Carbon footprint of New Zealand beef and sheep exported to different markets

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Contents

Abbreviations used

CF	Carbon Footprint
CH_4	Methane
CO_2	Carbon dioxide
EOL	End-of-Life
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LW	Live Weight
N_2O	Nitrous Oxide
NZ	New Zealand
UK	United Kingdom
USA	United States of America

1. Executive Summary

Introduction, Objectives & Methodology

Consumers, policy groups, government and producers wish to understand the total greenhouse gas (GHG) emissions associated with the food they eat (i.e. its carbon footprint) and to reduce them as part of the goal to reduce national and global GHG emissions. The objectives of this project were to determine the carbon footprint of New Zealand (NZ) beef and sheep meat products throughout the life cycle from farm to consumer for a number of overseas markets, including beef to the USA and Japan and sheepmeat to the UK, China and California.

An attributional life cycle assessment (LCA) methodology based on common international guidelines was applied that accounted for all GHG emissions associated with all inputs and processes at all stages from “cradle-to-grave”. It included wastes and end-of-life emissions (e.g. from packaging, food-waste and effluents). It also included shipping and transportation to illustrate the contribution from “food miles”. The carbon footprint was estimated using the latest 100-year Global Warming Potential (GWP100) metrics, as recommended by the International Organization for Standardization (ISO) and the main international sector LCA guidelines. However, additional analyses were carried out using the GWP* metric to examine the effects of changes in animal-derived methane during the previous 20 years, due to the current international interest in this alternative new metric. Other factors analysed included accounting for net carbon sequestration from woody vegetation on farms, method of allocation of GHG emissions between co-products (i.e. recognising that farms and abattoirs produce products other than meat), and emissions from processing and shipping.

Key findings

A summary of the carbon footprint of beef and sheep meat for the five product systems is given in Table i, while detailed cradle-to-farm gate results are given in Table ii. Some important results are:

Cradle-to-farm-gate:

- The farm stage was the main contributor at 90-95% of the total carbon footprint based on GWP100 in CO_2-equivalents (Table i). This was dominated by animal-related enteric methane and excreta nitrous oxide emissions (69-76% and 6-10% of the life-cycle total, respectively).
- For beef and sheep meat, the NZ farm-related emissions were at the low end of the published range for beef and sheep meat produced in other countries, while processing emissions were intermediate, and post-processing emissions within the wide range reported by others.
- Cradle-to-farm-gate GHG (GWP100) emissions for average NZ sheep and beef (weighted for traditional and dairy beef) were estimated at 6.01 and 8.97 kg CO_2e/kg LW sold, respectively.

- For beef, results were influenced by the contribution from dairy beef (cull dairy cows/heifers/calves), which had a 32% lower footprint/kg live-weight (LW) than 'traditional' (i.e. non-dairy-derived) beef (Table ii). However, the lower meat yield decreased this difference to 24% on a per-kg meat basis. (LW is used as the unit for the cradle-to-farm-gate stage since live animals leave the farm gate, whereas, for the total life cycle, the functional unit is meat)
- Sheep meat had a 36% lower carbon footprint per kg of meat (farm-stage) than beef, due in part to allocation of some (31%) emissions to the co-product wool. However, sheep meat had a greater bone component in the exported meat (evident from the meat:carcass-weight ratio of 75% for beef versus 89% for sheep meat), leading to more waste after eating.
- The cradle-to-farm-gate footprints for NZ beef and sheep meat had decreased slightly by 6 and 18%, respectively, over the previous 20 years. For sheep, this was associated with an increase over time in lambing % and heavier finishing weight of lambs.

Processing stage (including transport of animals from farm to abattoir):

- Meat processing contributed 2-4% of the total carbon footprint (based on GWP100 in CO_2-equivalents; Table i). Only about 2% of this was from transport of animals from farm to abattoir.
- Economic allocation between co-products (current internationally agreed method in FAO and European Community Product Environmental Footprint guidelines) resulted in 91-92% of emissions to meat (8-9% to other processing co-products). If mass allocation (i.e. based on the relative mass of co-products) had been applied, it would have allocated 39-41% to meat and a carbon footprint estimate at 51-56% lower than that using economic allocation.

Post-processing stages (including shipping and transport of processed meat):

- The post-processing stage contributed 2-6% of the total carbon footprint (based on GWP100 in CO_2-equivalents; Table i). This included shipping, which represented 1-4% of the total carbon footprint.

Cradle-to-grave (i.e. all life cycle stages):

- The cradle-to-grave carbon footprint of beef to global markets was at the low end of the range from published estimates for exported or domestic product in overseas countries (Table i). The corresponding carbon footprint for sheep meat was below that from the limited number of cradle-to-grave studies in overseas countries.

Table i. Summary of results for the carbon footprint of beef and sheep meat to overseas markets and comparison with the range of results from published LCA international studies of beef and sheep in other countries. Results are based on the use of the GWP100 metric and do not include carbon sequestration.

	Farm	**Processing[1]**	**Post-processing[2]**	**Footprint (Total)**
	kg CO_2e / kg meat			
Beef				
Beef to USA	20.90	0.52	0.66	22.08
Beef to Japan	20.90	0.52	0.36	21.79
Other published studies[3]	*19.87 to 30.67*	*0.25 to 1.27*	*0.24 to 3.84*	*20.60 to 35.10*
Sheep				
Lamb to UK	13.32	0.53	0.96	14.81
Sheep meat to China	13.32	0.53	0.92	14.77
Sheep meat to USA	13.32	0.53	0.77	14.62
Other published studies[3]	*13.20 to 14.97*	*0.57 to 0.76*	*0.76 to 4.13*	*16.07 to 19.66*

[1]Includes transport to abattoir and processing stage; [2]includes shipping and transport stages; [3]see Table 12 in the report for details of results from Australia, Italy, Mexico and USA.

Table ii. Summary of results for GHG emissions and metrics for the cradle-to-farm-gate for beef and sheep (per kg live-weight) produced in New Zealand for 2017/18. Results exclude carbon sequestration.

	Methane	N_2O	CO_2	GWP100 [AR5]	GWP*
	kg CH_4	kg N_2O	kg CO_2	kg CO_2e[1]	kg CO_2we[2]
Traditional beef	0.293	0.0049	0.68	10.09	-
Dairy beef	0.144	0.0035	1.97	6.88	-
Weighted-av. beef	0.241	0.0044	1.13	8.97	5.63
Sheep	0.181	0.0023	0.35	6.01	0.96

[1]Accounting for CO_2-equivalent factors of 27.75 for methane, 265 for N_2O and 1 for CO_2; [2]GWP* estimates accounting for changes in CH_4 over the previous 20 years.

Analyses accounting for GWP*, on-farm carbon sequestration, and mass allocation

LCA methodology and GHG assessment have a range of assumptions required and some limitations in methodology which are still evolving. For example, recent research has focused on better accounting for the warming effects of the short-lived gas methane, where it is associated with changes in rate of emission over time and research is assessing how it can be incorporated into a carbon footprint estimation. This is important given the high methane contribution to the carbon footprint based on GWP100 of approximately 75% of CO_2-equivalents. While GWP100 has been the most widely-used GHG metric for LCA, the IPCC describe a range of other metrics.

Recently, papers have been published introducing the GWP* as an alternative metric. There are also efforts internationally to assess its suitability for inclusion in LCA methodologies for livestock products. Accordingly, due to its potential as a future metric within LCAs for livestock products, it was considered worthy of investigation in this study.

Analysis of the effect of using the new GWP* metric for the cradle-to-farm-gate stage, which accounted for the change in total methane emissions during the previous 20-years (1998-2018), indicated a decrease in animal-related methane emissions for sheep. This was associated with a relatively large decline in total sheep numbers, although the amount of sheep meat produced has remained relatively constant. In contrast, there was little change in methane from traditional beef cattle over the 20 years, whereas it increased for dairy-derived cattle.

Applying GWP* for estimating the sheep carbon footprint for the farm-stage and accounting for the methane changes over the previous 20 years resulted in a cradle-to-farm-gate value of 0.96 kg CO_2we/kg LW (compared with 6.0 kg CO_2e/kg LW using GWP100 [AR5] in Table ii). The corresponding estimate for beef was 5.6 kg CO_2we/kg LW (compared with 8.7 kg CO_2e/kg LW in Table ii).

Trees are an important part of beef and sheep farms in NZ, and have a potential effect on carbon sequestration. In this study, the effect of accounting for woody vegetation on sheep and beef farms in NZ on net carbon sequestration was analysed using data on tree carbon stocks from a recent study, together with estimated emissions from harvested and deforested trees on farms and soil carbon changes by MfE. It indicated net NZ carbon sequestration of c. 5.5 million t CO_2, equating to a decrease in cradle-to-farm-gate carbon footprint for traditional beef and sheep LW of approximately 30%. Previous livestock LCA studies have focussed only on estimating GHG emissions with little or no consideration of carbon sequestration by trees within farm systems, except in some specialist agroforestry systems. These results indicate that woody vegetation on sheep and beef farms can be an important mitigation strategy for GHG emissions.

The report analyses both how emissions are allocated to meat on the basis of the economic value of the carcase (in which higher value meat receives a higher emissions allocation, while lower value by-products receive a lower emissions allocation), and by mass (in which the emissions are allocated to each kilogram of the carcase. The effect of using mass allocation would be to reduce the emissions from meat by almost half.

In conclusion, this study indicated that NZ beef and sheep meat supplied to widespread international markets has a full life-cycle carbon footprint at the bottom of the range of other published estimates, despite the long shipping distances sometimes involved. Accounting for net carbon sequestration from trees and shrubs on sheep and beef farms decreased the carbon footprint by approximately 30% on-farm or 20-27% across the product life cycle. Given the significance of animal-related methane emissions, more research is needed on the appropriateness of the GWP* metric to account for this relatively short-lived GHG.

2. Introduction

The emission of greenhouse gases (GHGs) is of global concern due to their impacts on climate change (e.g. IPCC, 2018). Food production has been identified as a significant contributor to global GHG emissions. This has led to a strong desire by producers and consumers to understand the emissions associated with different foods and how they can be reduced. The New Zealand (NZ) GHG Inventory (MfE, 2020) reports that agriculture contributes approximately one-half of the total national GHG emissions, and there is considerable ongoing research into options for decreasing agricultural emissions.

An accurate estimation of the total GHG emissions associated with the production and consumption of food needs to account for emissions and sequestration throughout all stages of the life cycle of a food product (often referred to as the carbon footprint of the product).

Life cycle assessment (LCA) is a key methodology to account for product life cycle emissions (ISO, 2006) and there have been various international groups that have worked on developing agreed LCA guidelines for determining the carbon footprint of products. For example, the Food and Agricultural Organization of the United Nations (FAO) initiated the Livestock Environmental Assessment and Performance (LEAP) partnership and the development of internationally-agreed guidelines for ruminant livestock supply chains (FAO, 2015a,b).

New Zealand is the world's largest exporter of sheep meat products globally and the sixth-largest beef exporter in 2020 (e.g. https://beef2live.com/story-world-beef-exports-ranking-countries-0-106903). Additionally, because NZ is isolated from many of its markets, it relies on shipping products worldwide, sometimes over considerable distances (e.g. up to about 20,000 km). Thus, it is important that the NZ beef and sheep sector understand the extent of GHG emissions throughout the various stages of the life cycle of their products, how it compares with emissions from other international producers, and the ability to reduce emissions.

As an exporting country it is critical that New Zealand claims about the emissions from our products are credible and based on the best available science, and that internationally emissions footprinting of products are done robustly, transparently, and reflect the actual impact on the climate of creating that product.

The aim of this project was to estimate the carbon footprint of a range of different beef and sheep products produced in NZ, covering the cradle-to-farm-gate, to processing and consumption in key overseas markets. It involved the development of detailed models and application of LCA using the latest representative NZ data and internationally-accepted GHG metrics. This report outlines the methodology, key input data used, and the results. It also includes several sensitivity analyses undertaken to understand the effects of data variability and uncertainty, as well as the implications of different GHG metrics and carbon sequestration. Internationally, there is currently a strong interest in accounting for short-lived GHG methane based on changes over time using the GWP* metric (e.g. Allen et al., 2018). This metric was evaluated in this report. Similarly, there is recognition in NZ and elsewhere (e.g. for agroforestry; Torres et al., 2017) about the inclusion of carbon sequestration by trees within the production system and the potential effect of including this for NZ sheep and beef farms was also evaluated in this report.

3. Methods

3.1 Goal and scope

This study's primary goal was to determine the carbon footprint of defined sheep and cattle products from the average of NZ livestock farm systems for the year 2017/18 using an attributional LCA methodology in accordance with ISO 14040:2006 and 14044:2006 standards to provide reliable and up-to-date data. The results of this study are also compared with those calculated from previously published studies. This study also aimed to examine the effects of accounting for carbon sequestration from trees on-farm and test the impact of using alternative GHG metrics, in particular, the new GWP* metric.

The scope of an LCA study is defined in ISO 14044:2006 section 4.2.3.1, and outlines the functional unit (FU), system boundary and cut-off criteria of the study. These are described below.

The FU is one kg of meat, varying with the five product systems included in this study for the full life cycle analysis (cradle to grave system boundary). Meat data was based on export statistics and for sheep meat, the FU covered the average for all edible cuts and included bone-in cuts. For beef it referred mainly to a boneless product. One kg of live weight (LW) is also used as the FU when analysing the life cycle up to the farm-gate (cradle to farm-gate boundary) for both beef and sheep systems.

