Carbon footprint of 10–18 month-old dairy beef production systems

Andre Mazzetto, Shelley Falconer, Amanda Judge, Mariana Barsotti and Stewart Ledgard

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Contents

1. Executive Summary

This cradle to farm-gate life cycle assessment (LCA) study evaluated the carbon footprint of dairy-derived steers (across a range of finishing ages and weights) compared to beef from the Class 9 Beef + Lamb New Zealand (B+LNZ) beef cattle system in New Zealand (NZ; a NZ 'average' system calculated from Class 1-8 farms B+LNZ Economic Survey). Specifically, it examined various growth scenarios and their subsequent impact on total greenhouse gas (GHG) emissions per kilogram of finished live weight (LW). The analysis focused on three key stages of cattle production: dairy calf production up to four days old (40 kg LW), rearing to weaning (100 kg LW) and finishing on pasture until reaching different target LWs. Farm data for dairy calf production and cattle finishing were based on NZ-average farm system data for 2021/22. Scenarios were analysed for steers from surplus dairy calves (spring or autumn-born) finished between 10 and 18 months of age and grown at an average of 700, 850 or 1,000 g LW/day.

The findings indicate that the carbon footprint of the studied dairy-derived beef is 32-48% lower than that of the average carbon footprint for mixed beef cattle in NZ. The reduction is largely driven by the primary output of the dairy system (milk) incurring the majority of the dairy system emissions, allowing production of the 4-day-old calf with low marginal emissions. Calving date had a minor influence, with the most effective strategies for reducing emissions being faster growth rates, shorter time to finishing, and improved feed conversion efficiency. The study emphasises the importance of considering interaction effects, particularly between finishing age and LW gain, which were shown to impact the carbon footprint significantly. Optimising those two variables together offers the greatest potential for emission reductions.

A sensitivity analysis was applied to estimate the impact of changing the birth weight from 40 kg to 37.5 kg LW (to account for Holstein calves vs beef cross calves). A second sensitivity analysis estimated the difference in the footprint between steers (current results), heifers and bulls. The final carbon footprint of the 37.5 kg calf was on average 0.81% higher than the 40kg LW calf (ranging from 0.39 to 1.30%) due to the extra amount of whole-milk powder (WMP) and calf meal at the rearing stage. For the different animal classes, the carbon footprint of bulls was on average 3.00% lower than steers (ranging from 1.75 to 3.60%), while the carbon footprint of heifers was on average 3.14% larger than steers (ranging from 2.13 to 3.77%).

Compared to existing literature, the carbon footprint values obtained in this study (after conversion to the same standard assessment methods for the average global warming potential over 100 years [GWP100] and dairy allocation) were lower than those reported for traditional and mixed beef systems and similar to dairy-derived beef systems.

2. Introduction

Food production significantly contributes to greenhouse gas (GHG) emissions, with the impact varying depending on food type and production system (Poore and Nemecek, 2018). Among livestock, beef production is often associated with a substantial carbon footprint (representing the total GHG emissions per kilogram of product). Opio et al. (2013) highlighted considerable global variability in the carbon footprint of beef production, with Oceania, Europe, and the USA exhibiting lower emissions compared to other regions. This variation is largely influenced by the specific farming systems and practices employed. Recent research in New Zealand (NZ) by Mazzetto et al. (2023) found that beef from cull dairy cows has a lower carbon footprint than beef from traditional beef cattle, due to the dual production of both milk and live weight (LW) of beef of dairy origin. For dairy production, total GHG emissions are allocated between milk and LW sold for meat. In contrast, beef systems rely solely on LW production, so all emissions are allocated to beef. A theoretical study by van Selm et al. (2021) suggested that replacing beef-breeding cows with surplus dairy calves could reduce GHG emissions from NZ cattle production by approximately 22%, noting only impacts on GHG emissions were studied.

Within NZ's current beef production systems, utilising surplus dairy calves offers significant opportunity to enhance production efficiency and lower the carbon footprint (i.e., total GHG emissions per kg product) of beef through optimising rearing and finishing practices. For example, fostering rapid cattle growth by providing high-quality pasture can enable earlier finishing. Finishing younger cattle may also present a pathway for reducing emissions per kg of product. A comprehensive evaluation of GHG emissions from animal production requires the use of life cycle assessment (LCA) methodology, which accounts for all emissions associated with the production system, including those from the cow that produces the calf, and the production of inputs used within the system (ISO, 2006; Ledgard et al., 2020; Wiedemann et al., 2015). This project employed LCA to calculate the carbon footprint of dairy-derived beef from surplus calves, applying various finishing efficiencies typical of an average NZ beef and sheep farm. The scope of the study was the carbon footprint of beef and not wider environmental or sustainability measures.

3. Methods

3.1 Goal and scope

The primary goal of this study was to determine the carbon footprint of 10 to 18 month-old dairy-derived beef animals using NZ-average spring and autumn calving dates and three average growth rate scenarios (700, 850 and 1,000 g LW gain/day). The beef carbon footprint from these scenarios was then compared to the carbon footprint of beef from a Class 9 B+LNZ average farm, beef from a dairy system (culled cows only) and international beef systems.

The functional unit analysed was one kg of finished LW. The study covered three stages of production of finished cattle:

- 4-day-old calf production at a dairy farm (assumed at 40 kg LW),
- rearing of calves to weaning (from 40 kg to 100 kg LW), and
- finishing on pasture to different LWs on a Class 9 B+LNZ farm (Figure 1).

In this report (as recommended by PAS 2050 (BSI, 2011)), capital was excluded from all calculations. Minor agri-chemicals such as treatments for intestinal parasites, mastitis and shed cleaning chemicals (for dairy only) were not accounted for in the carbon footprint assessments. Other research indicates these are likely negligible contributors (e.g. <0.1% of total GHG emissions).

