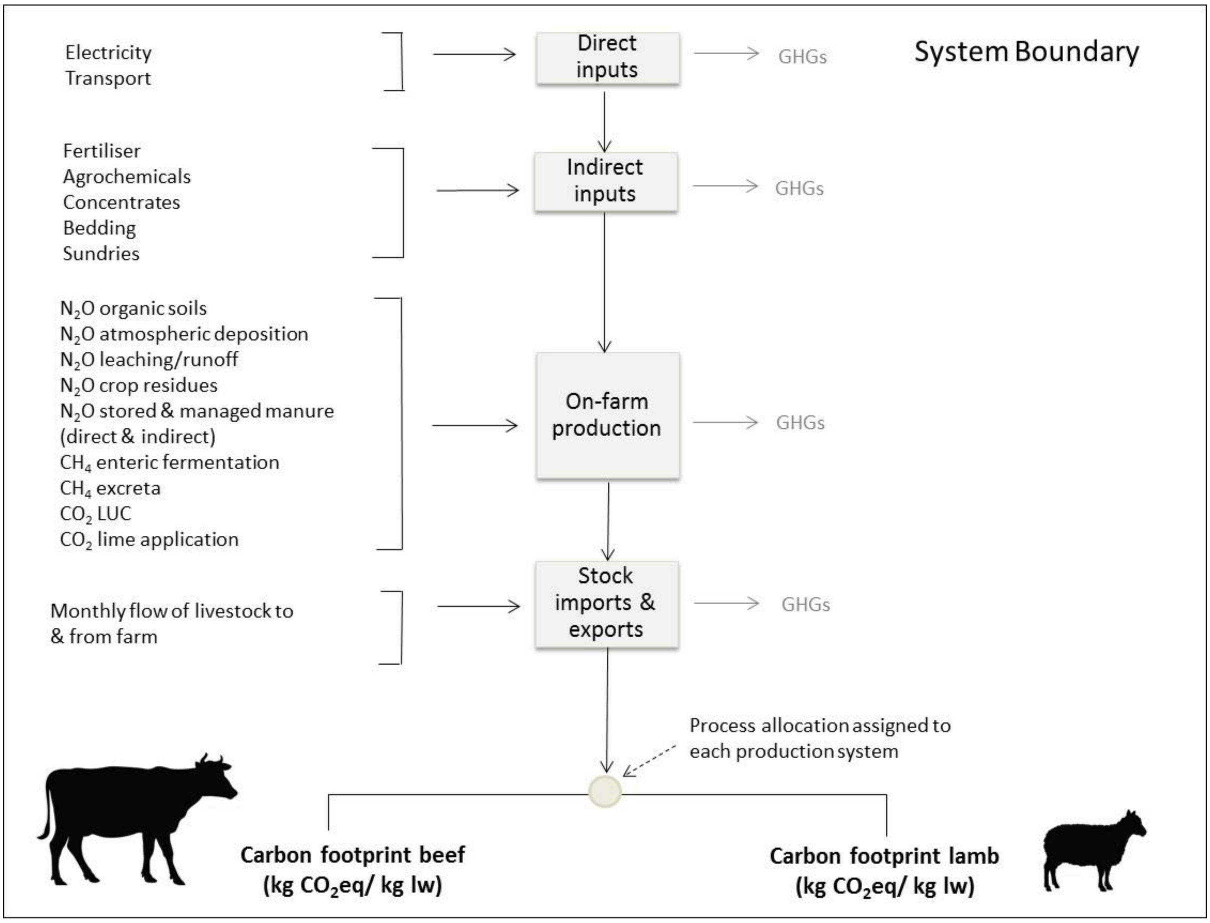


Figure 2 The percentage change of an enterprises 2009/10 CF to that of 2012/13. L = lamb only enterprises, M = mixed enterprises, B = beef only enterprises