The life cycle from cradle to grave covered five different product systems:

1. Sheep meat from the average NZ farm system, processed in NZ, chilled, and transported (refrigerated) via shipping to the UK and distributed via warehouse and retail outlets to consumers where it was cooked (by roasting) and consumed. Waste was included.
2. Sheep meat from the average NZ farm system, processed in NZ, chilled, and transported (refrigerated) via shipping to California and distributed via warehouse and retail outlets to consumers where it was cooked (by roasting) and consumed. Waste was included.
3. Sheep meat from the average NZ farm system, processed in NZ, frozen and transported (refrigerated) via shipping to China and distributed via warehouse and retail outlets to consumers where it was cooked (by hot-pot) and consumed. Waste was included.

4. Beef from the average NZ farm system, processed in NZ, chilled, and transported (refrigerated) via shipping to Japan and distributed via warehouse and retail outlets to consumers where it was cooked (by frying) and consumed. Waste was included.
5. Beef from the average NZ farm system, processed in NZ, frozen and transported (refrigerated) via shipping to the USA, processed to minced-beef and distributed via warehouse and retail outlets to consumers where it was cooked (by frying) and consumed. Waste was included.

The system boundary extended from the extraction of the raw materials associated with beef and sheep meat production through to the consumption and waste stages. A general system diagram for the whole supply chain is shown in Figure 1 (beef) and Figure 2 (sheep). Broadly, the main features of the chain include:

i) beef/sheep production on-farm, including the production of inputs (fertiliser, fuel, etc);

ii) processing into finished products;

iii) transporting and storing the products from NZ by ship and truck to an overseas regional distribution centre (RDC). It then went via retail outlets to the end point of consumption (either in a household or restaurant);

iv) Cooking at point of consumption and waste disposal.

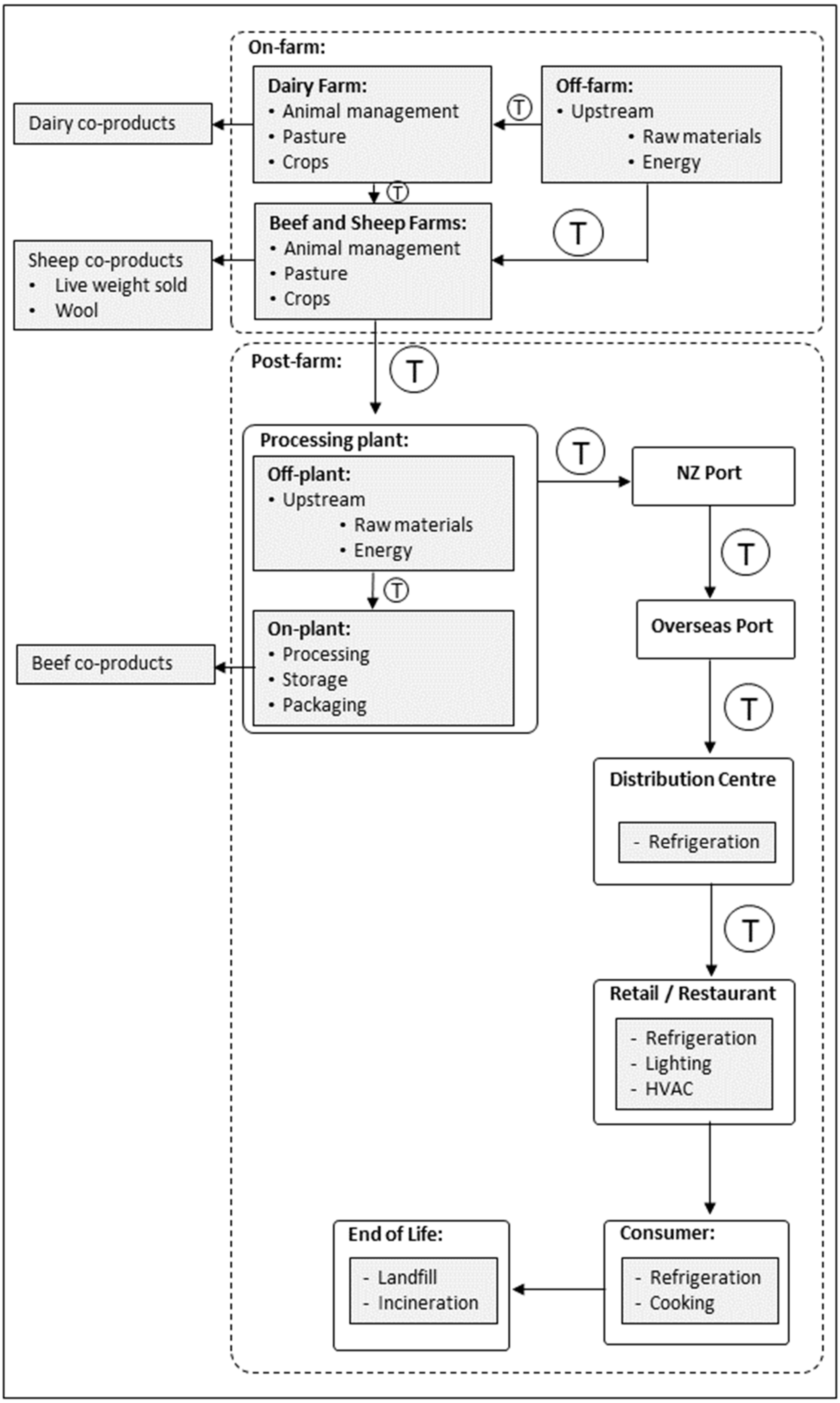

Figure 1. General diagram of the main life cycle stages for beef from cradle to grave. The "T" represents transportation steps along the value-chain.

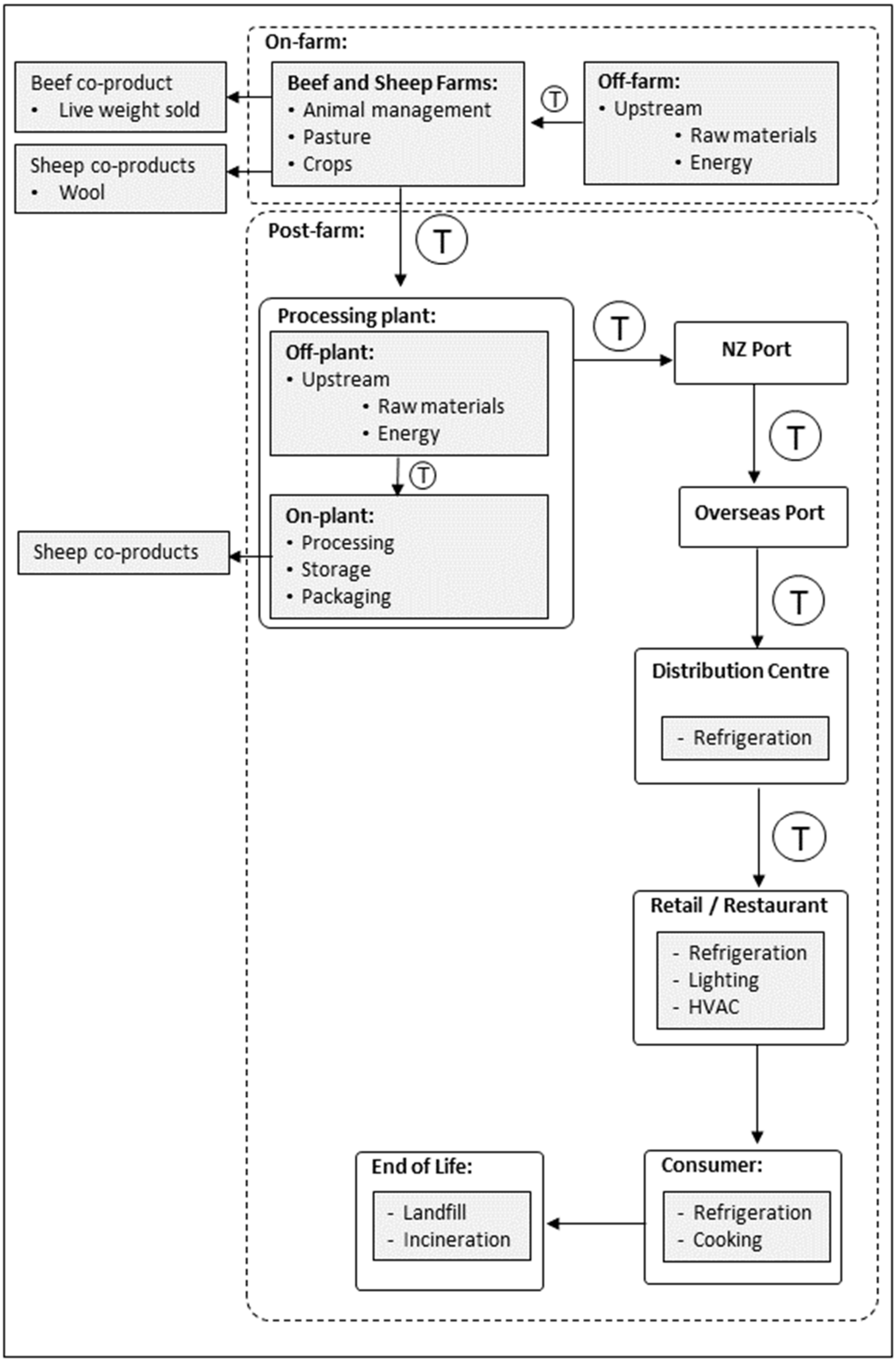

Figure 2. General diagram of the main life cycle stages for sheep meat from cradle to grave. The "T" represents transportation steps along the value chain.

When a production system has more than one product, it is necessary to account for this by apportioning the total GHG emissions between the various co-products (e.g. ISO, 2006). With an attributional LCA methodology, this involves the application of an allocation (i.e. separation of GHG emissions between co-products) method, and it can have a major effect on the overall emission footprint. The choice of the allocation methodology was made at four main parts of the study:

1) *Allocation between sheep and beef in the pastoral system*: system separation to avoid allocation was used for various on-farm operations where they could be specifically assigned to a single animal type. Where this was not possible, allocation based on biophysical causality was used, as recommended for ruminant supply chains (FAO, 2015a,b) and as used in a major NZ milk study (Ledgard et al., 2020). The dry matter intake (DMI) for each animal species on farms was calculated and used to allocate the GHG emissions between the different species accordingly.

2) *Allocation between wool and LW sold for meat from sheep*: a biophysical allocation approach was also used but based on protein requirements since that is a key determinant of productivity of wool and animal growth (FAO, 2015a). Thus, a protein mass allocation approach was applied based on the relative production of protein in wool and LW (e.g. Wiedemann et al., 2015).

3) *Allocation between milk and meat production from dairy farms*: system separation (where possible) and biophysical allocation (e.g. Ledgard et al., 2020) were used. For the latter, the GHG emissions from milk and meat (from culled dairy cows, heifers and surplus calves) production were allocated according to biological causality, which was based on the animal's physiological feed requirements to produce milk and meat (IDF, 2015). All specific inputs and GHG emissions associated with the animal growth phase, from birth to mature live-weight within the whole-farm system, were allocated to meat production. This resulted in a relative allocation between milk and meat in 2017/18 of 84% and 16%, respectively (Ledgard et al., 2020). It was assumed that the culled dairy cattle were sent directly from the dairy farm to the abattoir for meat processing.

4) *Allocation of co-products from sheep or beef cattle at the abattoir*: the most commonly accepted methodology for allocating emissions of the carcase is by economic allocation – that is, higher value parts are allocated higher emissions. Economic

allocation of products from sheep or cattle after meat processing was based on the monetary values (five-year average) of the whole animal, including the meat (with no differentiation between individual cuts), hides, ‘renderable’ material, blood and other components. A sensitivity analysis was also performed using mass allocation instead of economic allocation. The international meat sector has proposed mass allocation as a preferred method, and this proposal was included in a draft for the European Product Environmental Footprinting programme (PEF, 2018), although it has not currently been accepted. Others have proposed a more complex biophysical approach as being preferred and more consistent with approaches for the cradle-to-farm gate stage. Mass allocation had produced similar results to that for the new proposed biophysical allocation (Le Feon et al., 2020). However, there is no general agreement on the appropriate allocation method, even within the meat sector and sensitivity analysis with several methods has been recommended (Wilfart et al., 2021).

3.2 Inventory data

The approach was based on average data for all processes. For the farm stage, the technical description of beef and sheep farm systems relied on detailed data from the Beef + Lamb New Zealand (B+LNZ) statistics for the year 2017-2018 (details in Appendix 1). An NZ-average system was developed based on StatsNZ (2019) national animal data for NZ farms and NZ slaughter statistics. This was the most recent year with complete datasets. Additionally, a NZ average farm was summarised based on a weighted average of 484 farms surveyed across NZ by B+LNZ (Farm Class 9 from B+LNZ Economic Service data) for 2017/18. This provided a cross-check on estimates for the NZ-average system. Data from a previous separate study by Sise et al. (2020) for a 2017/2018 NZ average system was also accessed by the authors and analysed, providing an additional comparison. Sensitivity analysis of some key determining factors (e.g. age at slaughter) were also evaluated. In all cases, the non-animal farm-related emissions were based on Farm Class 9 data from B+LNZ, as described in Appendix 1. An additional analysis was also carried out using StatsNZ data on animal numbers based on an average of five years from 2016 to 2020. This approach had some data limitations, in that animal slaughter weight data for dairy cattle was unavailable for 2016-2017 and therefore was based on the average of the last three years. Farm input data from Beef + Lamb New Zealand was also unavailable for 2019 and 2020, and therefore average data for Class 9 farms for 2016-2018 was used.

For the meat processing stage, surveys asking for activity data were sent to the companies running the NZ beef-only and sheep-only processing plants and data from seven and four plants, respectively, were returned. We used data from plants that processed only beef or sheep to avoid complications when allocating emissions to the processing stage between different animal types.

Except for the oceanic distances between NZ and the overseas ports, no primary data were collected for the post-processing stages, including overseas transport, storage and consumption stages. Discussion with industry sources was used to form the base scenario assumptions for transport distances and storage times. Sensitivity analyses were carried out to determine whether more in-depth data collection was warranted.