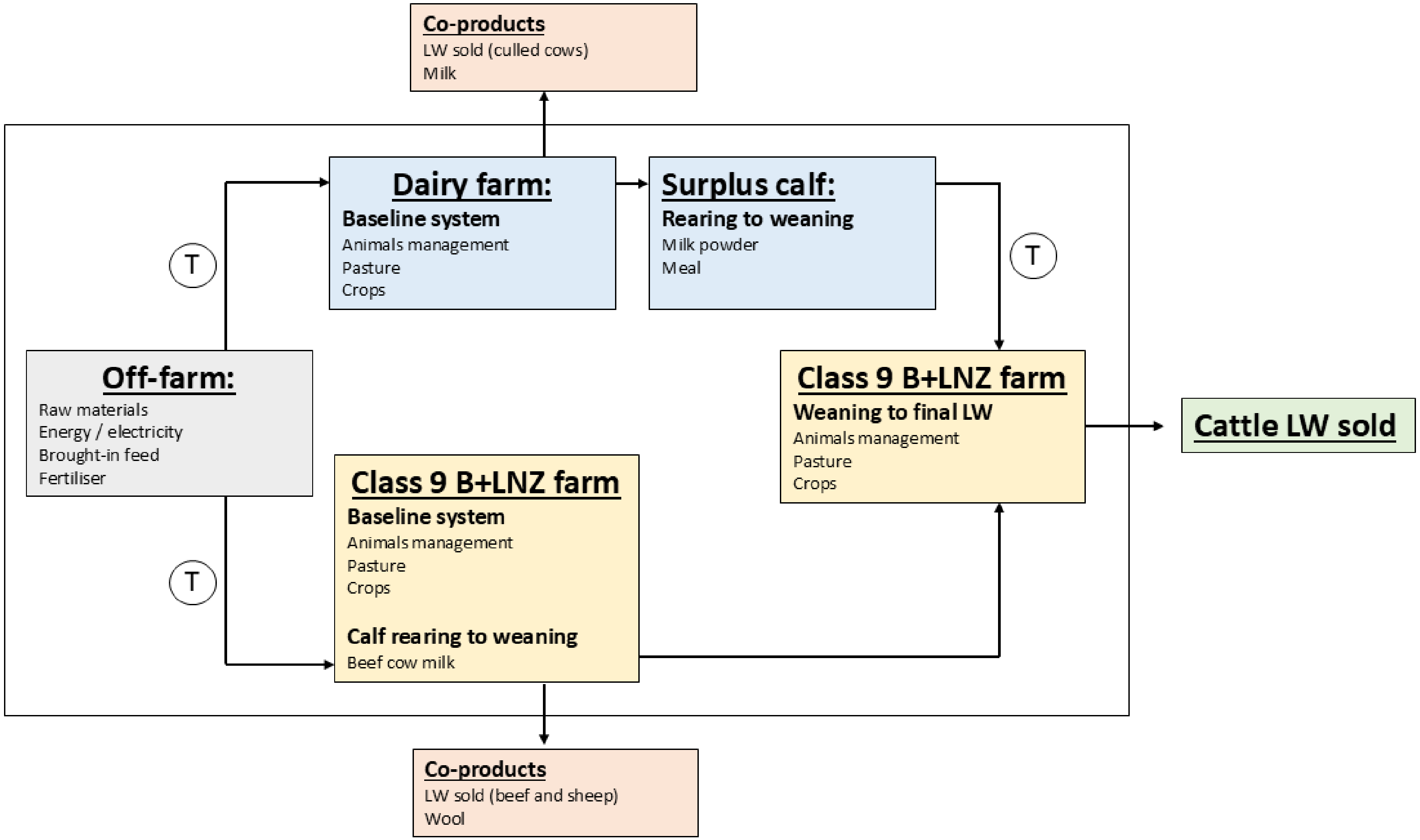

Figure 1. A general diagram of the main life-cycle stages for the dairy-beef system studied in this report and for Class 9 B+LNZ average beef cattle systems. LW: liveweight and T: transport.

3.2 Allocation

An attributional LCA approach was used, and allocation of total GHG emissions between co-products was required. The allocation methods applied at the on-farm stage for the Class 9 B+LNZ farm were:

- Allocation between beef cattle and sheep: System separation to avoid allocation was used for various on-farm operations where they could be specifically assigned to a single animal species (e.g., sheep fly-strike chemicals to sheep only). Where this was not possible, allocation based on biophysical causality was used, as recommended by the Food and Agriculture Organization (FAO,2015a,b). The metabolisable energy (ME) requirements for each animal species on-farm were calculated and used to allocate the GHG emissions between the different species. Some beef/sheep farms also had dairy cattle grazers (replacements or dry cow wintering). The ME for these animals was also determined and their related emissions were allocated to them.
- Allocation for the breeding component: To estimate the contribution of the breeding component of the beef herd to the total footprint, the same method described above (based on the ME requirements for each animal) was applied, separating the beef cattle into three separate cohorts: breeding herd, trading herd and others (e.g., dairy grazers).

The allocation method applied at the on-farm stage for the dairy farm was:

- Allocation between milk and meat at the dairy farm: The calculated GHG emissions for the dairy farm were allocated between the co-products of milk and LW sold for meat (calf and culled cows) based on the physiological feed requirements of the animal to produce milk and meat using the International Dairy Federation (IDF,2022) methodology.

3.3 Life Cycle Inventory Data

On-farm LCA models were developed for each farm system described in the subsections below, accounting for all cradle-to-farm-gate GHG emissions. The emissions associated with the background processes were calculated in the LCA software model (SimaPro) using modified processes from the ecoinvent database (Wernet et al., 2016) for NZ conditions. This included the emissions from the production and transport of inputs to the farm, such as from pesticides and pasture and crop seed production. Fertiliser and lime production emissions were sourced from NZ-specific LCA analyses (Ledgard and Falconer, 2019), while supplementary feed emissions were based on NZ research (Ledgard and Falconer, 2015) or the Agri Footprint database for imported feeds (Durlinger et al., 2014).

3.3.1 General methodology

The methodology described in this section applies to the dairy farm (section 3.3.2), the Class 9 B+LNZ average farm (section 3.3.3) and the scenarios analysis (section 3.3.4). The dry matter intake (DMI) of animals was estimated using the NZ GHG Inventory model methodology (MfE, 2024) for dairy, beef, and sheep. It is a comprehensive Tier 2 model that operates at a monthly time step and utilises data on livestock numbers, livestock performance and diet quality. Within the animal category, the model subdivides the population into animal sub-categories. DMI was estimated by calculating the energy required for maintenance, growth, gestation, lactation, and grazing (MJ ME per day) and dividing this value by the energy concentration of the diet consumed (MJ ME per kg DM). Methane emissions from enteric fermentation were calculated from the product of energy and DMI by animals using the NZ GHG Inventory model and the NZ emission factor. The N excreted by animals was calculated using the NZ GHG Inventory methodology. The total N intake was calculated for the pasture and bought-in feed sources. Pasture N intake was calculated by multiplying the DMI (based on the method outlined above) by the average N concentration of NZ pasture (from a review of monthly data from the NZ GHG Inventory). For all bought-in feed sources, N concentrations were based on the mean of samples submitted to NZ laboratories and reported by DairyNZ (2017). The N in milk and meat products (based on the NZ GHG Inventory) was then subtracted from total N intake to calculate the amount of N excreted. For dairy farms, the GHG emissions from farm dairy effluent (FDE) were accounted for using the latest NZ GHG Inventory methodology (MfE, 2024).

Direct nitrous oxide (N_2O) emissions were calculated by multiplying N inputs (urine, faeces and N fertiliser) by NZ specific emission factors corresponding to the fraction emitted to the atmosphere as N_2O (MfE, 2024). Methane emissions from dung and FDE were calculated by multiplying faecal dry matter (FDM, as affected by digestibility of feed) by specific emission factors according to MfE (2024) for FDM deposited on pastures and for effluent stored in an anaerobic lagoon, respectively. Direct carbon dioxide (CO_2) emissions from lime and urea application to soils were calculated according to NZ GHG inventory methodology (MfE, 2024).

3.3.2 NZ average dairy farm system

A NZ average dairy system carbon footprint for 2021/22 was calculated based on information from Fonterra. Regional farm carbon footprints were calculated, and a NZ average dairy system carbon footprint was then estimated based on a weighted average of total milk production per region.

Any missing farm data was gap-filled using DairyBase regional average input data calculated using DairyNZ/LIC (2020) statistics (for animal-based data) and a DairyNZ DairyBase 2021/22 survey (DairyNZ, 2022) of 390 farms (regionally based random survey; used mainly for fertiliser and supplementary feed data). Data were categorised into eight regions of NZ and an average farm system for each region was determined (Ledgard et al., 2020).

Apart from the emission sources described above, the dairy system footprint also included emissions from direct land use change (dLUC; land converted to pasture for dairy farming from forest amortised over 20 years) and emissions from the cultivation of peat soil (CO_2 and N_2O emissions - MfE, 2024). The fuel consumption for all agricultural activities, including animal management, pasture production, supplementary feed production and delivery, was calculated from analysing all single operations needed specifically for each scenario and parameterised in our LCA model (SimaPro Version 9.3.0.3). Electricity consumption was calculated as a function of cow numbers based on a NZ study by Sims et al. (2005) and as a function of irrigation based on a summary of types of irrigation systems, irrigation water (mm applied) and typical depth of pumping.

3.3.3 NZ average beef and sheep farm system

Primary data for a Class 9 NZ (weighted average of Class 1-8 farms) average farm for the 2021/2022 production year was obtained from the B+LNZ database (B+LNZ Economic Services). Animal numbers for the average farm were modified to create a balanced system (balanced stock reconciliation). This was done to ensure that the number of finished cattle sold aligned with the corresponding number purchased as store cattle within each livestock class (i.e., heifers or steers) while accounting for deaths.

All animal data were entered into a beef and sheep ME model (a Tier-2 monthly time-step model) based on the NZ GHG Inventory (MfE, 2024) to calculate their energy requirements. This accounted for differences in growth rate and maintenance requirements according to LW, as well as effects of monthly variation in feed quality with age of finishing.

