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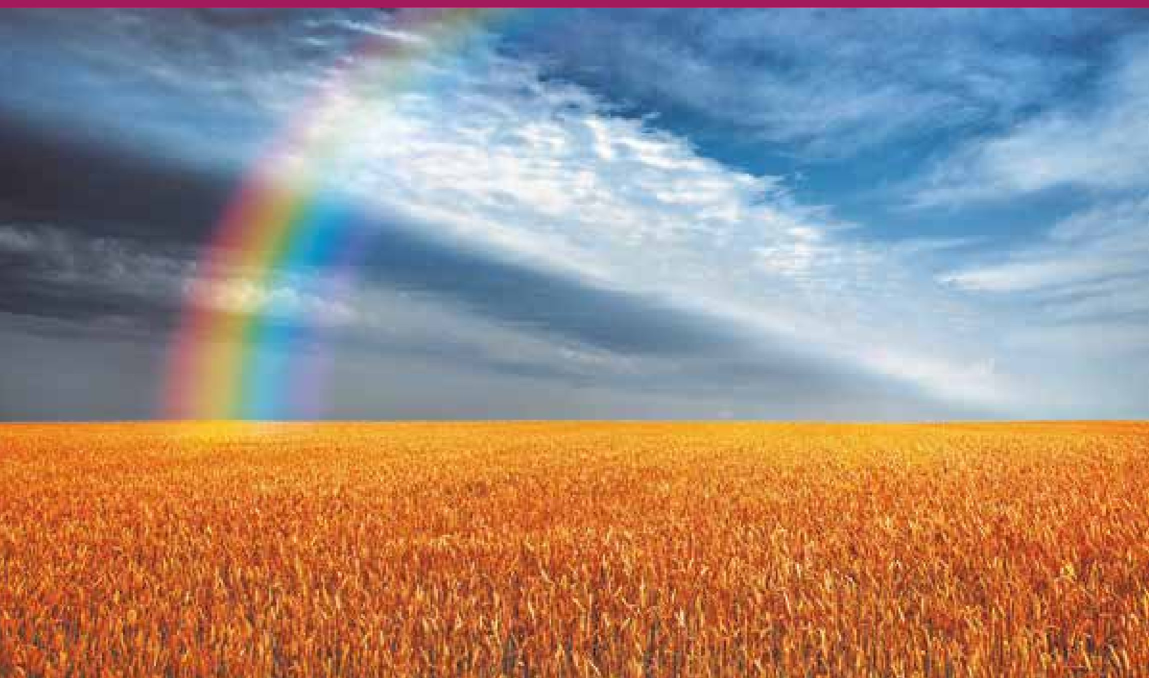

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1 Introduction

As discussed elsewhere in this book, one of the most common methods to evaluate environmental footprints of farming systems is life cycle assessment (LCA). Although LCA itself is suitable for and indeed adopted by a wide range of industries far beyond agriculture, what separates agriculture, and in particular pasture-based ruminant production systems, is the high degree of uncertainties associated with physical, chemical and biological processes that underpin production (McAuliffe et al., 2018a). In the presence of uncertainties, point-estimates provided by LCA models are unlikely to be informative enough to offer robust policy implications (Chen and Corson, 2014); when this is the case, the resultant environmental burdens must be expressed in the form of probability distributions and interpreted accordingly (McAuliffe et al., 2017).

For carbon footprint (CF) analysis of ruminant systems, one significant challenge of collating a life cycle inventory is uncertainty associated with emission factors (EFs), or parameters linking nutrient inputs into the system to greenhouse gas (GHG) emissions arising from the system (Pouliot et al., 2012). On commercial livestock farms, various factors can affect their relationships; for example, weather, soil, plant/animal genetics, management practice and interactions between them. Despite these variabilities, the majority of LCA

http://dx.doi.org/10.19103/AS.2018.0044.14

Chapter taken from: Weidema, B. P. (ed.), *Assessing the environmental impact of agriculture*, Burleigh Dodds Science Publishing, Cambridge, UK, 2019, (ISBN: 978 1 78676 228 3; www.bdspublishing.com)

studies adopt EFs derived outside the actual system boundary, most commonly as parameters defined as part of the Intergovernmental Panel on Climate Change guidelines (IPCC, 2006). As these 'generic' EFs are designed to be applicable to a wide spectrum of production environments within a single agroecological zone, a considerable level of uncertainty surrounds each of these values (Dudley et al., 2014). As a case in point, the two parameters for nitrous oxide (N_2O) emissions suggested by IPCC (2006), commonly known as EF_1 (% fertiliser N lost as N_2O) and EF_{3PRP} (% urine and dung N deposited on pasture lost as N_2O), are both deemed to have a 95% confidence interval between −67% and +300% of the respective point estimates.