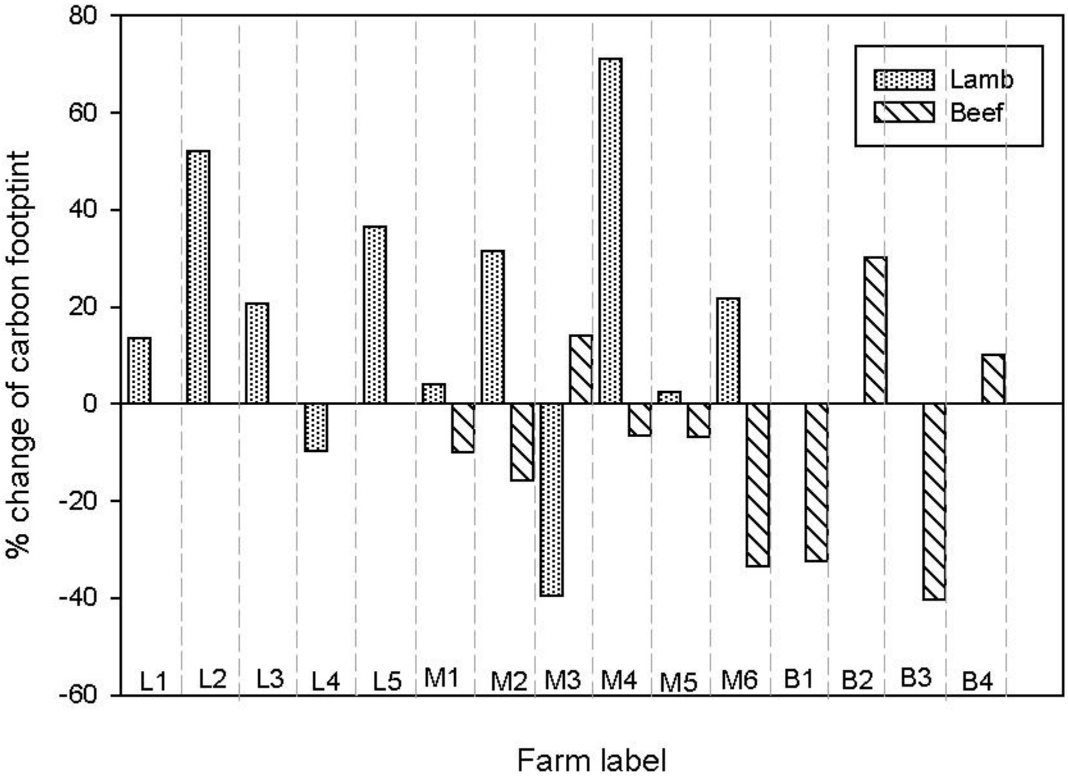


Figure 3 Relative contribution (%) of emission sources towards the final CF

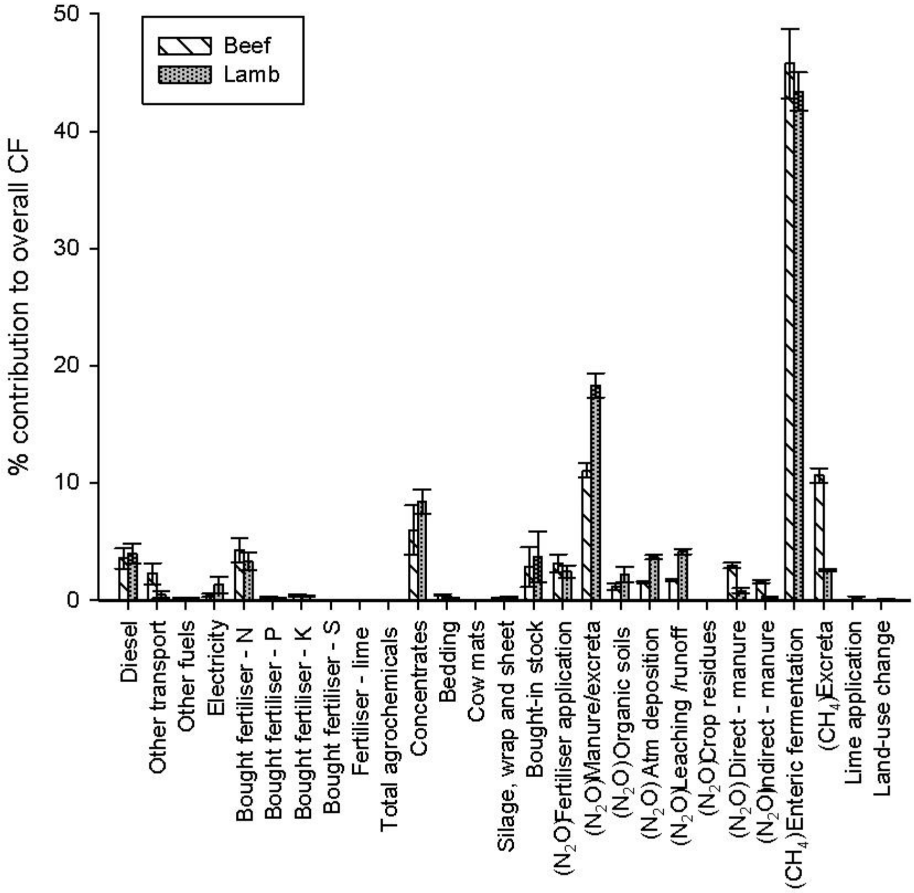


Figure 4 Mean emission sources of methane and nitrous oxide for beef and sheep carbon footprint