Secondary data included electricity use based on a survey using mainly expenses for electricity use and, therefore, are likely to be overestimated due to the inclusion of general home use. It also included data on the total use of herbicides and pesticides obtained from the national summary of Manktelow et al. (2005). Expert opinion (Trevor James, pers. comm.) was used to estimate the main forms of agrichemicals, the rate of application and, therefore, the potential areas treated in the farms. The use of fuel for transport and application of the agrichemicals was then calculated from this data. Emissions associated with agrichemical production were obtained using the ecoinvent database (Wernet et al., 2016).

This study did not account for the effects of net carbon sequestration by trees on NZ beef and sheep farms (this can be seen in a sensitivity analysis in Mazzetto et al., 2023).

3.3.4 Scenarios

All scenarios are described in detail in Appendix 1. Briefly, scenarios were set up for both spring and autumn calving dates. The animals were kept on farm for 10 to 18 months and had three different average growth rates (LW gain) ranging from 700 to 1000 g/day. Each scenario simulated a dairy-derived beef animal (steer), using a surplus calf derived from the NZ average dairy farm, reared to weaning (40 - 100 kg over three months [details presented below]) and finished at 10 to 18 months of age at 248 - 557 kg LW.

3.3.4.1 Calf birth stage (0 - 40 kg)

The 4-day old calves were assumed to be sourced from the average NZ dairy farm described above for the 2021/22 production year. The total GHG emissions associated with the 4-day old calf was calculated using LCA methodology, based on determining the total GHG emissions from the dairy production system and allocating the emissions between milk and LW (section 3.2; Ledgard et al., 2020).

3.3.4.2 Rearing stage (40 – 100 kg)

The rearing of calves was assumed to use a calf feeding system based on 30 kg of whole milk powder (WMP) and 85 kg of meal per calf (Fonterra, pers. comms). The carbon footprint of the WMP was calculated using LCA methodology for NZ average milk production and average milk powder processing and packaging emissions (Mazzetto et al., 2022). The calf meal contained 20% crude protein content (A. Khan, pers. comms) and is described in Table 1. The carbon footprint for each ingredient of the meal accounted for the production stage (e.g. production of crops), as well as processing, packaging and transport emissions. Animal GHG emissions from enteric methane are not accounted for in the first two months of the calf's life while the rumen is still developing (MfE, 2024). Enteric emissions were only calculated from the third month of the calf's life in the rearing to the weaning stage. Nitrous oxide and methane emissions from excreta were calculated for all months of life of the calf (MfE, 2024).

Table 1. Composition of the calf meal for the rearing stage

Ingredient	% Dry Matter
Maize grain	30
Soyabean meal	20
Lucerne	12.5
Barley grain	12.5
Soyabean hulls	8.5
Molasses	4
Dicalcium phosphate	1
Limestone	1
Salt	1
Vitamin	0.5
Others	9

3.3.4.3 Growing stage (100 kg – finished LW)

Weaned calves were assumed to be finished on an average Class 9 B+LNZ farm (as described in section 3.3.3).

The emissions per kg of calf for the final stage (100 kg to the final finishing weight) varied depending on the final LW of the calf. Total emissions were calculated in four steps:

1) Calculate total DMI, enteric fermentation and excreta-related emissions for the calf from 100 kg to the final weight (specific to each scenario).
2) To represent the total background emissions from the production of the calf in the Class 9 B+LNZ farm (i.e., related to all inputs and excluding enteric fermentation and excreta), the total GHG emissions for the average Class 9 farm were calculated, and the background (non-animal related) GHG emissions were determined. The latter covered emissions from

all farm inputs (e.g., fertilisers, lime, fuel, electricity use), farm activities (e.g., forage cropping, application of farm inputs) and any soil and land use emissions (e.g., N_2O emissions from forage crop residues). These background emissions were then correlated to total animal DMI so that the non-animal GHG emissions could be assigned to these dairy-derived cattle based on their calculated DMI.

3) The total DMI from calves calculated in step 1 was multiplied by the kg CO_2e / kg DMI defined in step 2. This represents the total background emissions necessary to grow the calf from 100 kg to the final weight.

4) Finally, emissions defined in step 1 (enteric fermentation and excreta) and in step 3 (background system) were summed to get total GHG emissions.

3.3.4.4 Comparison to other NZ beef

The scenarios described above were compared to beef from a Class 9 B+LNZ average farm and to a dairy-derived steer growing up to 600 kg finished at 28 months.

3.3.4.5 Sensitivity analysis

A sensitivity analysis was applied to estimate the impact of changing the birth weight from 40 kg to 37.5 kg LW (to account for Holstein calves vs beef cross calves). A second sensitivity analysis estimated the difference in the footprint between steers (current results), heifers and bulls. The same LWG pattern and final LW for each scenario was employed, changing only the animal class in the modelling.

3.3.4.6 Comparison to international beef

The scenarios described above were compared to beef footprints from international studies.

3.4 Greenhouse gas emission calculations

Calculation of the GHG emissions for each source was based on the use of the most recent and (where possible) region-specific emission factors. The study followed the guidelines from the NZ GHG Inventory (MfE, 2024) and the Intergovernmental Panel for Climate Change (IPCC). When region-specific emission factors were not available, factors were extracted from reputable databases, mainly ecoinvent (Wernet et al., 2016). The calculation accounted for relevant GHGs, including methane (CH_4), N_2O, CO_2 and refrigerant gases. Global Warming Potential (GWP) numbers were used for the carbon dioxide equivalent (CO_2e) emissions for a 100-year period (GWP100) (Assessment Report 6 [AR6] - CO_2: 1; biogenic CH_4: 27; fossil CH_4: 29.8; N_2O: 273 - Forster et al., 2021).

4. Results and Discussion

4.1 General results

The total emissions for the calf from the dairy farm (0 to 40 kg stage) were 463 kg CO_2e / calf. The main contributors to these emissions were enteric CH_4, excreta and direct land use change (dLUC), accounting for 52%, 13% and 12% of the total, respectively. These were followed by bought-in feed at 9% and the remaining sources accounted for less than 5% of the total emissions. The relative contribution of gases (in CO_2-equivalents) was 59% from CH_4, 28% from CO_2 and 13% from N_2O. The relatively high contribution from CO_2 is driven by emissions from dLUC, bought-in feed and peatland emissions.

The total GHG emissions for rearing of 4-day-old calves to weaning at 100 kg (40 to 100 kg stage) equated to 395 kg CO_2e / calf. The main contributors to these emissions were the production of WMP (71%), the production of meal (25%), followed by enteric CH_4 (3%). The remaining 1% was divided between emissions from excreta, transport of the WMP, and electricity.

The emissions per calf for the final stage (100 kg to the final finishing weight) varied depending on the final LW of the animal. The emissions from enteric fermentation and excreta-related emissions were combined with the total background emissions (0.12 kg CO_2e / kg DMI). The emissions for the 100 kg to the final finishing weight ranged from 3.07 – 6.16 kg CO_2e / kg LW.

Total emissions from all stages (0 to 40 kg, 40 to 100 kg and 100 kg to final weight) were then summed and divided by the final live weight, generating a footprint in kg CO_2e / kg LW for cattle specific to each scenario.

Figure 2 summarises the results for all the scenarios analysed. Tables of results are available in Appendix 2 (Tables A2.1, A2.2 and A2.3). The carbon footprints ranged from 6.67 to 7.33 kg CO_2e / kg LW for spring calving and 5.96 to 7.86 kg CO_2e / kg LW for autumn calving.