To facilitate evidence-based debates about the environmental impact of ruminant production systems and, by extension, the role of ruminants in global food security, it is therefore imperative to improve reliability of EFs in a more location-specific context. This, however, requires a significant investment into field-based research, something that is not always feasible for practical reasons. Through a review of recent literature and a quantitative case study, this chapter explores how this practical trade-off between feasibility and scientific rigour should be addressed.

2 LCA applied to ruminant production systems

LCA has been applied to all major ruminant production systems (beef, dairy, lamb and wool), albeit with different degrees of scrutiny into system-wide uncertainties. Frequently cited examples of works on the sheep sector include Biswas et al. (2010), Ripoll-Bosch et al. (2013) and Wiedemann et al. (2015a). For dairy, Üçtuğ (2019) provides an extensive literature review encompassing 31 studies. In addition, Poore and Nemecek (2018) is accompanied by a global database of agri-food LCA results covering both plant-based and animal-based commodities.

For the beef sector, de Vries et al. (2015) review and compare findings from 14 studies based on contrasting farming systems from around the world. It is noteworthy, however, that the popularity of beef LCA research has substantially increased over the last 3 years, likely due to reports indicating that the sector, and in particular grazing systems, are extremely heavy contributors to global GHG emissions (Herrero et al., 2016; Springmann et al., 2016). In response to such a rapid rise in attention paid to the industry, the remainder of this section will give a summary of 14 beef LCA studies that have been published between 2015 and 2018. Papers that are not written in English and that focus on end-point modelling are excluded here.

In Brazil, Dick et al. (2015) conducted an LCA of beef cattle in two grassland systems. The first system was based on traditional grazing practices where animals can wander freely and receive little or no supplementation. The second system, termed 'improved', involved weekly rotational grazing and the introduction of winter forage species. The system boundary was from raw material extraction to farm gate and the functional unit (FU) was 1 kg liveweight gain (LWG). Data on beef production within the two systems were sourced from published literature, and GHG emissions were calculated according to IPCC guidelines. Global warming potential (GWP) for the traditional system was found to be 22.5 kg CO_2-eq per kg LWG, while GWP for the improved system was 9.2 kg CO_2-eq per kg LWG. This dramatic reduction in GWP was attributed to higher quality forage with increased digestibility in the alternative system, resulting in faster LWG.

Mogensen et al. (2015) estimated CFs of beef production systems in Denmark and Sweden. The system boundary was from cradle to farm gate and the FU was 1 kg carcase weight (CW). Five Danish and four Swedish beef farming scenarios were developed, which were categorised depending on intensive or extensive production, and dairy or beef breeds of cattle. For feed production (pasture, silage and concentrates), carbon sequestration was considered based on IPCC guidelines and published literature. Grass-clover swards were included as part of an arable rotation where the swards remained for 2–3 years in a 5-year rotation. The GHG emissions were estimated using a combination of IPCC values and published data for Nordic conditions, the latter to estimate methane (CH_4) emissions from enteric fermentation and manure management. The resultant CF ranged from 8.9 to 17.0 kg CO_2-eq per kg CW for the dairy-bull fattening systems, while the CF for cow–calf systems ranged from 23.1 to 29.7 kg CO_2-eq per kg CW. Carbon sequestration resulted in GWP mitigation across all scenarios; among them, CO_2 reduction was largest in the grass-based systems, although these systems still generated the highest CF values despite elevated carbon uptake.

Wiedemann et al. (2015b) utilised LCA to examine the environmental impact of Australian beef and lamb being exported to the United States. The system boundary was from cradle (in Australia) to the distribution warehouse in the United States, and the FU was 1 kg retail ready meat. For beef systems, the study considered beef cattle bred in rangelands and finished on pasture, and dairy steers finished on grain feedlots for either 115 days or, for specialised breeds such as Wagyu, 330 days. Farm-level data were obtained from governmental surveys and published case studies. Regionally tailored herd models were used to calculate feed intake and for predicting GHG emissions. Data on slaughtering and processing (such as cutting and chilling) were derived from an industry survey of meat processing plants in Australia. The GWP ranged from 23.4 to 27.2 kg CO_2-eq per kg beef, with the grass-finished cattle performing least favourably. Across the three scenarios, the farming phase generated the highest GWP (93%), meat processing accounted for 4%, transportation 3%, while the warehousing had negligible impacts. However, the authors also considered differences in human edible protein conversion efficiency. Under this FU, pasture-based beef production performed considerably better than grain-fed beef by converting more non-human-edible protein into human-edible protein.