3.3 Greenhouse gas emission calculations

A detailed description of the approach for calculating the GHG emission for each source and life cycle stage can be found in Appendix 1. Generally, the most up-to-date and (where possible) region-specific emission factors were used. The study followed the NZ GHG Inventory and the Intergovernmental Panel for Climate Change (IPCC) guidelines. When region-specific emission factors were not available, factors were extracted from reputable databases, such as Ecoinvent (Wernet et al., 2016). The study accounted for relevant GHGs, including methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2) and refrigerant gases. The most updated Global Warming Potential (GWP) factors were used for the carbon dioxide equivalent (CO_2e) emissions for a 100-year period (Assessment Report 5 [AR5] i.e. CO_2: 1; CH_4: 27.75; N_2O: 265 based on no climate-carbon cycle feedback; Stocker et al., 2013).

While GWP100 has been the most widely-used GHG metric for LCA, the IPCC describe a range of other metrics.Recently, publications (e.g. Allen et al., 2018; Lynch et al., 2020) introduced GWP* as an alternative metric to differentially account for effects of changes in emissions of short-lived gases (particularly methane) over time on global temperature. This is important for livestock agriculture, where biogenic methane emissions are significant.

3.4 Effect of using different GHG metrics and carbon sequestration

Sensitivity analysis on the effects of using different GHG metrics and accounting for carbon sequestration in trees on farm were examined for the cradle-to-farm-gate system boundary, as well as the various specific sensitivity analyses on effects of specific data and emission factors that were outlined in the previous sections.

3.4.1 GHG metrics

The influence of the GHG metric was tested using three different approaches. Firstly, we tested different CO_2e values for the GWP100, using the fourth Assessment Report (AR4) (i.e. CO_2: 1; CH_4: 25; N_2O: 298 – IPCC, 2006). Secondly, the global temperature potential (GTP) metric was evaluated, based on CO_2e factors of CO_2: 1; CH_4: 4; N_2O: 234 assuming no climate-carbon cycle feedback; Stocker et al., 2013). GTP compares the warming at a future point in time from an emission of non-CO_2 gases against that from CO_2. The third analysis was performed by recalculating the CH_4 emissions and the final carbon footprint using a warming-equivalent (CO_2-we) approach. Recently, researchers proposed a new methodology (GWP*) to account for the surface temperature effects of gases with different lifetimes. Because it accurately reflects the surface warming of a time-series of gases, GWP* gives a stronger warming effect than GWP100 when CH_4 emissions are rising, and a smaller effect when CH_4 emissions are stable or falling. This reflects the actual physical effects on surface temperatures, whereas GWP100 does not (Allen et al., 2018). The GWP* metric calculation requires at least two emission pulses to estimate the different points in time to account for the emission rate change required to estimate CO_2-we. To account for methane's effect over time (e.g. Allen et al., (2018) used a 20-year period), we extracted data from 20 years prior to the current analysed season (current: 2017/2018; 20 years before: 1997/1998 season) and calculated the CH_4 emissions for the on-farm stage (enteric and manure CH_4). We used the equation by Lynch et al. (2020) to calculate the CO_2-we for methane.

$$E_{CO2-we\ (CH4)} = \left(4 * E_{CH4_t} - 3.75 * E_{CH4_{(t-20)}}\right) * GWP_{100}$$

Where:

$E_{CO2\text{-we (CH4)}}$ – $CO_{2\text{-we}}$ emission for CH_4, considering two emission pulses, in kg $CO_{2\text{-we}}$;
$E_{CH4\ t}$ - Emission (or pulse) of CH_4 currently (season 2017/2018) in kg CH_4;
$E_{CH4\ (t-20)}$ – Emission (or pulse) of CH_4 20 years before current pulse (season 1997/1998) in kg CH_4;
GWP_{100} - GWP_{100} value for CH_4 (27.75 – AR5).

The final emission considering all GHG was calculated following the equation below:

$$E\ total_{(CO2-we)} = \left(E_{CO2} * GWP_{100_{CO2}}\right) + \left(E_{N2O} * GWP_{100_{N2O}}\right) + E_{CO2-we(CH4)}$$

Where:

E total $_{(CO2\text{-we})}$ – $CO_{2\text{-we}}$ emission for the three main GHG in kg $CO_{2\text{-we}}$;
E_{CO2} - Emission of CO_2 for the current year (season 2017/2018) in kg CO_2;
$GWP_{100\ CO2}$ - GWP_{100} value for CO_2 (1 – AR5);
E_{N2O} – Emission of N_2O for the current year (season 2017/2018) in kg N_2O;
$GWP_{100\ N2O}$ - GWP_{100} value for N_2O (265 – AR5).

Based on the final warming-equivalent emission, the carbon footprint was recalculated considering the live weight sold for the current year, following the equation below:

$$CF_{(CO2-we)} = \frac{E\ total_{(CO2-we)}}{LW\ sold}$$

Where:

CF $_{(CO2\text{-}we)}$ – Carbon footprint calculated as warming-equivalent ($CO_{2\text{-}we}$) emission for the three main GHG in kg $CO_{2\text{-}we}$ kg LW^{-1};
E total $_{(CO2\text{-}we)}$ – $CO_{2\text{-}we}$ emission for the three main GHG in kg $CO_{2\text{-}we}$;
LW sold – live weight sold for the current year (2017/2018) in kg.

3.4.2 Carbon sequestration

Consideration of carbon sequestration is important if other products are using offsetting in order to make claims about "carbon zero" or other climate claims.

This analysis was performed by considering the potential effects of carbon sequestered by trees within sheep and beef farms. The underlying basis for this analysis was a recent report by Auckland University of Technology (Case and Ryan, 2020) and a newly-released report by MfE (2021).

The MfE (2021) report was only published near the end of this project and therefore, a preliminary estimate of net carbon sequestration was also carried out using information from Case and Ryan (2020) for carbon stocks and from MPI (2019) and MfE (2020) for harvesting, deforestation and soil carbon changes. Details on the methods used for this preliminary assessment and results are presented in Appendix 2.

4. Results and Discussion

4.1 Cradle to farm-gate stage

4.1.1 Beef cattle

Summary

- The NZ average cradle-to-farm-gate carbon footprint for all beef (weighted average for traditional and dairy-derived beef) for 2017/18 was 8.97 kg CO_2e/kg LW sold (Table 1). This was based on the relative LW sold from traditional and dairy-derived beef of 65:35.
- The corresponding estimates for traditional beef from sheep and beef farms and dairy-derived beef from dairy farms were 10.09 and 6.88 kg CO_2e/kg LW sold, respectively.
- Sensitivity and uncertainty analysis (detailed in the following section) showed that these estimates based on NZ average data provided an accurate estimate for current beef cattle production.
- The NZ average cradle-to-farm-gate carbon footprint for beef had decreased slightly during the past 20 years (by 4-6%). In 1997/98 it was 10.74 kg CO_2e/kg LW sold for traditional beef and 9.36 kg CO_2e/kg LW sold for the weighted average of traditional and dairy-derived beef.

Details of sensitivity analysis of carbon footprint estimates

The animal-specific emissions (i.e. enteric CH_4 and manure CH_4 and N_2O emissions) contributed over 80% of total cradle-to-farm-gate emissions. Therefore, it was important to consider the variability of data used to calculate these emissions and differences between years. The summarised average estimates presented above were based on the use of the NZ average animal data of StatsNZ (2019). Sensitivity analysis of the corresponding results using data from the Beef + Lamb New Zealand Class 9 farm system (i.e. weighted average from all farm classes across NZ) and the modelling of national data by Sise et al. (2020), as well as some differences in the timing of finishing cattle, indicated a relatively small range in energy requirements per kg LW sold, which is the determinant of feed intake and therefore animal-related emissions. These were 135.1, 122.6 and 146.4 MJ ME/kg LW-sold for the NZ average, Sise et al. (2020; with a wide spread in sale dates and weights) and Class 9 farm systems, respectively. Variation in the timing of cattle sales for processing (with no change in LW sold) for the NZ-average ranged from 123-147 MJ ME/kg

LW-sold. This overall range of approximately ±10% flowed through to a similar range in animal related GHG emissions.

The range in NZ-average carbon footprint of beef from sheep and beef farms for 2017/18 covering the cradle-to-farm-gate varied from 8.9 kg CO_2e/kg LW for the Sise et al. (2020) data to 10.4 kg CO_2e/kg LW using Class 9 data (Table 1). It should be noted that the estimate reported by Sise et al. (2020) was based on data for animal numbers that changed monthly, and assumptions were required about the relative deaths and sales over time. It also required estimates of LW sold aligning to the monthly pattern of cattle LWs calculated over time by Sise et al. (2020).

The estimate for NZ average for 2017/18 of 10.09 kg CO_2e/kg LW was the same as that for the (less precise) estimate for 2016-2020, but it was 6% higher for the 1998/99 data (Table 1). While the latter had much lower input-related emissions (due to no cropping and less fertiliser use), the animal-related emissions were higher, most evident from the 15% higher enteric methane per kg LW for 1998/99 compared to 2017/18 (Table 1).

Table 1. Cradle-to-farm-gate GHG emissions per kg live-weight sold (kg CO_2e/kg LW) for traditional beef cattle from average NZ beef and sheep farms for 2017/18 compared to 2016-2020 and 1998/99. Estimates for 2017/18 are also presented based on B+LNZ Class 9 and animal data from Sise et al. (2020).

	NZ av. 2017/18	Sise et al. 2017/18	Class 9 2017/18	NZ av. 2016-2020	NZ av. 1998/99
	kg CO_2e/kg LW				
Enteric CH_4	**8.02**	6.98	8.36	8.10	9.19
Manure CH_4	**0.11**	0.09	0.11	0.11	0.13
Manure N_2O	**1.04**	0.92	1.09	1.05	1.12
Fertilisers	**0.41**	0.41	0.37	0.38	0.08
Lime	**0.07**	0.07	0.07	0.07	0.07
Forage crops/feeds	**0.10**	0.14	0.12	0.10	0.00
Fuel & electricity	**0.11**	0.11	0.10	0.11	0.02
Dairy-derived calves to weaning	**0.20**	0.23	0.15	0.20	0.12
Other	**0.03**	0.01	0.01	0.03	0.01
TOTAL	**10.09**	**8.96**	**10.38**	**10.15**	**10.74**

For the NZ-average system, the relative CO_2e contribution from CH_4, N_2O and CO_2 were 81%, 13% and 6%, respectively, based on the use of GWP100 (Table 2). Animal enteric CH_4 constituted 80% of total CO_2e emissions, while manure CH_4 was 1% and excreta N_2O was 10% of the total.

The fertiliser contribution (from production, transport and field emissions) was 4%, with the next largest at 2% contribution from the production of weaned calves from the dairy sector. This pattern was similar across the other systems analysed, except for 1998/99 as noted earlier, where all input-related emissions were minor, but enteric methane was much higher than for 2017/18.

Table 2. Contribution of different GHGs to the cradle-to-farm-gate GHG emissions per kg live-weight sold (kg CO_2e/kg LW) for traditional beef cattle from average NZ farms for 2017/18 compared to 1998/99. Estimates for 2018/19 are also presented based on B+LNZ Class 9 and animal data from Sise et al. (2020).

GHG	**NZ av. 2017/18**	**NZ av. 2017/18**	Sise et al. 2017/18	Class 9 2017/18	NZ av. 2016-2020	NZ av. 1998/99
	kg GHG[1]/kg LW	kg CO_2e[2]/kg LW				
Methane	0.293	**8.12**	7.07	8.47	8.21	9.31
Nitrous oxide	0.0049	**1.28**	1.16	1.31	1.29	1.11
Carbon dioxide	0.68	**0.68**	0.77	0.60	0.65	0.32
TOTAL	**-**	**10.09**	**8.97**	**10.38**	**10.15**	**10.74**

[1]weight of individual GHG, e.g. kg CH_4, kg N_2O and kg CO_2; [2]using GWP100

Accounting for dairy-derived beef

The cradle-to-farm-gate emissions from dairy farm-sourced beef (cull cows, heifers and surplus calves) for 2017/18 was 6.9 kg CO_2e/kg LW, 32% lower than that for NZ-average beef from beef and sheep farms (Table 3). This was mainly due to the much lower enteric methane emissions per kg LW, with only the contribution from the brought-in feeds being higher for dairy beef. The difference between traditional and dairy beef was even greater for 1998/99, being 45% lower for dairy beef. The latter result is less certain than for 2017/18 since the dairy carbon footprint data was based on results for 2004/05, which was assumed to be the same as for 1998/99. However, there was no land use change (LUC) data in 1998/99, which was the main reason for the lower dairy beef carbon footprint in 1998/99. For 2017/18, the inclusion of estimated LUC data from the conversion of exotic forest land to dairy pasture (which added 18% to the dairy beef carbon footprint) could be questioned since it is an indirect estimate. At the national level, the total area of forest has increased over the past 20 years while pasture land has decreased (MfE, 2020; national estimation of LUC is often related to national changes in land use and the broad change in land uses that affect it, e.g. Blonk LUC tool; Blonk, 2017).

The lower dairy beef carbon footprint can be attributed mainly to the much lower contribution from dairy cows that produce milk, meat and calves. Most of the GHG emission for dairy farms is allocated to milk production (86%), while the remaining emission is allocated to meat (14% -

Ledgard et al., 2020). In contrast, beef cows only produce meat and calves (e.g. van Selm et al., 2021). Dairy cow reproduction is also more efficient than beef cows, with a higher calving % and most dairy heifers calving at 2-years-age, compared with some beef heifers having their first calf at 3-years-age (Sise et al., 2020; although specific national data on heifer calving rate is lacking). For dairy beef, animal-related emissions again dominated at 66% of the total, but there were larger contributions from brought-in feeds and fertilisers at 10% and 7%, respectively. Rotz et al. (2019) also showed that inclusion of dairy beef resulted in an average decrease in carbon footprint of all beef in different regions across USA by up to 25%.