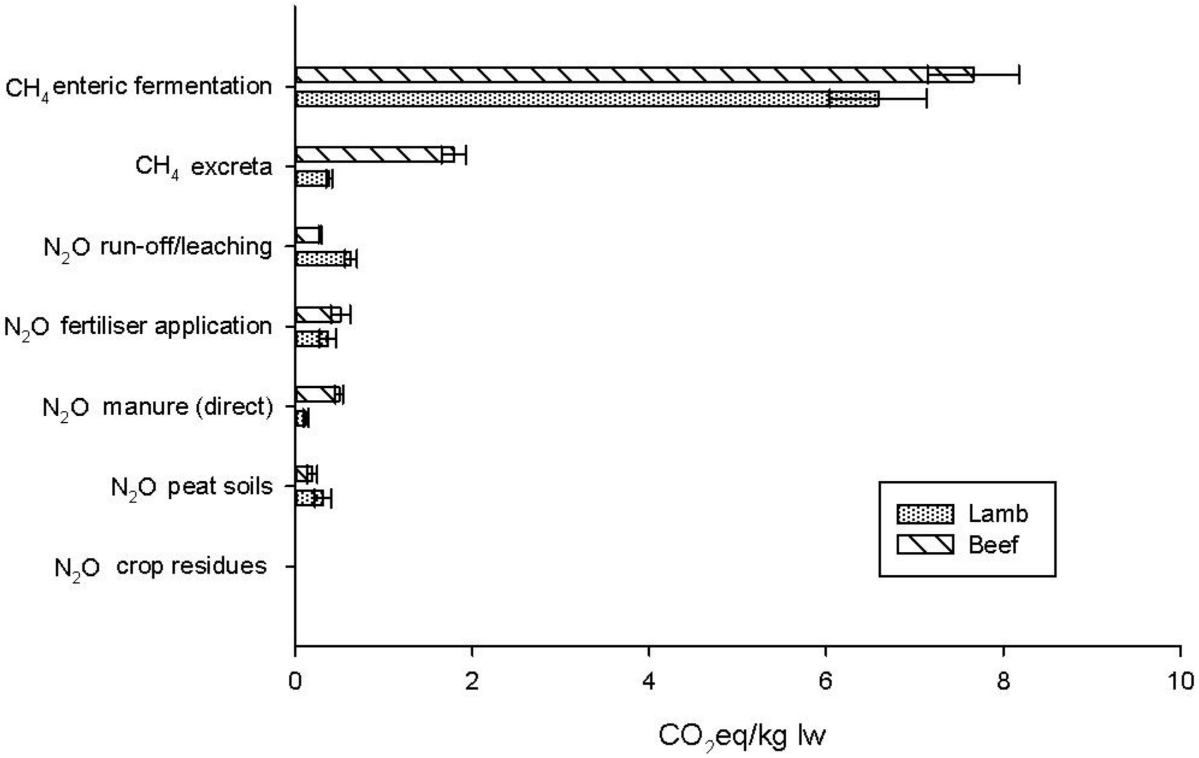
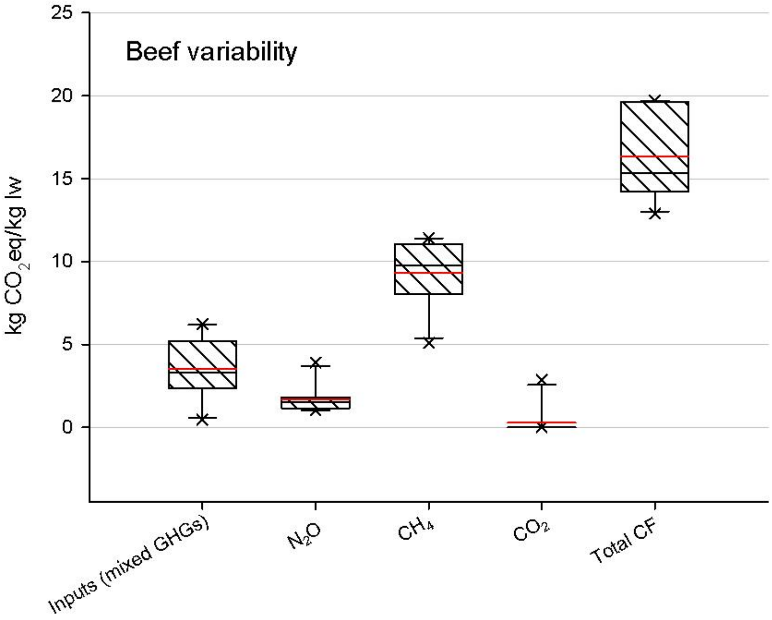