In an effort to capture temporal variations in on-farm GHG emissions, Hyland et al. (2016) assessed the CF of 15 livestock enterprises over 2 time periods 3 years apart (2009/10) and 2012/13). In addition to calculating farm-level emissions intensities, the authors also used a range of sensitivity analyses to investigate potential mitigation strategies. The system boundary of the study was set as cradle to farm gate, and the FU as 1 kg liveweight (LW). Across the 15 livestock enterprises examined, five specialised in lamb, four specialised in beef, while six were mixed beef and sheep farms. Emissions intensities were calculated according to IPCC (2006) Tier 1 and 2 guidelines. In tackling the issue of mixed farming allocation, where possible Hyland et al. (2016) used system expansion; however, in certain cases, this was not possible due to a lack of differentiation and economic allocation was used instead. Between two data periods, lamb emissions were found to increase by 12%, while beef emissions decreased by 12%. However, these differences were not found to be statistically significant. Unsurprisingly, CH_4 emissions primarily resulting from enteric fermentation were the greatest GHG burdens across all enterprises. Regarding the scenario analysis aimed at reducing on-farm emissions, the authors suggested that the primary focus for farmers should be on improved resource use efficiency. The inclusion of legumes such as red (*Trifolium pratense*) and white (*Trifolium repens*) clover on suitable soils was also highlighted as an important technique to reduce fertiliser requirements.

Examining the impacts of Canadian grazing management strategies on GHG intensities from beef herds, Alemu et al. (2017) modelled a typical herd structure of 120 cows, 4 bulls and their progeny over an 8-year period. A range of different grazing strategies were considered: light continuous grazing for all cattle; heavy continuous grazing for all cattle; light continuous grazing for cow–calf pairs and moderate rotational grazing for backgrounded cattle; and heavy continuous grazing for cow–calf pairs and moderate rotational grazing for backgrounded cattle. The system boundary was set as cradle-to-farmgate, and results based on two FUs (LW and CW) were reported side-by-side. The authors used Holos (a Canadian whole-farm model) to estimate farm-level emissions, and soil carbon changes were considered using the Introductory Carbon Balance Model, while farm management data were sourced from previous management studies. Emissions intensities were found to have narrow ranges (14.5–16.0 kg CO_2-eq/kg LW and 24.1–26.6 kg CO_2-eq/kg CW) across the grazing scenarios; however, GHG emissions tended to decrease as stocking density increased. Inclusion of soil as a carbon sink reduced impacts by up to 25%. The authors highlight the complexities in crediting a grassland system as a carbon sink due to the extremely dynamic nature of carbon flows.

Berton et al. (2017) applied the LCA method to examine the environmental footprint of the integrated French–Italian beef production system. The system boundary was set as cradle-to-farmgate; however, unlike many other studies, this boundary accounted for a cow–calf operation in one country, France, with animals ready for fattening transported to another country, Italy. All inputs and outputs (including transportation) associated with each stage were accounted for, and impacts were scaled to a FU of 1 kg LW (described as bodyweight). The authors considered a range of impact categories made up of GWP, acidification potential (AP), eutrophication potential (EP), cumulative energy demand (CED) and land use (LU) reported as land occupation. Regarding allocation of burdens to coproducts of the cow–calf operation, a mass approach was adopted along with a sensitivity analysis to consider the effect of this assumption. French farms (40) and Italian farms (14) were modelled based on the best available data. The authors found that the burdens arising directly from the farms were greater than upstream processes in general; the only exception to this finding was CED, where energy demand was higher for off-farm processes for production of feed and agrochemicals. In terms of total impacts, the authors highlighted positive correlations between direct environmental burdens (GWP, AP and EP) and resource requirements (CED and LU) and pointed out that agricultural policy design needs to account for multiple indicators rather than focusing on one.

In Italy once again, Buratti et al. (2017) compared the CF of conventional and organic beef production systems. Data were collected from two case study farms in the Umbria region of Italy, both of which operated as cow–calf systems rather than specialist fattening operations. The system boundary was from cradle-to-farmgate, and the FU was 1 kg LW of heifers and bullocks ready for slaughtering. Feed production primarily occurred on each of the farms, and burdens arising from fodder were modelled based on production data provided by the farms. The few imported products were treated as background processes and sourced from *ecoinvent* V3. Fertilising strategies differed between the enterprises. For example, the 'organic' system solely used livestock manure to fertilise feed crops, while the 'conventional' system used mineral N in addition to manure. Both systems transported excess manure to nearby but external cropland. The GHG emissions were estimated using IPCC (2006) Tier 2 guidelines for all foreground sources, and, regarding enteric fermentation, the authors estimated Y_m values (CH_4 conversion factors) according to the digestible energy of the feed. The authors reported that lower GHG emissions were generated when producing organic feed due largely to lower mineral N requirements; however, interestingly, this did not translate to total CF rankings. The conventional system had a lower CF than the organic system, primarily driven by the shorter finishing times required.