Table 3. Cradle-to-farm-gate GHG emissions per kg live-weight sold (kg CO_2e/kg LW) for beef from NZ average beef and sheep farms and from dairy farms (dairy beef) for 2017/18 and 1998/99. Estimates are also given for a weighted NZ average based on the relative amounts of beef from the two different farm types.

	NZ av. 2017/18	Dairy beef 2017/18	Weighted NZ av. 2017/18	NZ av. 1998/99	Dairy beef 1998/99	Weighted NZ av. 1998/99
	kg CO_2e/kg LW					
Enteric CH_4	**8.02**	3.81	6.55	9.19	4.25	7.79
Manure CH_4	**0.11**	0.08	0.10	0.13	0.07	0.11
Manure N_2O	**1.04**	0.62	0.90	1.12	0.79	1.02
Fertilisers	**0.41**	0.47	0.43	0.08	0.54	0.21
Lime	**0.07**	0.04	0.05	0.07	0.02	0.05
Forage crops/feeds	**0.10**	0.71	0.31	0.00	0.09	0.03
Fuel & electricity	**0.11**	0.05	0.09	0.02	0.06	0.03
Dairy-derived calves[1]	**0.20**	n.a.	0.13	0.12	n.a.	0.09
Other	**0.03**	1.10 (0.06)[2]	0.41 (0.06)[2]	0.01	0.08	0.03
TOTAL	**10.09**	**6.88 (5.84)**[2]	**8.97 (8.59)**[2]	**10.73**	**5.90**	**9.36**

[1] to weaning; [2] Excluding Land Use Change for dairy (i.e. exotic forest land converted to dairy); n.a. not available

Breakdown of the main contributions to the on-farm carbon footprint

Methane was the dominant GHG contributing 81-87% and 58-75% to the carbon footprint of traditional beef and dairy beef, respectively (Table 4). Corresponding values for N_2O were 10-13% and 13-18%, respectively, while differences were largest for CO_2 at 2-6% and 9-29%, respectively. This data refers to the GWP100 estimates, with adjustment for the AR5 CO_2-equivalent factors based on individual gas emissions of 0.241 kg CH_4, 0.0044 kg N_2O and 1.13 kg CO_2.

Table 4. Contribution of different GHGs to the cradle-to-farm-gate GHG emissions per kg live-weight sold (kg CO_2e/kg LW; using GWP100) for beef from NZ average beef and sheep farms and from dairy farms (dairy beef) for 2017/18 and 1998/99. Estimates are also given for a weighted NZ average based on the relative amounts of beef from the two different farm types.

	NZ av. 2017/18	Dairy beef 2017/18	Weighted NZ av. 2017/18	NZ av. 1998/99	Dairy beef 1998/99	Weighted NZ av. 1998/99
	kg CO_2e/kg LW					
Methane	**8.12**	3.99	6.69	9.31	4.34	7.91
Nitrous oxide	**1.29**	0.92	1.15	1.11	1.05	1.09
Carbon dioxide	**0.68**	1.97 (0.93)[1]	1.13 (0.77)[1]	0.31	0.51	0.36
TOTAL	**10.09**	**6.88 (5.84)**[1]	**8.97 (8.61)**[1]	**10.73**	**5.90**	**9.36**

[1] Excluding Land Use Change for dairy (i.e. forest land converted to dairy)

Data from StatsNZ (2020) showed that the relative amounts of cattle LW slaughtered (based on CW data adjusted for LW/CW) from ‘traditional’ beef relative to dairy-beef was 65:35 in 2017/18 and 72:28 in 1998/99. Thus, a weighted average of cattle from sheep+beef and dairy farms for 2017/18 (according to relative LW sold of 65:35) resulted in emissions of 8.97 kg CO_2e/kg LW sold (Tables 3 and 4). The relative CO_2e contribution, based on the use of GWP100, from CH_4, N_2O and CO_2 were 75%, 13% and 12%, respectively. Animal enteric CH_4 constituted 73% of total CO_2e emissions, while manure CH_4 was 1%, excreta N_2O was 10%, and fertilisers contributed 5% of the total. The weighted average for 1998/99 was 4% higher than for 2017/18, associated with traditional beef being 6% higher while dairy beef was 14% lower.

Comparison with other published carbon footprint estimates

The weighted average result is at the low end of the range of 8-31 kg CO_2e/kg LW from the recent review by Mazzetto et al. (2021). It is lower than the average for USA beef (including weighting for dairy beef) of 10.9 kg CO_2e/kg LW in a recent detailed study by Asem-Hiablie et al. (2018; using the same GWP100 factors as in this study). The USA study included a range for traditional beef of 8.7-20.6 kg CO_2e/kg LW depending on the region in the USA, while the range for dairy cow beef was 6.0-8.7 kg CO_2e/kg LW and for the weighted average was 8.6-13.9 kg CO_2e/kg LW (Rotz et al., 2019).

4.1.2 Sheep

Summary

- The NZ average for sheep from sheep and beef farms for 2017/18 covering the cradle-to-farm-gate was 6.01 kg CO_2e/kg LW sold (Table 5).
- The carbon footprint for sheep in 2017/18 was 18% lower than in 1998/99, with the latter being 7.29 kg CO2e/kg LW sold. This was associated with an increase over time in lambing % and heavier finishing weight of lambs.

Details of sensitivity analysis of carbon footprint estimates

The estimate of the carbon footprint of sheep LW sold in 2017/18 varied by up to 10%, depending on the dataset, with the NZ average being intermediate between that of Sise et al. (2020) and the Class 9 farm (Tables 5 and 6). The estimated carbon footprint of NZ-average sheep meat for 2017/18 was the same as that for 2016-20.

The estimated carbon footprint for sheep LW sold in 1998/99 was lower than for 2017/18. However, more assumptions were required for the 1998/99 data, including assuming no change in animal sales pattern for processing (although at lower finished LWs per animal), no N fertiliser used and no forage crops on-farm. All estimates included accounting for allocation of GHG emissions between LW sold and wool, which equated to 31% to wool for 2017/18 and 37% for 1998/99 (i.e. 63-69% to LW sold for meat). This contributed to the carbon footprint for sheep LW sold being approximately 40% lower than for 'traditional' cattle LW sold from the NZ average farm system since beef cattle have no other co-products on-farm.

Table 5. Cradle-to-farm-gate GHG emissions per kg live-weight sold (kg CO_2e/kg LW) for sheep from average NZ farms for 2017/18 compared to 1998/99. Estimates for 2018/19 are also presented based on B+LNZ Class 9 and animal data from Sise et al. (2020). Results are net of allocation of emissions to wool as a co-product.

	NZ av. 2017/18	Sise et al. 2017/18	Class 9 2017/18	NZ av. 2016-2020	NZ av. 1998/99
			kg CO_2e/kg LW		
Enteric CH_4	**4.99**	4.63	5.11	5.00	6.55
Manure CH_4	**0.05**	0.05	0.06	0.05	0.07
Manure N_2O	**0.43**	0.38	0.47	0.43	0.54
Fertilisers	**0.30**	0.31	0.28	0.27	0.06
Lime	**0.05**	0.06	0.05	0.05	0.05
Forage crops	**0.08**	0.08	0.07	0.07	0.00
Fuel & electricity	**0.08**	0.08	0.07	0.08	0.02
Other	**0.03**	0.03	0.02	0.03	0.00
TOTAL	**6.01**	**5.62**	**6.13**	**5.99**	**7.29**

Table 6. Contribution of different GHGs to the cradle-to-farm-gate GHG emissions per kg live-weight sold (kg CO_2e/kg LW) for sheep from average NZ farms for 2017/18 compared to 1998/99. Estimates for 2018/19 are also presented based on B+LNZ Class 9 and animal data from Sise et al. (2020). Results are net of allocation of emissions to wool as a co-product.

	NZ av. 2017/18	**NZ av. 2017/18**	Sise et al. 2017/18	Class 9 2017/18	NZ av. 2016-2020	NZ av. 1998/99
	kg GHG[1]/kg LW	kg CO_2e[2]/kg LW				
Methane	0.181	**5.05**	4.67	5.17	5.05	6.62
Nitrous oxide	0.0023	**0.61**	0.58	0.64	0.60	0.54
Carbon dioxide	0.35	**0.35**	0.37	0.32	0.34	0.13
TOTAL	**-**	**6.01**	**5.62**	**6.13**	**5.99**	**7.29**

[1]weight of individual GHG, e.g. kg CH_4, kg N_2O and kg CO_2; [2]using GWP100

Breakdown of the main contributions to the on-farm carbon footprint

Animal enteric CH_4 was the dominant contributor to the footprint (using GWP100), at 83-84% for 2017/18 systems and 91% for 1998/99. Manure N_2O was the next main contributor at 7-8% across all systems, followed by fertiliser production and use at 5-6% for 2017/18 but only 1% for 1998/99. The latter was largely due to no N fertiliser use on the 1998/99 farm, while the rate of other fertiliser nutrients applied was assumed to be the same across all systems.

This data refers to the GWP100 estimates, with adjustment for the AR5 CO_2-equivalent factors based on individual gas emissions of 0.181 kg CH_4, 0.0023 kg N_2O and 0.35 kg CO_2.

For the NZ-average system for 2017/18, the relative CO_2e contribution from CH_4, N_2O and CO_2 were 84%, 10% and 6%, respectively, based on the use of GWP100 (Table 6). These are similar to the other 2017/18 systems and the 2016-20 system, but were 92%, 7% and 1%, respectively for the 1998/99 NZ average system. The latter low CO_2 component was due to fewer inputs through no N fertiliser used and no forage cropping.

Comparison with other published carbon footprint estimates

The NZ average result of 6.01 kg CO_2e/kg LW is at the lower end of the range of 6.8 to 23.1 kg CO_2e/kg LW from the recent review by Mazzetto et al. (2021). However, as noted in that report, the results were greatly influenced by differences in the methodologies used between studies. A recent study of sheep meat from California by Dougherty et al. (2019) resulted in estimated carbon footprint (using the same protein mass allocation method and GWP factors) of lamb of 6.6-10.1 kg CO_2e/kg LW, varying with the type of sheep farming system.

4.1.3 Consideration of different GWP100 metrics, GWP* and carbon sequestration

4.1.3.1 Effects of different climate change metrics

Currently the GWP100 metric is the de facto standard in carbon footprinting. This represents the warming contribution of a certain gas over 100 years relative to CO2. However, it creates a misleading picture of cumulative emissions of short-lived gases such as methane over time. Sensitivity analysis results for different climate change metrics covering the cradle-to-farm-gate boundary are presented in Table 7. Since methane (CH_4) is the main GHG for both beef and sheep production, changing the CO_2e characterisation factor for CH_4 from GWP 100 AR5 without climate-carbon cycle feedback (CH_4 = 27.75) to GWP 100 AR4 (CH_4 = 25) or GTP (CH_4 = 4) resulted in a reduction of the calculated total footprint, despite the higher CO_2e characterisation factor for N_2O in GWP 100 AR4 (298) compared with GWP 100 AR5 (265). However, using GWP 100 AR5 with climate-carbon cycle feedback (CH_4 = 34) increased the calculated carbon footprint due to the higher methane factor. There has been mixed-use of the latter method in the literature, although it is the recommendation in ISO14067.

Table 7. Cradle to farm-gate carbon footprint (in kg CO_2e / kg LW) for the average NZ beef and sheep production in 2017/18 under three different climate change metrics (Global Warming Potential [GWP] and Global Temperature change Potential [GTP]).

Beef	GWP100 AR5 (2013)		GWP100 AR4 (2007)	GTP100
	Without CCF[1]	With CCF[1]	Without CCF[1]	
Methane	6.69	8.20	6.03	0.96
Nitrous oxide	1.15	1.29	1.30	1.03
Carbon dioxide	1.13	1.13	1.13	1.13
TOTAL	**8.97**	**10.62**	**8.46**	**3.12**

Sheep	GWP100 AR5 (2013)		GWP100 AR4 (2007)	GTP100
	Without CCF[1]	With CCF[1]	Without CCF[1]	
Methane	5.05	6.19	4.55	0.73
Nitrous oxide	0.61	0.69	0.69	0.54
Carbon dioxide	0.35	0.35	0.35	0.35
TOTAL	**6.01**	**7.23**	**5.59**	**1.62**

[1] with or without climate-carbon cycle feedback

GWP100 AR4 values are provided to show the change from the earlier GWP characterisation factors and because many publications were based on the use of AR4. The GTP metric aims to represent the temperature change at the end of the period relative to CO_2 (100 years), recognising the short-lived GHGs (as methane) with low characterisation factors. However, it is rarely reported in carbon footprint analyses, and most focus regarding the methodology is currently on GWP*.

*GWP**

The GWP* metric (Allen et al., 2018) has a similar goal to GTP but relies on a specific equation depending on the timeframe analysed.

The GWP* approach has been suggested as being most relevant for evaluating absolute emissions for the whole sector or country-level changes over time (Allen et al., 2018) and (to the best of the author's knowledge) has been applied for footprinting purposes only once (Riddout, 2021). Riddout (2021) modelled Australian sheep and estimated negative CH_4 numbers in his final calculation associated with a decline in sheep numbers over time. While GWP* is largely untested for use in carbon footprinting by the wider scientific community, it is currently being examined by international groups, including FAO LEAP and IDF.

While GWP100 is the accepted metric for describing the warming impact of greenhouse gases, it is acknowledged to have shortcomings when it comes to the temperature response of short-lived emissions such as methane (Allen et al., 2018). Lynch et al. (2020) indicated that GWP100 understates the impact of methane on warming if methane is increasing and it overstates the impact of methane on warming if methane is decreasing.