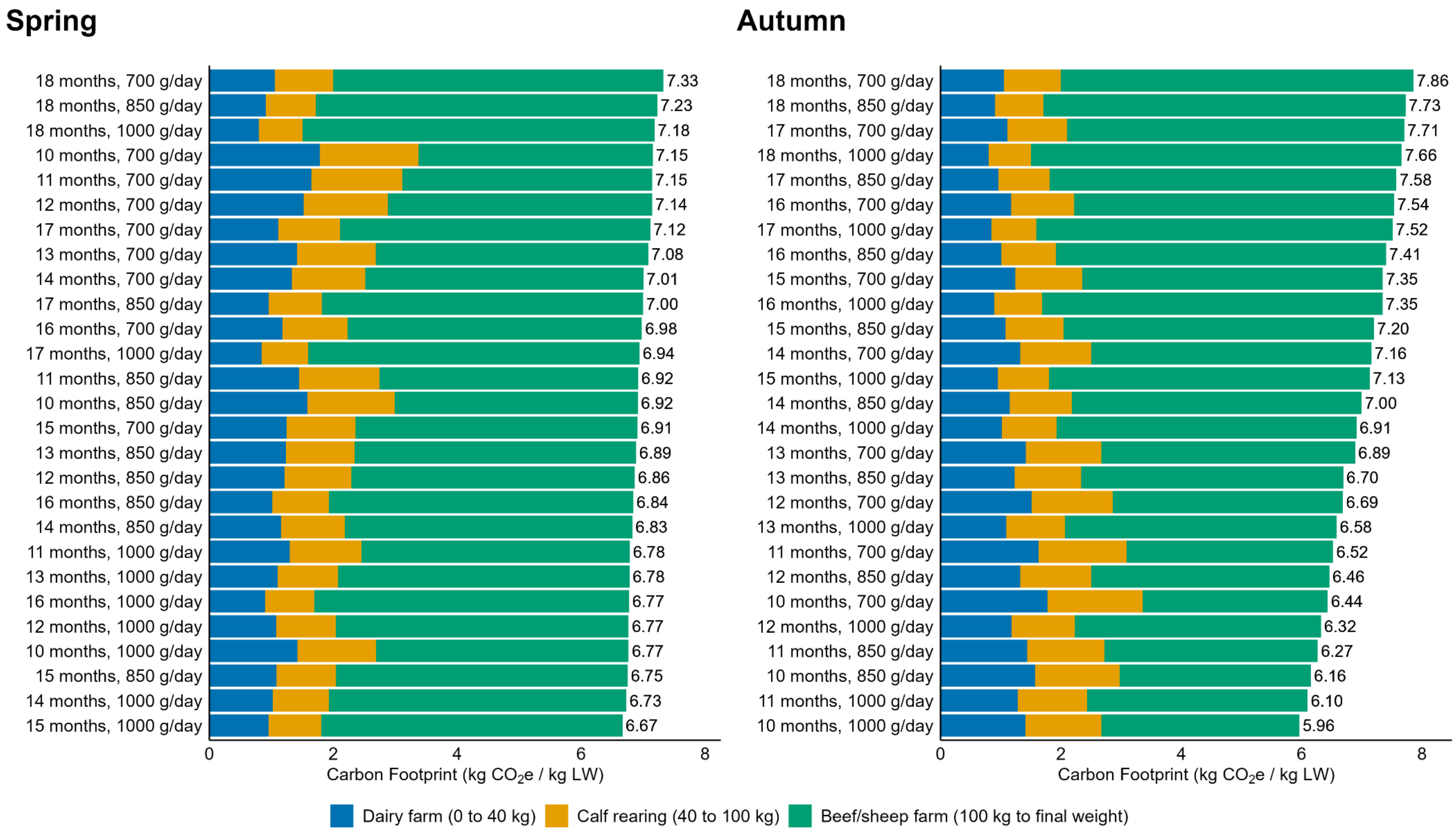

Figure 2. Carbon footprints (in kg CO_2e / kg LW) of the scenarios analysed (different calving seasons, finishing age and assumed growth rate)

A one-way ANOVA was performed and found that calving date was not statistically significant ($p = 0.817$ - Table A3.1 in Appendix 3). This suggests that the season in which animals are born does not substantially influence their carbon footprints. Therefore, optimising calving date alone is unlikely to result in meaningful reductions. On average, spring-calved animals had slightly lower footprints than autumn-calved ones (Figure 3). Local and regional analyses would be required to determine when or if the calving date changed individual farm carbon footprints.

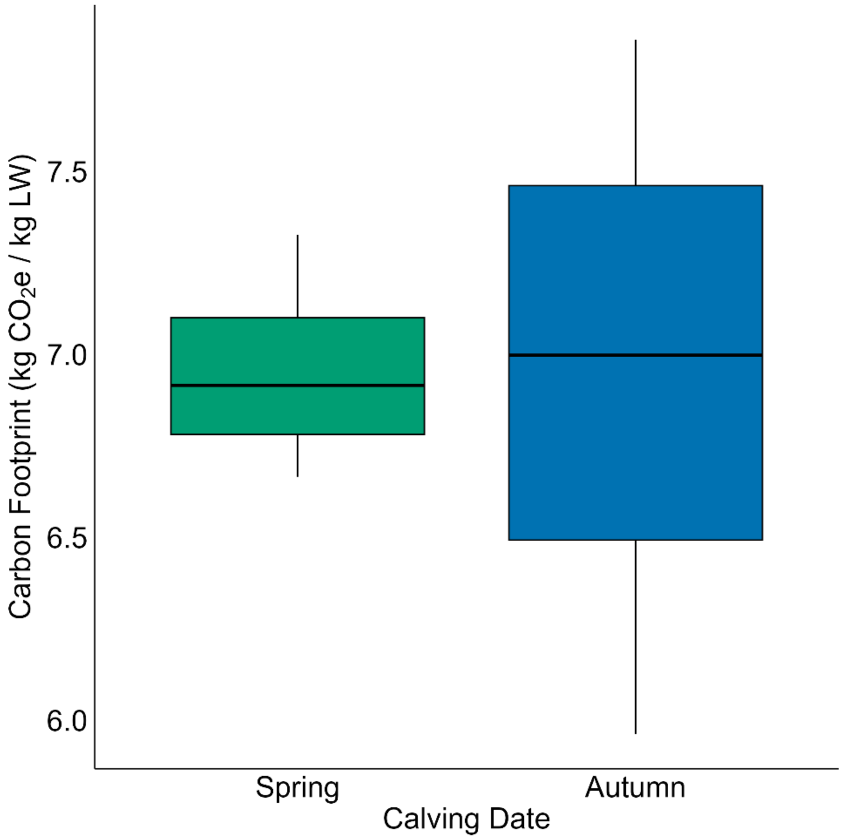

Figure 3. Boxplots showing the carbon footprints (in kg CO_2e / kg LW) for different calving date scenarios. Note that the y-axis starts at 6 kg CO_2e / kg LW.

The main factor affecting the difference in carbon footprint between spring- and autumn-calved cattle finished at the same age and LW was the months of growth and the associated differences in ME content of pasture over time. For example, the relatively higher carbon footprint of 10-month cattle born in spring was associated with more growth during months of relatively lower ME content (summer and autumn) and, therefore, higher dry matter intake than for the corresponding autumn-born 10-month cattle. This was also the reason for the higher carbon footprint of autumn-born 18-month cattle compared to 18-month-old cattle born in spring.

The footprint reductions from these scenarios compared to a Class 9 B+LNZ average beef cattle system carbon footprint (11.50 kg CO_2e / kg LW) ranged from 32 to 48%. The main reason for this difference is the lower footprint of the calf on the dairy farm (0 to 40 kg stage) and to weaning (40-100 kg), with the interaction between the different factors considered in the scenario (described in detail below – Table A3.2 in Appendix 3).

Regression analysis revealed that the interaction between finishing age and LWG significantly affects the carbon footprint ($p < 0.001$). The interaction term was highly significant, with a negative coefficient, indicating that the carbon footprint decreases with higher live weight gain, but the benefit diminishes as finishing age increases. This is evident in Figure 4, where the decrease in carbon footprint with increased LWG diminished with increased finishing age. These findings highlight the need to jointly optimise finishing age and live weight gain.