De Figueiredo et al. (2017) examined the GHG balance and CF of three pasture-based beef finishing systems in Brazil. Three pasture systems all consisting of *Brachiaria spp*. were defined as: a degraded pasture receiving no external inputs; a managed pasture receiving annual fertiliser with animals receiving strategic supplementation consisting of maize (*Zea mays*) bran (82%), milled soybean (*Glycine max*) (14%), urea (3%) and mineral salt (1%) for a 6-month period during dry season at a rate of 4 g/kg bodyweight; and a crop–livestock–forest integration system, a more complex system involving afforestation and rotational crop production and the same supplementation described under managed pasture. Both values were calculated using IPCC (2006) guidelines; the GHG balance was reported in terms of land area (1 ha), whereas the CF was reported as 1 kg LW leaving the farmgate. On an area basis, degraded pasture was found to have the lowest GHG balance, due to considerably lower stocking rates and no fertiliser requirement. Nevertheless, this finding was reversed in terms of 1 kg LW and degraded pasture was found to be the least efficient system due to low animal productivity. Between the two improved pastures, managed pasture was found to have considerably lower emissions (in terms of LW) than crop–livestock–forest, with livestock productivity again being a key factor. The crop–livestock–forest system brings its own merits in terms of other impact categories not assessed, such as improved biodiversity and utilising land to produce timber and crops as coproducts from the system. Overall, the authors conclude that land designated as degraded pasture should be improved wherever feasible. This study further questions the use of area as an FU for system-level environmental evaluation.

Florindo et al. (2017) used the LCA methodology in combination with life cycle costing (LCC) to evaluate both the CF and economic performance of beef cattle in the Brazilian Midwest. The authors point out that LCA studies often recommend mitigation strategies to reduce environmental footprints while failing to account for economic viability, a trade-off they explicitly consider. Primary data for the study, including machinery costs and management activity, were collected directly from a beef farm comprising 1350 ha of grassland. The farm maintains 1830 animals consisting of breeding stock as well as growing and finishing cattle. As part of the diversification strategy, the farm is split into four different production systems, differentiated by feeding regimes, stocking densities and slaughter weights. Feeding regimes were determined as with or without strategic supplementation which varied depending on the life stage of the cattle (e.g. creep feed). The protein mineral supplement included cornmeal (36%), soybean meal (12%) and urea (11%). Creep feed was made up of 30% cornmeal and 51% soybean meal, while a 14% crude protein ration provided based on LW consisted of 72% cornmeal and 18% soybean meal. GHG emissions were calculated according to IPCC (2006) Tier 2 guidelines. Regarding LCC, the production system with the longest duration in terms of grazing was found to be the most cost-effective feed source, due to reduced supplementary feeding requirements. However, despite this positive aspect, it also resulted in the largest total financial cost due to lower stocking densities, and therefore, greater capital expenditure for land use. The same finding was true for GHG emissions; higher stocking rates and lower grazing durations generated lower CFs, despite the subsequent lower finishing weights. This demonstrates the benefits of strategic supplementation, particularly in geographical regions affected by severe weather (extremely dry seasons in this instance). Care must be taken, however, at interpretation of these results, as strategic supplementation could potentially increase the level of food–feed competition (Wilkinson and Lee, 2018).

Utilising interdisciplinary skills and expertise, Hessle et al. (2017) examined how Swedish beef and milk production systems could be environmentally and economically optimised under a range of different scenarios. Input was provided by experts in economics, LCA and supply chain management. The focus of this study was the environmental comparison of the reference situation (business-as-usual) with three hypothetical yet realistic scenarios. The three expertly designed scenarios were based around Swedish environmental objectives and set as follows: an 'ecosystem' scenario aimed at reducing impacts on biodiversity; a 'nutrient' scenario which focused on optimising plant nutrient use and supply; and a 'climate' scenario primarily concerned with reducing anthropogenic GHG impacts. The overarching goal of each alternative scenario was to maintain or improve production efficiency, while simultaneously mitigating environmental impacts. Once the study panel had agreed upon the alternative systems, LCA models were constructed using a combination of literature and expert opinion. In most instances, the improved systems demonstrated reduced negative impacts. However, there were notable trade-offs; for example, the ecosystem scenario required more land being used as grassland to improve biodiversity, which in turn caused negative impacts on eutrophication (freshwater and marine) and CED across both beef and dairy systems. Despite this, the authors concluded that a common denominator in improving these livestock systems was a more efficient use of resources such as energy and feed.

Tichenor et al. (2017) analysed differences in environmental performances between intensively managed grass-fed beef production and confinement dairy beef production systems in the Northeast United States. The system boundary was from cradle-to-farmgate and the authors considered hot CW as the FU to maximise comparative potential with previous North American studies. The impact categories considered were GWP, AP, EP, fossil fuel demand, water depletion and LU. For dairy beef, the authors adopted biophysical allocation at the ratio of 9.4%/0.4%/90.2% for beef/veal/milk, respectively. They also considered economic allocation in a sensitivity analysis, at the rate of 7.8%/0.9%/91.3%. Across GWP, EP, AP and LU, grass-fed was found to have higher burdens than dairy beef. On the other hand, dairy beef required more fossil fuel and water than grass-fed. The authors also considered impacts on a per ha basis, which resulted in lower AP and EP burdens for grass-fed. A sensitivity analysis to account for carbon sinks in grassland was also considered. While this inclusion substantially reduced the GWP of grass fed, it was not enough to offset the benefits of productivity from DB. The authors echoed the argument of Berton et al. (2017) that future research should consider multifaceted aspects of grass-fed systems that are socially important.