Figure 5 Variability, median, mean, 25th and 75 percentile (boxes), 10th and 90th percentiles (whiskers) and extreme vales (crosses) of gross GHG emissions for lamb (blue) and beef (red)



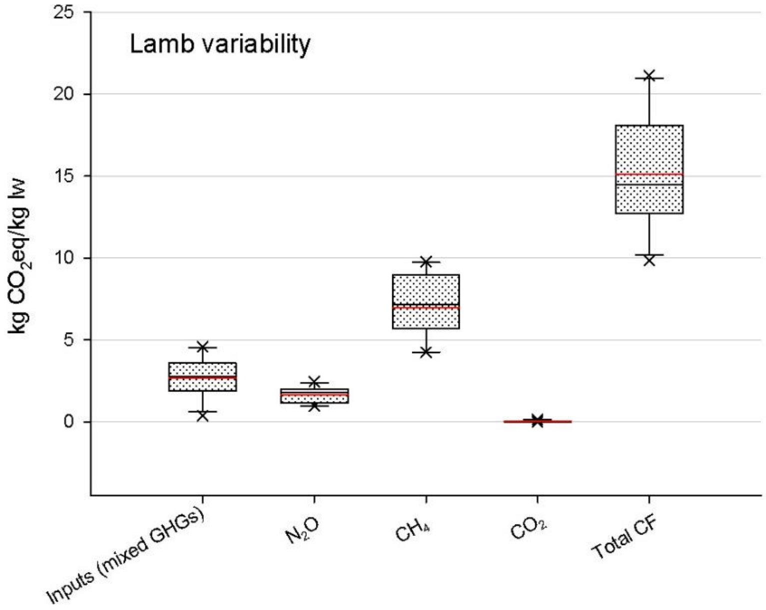


Figure 6 Scenario analyses of potential footprint reduction strategies. The graph represents how changes in management activities alter the footprint when all other variables are held constant. C = concentrate use reduction, F = fertiliser reduction, MM = efficient manure management, and Prod efficiency = matching the efficiencies of the lowest emitters