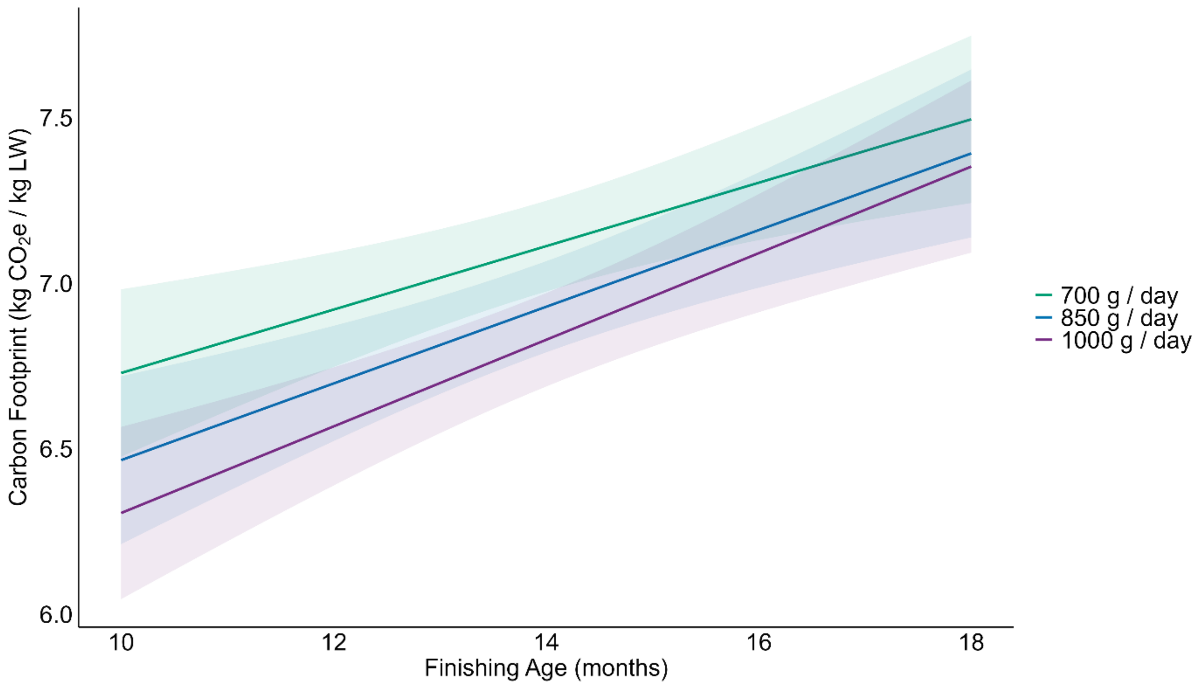

Figure 4. Relationships between carbon footprints (in kg CO_2e / kg LW) and finishing age (from 10 to 18 months) over the different Live Weight Gains simulated in this study. Note that the y axis starts at 6 kg CO_2e / kg LW. Shaded areas represent the confidence interval.

Live weight sold was not a significant predictor of the carbon footprint in the model ($p = 0.420$). This suggests that targeting heavier final weights alone does not significantly reduce emissions per kilogram of live weight. Although heavier animals may spread emissions over more weight, the lack of significance implies that live weight sold must be considered alongside other factors, such as growth efficiency and finishing age, to reduce emissions intensity effectively. This finding emphasises the importance of examining potential trade-offs, such as increased feed intake and resource use, which could offset any efficiency gains from simply increasing the final live weight. The results from analysis of average farm data suggest that achieving lower emissions intensity requires a more comprehensive approach than aiming for heavier slaughter animals.

The carbon footprint for growing a dairy-derived steer to 600 kg LW (from spring calving) was 8.92 kg CO_2e / kg LW (finishing age at 28 months, 660 g/day). This is higher than results for the range in the scenario analyses where cattle were finished at 10 to 18 months of age at 5.96 to 7.86 kg

CO_2e / kg LW (Figure 2) and indicate the carbon cost of growing for longer to heavier weights, as well as the interaction with growth rate.

The footprint of the culled dairy cow was 6.20 kg CO_2e / kg LW. This is lower than that for the studied dairy-derived beef and much lower than for current Class 9 B+LNZ average beef cattle system. This illustrates the effects of the significant allocation of total GHG emissions to milk, as shown by Mazzetto et al. (2023).

4.2 Sensitivity analyses

A sensitivity analysis was applied to estimate the impact of changing the birth weight from 40 kg to 37.5 kg LW (to account for Holstein calves vs beef cross calves). The amount of WMP was adjusted to 34.2 kg and the amount of calf meal adjusted to 90 kg to allow for the faster growth of the calf from 37.5 kg to 100 kg during the rearing stage. A second sensitivity analysis estimated the difference in the footprint between steers (current results), heifers and bulls. The same LWG pattern and final LW for each scenario was employed, changing only the animal class in the modelling.

Figure 5 described the results for both sensitivity analyses. Tables with the results for each scenario and sensitivity are available in Appendix 4 (Tables A4.1 to A4.3). The final carbon footprint of the 37.5 kg calf was on average 0.81% higher than the 40kg LW calf (ranging from 0.39 to 1.30%) due to the extra amount of WMP and calf meal at the rearing stage. For the different animal classes, the carbon footprint of bulls was on average 3.00% lower than steers (ranging from 1.75 to 3.60%), while the carbon footprint of heifers was on average 3.14% larger than steers (ranging from 2.13 to 3.77%).

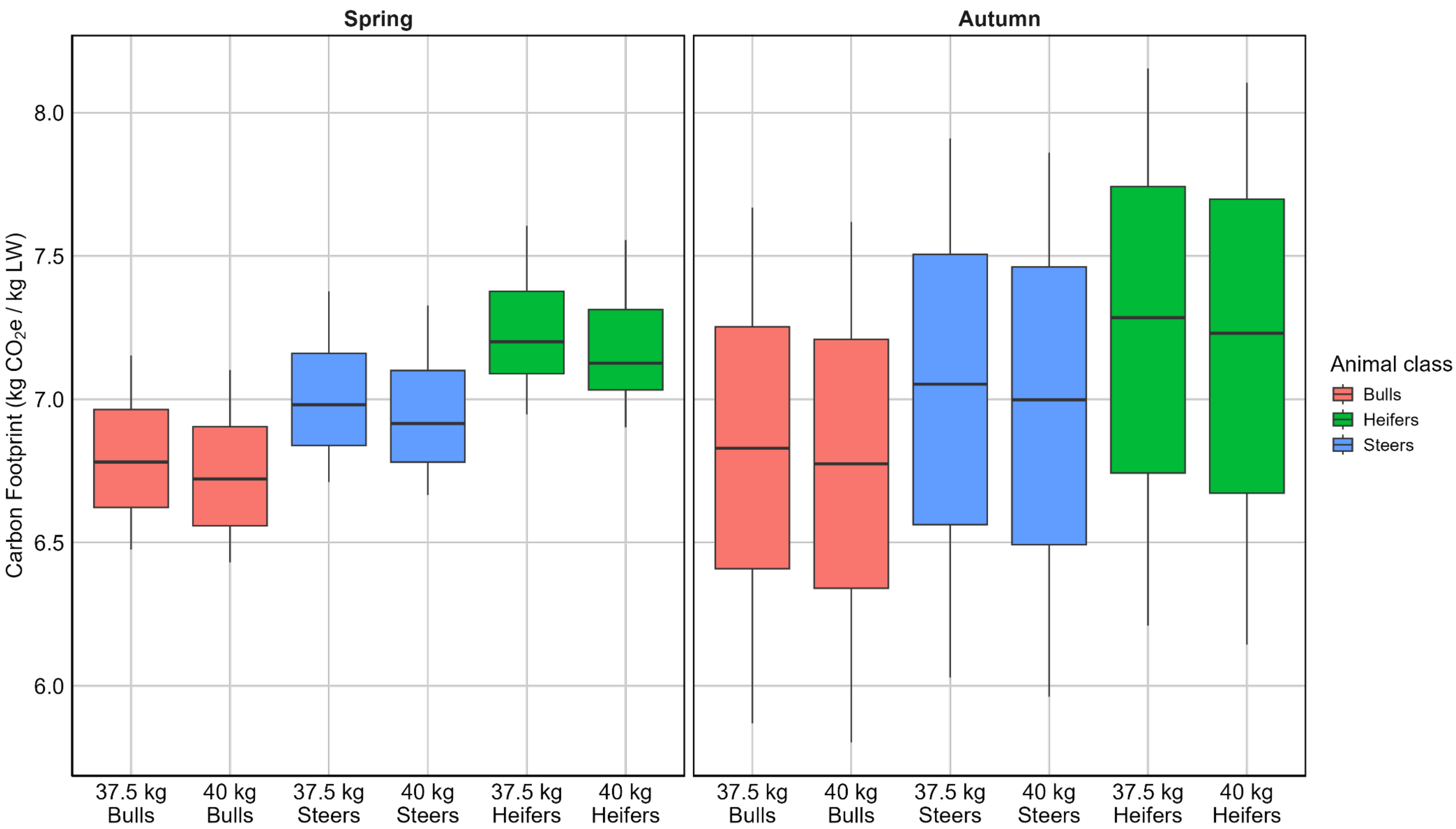

Figure 5. Carbon footprint (in kg CO_2e / kg LW) for the sensitivity analyses comparing different calf birth weights (40 and 37.5 kg) and different animal classes (steers, heifers and bulls). Note that the y axis starts at 6 kg CO_2e / kg LW.