Wiedemann et al. (2017) examined resource use and GHG emissions associated with seven Australian feedlot beef systems. The authors adopted a gate to gate approach, with a primary focus on impacts arising from the grain-finishing stage. The FU for comparisons between the finishing stages was 1 kg LWG, while values for the entire system (including cow–calf enterprise) were reported as 1 kg LW. Three classes of cattle were considered: short-fed (55–80 days) for domestic market; mid-fed (108–164 days); and long-fed (>300 days) for alternative export markets. Similar to Hyland et al. (2016), Wiedemann et al. (2017) found that CH_4 emissions aggregated across enteric fermentation and manure management were the most significant contributors to emissions intensities. Across the three management strategies, long-fed generated more GHG emissions than mid-fed which in turn generated more emissions than short-fed, due largely to the length of production cycles. The same rankings were observed for fossil energy demand. However, the opposite rankings were noted for water consumption, an impact category with high importance in the arid regions of Australia. While the differences were not significant between short- and mid-fed, long-fed cattle had considerably lower freshwater usage due to reduced irrigated water usage. In terms of cradle-to-gate analysis, the finishing systems were found to contribute 26–44% of the total emissions intensity, with higher maximum impacts (up to 72%) recorded for total energy demand. The authors note that switches from pasture-based to grain-based systems have reduced Australia's national emissions intensity from beef cattle, but these switches have been met with a trade-off of increased national energy demand. This signifies the complexities of drawing conclusions across multiple impact categories.

Willers et al. (2017) sought to identify environmental hotspots in semi-intensive beef production systems in Brazil's Northeast. The study accounted for two farms: the cow–calf operation and a separate but nearby finishing system. Similar to most beef LCA studies, the authors adopted a cradle-to-farmgate system boundary and an FU of 1 kg LW leaving the finishing farm. Primary data were gathered from the managers of both farms, while background processes were sourced from *ecoinvent* V2. The authors considered five impact categories: GWP (reported as climate change); AP (reported as terrestrial acidification); EP (reported as freshwater eutrophication), LU (reported as agricultural land occupation) and fossil fuel depletion. Following Berton et al. (2017), Willers et al. (2017) used mass allocation to disentangle burdens arising from coproducts at the cow–calf stage. Regarding the identification of hotspots, the authors diverted from conventional approaches and considered pasture processes as separate entities to their modelled livestock. This resulted in an unusual attribution of the overall burdens, whereby ‘grassland production’ has higher effects on all impact categories than ‘livestock burdens’, making inter-study comparison of the results (de Vries et al., 2015) rather difficult.

Bragaglio et al. (2018) analysed the environmental footprints of a range of different beef production systems in Italy utilising data collected from 25 farms. The systems studied were: specialised extensive; high grain fattening; intensive cow–calf constantly kept in confinement and native breed (Podolian) maintained on pasture and finished in housing. The authors considered GWP, water depletion, LU, AP and EP within a system boundary set as cradle-to-farmgate and an FU of 1 kg LW. In terms of GWP, the intensive systems (high grain fattening and cow–calf confinement) were found to have lower impacts due largely to improved growth rates. However, the authors found that the systems with durations of pasture grazing (specialised extensive and Podolian) had lower AP than cow–calf confinement. There was no significant difference noted for water depletion, while high grain fattening and Podolian demonstrated the lowest burdens in terms of water quality (EP). Significantly higher LU was required for specialised extensive and Podolian; however, the authors also acknowledged that competition with human edible feed was lower for the grazing systems, particularly Podolian. A theme recurrent throughout grazing livestock LCA studies, namely the omission of ecosystem services and other societal benefits (e.g. improved animal welfare and meat quality) provided by grassland systems, is also highlighted by the authors. Bragaglio et al. (2018) conclude by acknowledging the importance of future LCA studies addressing these aspects of livestock systems that are more difficult to quantify.

Analytical approaches adopted by the above 14 studies are summarised in Table 1, with particular attention to the treatment of major sources of uncertainty inherent in beef production systems. Overall, it demonstrates a considerable gap in knowledge regarding uncertainty within the existing literature. For example, none of the 14 studies used individual livestock data, meaning that intra-herd distributions of animal properties and performances could not be considered. Eight out of 14 papers did use farm-level aggregated data; nonetheless, only one of them included primary information on forage quality, a parameter widely known to be affected by farm management and, in turn, contribute to the uncertainty surrounding CH_4 emissions through enteric fermentation. Only three studies conducted Monte Carlo analysis, reiterating the lack of attention bestowed upon uncertainty on the whole among LCA studies (Imbeault-Tétreault et al., 2013).