When the GWP* method was applied to estimate the carbon footprint, it resulted in a negative final CH_4 emission value (Table 8) because sheep emissions have decreased over the last 20 years in NZ. Since "negative" emissions are usually related to the removal of GHG from the atmosphere (which is not the case here), we chose to represent the GWP* number for methane as "zero". This led to a very low estimate for the carbon footprint of sheep of 0.96 kg CO_2-we/kg LW due to the zero net contribution from CH_4 (Table 9).

Using GWP* resulted in a lower final CH_4 emission value for beef, and when combined with nitrous oxide and carbon dioxide, it resulted in a final GWP* estimate for NZ weighted-average beef of 5.82 kg CO_2-we/kg LW. This was 35% lower than the estimate using GWP 100 (AR5). Although the CH_4 emissions from 'traditional' beef animals showed little change during the last 20 years (-2%), there was a more significant contribution from the dairy herd over the last 20 years to the total NZ beef production, associated with a 55% increase in cow numbers (DairyNZ/LIC, 2019). As discussed, the GHG emissions from the dairy beef (culled cows, heifers and surplus calves from dairy farms) represented 27% of the total beef GHG emissions for NZ in 2017/18, despite contributing 35% of the beef LW sold for meat processing.

However, it should be noted that this application of GWP* may be a small overestimation of the reduction in $CO_{2\text{-we}}$ from CH_4 and therefore in the carbon footprint, since it does not account for the delayed effect from a change in levels of CH_4 emission over time. Currently GWP* researchers are ~~now~~ integrating this delay effect into their methodology. This use of GWP* is a relatively new approach, and there are a number of groups looking into how it could be used for international acceptance in carbon footprint assessment. An important aspect of this is defining how different estimates over different times are accounted for (this study used only one 20-year comparison).

A potentially useful assessment of GWP* (beyond the scope of this project) would be to examine the change over time in the total CH_4 and GHG emissions for all livestock, including dairy and deer (or specifically for each livestock sector) in NZ.

Table 8. Methane emission (in t) and carbon footprint (in kg CO_2-we / kg LW) for the main on-farm sources of CH_4 using the GWP* approach

Beef[2]	1997/98 emission t CH_4	2017/18 emission t CH_4	CO_2-we (CH_4)[1] t CO_2-we	LW sold (2017/18) t LW	Footprint for CH_4 using GWP* kg CO_2-we / kg LW
Enteric fermentation	308,669	330,821	4,600,231	1,400,584	3.28
Excreta	4,343	4,899	91,768	1,400,584	0.07
Total	**313,013**	**335,720**	**4,691,998**	**1,400,584**	**3.35**

Sheep	1997/98 emission t CH_4	2017/18 emission t CH_4	CO_2-we (CH_4)[1] t CO_2-we	LW sold (2017/18) t LW	Footprint for CH_4 using GWP* kg CO_2-we / kg LW
Enteric fermentation	435,568	287,420	-13,422,618	1,104,475	-12.15
Excreta	4,445	3,116	-116,671	1,104,475	-0.11
Total	**440,013**	**290,536**	**-13,539,289**	**1,104,475**	**-12.26**

[1] following the equation from Lynch et al. (2020) ; [2] NZ weighted average for traditional and dairy beef

Table 9. Carbon footprint for the average NZ beef and sheep production using the GWP* approach compared to the GWP100 AR5 approach

Beef	GWP100 AR5 (2013)	GWP*
	kg CO_2e / kg LW	kg CO_2we / kg LW
Methane	6.69	3.35
Nitrous oxide	1.15	1.15
Carbon dioxide	1.13	1.13
TOTAL	**8.97**	**5.63**

Sheep	GWP100 AR5 (2013)	GWP*
	kg CO_2e / kg LW	kg CO_2we / kg LW
Methane	5.05	0[1]
Nitrous oxide	0.61	0.61
Carbon dioxide	0.35	0.35
TOTAL	**6.01**	**0.96**

[1] The calculated result was negative (-12.26 kg $CO_{2\text{-we}}$ / kg LW – Table 8), but since there is no agreement on how to treat negative footprints in LCA, we chose to represent the GWP* result as zero for sheep.

4.1.3.2 Carbon sequestration

Estimates of net carbon (C) sequestration associated with woody vegetation on sheep and beef farms across NZ recently published by MfE (2021) equated to approximately 5.5 million t CO_2/year. This included accounting for C stocks in trees, deforestation, harvesting and changes in soil C. The preliminary estimates made in this study (prior to the release of the MfE report) were similar at approximately 5.9 million t CO_2/year (details given in Appendix 2). This is lower than the average estimate for C stocks only by Case and Ryan (2020) of approximately 15.0 million t CO_2/year.

The estimated net C sequestration in woody vegetation (using MfE (2021) data) equates to 29% of the total calculated GHG emissions from agricultural production on NZ sheep and beef farms. This is based on using data in Tables 1 and 5 for cattle and sheep carbon footprints per kg LW with the national amounts of LW sent to abattoirs in 2017/18, giving a total of 18.7 million t CO_2e for the cradle-to-farm-gate emissions from total NZ meat and wool (excluding dairy beef). Animal biological emissions (i.e. enteric and excreta CH_4 and excreta N_2O only) from sheep and beef farms equated to 17.13 million t CO_2e in 2017/18. Therefore, the net C sequestration in vegetation (accounting for harvesting and deforestation) would equate to 32% of the animal biological emissions.

These estimates correspond to a 29% decrease in carbon footprint (cradle-to-farm-gate) for sheep and traditional beef from NZ sheep and beef farms relative to the Base, which takes no account for C sequestration (Table 10). The corresponding reduction for all beef (including dairy-beef) is 21% since there is no estimated C sequestration from trees on dairy farms. This equates to a decrease in the life cycle carbon footprint of 26-28% for sheep and traditional beef or 21% for NZ-average beef.

Use of estimates that account for net C sequestration due to trees within the farm system should be acceptable for use in total GHG accounting and carbon footprinting. On these NZ sheep and beef farms, trees are often an integral component of each farm and reflect mitigation practices. Tree carbon sequestration has been included in a limited number of studies, including agroforestry (Torres et al., 2017). However, they have not been included in an integrated carbon footprint estimate. This differs from carbon off-setting, which are unrelated to a product carbon footprint and not accepted in guidelines (e.g. ISO14067) as part of reported carbon footprint values. However, if net C sequestration from trees within farm systems is included, it should be reported separately to illustrate the mitigation benefit, as noted for carbon storage in ISO14067 and for LUC in LEAP large ruminant guidelines (see also Appendix 2, Figure A3).

Table 10. Effect on the carbon footprint of sheep and beef (cradle-to-farm-gate) when accounting for carbon sequestration (Cseq) associated with woody vegetation on sheep and beef farms in NZ. Data for stocks of carbon in vegetation (for average) are from Case and Ryan (2020), while net Cseq values accounted for C stocks, emissions of CO_2 from harvested forest, and deforestation (i.e. change from forest to pasture) and soil C changes. The latter are from preliminary estimates in this report (Appendix 2) and from the recent report of MfE (2021)

	Base (no C-seq) (GWP 100 AR5)	-Net Cseq (Appendix 2)	**-Net Cseq [from MfE 2021]**	-Cseq Stocks (from Casey and Ryan 2020 average)
	kg CO_2e / kg LW			
Sheep	**6.01**	4.13	**4.26**	1.21
Traditional beef	**10.09**	6.93	**7.16**	2.04
All beef (incl. dairy)	**8.97**	6.92	**7.06**	3.72

4.2 Transport from farm to processing plant

The trucking of cattle and sheep from farm to the processing plant was estimated to emit 5.8 kg CO_2e/t LW for cattle and 5.7 kg CO_2e/t LW for sheep from sheep and beef farms. This was based on a weighted average for the different farm classes across NZ and a marginally shorter distance to sheep-processing plants than to beef processing plants. The corresponding value for cattle from dairy farms (i.e. cull cows and surplus calves) is unknown, and therefore the same value of 5.8 kg CO_2e/t LW was used as for traditional beef cattle.

4.3 Processing stage

The primary data from meat processing plants was used to calculate GHG emissions for the processing stage. An important part of the calculations involves accounting for the change from LW (leaving the farm gate and transported to abattoirs) to meat that leaves the abattoir gate. This was based on national data on average LW to carcass weight (CW) ratio from Muir et al. (2008) and StatsNZ (2020) of 54% for traditional cattle, 48% for cull dairy cows and heifers, 40% for calves, 47% for lambs and 48% for other sheep. A 5-year average summary from export data for the carcass weight to meat weight provided by B+LNZ had values of 75% for all cattle meat, 88% for lamb and 91% for mutton. This data were used to convert LW to meat.

Additionally, an economic allocation factor to allocate emissions between meat and other co-products was calculated based on 5-year average (2016-2020) data for meat, hide, 'renderable' material and other by-products according to Free on Board (FOB) data. (Note that all meat cuts were treated the same (i.e. there was no economic allocation based on different meat cuts – just between meat and co-products).

An exception was the cattle 'renderable' material where instead of using data for tallow and meat meal (rendered products), an estimate for the lower price paid to abattoirs was used (based on industry information).

Results for the relative economic value and mass of the different co-products for beef and sheep meat (the latter as a weighting for lamb and mutton according to the relative amounts of each of 79:21) are given in Appendix Tables A7 and A8. Thus, values for the cradle-to-farm-gate and farm-to-abattoir-transport GHG emissions in kg CO_2e/kg LW were divided by the ratio of meat to LW, and multiplied by the allocation %, to get kg CO_2e/kg meat. This is required because the LW from the farm contributes to all co-products and waste and not only meat.

4.3.1 Beef cattle

The seven beef-only cattle processing plants that provided data on their inputs and amounts of cattle processed showed wide variation in inputs. The most remarkable differences were related to the types of non-electricity energy used (from coal-only to natural gas only, or a mix including LPG) and the wastewater processing methods. The latter was either on-site or off-site and included aerobic or physical-chemical treatment, with all plants using some type of solids-separation system. These differences were associated with differences in the GHG emissions per kg of meat produced (Figure 3).

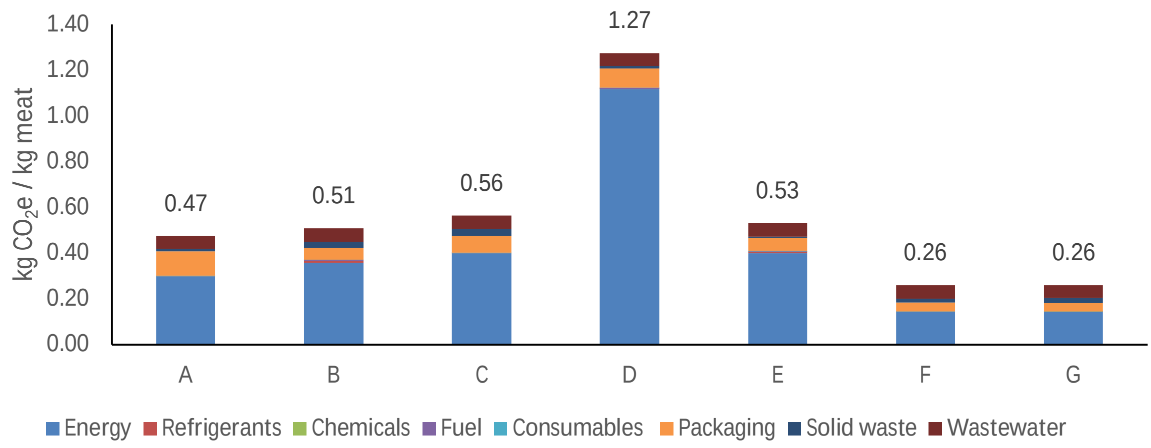

Figure 3. Processing GHG emissions (kg CO_2e / kg meat) for the different beef-only processing plants. The main thermal energy sources were natural gas for plants A, C, F and G, coal for B and D, and fuel oil for E.

The beef processing stage resulted in average GHG emission (weighted for relative meat processed across plants) of 0.51 kg CO_2e / kg meat. The energy use was the largest source of emissions, contributing 72% of the total average emissions (range 54-88%). The reason for the higher contribution from energy (and consequently higher total processing emissions) for plant D was the use of coal as the main source of non-electricity energy. Packaging and wastewater represented 12 and 11% of the average total processing emissions, respectively, while other sources accounted for less than 5% each.

The current processing emissions per kg beef is similar to that for the average for generic beef in the previous study using data from nine plants surveyed in 2010 (0.50 kg CO_2e / kg meat; Lieffering et al., 2010). The main sources of emissions in the previous report were energy (56%) and waste (37% - accounting for both solid and water waste). Higher waste-related emissions in the previous study were associated with different methodology and differences in the fate of wastewater used to calculate the GHG emissions. Packaging represented only 3% of the previous total processing emissions, compared with 12% in the current study. For the previous report, data for packaging only accounted for cardboard and did not account for the various plastic wrappings (polypak, trays, strapping and cling-film; polypak) which were a large contributor to total packaging emissions in the present study. Furthermore, the previous study didn't consider the production of consumables. The average estimate of processing emissions per kg of beef for the processing stage was generally lower than in other studies (Table 11). This study's results should give a good representation of the NZ average since the number of cattle processed by the seven plants surveyed represented approximately 34% of the national number of cattle slaughtered (based on StatsNZ slaughter statistics).

Table 11. Summary of the greenhouse gas (GHG) emissions for the beef processing stage across a range of published studies

Study	Country	GHGs (kg CO_2e / kg meat)
Lieffering et al., 2010	New Zealand	0.50
Sanders et al., 2014	USA	0.39
Wiedemann et al., 2015	Australia	0.98
Huerta et al., 2016	Mexico	1.13
Asem-Hiable et al., 2018	USA	0.59
Vitali et al., 2018	Italy	1.27
This study (2020)	**New Zealand**	**0.51**

4.3.2 Sheep

As noted for the beef-only processing plants, the sheep-only plants also showed a wide variation in the inputs used. The differences in inputs were associated with differences in the GHG emissions per kg of meat produced (Figure 4). Two plants also processed calves (plants H and J), but it was not possible to differentiate between animal type and therefore, results were estimated based on the kg carcass-weight processed.