5. Literature review

5.1 Methodology

A literature review was conducted using the Scopus (https://www.scopus.com/) and Ovid (https://ovidsp.ovid.com/) search engines, resulting in 276 documents from the combination of the key words: “life cycle assessment”, or “LCA”, and “beef”, and “greenhouse gas”, or “GHG”, or “carbon footprint”, or “climate change”. These literature sources were screened to identify studies reporting the carbon footprint of beef cattle production. White papers or “grey literature” were excluded. All studies found were screened for relevance based on the title. Relevant titles were screened by abstract, and the full text was reviewed. The review was finished in September 2024, and papers published after this date are not included.

Papers were selected based on the following criteria:

1) The study used biophysical allocation (IDF, 2015) if pertaining to a dairy farm or studied pure beef systems (no need for allocation);
2) Studies reported footprints in a similar functional unit as used in this report (kg LW) or had data that allowed the conversion to kg LW;
3) Studies used AR5 GWP100 (CO_2: 1; biogenic CH_4: 27.75; fossil CH_4: 29.8; N_2O: 265 - Stocker et al., 2016) or had data that allowed the conversion to AR5 GWP100. These values were chosen to maximise the number of papers assessed in the review.

The results from this study were then converted to AR5 GWP100 and reverted back to the IDF 2015 allocation to be comparable to the results in the literature review.

In every step of the study selection, papers were scanned for data that would allow the recalculation of footprints. If data were unavailable, we contacted the authors and asked for supplementary data. If the author did not have the data available, or did not answer, we excluded the paper from the database. To represent the most up-to-date farm management practices possible, we excluded papers over ten years old (cut-off date was 2014).

For each publication selected, a specific study code was assigned. The following characteristics were recorded in the database: author, year, country, region, allocation method, allocation percentage (%), GWP method, functional unit (FU), carbon footprint [kilograms of carbon dioxide equivalents (CO_2e) per kilogram of FU], breakdown of the footprint by GHG (% of total footprint related to CH_4, CO_2, and N_2O), dressing out percentage, liveweight and carcass weight.

5.2 Literature review results

A total of 24 papers from 16 different countries were selected. All studies presented values for the carbon footprint of beef production, while some studies also presented data for dairy-derived beef production. All results were recorded and are summarised below (Figure 6).

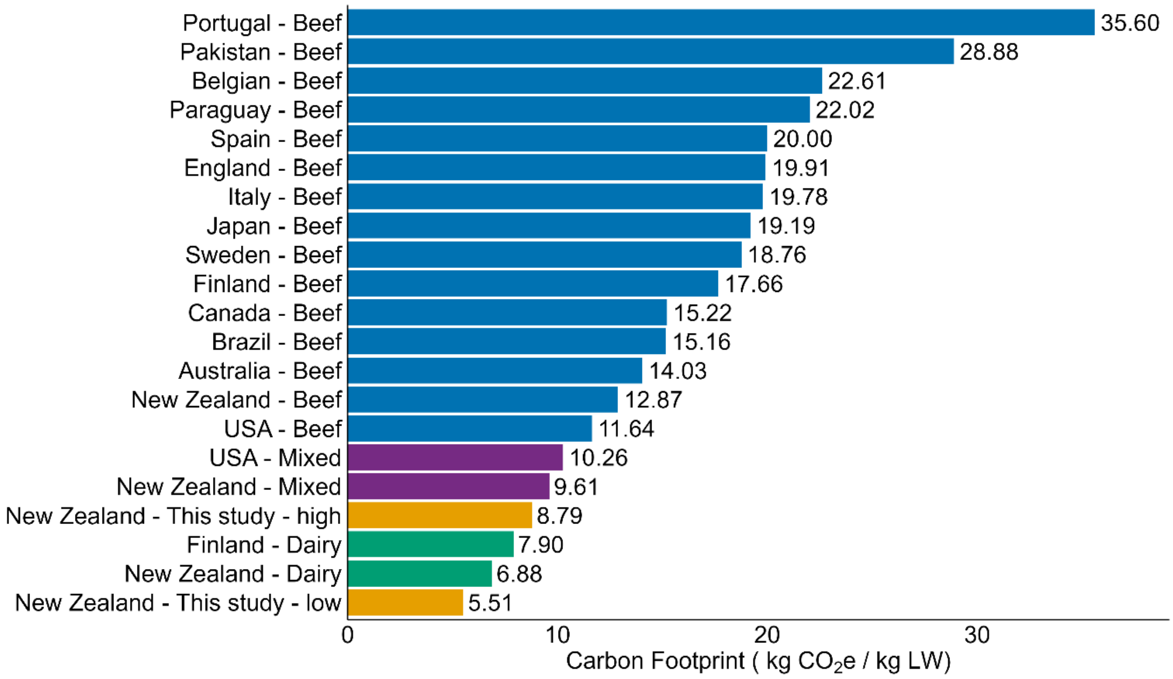

Figure 6. Carbon footprints (in kg CO_2e / kg LW) derived from the literature review undertaken. "Beef": traditional beef farms, "Mixed": systems that account for both dairy-derived and traditional beef; "Dairy": dairy beef (culled cows and calves).

Carbon footprints ranged from 11.64 to 35.60 kg CO_2e / kg LW for traditional beef animals, 9.61 to 10.26 kg CO_2e / kg LW for mixed systems (traditional and dairy-derived animals) and 6.88 to 7.90 kg CO_2e / kg LW for dairy beef. As discussed in Section 4, the main reason for the difference between traditional and dairy-derived beef was the allocation between milk and meat (or LW sold) at the dairy farm. On average, 85% of the total emissions from a dairy farm were attributed to milk (IDF, 2022).

The results obtained in this study had to be converted to AR5 GWP100 and reverted back to the IDF 2015 allocation method to be comparable with the literature review results. The conversion resulted in a footprint for the 10-to-18-month cattle ranging from 5.51 to 8.79 kg CO_2e / kg LW, significantly lower than that observed for traditional beef animals (Beef - Figure 6). This was also lower than for mixed systems (Mixed – Figure 6) and similar to that observed for dairy beef in other countries (Dairy - Figure 6).

A limitation of this literature review was that the results presented may not fully represent national averages or broader trends within the countries analysed. The studies included in this review were selected based on specific criteria, such as relevance to the research topic, methodological rigour, and data availability (described in section 5.1). Consequently, the findings are shaped by the scope of these criteria. In some instances, results from individual countries are based on a single study, which may not accurately capture the diversity of conditions, policies, or practices across different regions within that country. There will also be methodological differences across studies that couldn't be harmonised (such as dry matter intake models and specific emission factors) that influence the carbon footprint results. Therefore, significant caution must be exercised when any comparisons are made, recognising that the findings reflect individual studies and are not necessarily indicative of broader national or regional patterns in carbon footprints.