Table 1 Sources of uncertainty identified in recent LCA studies of beef production systems

Study	Animal growth over time	Animal categories	Foreground data source	Feed quality	Emission factors for carbon footprints	Monte Carlo analysis
Dick et al. (2015)	Split between first year and subsequent years	9	National statistics	Literature	IPCC Tier 2	✗
Mogensen et al. (2015)	Fixed average daily gain (ADG) per system	6	Literature	Literature	Danish specific and IPCC Tier 2	✗
Wiedemann et al. (2015b)	Fixed ADG	4	Farm	National statistics	Australian specific	✔
Hyland et al. (2016)	Monthly growth rates for growing stock	Unspecified	Farm	National statistics	UK specific and IPCC Tiers 1/2	✗
Alemu et al. (2017)	Fixed ADG per animal category	7	Literature and experimental data	Measured data	Canadian specific and IPCC Tier 2	✗
Berton et al. (2017)	Split into three growth stages on each farm	5	Farm	Literature	French specific and IPCC Tier 2	✗
Buratti et al. (2017)	Fixed ADG per animal category	7	Farm	Literature	IPCC Tier 2	✗
de Figueiredo et al. (2017)	Fixed ADG per system	Unspecified	Literature	Unspecified	Brazilian specific and IPCC Tier 1	✗
Florindo et al. (2017)	Varied ADG by age and scenario	4	Farm	Unspecified	IPCC Tier 2	✗
Hessle et al. (2017)	Unspecified	5	National statistics	Literature	IPCC (unspecified tier)	✗
Tichenor et al. (2017)[d]	Unspecified	6	Literature	Not applicable (only examines land use)	Not applicable (only examines land use)	✗
Wiedemann et al. (2017)	Varied ADG by farm and scenario	3	Farm	National statistics	Australian specific	✔
Willers et al. (2017)	Unspecified	4	Farm	Unspecified	IPCC (unspecified tier)	✔
Bragaglio et al. (2018)	Fixed ADG per system	3	Farm	Literature	IPCC Tier 2	✗

Furthermore, none of the above studies adopted site-specific EFs for calculating GHG emissions. This finding is perhaps unsurprising given the considerable effort required to measure GHG fluxes at the farm scale; conducting field trials specifically for an LCA study is unlikely to be financially justified. Should an opportunity exist, however, introduction of site-specific EFs may provide an effective and computationally straightforward means to improve accuracy of CF estimation because, as already discussed in Section 1, uncertainty associated with these parameters is one of the important practical barriers to draw useful policy implications for farm management. An important operational question, then, is as follows: under practical constraints concerning staff and budgetary availability, which EFs should we prioritise to measure on the farm? The next section outlines the procedure of a virtual experiment designed to solve this problem. To the best of our knowledge, such an attempt has not previously been made in LCA literature.

3 Case study: materials and methods

The case study was carried out using data from the permanent pasture-based beef enterprise (farmlet) of the North Wyke Farm Platform National Capability (Orr et al., 2016), an instrumented farm-scale grazing trial located in Devon, UK (50°46′10″N, 3°54′05″W). Under the attributional approach, the system boundary was defined as 'cradle-to-gate' or from the production of raw materials to the departure of live animals for slaughter, and encompassed both cow–calf and finishing operations, which are adjacent to each other but do not share pasture or other resources. The FU was set as 1 kg LW of prime beef (calves) departing the farm. Environmental burdens attributable to the sale of culled cows were portioned out from the system-wide CF using economic allocation.

Farm management practices and the data collection strategy at the study site are detailed elsewhere (Takahashi et al., 2018). Briefly, 30 Charolais × Hereford-Friesian calves and their dams constitute each year's herd, with the number of cows in the LCA model adjusted to account for extra heifers required to replace culled cows. As with the majority of beef farms in South West England, cattle graze in summer and are housed in winter, with both LWG of calves and the forage quality of pasture and silage evaluated at regular (2–4 week) intervals. All physical inputs into the system were appropriately recorded.

The present study utilised data associated with a generation of calves born in spring 2015 and slaughtered in winter 2016. On-farm GHG emissions from both livestock and pastures were calculated using the IPCC (2006) Tier 2 approach. Based on our earlier finding that ignoring the inter-animal difference in growth efficiency leads to a biased estimate of the farm-scale CF

(McAuliffe et al., 2018b), emissions for finishing animals were initially calculated for each individual animal separately and subsequently pooled together to create a whole-farm inventory. The resultant CF (kg CO_2-eq/kg LW) was expressed as a 95% confidence interval, which was derived by a Monte Carlo analysis with 1000 iterations. For each iteration, values for EFs were drawn from the distributions recommended by IPCC (2006); further details of this process are described in McAuliffe et al. (2018b).