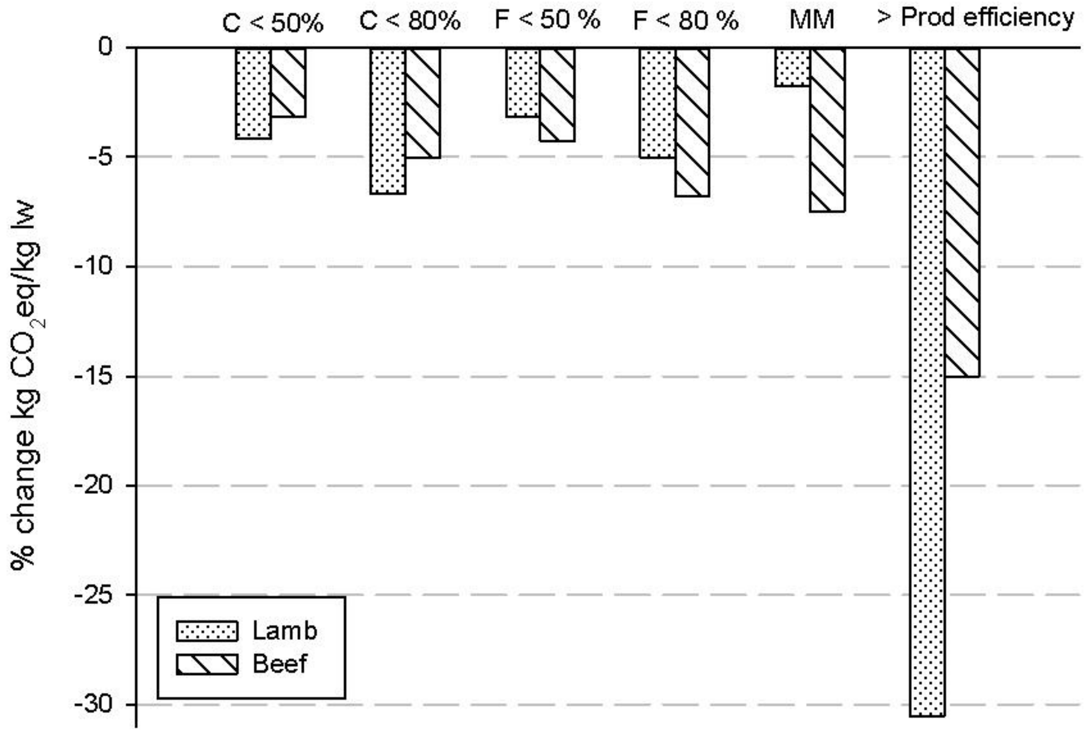


Table 1 Participants’ perception of greenhouse gas emissions associated with production

	Strongly disagree	**Disagree**	**Unsure**	**Agree**	**Strongly agree**
I take the environment into consideration even if it lowers profit	1	8	0	6	0
It's possible to reduce my farm’s footprint without affecting productivity	0	4	3	8	0
Livestock farmers should bear responsibility for their emissions	1	3	2	8	1
Livestock farming contributes towards climate change	0	4	7	3	1
Mitigation strategies should make economic sense	0	0	1	4	10
The best mitigation strategies are too costly to adopt	0	2	5	5	3
Climate change is a global issue; whatever changes I carry out on my farm are of little value	0	2	2	5	6
I am interested in trying different mitigation methods to reduce the farm’s footprint	0	1	2	9	3
Switching to a more climate-friendly farming methods would not involve much change from my current operation	0	1	0	6	8
I plan to reduce my farm’s footprint over the next 10 years	0	1	3	7	4
My farm’s footprint is small in comparison to similar farming operations	0	0	3	7	5

Table 2 Farm carbon footprint (kg CO_2eq/kg liveweight) from 2009/10 and 2012/13

Lamb			**Beef**		
Farm	2009/10	2012/13	Farm	2009/10	2012/13
L1	13.57	15.42	B1	21.07	14.23
L2	9.08	13.82	B2	11.20	14.58
L3	8.94	10.79	B3	24.65	14.74
L4	22.22	20.07	B4	13.99	15.40
L5	10.77	14.70	M1	20.57	18.54
M1	17.73	18.45	M2	21.37	18.01
M2	14.30	18.80	M3	14.71	16.80
M3	16.70	10.13	M4	14.72	13.77
M4	9.59	16.40	M5	14.67	13.69
M5	15.19	15.56	M6	24.07	16.03
M6	18.30	22.28	-	-	-

Table 3 Mean GHG emission sources for beef and lamb in the years 2009/10 and 2012/13. Emissions are expressed as kg CO_2eq/kg liveweight

	Lamb				**Beef**			
	2009/10	**CV (%)**	**2012/13**	**CV (%)**	**2009/10**	**CV (%)**	**2012/13**	**CV (%)**
GHGs from inputs								
Diesel	0.63	65.45	0.51	35.11	0.75	80.08	0.48	35.54
Transport	0.08	16.27	0.07	15.58	0.49	91.67	0.37	66.34
Other fuels	0.03	2.56	0.02	2.33	0.04	3.71	0.01	1.66
Electricity	0.13	31.45	0.24	38.83	0.06	7.94	0.07	7.54
Fertilisers (inc. lime)	0.61	8.20	0.65	11.95	0.72	9.78	1.14	17.39
Agrochemicals	0.00	0.29	0.00	0.44	0.01	1.19	0.00	0.62
Bedding	0.03	6.61	0.02	1.74	0.10	8.42	0.05	4.18
Silage wrap & sheet	0.04	3.088	0.03	3.45	0.04	4.70	0.03	1.67
Bought-in stock	0.84	179.53	0.43	99.97	0.55	102.35	0.54	123.35
concentrate feeds	1.15	74.26	1.56	55.53	1.36	132.25	0.98	90.66
N_2O emissions								
N application	0.39	25.33	0.42	39.60	0.48	31.60	0.75	26.22
Manure/excreta	2.59	135.50	2.98	89.76	2.24	88.02	1.56	32.88
Organic soils	0.22	26.40	0.36	46.77	0.155	18.922	0.16	20.32
Atmospheric deposition	0.52	27.01	0.60	17.95	0.30	9.63	0.22	4.75
Leaching/runoff	0.58	30.49	0.67	20.20	0.31	10.84	0.25	5.34
Crop residues	0.00	0.50	0.00	0.03	0.00	0.65	0.00	0.12
Stored & managed manure - direct	0.14	10.39	0.13	12.62	0.57	20.36	0.48	13.31
Volatilisation - stored & managed manure	0.04	3.12	0.04	3.79	0.28	12.06	0.26	12.81
CH_4 emissions								
Enteric fermentation	6.21	237.317	6.88	188.40	8.11	266.60	6.81	157.58
Excreta	0.37	14.18	0.39	14.18	1.93	61.27	1.62	47.28
Land use change								
Lime application	0.04	13.93	0.00	188.40	0.00	266.30	0.00	157.58
Land-use change	0.37	5.51	0.00	14.18	0.00	61.27	0.00	47.28
Carbon footprint	**14.68**	8.20	**16.00**	11.95	**18.48**	9.78	**15.78**	17.39