As mentioned above, a conversion of the results from the most updated allocation method (IDF 2022) to the previous method (IDF, 2015) was necessary in order to compare the results from the literature. The 2015 IDF guidelines for allocating emissions between milk and meat relied on the methodology proposed by Thoma et al. (2013). A key drawback of this approach was its inability to distinguish between various types of animals leaving the farm, such as calves or cull cows. Furthermore, the methodology constrained the acceptable beef-to-milk ratio to a narrow range, typically between zero and 3%. The latest revision of the IDF guidelines (2022) introduced an enhanced algorithm designed to more effectively allocate emissions among co-products. The new method considers the energy required for milk production (lactation) and growth. This updated method, based on the work of Nemecek and Thoma (2020), provides a more robust and scientifically grounded method for distributing emissions across milk and meat, allowing the separation of the footprints between culled cows and calves.

6. Conclusions

This study aimed to investigate the factors driving the carbon footprint of LW production from dairy-derived cattle growing up to 10 to 18 months, focusing on variables such as live weight gain, live weight sold, and calving date. The results showed that the footprint of these dairy-derived animals was 32 to 48% lower than the Class 9 B+LNZ average beef cattle system in New Zealand. The main factors influencing these results are the allocation between milk and LW at the dairy farm, the calf weaning system and its associated emissions and the interaction between the variables explored in the study. The study considered opportunities to reduce the carbon footprint, but it did not consider the wider system needs e.g. high-quality beef bulls/semen for producing dairy-cross calves and implications for other environmental indicators of sustainability for the studied systems and sector.

This study found that calving date had a small effect but was not a major factor in reducing emissions. More impactful strategies lie in promoting faster growth rates, shortening the time to slaughter, and improving feed conversion efficiency. The analysis reveals that interaction effects, particularly between finishing age and live weight gain, are key determinants of the carbon footprint in this study. Managing these variables independently is insufficient to achieve significant carbon footprint reductions. Instead, the results demonstrate that efficient systems where growth efficiency and finishing timing are managed in tandem can significantly reduce emissions, as shown by the highly significant interaction effect ($p < 0.001$).

The results obtained in this study (when converted to GWP100 AR5 and reverting back to IDF (2015) allocation methodology, for comparison with other studies) were lower than the range obtained in a literature review (11.64 to 35.60 kg CO_2e / kg LW for traditional beef).

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Appendix 1: Scenario descriptions

The descriptions of the scenarios are listed in the following table.

Table A1-1. Description of the scenarios analysed. All calves are derived from a dairy farm.

Scenario	Calving date	Growth rate (g/day)	Finished age (months)	Finished weight (kg LW)
S_10_700	spring	700	10	248.40
S_11_700	spring	700	11	269.40
S_12_700	spring	700	12	291.10
S_13_700	spring	700	13	312.80
S_14_700	spring	700	14	333.80
S_15_700	spring	700	15	355.50
S_16_700	spring	700	16	376.50
S_17_700	spring	700	17	398.20
S_18_700	spring	700	18	419.90
A_10_700	autumn	700	10	249.77
A_11_700	autumn	700	11	271.40
A_12_700	autumn	700	12	293.17
A_13_700	autumn	700	13	313.60
A_14_700	autumn	700	14	334.98
A_15_700	autumn	700	15	356.10
A_16_700	autumn	700	16	377.70
A_17_700	autumn	700	17	399.10
A_18_700	autumn	700	18	420.80
S_10_850	spring	850	10	280.20
S_11_850	spring	850	11	305.70
S_12_850	spring	850	12	365.97
S_13_850	spring	850	13	358.40
S_14_850	spring	850	14	383.90
S_15_850	spring	850	15	410.25
S_16_850	spring	850	16	435.75
S_17_850	spring	850	17	462.10
S_18_850	spring	850	18	488.45
A_10_850	autumn	850	10	281.87
A_11_850	autumn	850	11	308.15
A_12_850	autumn	850	12	334.57
A_13_850	autumn	850	13	359.20
A_14_850	autumn	850	14	385.23
A_15_850	autumn	850	15	410.85
A_16_850	autumn	850	16	437.10

A_17_850	autumn	850	17	463.00
A_18_850	autumn	850	18	489.35
S_10_1000	spring	1000	10	312.00
S_11_1000	spring	1000	11	342.00
S_12_1000	spring	1000	12	411.57
S_13_1000	spring	1000	13	404.00
S_14_1000	spring	1000	14	434.00
S_15_1000	spring	1000	15	465.00
S_16_1000	spring	1000	16	495.00
S_17_1000	spring	1000	17	526.00
S_18_1000	spring	1000	18	557.00
A_10_1000	autumn	1000	10	313.97
A_11_1000	autumn	1000	11	344.90
A_12_1000	autumn	1000	12	375.97
A_13_1000	autumn	1000	13	404.80
A_14_1000	autumn	1000	14	435.48
A_15_1000	autumn	1000	15	465.60
A_16_1000	autumn	1000	16	496.50
A_17_1000	autumn	1000	17	526.90
A_18_1000	autumn	1000	18	557.90

LW: live weight

Appendix 2: Scenario results

Table A2.1 - Carbon footprints of steers with an assumed average 700 g/day growth rate. Spring or Autumn refers to the season when calves were born, while months refer to the finishing age.

Scenario	0-40 kg	40-100 kg	100-final kg	Total
	kg CO_2e / kg LW			
Spring – 10 months	1.78	1.59	3.78	7.15
Spring – 11 months	1.65	1.47	4.03	7.15
Spring – 12 months	1.52	1.36	4.26	7.14
Spring – 13 months	1.42	1.26	4.40	7.08
Spring – 14 months	1.33	1.18	4.49	7.01
Spring – 15 months	1.25	1.11	4.55	6.91
Spring – 16 months	1.18	1.05	4.75	6.98
Spring – 17 months	1.11	0.99	5.01	7.12
Spring – 18 months	1.06	0.94	5.33	7.33
Autumn – 10 months	1.78	1.58	3.08	6.44
Autumn – 11 months	1.63	1.46	3.43	6.52
Autumn – 12 months	1.51	1.35	3.83	6.69
Autumn – 13 months	1.41	1.26	4.22	6.89
Autumn – 14 months	1.32	1.18	4.66	7.16
Autumn – 15 months	1.25	1.11	4.99	7.35
Autumn – 16 months	1.17	1.05	5.32	7.54
Autumn – 17 months	1.11	0.99	5.60	7.71
Autumn – 18 months	1.05	0.94	5.87	7.86

LW: Live weight

Table A2.2 - Carbon footprints of steers with an assumed average 850 g/day growth rate. Spring or Autumn refers to the season when calves were born, while months refer to the finishing age.

Scenario	0-40 kg	40-100 kg	100-final kg	Total
	kg CO_2e / kg LW			
Spring – 10 months	1.58	1.41	3.92	6.92
Spring – 11 months	1.45	1.29	4.18	6.92
Spring – 12 months	1.21	1.08	4.57	6.86
Spring – 13 months	1.24	1.10	4.55	6.89
Spring – 14 months	1.15	1.03	4.64	6.83
Spring – 15 months	1.08	0.96	4.70	6.75
Spring – 16 months	1.02	0.91	4.92	6.84
Spring – 17 months	0.96	0.86	5.18	7.00
Spring – 18 months	0.91	0.81	5.51	7.23
Autumn – 10 months	1.57	1.40	3.18	6.16
Autumn – 11 months	1.44	1.28	3.55	6.27
Autumn – 12 months	1.33	1.18	3.95	6.46
Autumn – 13 months	1.23	1.10	4.36	6.70
Autumn – 14 months	1.15	1.03	4.82	7.00
Autumn – 15 months	1.08	0.96	5.16	7.20
Autumn – 16 months	1.01	0.90	5.49	7.41
Autumn – 17 months	0.96	0.85	5.76	7.58
Autumn – 18 months	0.91	0.81	6.01	7.73

LW: Live weight

Table A2.3 - Carbon footprints of steers with an assumed average 1,000 g/day growth rate. Spring or Autumn refers to the season when calves were born, while months refer to the finishing age.