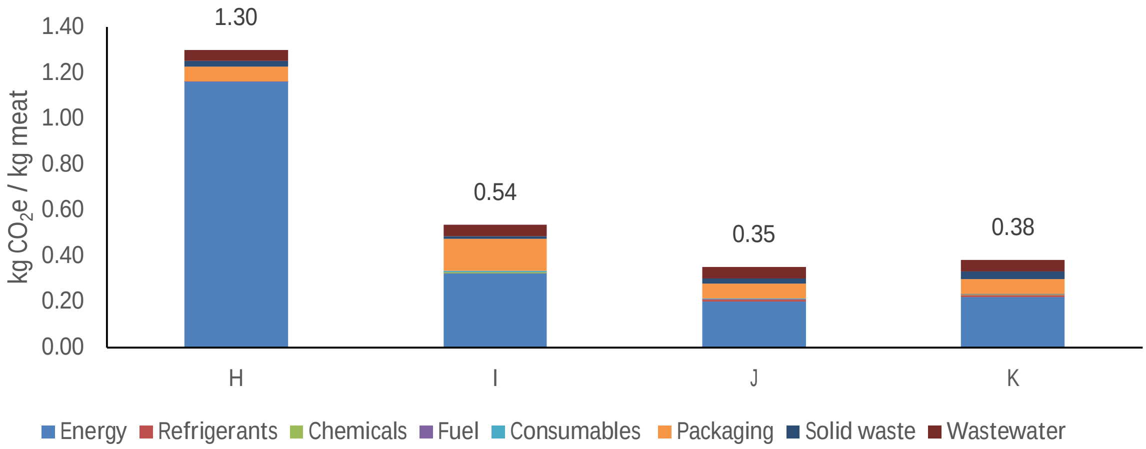

Figure 4. Processing GHG emissions (kg CO_2e / kg meat) for the different sheep-only processing plants. The main thermal energy sources were LPG for plant H and natural gas for I, J and K.

The sheep meat processing stage resulted in average GHG emissions (weighted for relative meat processed across plants) of 0.52 kg CO_2e / kg meat. Energy use was the largest source of emissions, contributing to 66% of the total average processing emissions (range 57-89%). Similar to the beef-only processing plants, packaging (18%) and wastewater (10%) also showed an important share of the emissions, while other sources accounted for less than 5% each. The average result is lower than from the two other two published studies, in NZ and Australia (Table 12). However, it should be noted that the data was only received from four sheep processing plants. It is unclear how representative these plants were of the national range of plants, especially since it does not include any of the older plants that process larger sheep numbers than for these four plants.

Table 12. Summary of the greenhouse gas (GHG) emissions for the sheep processing stage from published studies

Study	Country	GHGs (kg CO_2e / kg meat)
McDevitt et al., 2009	New Zealand	0.57
Wiedemann et al., 2015	Australia	0.92
This study (2020)	**New Zealand**	**0.52**

To compare the results with the previous report (McDevitt et al., 2009), the current average was recalculated to a different functional unit (0.22 kg CO_2e / kg LW). The result is lower than the previous report (0.33 kg CO_2e / kg LW). However, the relative share of energy-related emissions was similar at 47% compared to 51% in the current study. Waste emissions (both solid and water waste) previously represented 26% of total processing emissions, more than when compared with the current report (11% to wastewater and 4% to solid waste). It should also be noted that the previous study also included a number of plants with rendering facilities and these plants had higher energy-related emissions than for the non-rendering sites in the current study (Lieffering et al., 2010). Results from this study should give a moderate representation only of the NZ average since the number of sheep processed by the four plants that returned surveyed data represented approximately 9% of the national number of sheep slaughtered (based on StatsNZ slaughter statistics) or about 20% of recorded sheep-only processing plants in the list of approved abattoirs in NZ (https://kavmal.tripod.com/new_zealand.html).

4.3.3 Effect of using economic or mass allocation for processing

The numbers described above were based on economic allocation (based on economic value of co-products; section 3.1) for both beef and sheep processing plants, which is the currently recommended method in the LEAP and PEF guidelines for livestock processing. However, there is disagreement about the appropriate method between some groups including between processors (Wilfart et al., 2021).

A biophysical allocation approach (based on energy requirements for growth and maintenance of the different animal tissues and organs) has been recommended by some (and aligns with methods used in the cradle-to-farm-gate) but it is complex and only one published study used it, although it produced similar allocation % values to that using simple mass allocation (Le Feon et al., 2020).

An alternative is mass allocation - When applying mass allocation (based on allocation of emissions between the various co-products according to their relative total mass), the average GHG results were significantly lower (Table 13). Economic allocation to meat accounted for 91-92% for beef and sheep (i.e., 8-9% to other processing co-products), while mass allocation would account for 39% and 42% for beef and sheep, respectively (Table 13; see greater detail in Appendix section 8.2.1). These economic allocation factors are similar to those for the red-meat default values for the European Product Environmental Footprinting programme (PEF, 2018) at 92 and 95% for beef and sheep meat, respectively. These are slightly higher than the ones found in the previous studies (85-88%), in part because the previous studies used prices for tallow and meal (i.e. finished products that have additional beef processing emissions not accounted for in this study) rather than that for the sold beef renderable material as used in the present study.

If mass allocation had been applied instead of economic allocation, the cradle-to-grave carbon footprint values for beef and sheep meat outlined in section 4.4 would decrease by 51-56%.

Table 13. Processing GHG emissions for beef-only and sheep-only processing plants and cradle-to-grave carbon footprints using two different allocation methods (economic and mass).

	Beef	Sheep
Allocation (%)		
Economic allocation	91	92
Mass allocation	39	42
GHG emissions for <u>Processing stage only</u> (kg CO_2e / kg meat)		
Economic allocation	0.51	0.52
Mass allocation	0.22	0.23
Cradle-to-grave carbon footprint (kg CO_2e / kg meat)		
Economic allocation	21.79 - 22.08[1]	14.62 - 14.81[1]
Mass allocation	9.90 – 10.19	7.40 – 7.59

[1]a range is given to cover the variation due to the different consumer countries in the study

4.4 Post-processing and full Life Cycle

Summary:

- All post-processing stages made up only 1.7-3.0% and 5.3-6.5% of the cradle-to-grave carbon footprint for the beef and sheep supply chains, respectively.
- Shipping was a minor contributor to the total cradle-to-grave carbon footprint for the beef and sheep supply chains at only 0.8-2.8%, while all transport stages made up 0.9-3.3% of the total.
- The other main contributor of post-processing emissions was cooking at 15-57%.
- There was little variation across the range of markets studied in the cradle-to-grave carbon footprint of beef or sheep meat, at 21.7-22.0 kg CO_2e / kg meat for beef and 14.5-14.7 kg CO_2e / kg meat for sheep meat. It was lower for sheep meat than beef due to the 36% lower cradle-to-farm-gate contribution.
- The cradle-to-grave carbon footprint for the NZ beef and sheep supply chains were at the low end of the range of the limited number of other published studies for beef and sheep meat produced in overseas countries.

4.4.1 LCA of NZ beef to the USA

4.4.1.1 Post-processing stage

The post–processing stage included trucking a frozen bulk box of meat to a NZ port where it was then shipped to the USA. Once in the USA, it was trucked to a processing facility where it was minced into patties and repacked. The next step was transportation to a distribution centre where it was trucked and consumed in a fast-food restaurant. The end-of-life stage for the packaging components was also accounted for in this stage. See Appendix 1, section 8.3 for more detail.

The GHG emissions for the **post-processing stage were 0.66 kg CO_2e / kg meat,** which represented 3% of the cradle-to-grave carbon footprint. Shipping was the most important source contributing to 46% of the post-processing footprint, followed by repacking (which includes emissions from the grinding process), cooking and transport contributing 17%, 15% and 14%, respectively (Figure 5). End-of-Life and refrigeration stages made up the remaining 8% (5% and 3%, respectively)

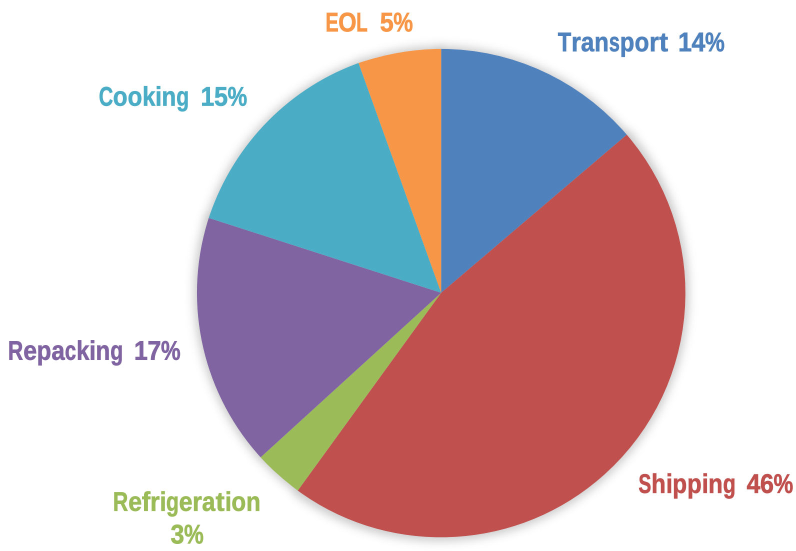

Figure 5. Summary of the contribution of different sources to the post-processing GHG emissions for NZ beef to the USA.

4.4.1.2 The total carbon footprint

The total carbon footprint (cradle to grave) of NZ beef exported to the USA was 22.08 kg CO_2e / kg meat. The cradle-to-farm-gate stage was the largest contributor to the total footprint at 95% (Figure 6 and Table 12).

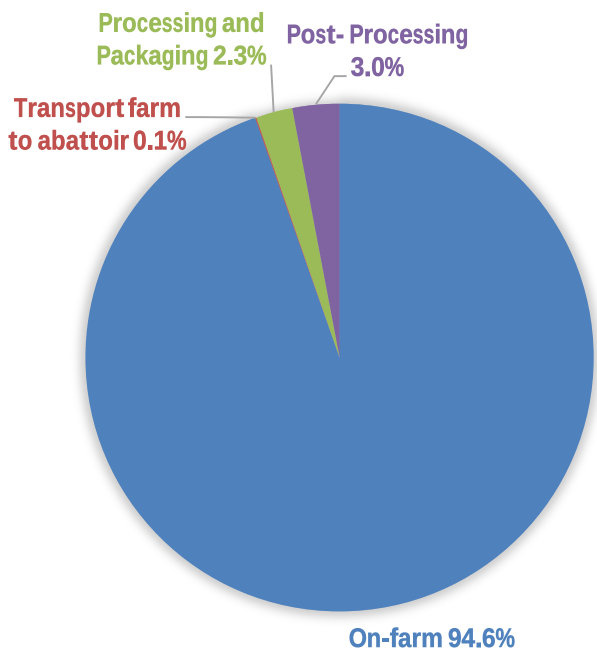

Figure 6. Relative contribution of different life cycle stages to the carbon footprint of beef produced and processed in NZ, frozen and shipped to the USA, minced, and consumed in a fast-food restaurant.

4.4.2 LCA of NZ beef to Japan

4.4.2.1 Post-processing stage

The post–processing stage included trucking NZ beef to an NZ port, where it was then shipped to Japan. In Japan, it was transported to a distribution centre where it was trucked and consumed in a restaurant. End-of-life for the packaging components was also accounted for in this stage. See Appendix 1, section 8.3 for more detail.

The carbon footprint for the post-processing stage was 0.36 kg CO_2e / kg meat. Shipping was the most important source contributing to 47% of the footprint, followed by cooking at 30% (Figure 7). Refrigeration, transport, and EOL contributed to 10%, 7% and 5%, respectively.

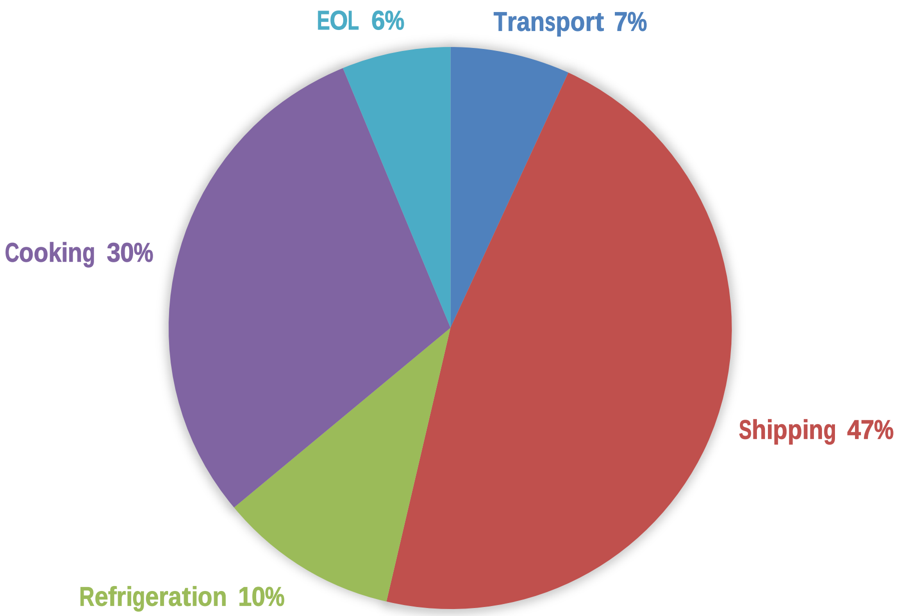

Figure 7. Summary of the contribution of different sources to the post-processing GHG emissions for NZ beef to Japan.