Following the baseline CF estimation under which all EFs were assumed to be uncertain and follow predetermined probability distributions, eight groups of EFs (Table 2) were individually assumed to be certain at three levels defined by IPCC (2006): point estimate as well as lower and upper limits of the 95% confidence interval. By design, the CF derived under this setting was expected to have a narrower range than the baseline result, as one source of uncertainty had been eliminated from the model. These outputs represent hypothetical CFs when a particular group of site-specific EFs are perfectly quantified on the farm and therefore indicate the information value of pinpointing the corresponding EFs. Alternatively, as the true EFs are likely to lie somewhere between lower and upper limits of the IPCC 95% range, the difference in CF distributions derived under these two values can be seen as the level of uncertainty associated with the relevant EFs; a larger difference here suggests a higher priority for field measurements to obtain locally more accurate EF values. Overall, 25 CFs were derived, a baseline and 24 variants with distinct EFs (8 groups x 3 values).

Throughout the analysis, emissions pertaining to background processes were sourced from *Agri-footprint* v3 (Durlinger et al., 2017) and *ecoinvent* V3 (Wernet et al., 2016) databases. All CFs were calculated under the IPCC (2013) 100-year average impact assessment method on *SimaPro* v8.2.3.

Table 2 Emission factors considered in the case study

Source	IPCC (2006) notation	IPCC (2006) reference
CH_4 enteric fermentation	EF	Equation 10.21
CH_4 manure management	$EF_{(T)}$	Equation 10.23
N_2O manure management	EF_3	Table 10.21
N_2O inorganic fertiliser (ammonium nitrate)	EF_1 (for $F_{SN)}$)	Table 11.1
N_2O organic fertiliser (manure)	EF_1 (for $F_{ON)}$)	Table 11.1
N_2O grazing	EF_{3PRP}	Table 11.1
N_2O volatilisation	EF_4	Table 11.3
N_2O leaching	EF_5	Table 11.3

Note: Emissions associated with other sources (including background processes) were assumed to be uncertain throughout the case study.

4 Case study: results and discussion

The mean baseline CF was estimated to be 22.8 kg CO_2-eq/kg LW, with a confidence interval of 21.3–25.2 kg CO_2-eq/kg LW (Fig. 1). These results are at the higher end of values and ranges reported by previous studies undertaken in comparative environments (reviewed in Section 1); while the reason behind this has not been completely elucidated, it is thought to be due to a combination of the low stocking rate and the high replacement of the breeding herd to ensure safe delivery of calves for fattening experiments. Assuming subsets of EFs to take point estimate values without uncertainty did not change the CF distribution to any noticeable extent, although knowledge in CH_4 emissions from manure management and N_2O emissions from inorganic fertiliser application reduced the width of the confidence interval by 0.4 and 0.3 kg CO_2-eq/kg LW, respectively (Fig. 1). Interestingly, certainty regarding CH_4 emissions from enteric fermentation, widely considered to be the single largest source of ruminant-originated GHG emissions, contributed very little to the certainty regarding the resultant CF, likely because of the symmetric (triangular), rather than asymmetric (lognormal), nature of the probability distribution assumed under the baseline model (McAuliffe et al., 2018b).

Comparisons of CFs derived under lower and upper limits of EF values revealed, however, that on-farm measurement of enteric CH_4 may still be one

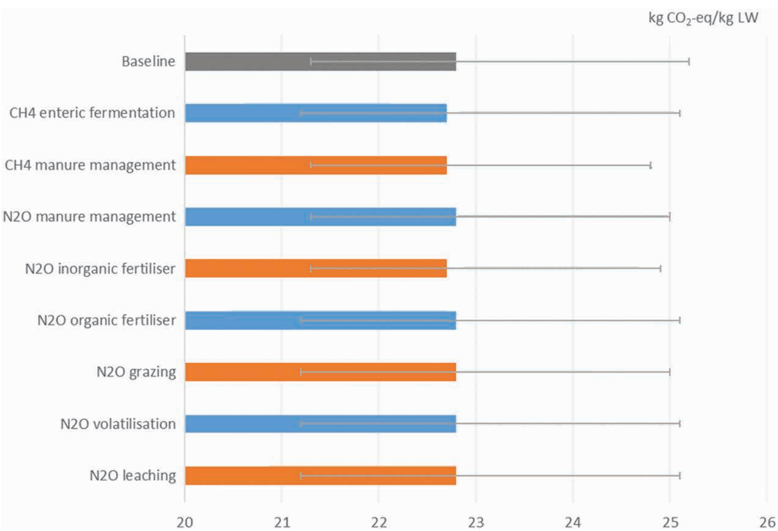

Figure 1 Carbon footprints of beef production systems estimated with one group of emission factors fixed at the IPCC point estimate. Error bars show the 95% range derived from Monte Carlo simulation, where all but one group of emission factors were assumed to follow IPCC uncertainty distributions. The baseline result accounts for all sources of uncertainty.