Table 4 Farm characteristics and total liveweight produced for slaughter/ha for both sampling years. For mixed farming systems, liveweight produced for slaughter/ha represents the total volume of beef and lamb sold for slaughter

Farm Label	Farm specialisation	Farm size (ha)	Elevation (m)	Slaughter weight (kg/ha) 2009/10	Slaughter weight (kg/ha) 2012/13
L1	Sheep	117.35	310	27.43	41.75
L2	Sheep	110.00	220	291.55	223.09
L3	Sheep	30.45	70	82.76	67.00
L4	Sheep	69.00	120	77.59	58.06
L5	Sheep	460.00	350	156.96	27.01
B1	Beef	95.91	290	107.39	268.48
B2	Beef	64.75	70	66.72	83.40
B3	Beef	93.58	150	180.12	324.44
B4	Beef	49.37	110	317.84	243.30
M1	Mixed	106.00	340	180.67	165.09
M2	Mixed	203.00	210	205.56	365.57
M3	Mixed	71.68	200	290.90	254.74
M4	Mixed	673.00	100	198.66	119.05
M5	Mixed	370.00	240	146.86	129.03

Table 5 GHG emissions and farm characteristics of the 25% of farms with the lowest carbon footprint (CF-), and the 25% of farms with the greatest carbon footprint (CF+). Significant differences ($p < 0.05$) between the specific categories are highlighted by an asterisk

	Beef (CF-)	Beef (CF+)	Lamb (CF-)	Lamb (CF+)
Carbon footprint (kg CO_2eq/kg lw)	**13.46***	**22.34***	**9.83***	**20.36***
GHGs concentrates (kg CO_2eq/kg lw)	1.16	1.32	**0.62***	**1.65***
GHGs bought fertiliser (kg CO_2eq/kg lw)	0.57	0.68	0.27	0.64
GHG total inputs (kg CO_2eq/kg lw)	2.48	4.56	2.82	4.04
N_2O fertiliser application (kg CO_2eq/kg lw)	0.39	0.45	0.16	0.44
N_2O organic soils (kg CO_2eq/kg lw)	0.24	0.19	0.04	0.15
N_2O deposition and run-off (kg CO_2eq/kg lw)	**0.43***	**0.71***	**0.71***	**1.80***
N_2O stored and managed manure (direct) (kg CO_2eq/kg lw)	0.43	0.68	0.10	0.14
N_2O stored and managed manure (indirect) (kg CO_2eq/kg lw)	0.22	0.35	0.10	0.08
N_2O crop residues (kg CO_2eq/kg lw)	0.00	0.00	0.00	0.00
Total N_2O (kg CO_2eq/kg lw)	**1.71***	**2.38***	**1.12***	**2.62***
CH_4 enteric fermentation (kg CO_2eq/kg lw)	**6.15***	**10.14***	**3.92***	**8.96***
CH_4 excreta (kg CO_2eq/kg lw)	1.58	2.33	**0.23***	**0.53***
CH_4 total (kg CO_2eq/kg lw)	**7.73***	**12.47***	**5.78***	**9.49***
CO_2 total (kg CO_2eq/kg lw)	0.00	0.00	0.61	0.00
Farm size (ha)	378.02	173.69	140.09	163.4
Elevation (m)	**107***	**246***	172	206
Breeding stock (animals/ha)	0.24	0.35	4.02	5.00
Growing stock (animals/ha)	0.29	0.62	4.96	4.82
Total slaughter rate (%)	**70.92***	**31.40***	**62.82***	**95.93***