4.4.2.2 The total carbon footprint

This product full life cycle covered average NZ beef produced and processed in NZ, chilled, and shipped to Japan, where it was consumed in a restaurant. **The carbon footprint of the beef through this life cycle was 21.79 kg CO_2e / kg meat**. The cradle-to-farm-gate stage was the largest contributor to the total footprint at 96% (Figure 8).

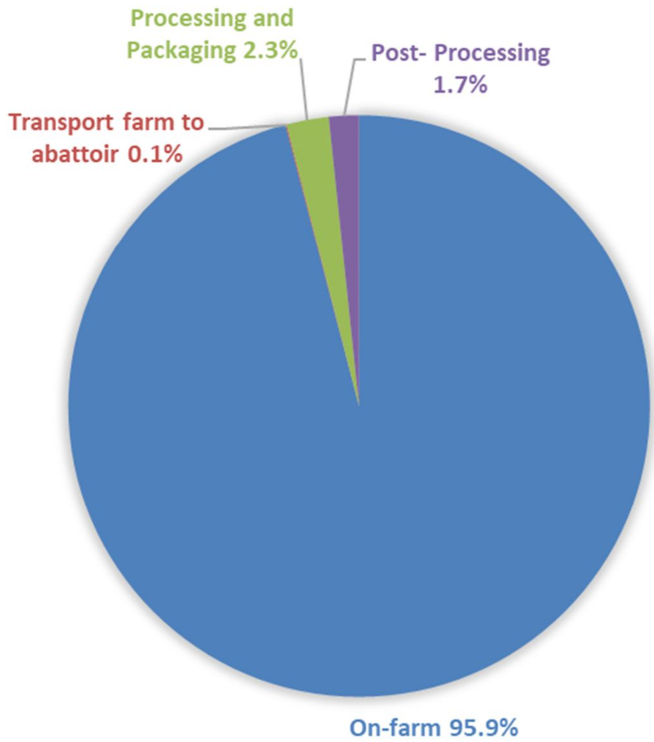

Figure 8. Relative contribution of different life cycle stages to the carbon footprint of beef produced and processed in NZ, chilled, and shipped to Japan where it was consumed in a restaurant.

4.4.3 Comparison of the carbon footprint for NZ beef with that produced in other countries

Results from this study were compared with those from other published studies. However, it is important to note that there are generally some differences in methodology and its application between studies, thereby making exact comparison difficult. Where such differences were evident, it is noted in the discussion. Some studies also differed in the GWP100 method (AR4 or AR5) and therefore, results are presented using the same method in Table 14 for comparison purposes.

The estimated carbon footprint (cradle to grave) for beef exported to both Japan and the USA (21.79 and 22.08 kg CO_2e / kg meat, respectively) were lower than that from the detailed study for average USA beef produced and consumed in the USA by Asem-Hiable et al. (2018) of 48.4 kg CO_2e / kg consumed-beef. However, the latter study accounted for various losses during processing, retail and consumer stages that were not accounted for in the present study.

When the FU in the USA study was adjusted to the same as in the present study (i.e. kg of meat), the carbon footprint equated to 35.1 kg CO_2e / kg meat (see Table 14). The higher value was largely associated with higher cradle-to-farm gate GHG emissions (Table 14). The latter included a component of dairy beef (as in the present study), but the traditional beef cattle were based on a mix of systems involving extensive breeding systems and cattle finished in feedlots.

Table 14. Summary of published beef and sheep meat carbon footprint studies with system boundaries beyond the farm and processing stages, compared with those from the current study. Results are largely based on use of GWP100 AR4, except for this study where results are given using AR4 and AR5.

Study	Country	Boundary	Farm type	Farm	Processing	Post-processing	Footprint (Total)
				kg CO_2e / kg meat			
Beef							
Lieffering et al., 2010	New Zealand	Grave (to mixed markets)	NZ average	20.10	0.50	1.68	22.30
Sanders et al., 2014	USA	up to food consumption		27.00	0.39	3.43	30.82
Wiedemann et al., 2015	Australia	up to USA warehouse	Beef grass	25.49	0.98	0.76	27.22
Wiedemann et al., 2015	Australia	up to USA warehouse	Beef medium-fed grain	21.62	0.98	0.76	23.36
Wiedemann et al., 2015	Australia	up to USA warehouse	Beef long-fed grain	23.82	0.98	0.76	25.56
Huerta et al., 2016	Mexico	up to retail	Extensive system	20.37	1.13	0.24	21.73
Huerta et al., 2016	Mexico	up to retail	Intensive system	19.87	0.25	0.48	20.60
Asem-Hiable et al., 2018	USA	Grave	Pasture + Feedlot	30.67[1]	0.59[1]	3.84[1]	35.10[1]
Vitali et al., 2018	Italy	up to food consumption	Organic beef	20.98	1.27	2.22	24.47
This study (2021)	***New Zealand***	***Grave – exported to the USA***	***NZ average***	***20.90***	***0.52[2]***	***0.66***	***22.08***
This study (2021)	***New Zealand***	***Grave – exported to Japan***	***NZ average***	***20.90***	***0.52[2]***	***0.36***	***21.79***
This study (2021)[3]	***New Zealand***	***Grave***	***NZ average***	***19.70***	***0.52[2]***	***0.36 – 0.66***	***20.59 – 20.88***
Sheep							
McDevitt et al., 2009	New Zealand	Grave (to the UK)	NZ average lamb	14.97	0.57	4.13	19.66
Lieffering et al. (2010)	New Zealand	Grave (to the UK)	NZ average mutton	13.20	0.57	4.13	17.90
Wiedemann et al., 2015	Australia	up to USA warehouse	Conventional	14.40	0.76	0.76	16.07
This study (2021)	***New Zealand***	***Grave – exported to the UK***	***NZ average***	***13.32***	***0.53[2]***	***0.96***	***14.81***
This study (2021)	***New Zealand***	***Grave – exported to China***	***NZ average***	***13.32***	***0.53[2]***	***0.92***	***14.77***
This study (2021)	***New Zealand***	***Grave – exported to the USA***	***NZ average***	***13.32***	***0.53[2]***	***0.77***	***14.62***
This study (2021)[3]	***New Zealand***	***Grave***	***NZ average***	***12.38***	***0.53[2]***	***0.77 – 0.96***	***13.69 – 13.88***

[1] Data was adjusted to a meat component equating to 40% of LW, to align with the current study; [2] Includes transport to abattoir and processing stage; [3] Emissions using AR4 (2007) GWP factors

The USA feedlot-finished cattle were finished at a higher average LW (581 kg versus 544 kg in the present study for the weighted-average for heifers, steers and bulls) and at a younger age (16 months versus 28.5 months), but required crop feed production while on the feedlot. It was not possible to distinguish between different classes of cattle and their relative contribution to the overall average carbon footprint in the USA study.

The study by Asem-Hiablie et al. (2018) had much higher post-processing GHG emissions than other studies in Table 14. This was due to several factors, including accounting for consumer travel (most studies exclude this stage due to the high uncertainty in estimating it), as well as including restaurant-related emissions beyond cooking, refrigeration and HVAC (such as infrastructure and various consumables and additional packaging). If those same post-processing emissions had been applied in the current study for NZ beef to the USA, it would have resulted in a carbon footprint of 25.2 kg CO_2e / kg meat (instead of 21.4 kg CO_2e / kg meat).

Other published beef studies in Table 14 showed carbon footprint values of 20.6-30.8 kg CO_2e / kg beef that were similar to those for the current study. While the studies varied markedly in post-processing values, the processing emissions of 0.3-1.1 kg CO_2e / kg meat included the average estimate in the current study (0.51 kg CO_2e / kg meat), and were of a similar magnitude for the cradle-to-farm-gate component at 20-27 kg CO_2e / kg meat compared to 20.2 kg CO_2e / kg meat for the current study. These other studies calculated the beef footprint using different boundaries, such as up to retail (Huerta et al., 2016), food consumption (Sanders et al., 2014; Vitali et al., 2018) or international warehouse (Weideman et al., 2015) stages, not allowing a direct comparison with the results from this study. Furthermore, all the studies mentioned above used the AR4 GWP factors, while this study used AR5 factors. Table 7 showed the impact changing the GWP values from AR5 (8.97 kg CO_2e / kg LW) to AR4 (8.46 kg CO_2e / kg LW) for the on-farm footprint. When converting the on-farm AR4 number from this report (Table 7) to the final functional unit (kg of meat), the result was 19.70 kg CO_2e / kg meat for the on-farm stage, lower than the other studies (Table 12). The final footprint using AR4 GWP factors for this study was 20.82 and 20.52 kg CO_2e / kg meat for the USA and Japan, respectively, which is at the lower end of the range when compared to the other studies (Table 12).

Similarly, the earlier NZ beef carbon footprint study (Lieffering et al., 2010) used the AR4 GWP factors, but it covered the full cradle-to-grave. When the AR4 recalculation for the current study is compared against the Lieffering et al. (2010) study, it is slightly lower (2% lower for farm stage and 7-8% lower for total footprint) for the current study.

4.4.4 LCA of NZ lamb to the UK

4.4.4.1 Post-processing stage

The post-processing stage included transport of chilled lamb to the UK, where it was stored at a distribution centre, distributed to a supermarket, purchased by a consumer, roasted, and eaten at home. The EOL of the packaging was also accounted for in this stage. See Appendix 1 section 8.3 for more detail.

The GHG emissions for the **post-processing stage were 0.96 kg CO_2e / kg meat**, which represented 3% of the cradle-to-grave carbon footprint. Shipping was the most important source contributing to 43% of the footprint, which was followed by cooking at 38% (Figure 9). Transport, refrigeration, EOL and the retail store contributed 9%, 4%, 3% and 2%, respectively.

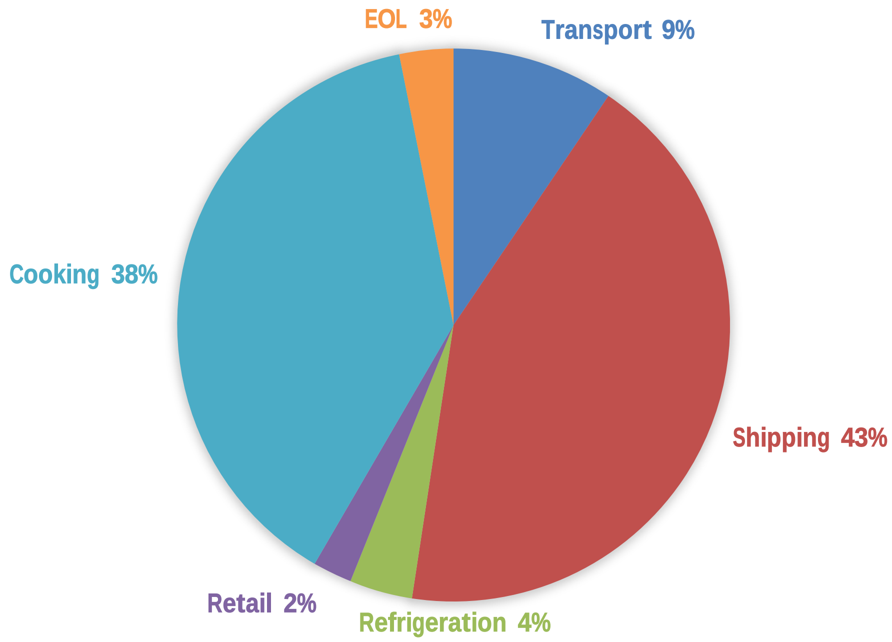

Figure 9. Summary of the contribution of different sources to the post-processing GHG emissions for NZ sheep meat to the UK.

4.4.4.2 The total carbon footprint

This product full life cycle covered average NZ lamb (or sheep meat) produced and processed in NZ, chilled and shipped to the UK where it was consumed at home. **The carbon footprint of the lamb through this life cycle was 14.81 kg CO_2e / kg meat**. The cradle-to-farm-gate stage was the largest contributor to the total footprint at 90% (Figure 10).

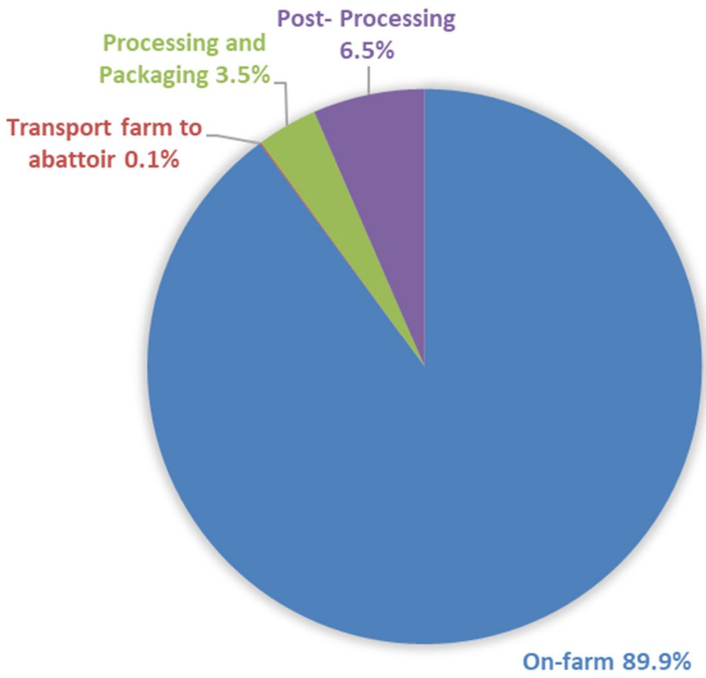

Figure 10. Relative contribution of different life cycle stages to the carbon footprint of lamb produced and processed in NZ, chilled and shipped to the UK where it was consumed at home.