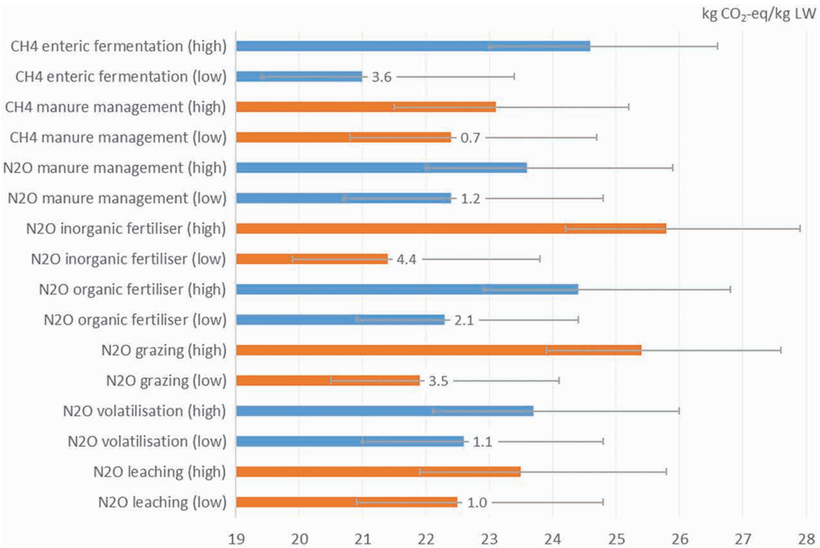

Figure 2 Carbon footprints of beef production systems estimated with one group of emission factors fixed at lower and upper limits of the IPCC 95% confidence interval. The number under each group depicts the difference in means between the two scenarios, which represents the value of knowing that particular emission factor through site-specific field trials. Error bars show the 95% range derived from Monte Carlo simulation, where all but one group of the emission factors were assumed to follow IPCC uncertainty distributions.

of the most effective approaches to reduce uncertainty (Fig. 2). The difference in mean CFs between two scenarios was estimated to be 3.6 kg CO_2-eq/kg LW, the second largest after N_2O emissions from inorganic fertiliser application (4.4 kg CO_2-eq/kg LW) and closely followed by N_2O emissions from excreta deposited during grazing (3.5 kg CO_2-eq/kg LW). The high information value of the latter two EFs is attributable to the high degree of uncertainty identified for these parameters by IPCC (2006), as discussed in Section 1 and quantitatively supported by Fig. 1. On the other hand, improved knowledge of enteric CH_4 EF reduced uncertainty surrounding the overall CF because of its large contribution to the total environmental burdens, even though its own variation is confined to a relatively small range. The remaining five groups of EFs were shown to have considerably less impact on the CF.

5 Conclusion

The above analysis revealed that uncertainty surrounding climate impacts of ruminant systems can potentially be reduced through on-farm measurements of GHG fluxes, but not all measurements carry the same degree of information value.

In temperate grassland regions, the priority for measurements should be given to N_2O from inorganic fertilisers applied and manure deposited to the soil, as well as CH_4 from enteric fermentation. It is acknowledged that, strictly speaking, these site-specific EFs will still be accompanied by their own uncertainty, which stems from intra-farm variability in soil, weather, plant genetics, animal genetics, rumen microbial ecology and other confounding factors. Nevertheless, these local sources of uncertainty are likely to be considerably smaller than uncertainty about the farm location that needs to be embedded into generic EFs. In turn, CF analysis carried out under reduced uncertainty will likely offer more policy implications that are directly applicable to local production environments.

6 Acknowledgements

The case study component of this chapter was supported by the Biotechnology and Biological Sciences Research Council (BBS/E/C/000I0320 and BBS/E/C/000J0100).

7 Where to look for further information

- The foundation theory behind the above discussion is summarised in: Heijungs R and Suh S (2002) *The Computational Structure of Life Cycle Assessment* (https://doi.org/10.1007/978-94-015-9900-9), Kluwer Academic Publishers.
- Oxford University Research Archive (https://doi.org/10.5287/bodleian:0z9MYbMyZ) stores a streamlined global database of CFs associated with food and beverage production. Also see Poore and Nemecek (2018).
- Global Farm Platform network (http://www.globalfarmplatform.org) is a worldwide initiative to compare sustainability of livestock production systems across different agroecological zones. Also see Eisler et al. (2014).
- North Wyke Farm Platform data portal (https://www.rothamsted.ac.uk/north-wyke-farm-platform) provides a wealth of raw data collected from farm-scale grazing trials, including those used in the present case study. Also see Orr et al. (2016) and Takahashi et al. (2018).

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