Scenario	0-40 kg	40-100 kg	100-final kg	Total
	kg CO_2e / kg LW			
Spring – 10 months	1.42	1.27	4.08	6.77
Spring – 11 months	1.30	1.16	4.33	6.78
Spring – 12 months	1.08	0.96	4.73	6.77
Spring – 13 months	1.10	0.98	4.70	6.78
Spring – 14 months	1.02	0.91	4.79	6.73
Spring – 15 months	0.95	0.85	4.86	6.67
Spring – 16 months	0.90	0.80	5.08	6.77
Spring – 17 months	0.84	0.75	5.35	6.94
Spring – 18 months	0.80	0.71	5.68	7.18
Autumn – 10 months	1.41	1.26	3.29	5.96
Autumn – 11 months	1.29	1.15	3.67	6.10
Autumn – 12 months	1.18	1.05	4.09	6.32
Autumn – 13 months	1.10	0.98	4.51	6.58
Autumn – 14 months	1.02	0.91	4.99	6.91
Autumn – 15 months	0.95	0.85	5.33	7.13
Autumn – 16 months	0.89	0.80	5.66	7.35
Autumn – 17 months	0.84	0.75	5.92	7.52
Autumn – 18 months	0.79	0.71	6.16	7.66

LW: Live weight

Appendix 3: Summary of statistical analyses

Table A3.1 – ANOVA results for comparison between spring and autumn calving date scenarios.

	df	Sum Squares	Mean SQ	Statistic	p. value[1]
Calving date	1	0.0095	0.0095	0.0538	0.8174
residuals	52	9.1887	0.1767	-	-

[1] $p<0.05$ is statistically significant at the 5% level

Table A3.2 – Multiple linear regression model (with interaction terms: LWG and finishing age; carbon footprint is the response variable)

	estimate	Std error	Statistic	p. value[1]
Intercept	7.2155	1.5128	4.7695	1.758984e-05
Finishing age	8.0129e-03	0.1022	0.0783	0.9378
LWG	-2.3234e-03	0.0017	-1.3522	0.1826
LW sold	4.6827e-03	0.0057	0.8133	0.4200
Calving_date	-3.2601e-02	0.0754	-0.4322	0.6675
Finishing age & LWG	-1.5773e-05	0.0002	-0.0782	0.9379

[1] $p<0.05$ is statistically significant at the 5% level

LW: Live weight

LWG: Live weight gain

Appendix 4 - Sensitivity Analysis

Table A4.1 - Carbon footprints of steers with different birth weights and live weight gains (LWG). Spring or Autumn refers to the season when calves were born, while months refer to the finishing age.

Birth weight	37.5 kg birth LW			40 kg birth LW		
Unit	kg CO_2e / kg LW			kg CO_2e / kg LW		
Average LWG	700 g/day	850 g/day	1000 g/day	700 g/day	850 g/day	1000 g/day
Spring – 10 months	7.24	6.99	6.83	7.15	6.92	6.77
Spring – 11 months	7.22	6.99	6.85	7.15	6.92	6.78
Spring – 12 months	7.22	6.92	6.82	7.14	6.86	6.77
Spring – 13 months	7.15	6.95	6.83	7.08	6.89	6.78
Spring – 14 months	7.07	6.88	6.78	7.01	6.83	6.73
Spring – 15 months	6.97	6.80	6.71	6.91	6.75	6.67
Spring – 16 months	7.04	6.89	6.81	6.98	6.84	6.77
Spring – 17 months	7.17	7.04	6.98	7.12	7.00	6.94
Spring – 18 months	7.38	7.27	7.22	7.33	7.23	7.18
Autumn – 10 months	6.52	6.23	6.03	6.44	6.16	5.96
Autumn – 11 months	6.60	6.34	6.16	6.52	6.27	6.10
Autumn – 12 months	6.76	6.52	6.38	6.69	6.46	6.32
Autumn – 13 months	6.96	6.75	6.63	6.89	6.70	6.58
Autumn – 14 months	7.23	7.05	6.96	7.16	7.00	6.91
Autumn – 15 months	7.41	7.26	7.18	7.35	7.20	7.13
Autumn – 16 months	7.59	7.45	7.39	7.54	7.41	7.35
Autumn – 17 months	7.76	7.62	7.56	7.71	7.58	7.52
Autumn – 18 months	7.91	7.77	7.70	7.86	7.73	7.66

LW: Live weight

Table A4.2 - Carbon footprints of heifers with different birth weights and live weight gains (LWG). Spring or Autumn refers to the season when calves were born, while months refer to the finishing age.

Birth weight	37.5 kg birth LW			40 kg birth LW		
Unit	kg CO_2e / kg LW			kg CO_2e / kg LW		
Average LWG	700 g/day	850 g/day	1000 g/day	700 g/day	850 g/day	1000 g/day
Spring – 10 months	7.41	7.20	7.07	7.33	7.13	7.00
Spring – 11 months	7.42	7.21	7.10	7.34	7.14	7.03
Spring – 12 months	7.42	7.16	7.07	7.35	7.11	7.02
Spring – 13 months	7.36	7.18	7.08	7.30	7.13	7.03
Spring – 14 months	7.28	7.12	7.02	7.22	7.06	6.97
Spring – 15 months	7.18	7.03	6.95	7.12	6.98	6.90
Spring – 16 months	7.25	7.12	7.05	7.20	7.07	7.00
Spring – 17 months	7.39	7.27	7.21	7.34	7.22	7.17
Spring – 18 months	7.61	7.50	7.44	7.56	7.46	7.40
Autumn – 10 months	6.66	6.39	6.21	6.57	6.32	6.14
Autumn – 11 months	6.76	6.52	6.36	6.68	6.45	6.30
Autumn – 12 months	6.94	6.73	6.59	6.87	6.66	6.54
Autumn – 13 months	7.15	6.97	6.86	7.09	6.91	6.81
Autumn – 14 months	7.44	7.28	7.20	7.38	7.23	7.15
Autumn – 15 months	7.64	7.50	7.42	7.58	7.44	7.37
Autumn – 16 months	7.83	7.70	7.63	7.77	7.65	7.58
Autumn – 17 months	8.00	7.86	7.79	7.95	7.82	7.75
Autumn – 18 months	8.15	8.01	7.92	8.10	7.97	7.89

LW: Live weight

Table A4.3 - Carbon footprints of bulls with different birth weights and live weight gains (LWG). Spring or Autumn refers to the season when calves were born, while months refer to the finishing age.

Birth weight	37.5 kg birth LW			40 kg birth LW		
Unit	kg CO_2e / kg LW			kg CO_2e / kg LW		
Average LWG	700 g/day	850 g/day	1000 g/day	700 g/day	850 g/day	1000 g/day
Spring – 10 months	7.09	6.81	6.62	7.01	6.74	6.56
Spring – 11 months	7.06	6.79	6.62	6.99	6.73	6.56
Spring – 12 months	7.04	6.70	6.57	6.97	6.65	6.52
Spring – 13 months	6.97	6.73	6.59	6.90	6.67	6.54
Spring – 14 months	6.88	6.66	6.54	6.82	6.61	6.49
Spring – 15 months	6.78	6.58	6.48	6.72	6.53	6.43
Spring – 16 months	6.84	6.67	6.58	6.78	6.62	6.54
Spring – 17 months	6.96	6.81	6.74	6.90	6.77	6.70
Spring – 18 months	7.15	7.03	6.98	7.10	6.99	6.94
Autumn – 10 months	6.41	6.09	5.87	6.32	6.02	5.80
Autumn – 11 months	6.47	6.18	5.98	6.39	6.11	5.92
Autumn – 12 months	6.61	6.34	6.17	6.53	6.28	6.12
Autumn – 13 months	6.79	6.55	6.41	6.72	6.49	6.36
Autumn – 14 months	7.03	6.83	6.72	6.97	6.77	6.67
Autumn – 15 months	7.20	7.02	6.93	7.14	6.97	6.88
Autumn – 16 months	7.37	7.21	7.13	7.31	7.16	7.09
Autumn – 17 months	7.52	7.37	7.30	7.47	7.32	7.26
Autumn – 18 months	7.67	7.52	7.45	7.62	7.47	7.41

LW: Live weight