4.4.5 LCA of NZ sheep meat to China

4.4.5.1 Post-processing stage

The post-processing stage included the transport of frozen sheep meat to China, where it is stored at a distribution centre and then distributed to a supermarket. It was assumed to be purchased by a consumer who took it home and cooked it using a hot-pot. The EOL of the packaging was also considered (see Appendix 1, section 8.3 for more detail).

The carbon footprint for the post-processing stage was 0.92 kg CO_2e / kg meat. Cooking was the most important source contributing 57% of the footprint, followed by shipping at 21% (Figure 11). Refrigeration, retail, EOL and transport stages contributed to 7%, 6%, 5% and 3%, respectively.

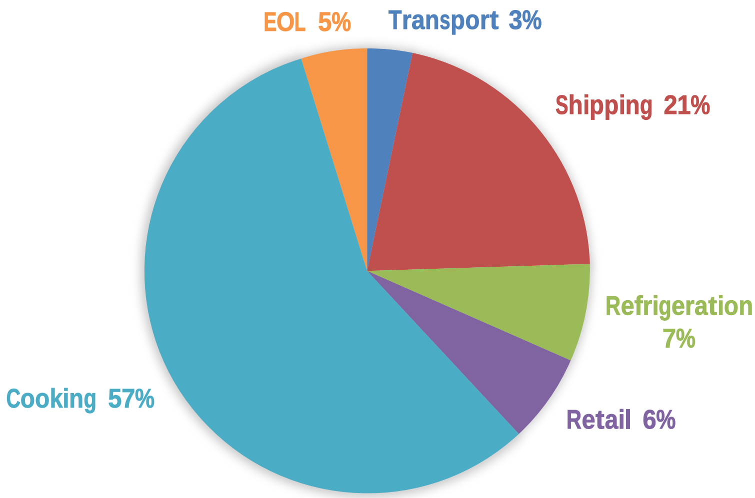

Figure 11. Summary of the contribution of different sources to the post-processing GHG emissions for NZ sheep meat to China.

4.4.5.2 The total carbon footprint

This product full life cycle covered average NZ sheep meat produced and processed in NZ, frozen and shipped to China, where it was consumed at home. **The carbon footprint of the sheep meat through this life cycle was 14.77 kg CO_2e / kg meat**. The cradle-to-farm-gate stage was the largest contributor to the total footprint at 90% (Figure 12).

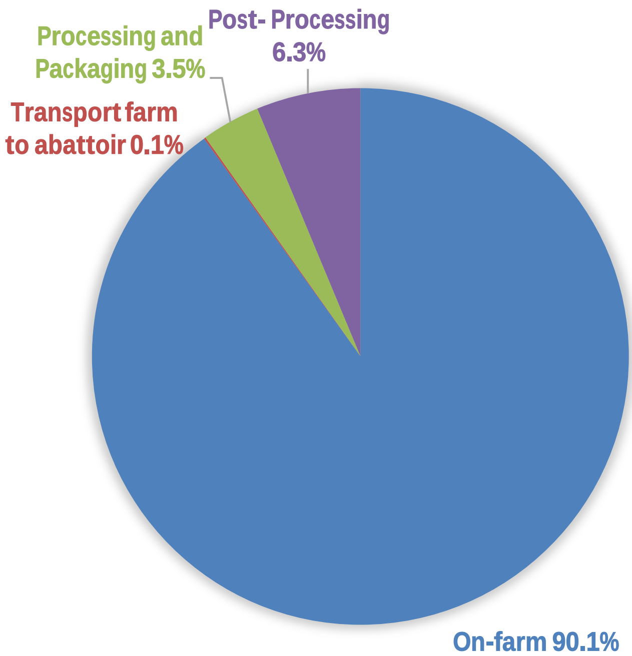

Figure 12. Relative contribution of different life cycle stages to the carbon footprint of sheep meat produced and processed in NZ, frozen and shipped to China where it was consumed at home.

4.4.6 LCA of NZ sheep meat to the USA (California)

4.4.6.1 Post-processing stage

The post-processing stage included transport of chilled sheep meat to California, where it was stored at a distribution centre and then distributed to a restaurant. The sheep meat was assumed to be roasted and the EOL of the packaging was also accounted for (see Appendix 1, section 8.3 for more detail).

The carbon footprint for the post-processing stage was 0.77 kg CO_2e / kg meat. Cooking was the most important source contributing to 55% of the footprint, followed by shipping at 26% (Figure 13). Transport, EOL and refrigeration contributed to 12%, 5% and 2%, respectively.

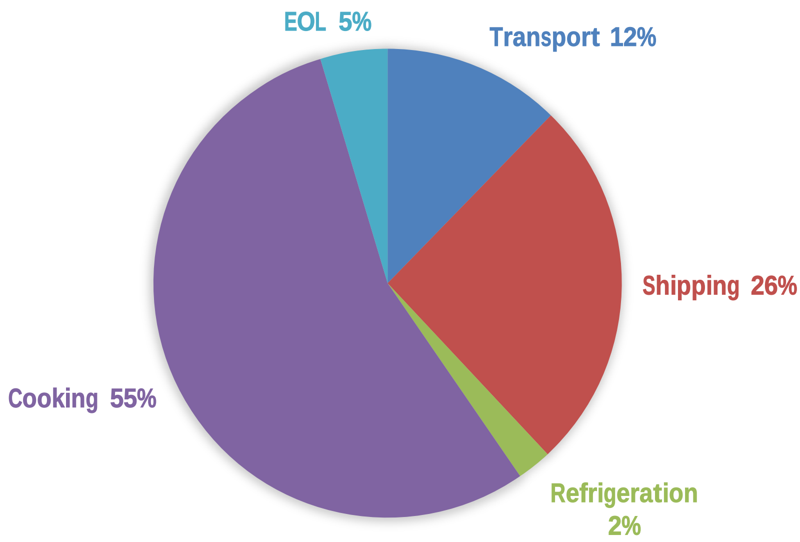

Figure 13. Summary of the contribution of different sources to the post-processing GHG emissions for NZ sheep meat to California, USA.

4.4.6.2 The total carbon footprint

This product life cycle covered average NZ sheep meat produced and processed in NZ, chilled, and shipped to California, where it was assumed to be consumed at a restaurant. **The carbon footprint of the sheep meat through this life cycle was 14.62 kg CO_2e / kg meat**. The cradle-to-farm-gate stage was the largest contributor to the total footprint at 91% (Figure 14).

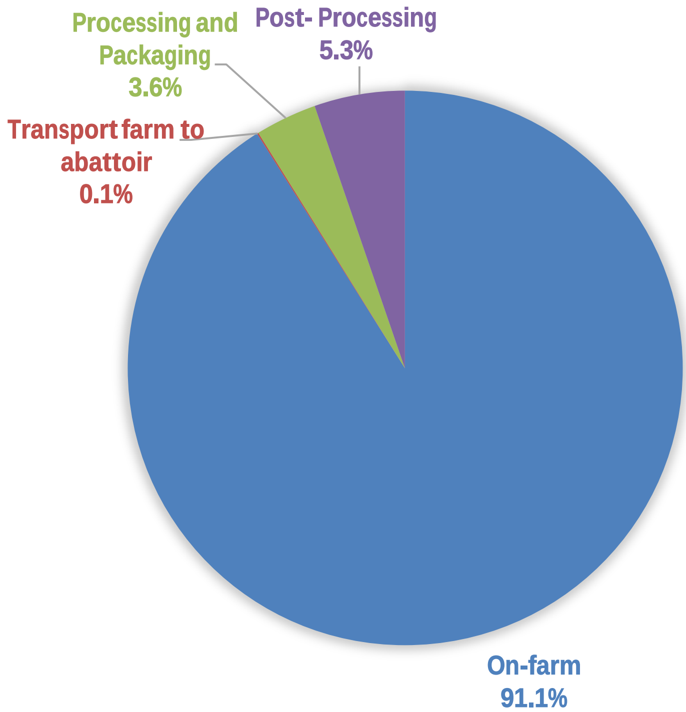

Figure 14. Relative contribution of different life cycle stages to the carbon footprint of sheep meat produced and processed in NZ, chilled and shipped to California, where it was consumed at a restaurant.

4.4.7 Comparison of the carbon footprint of NZ lamb/sheep meat with that produced in other countries

There are few other published studies for lamb and/or mutton through a full cradle-to-grave life cycle against which the results from this study can be compared (Table 14). Both of the other studies used AR4 GWP factors.

When converting the values from this study using AR4 GWP factors, the “cradle-to-grave” footprints are 13.88, 13.84 and 13.69 kg CO_2e / kg meat to the UK, China and California, respectively. These values are lower for all life cycle stages when compared with the previous NZ study using AR4 GWP factors (McDevitt et al., 2009; Lieffering et al., 2010), which had totals of 19.7 and 17.9 kg CO_2e / kg meat for lamb and mutton, respectively.

The current estimates from this study were also lower than in the Australian study of Wiedemann et al. (2015), except for the post-processing stage. However, Wiedemann et al. (2015) had the final system boundary as the warehouse at the overseas market, compared to a cradle to grave assessment in this study. If the post-processing emissions from this study were recalculated for the same boundary as Wiedemann et al. (2015) (considering transport from the processing plant to port, storage at the port, shipping, storage at overseas port, transport to warehouse and storage at the warehouse), the post-processing stage emissions would be 0.47, 0.24 and 0.23 kg CO_2e / kg meat for lamb to

UK, China and the USA, respectively. All those values are lower than the values from Wiedemann et al. (2015) of 0.76 kg CO_2e / kg meat.

Other factors that showed small differences between studies were the factors for conversion between LW and meat and the economic allocation factor. Wiedemann et al. (2105) used a meat:LW ratio of 42.7% for lamb, while the average for sheep meat in this study was 41.3%. The corresponding economic allocation values were 88.4% for Australian lamb and 91.4% for NZ sheep meat.

The carbon footprint estimates in this study are also less than the estimate from the screening study of the European Product Environmental Footprint initiative (PEF, 2019) which had a carbon footprint for lamb (based on UK, Spanish and NZ data) to the processor gate of 24 kg CO_2e/kg meat (appears to be for CW), and an estimate for typical beef of 32 kg CO_2e/kg meat (PEF, 2019). An early Swedish report (Wallman et al., 2011) provided estimates for lamb in Sweden and Norway to the post-processing stage of 16 kg CO_2e / kg CW using mass allocation. This would increase to approximately 26 kg CO_2e / kg meat if adjusted to meat and economic allocation to align with methods used in the current study.

In general, the carbon footprint for exported NZ lamb or sheep meat was lower than or similar to that for domestic production in those countries and for other countries exporting to those markets.

4.4.8 Sensitivity analysis for shipping and meat waste

A sensitivity analysis was carried out to investigate the effect of the overseas shipping. If the distance for shipping or the shipping emission factor was doubled (values used for each market are available in Appendix 1, Table A13), the footprint for the post-processing stage would increase by between 21% and 47%. In the worst-case scenario (beef to Japan), the final footprint (cradle-to-grave) would increase by 1.0% (from 21.79 to 21.95 kg CO_2e / kg meat).

A second sensitivity analysis was carried out to determine the effect of food loss or meat waste on the post-processing stage. Based on PEFCR (2018) values, 4% of meat is lost in the distribution phase (transport, storage and retail), and 11% is lost in the consumer phase. Therefore, a total of 15% of the meat can be lost in the post-processing stage. Two scenarios were estimated assuming either the meat waste was 100% landfilled or 100% industrially composted (Table 15). If the food waste were sent to landfill, the footprint of the post-processing stage would be increased by 2-4%. If the food waste were composted industrially, the footprint would be increased by 1-2% (Table 15). Considering the worst-case scenario (+4.3% increase of chilled beef's footprint to Japan – Table 13), the final footprint would change from 21.79 to 21.80 kg CO_2e / kg meat, representing less than 0.1% change.

Table 15. Effect of including 15% meat waste after consumption and applying it all to landfill or industrial composting on the post-processing GHG emissions

Product	Base footprint	100% landfill	100% industrial compost
		($kgCO_2eq$/kg meat)	
Beef			
Frozen beef to USA	0.66	0.68 (+2.3%)	0.67 (+1.2%)
Chilled beef to Japan	0.36	0.38 (+4.3%)	0.37 (+2.1%)
Sheep			
Chilled lamb to the UK	0.96	0.97 (+1.6%)	0.96 (+0.8%)
Frozen sheep meat to China	0.92	0.94 (+1.7%)	0.93 (+0.8%)
Sheep meat to California	0.77	0.78 (+2.0%)	0.78 (+1.0%)

4.4.9 Effect of the sensitivity analyses on the final footprint

Table 16 summarises the sensitivity analyses with the most significant impacts on the final footprint. The use of mass allocation (instead of economic allocation for the processing stage) had the largest impact on the beef footprint (Table 16). The new GWP* metric led to a significant reduction in the footprint for the sheep meat, mainly because of the “zero” value attributed to CH_4 due to the reduction in CH_4 emission over the last 20 years (Table 16). The combination of these sensitivity analyses would lead to further reductions (Table 16). It is important to note that the results in Table 16 are indicative of potential footprints if such metrics are applied. These alternative metrics are all currently being evaluated by international groups to consider their applicability and how they might be integrated into future LCA methods. In the meantime, the GWP100 AR5, without considering the carbon sequestration from trees and using economic allocation at the processing stage is the standard recommendation in various LCA guidelines including PEF and LEAP

Table 16. Summary of results for the carbon footprint of beef and sheep meat to overseas markets per stage of production, considering the different sensitivity analyses applied for each stage (GWP* and Carbon sequestration for the on-farm stage; Mass allocation for the cradle-to-processing stage). Values are averages for the different markets for beef (USA and Japan) and sheep meat (USA, China and UK).

	GWP100 AR5	GWP*	GWP100 AR5 + Carbon sequestration	GWP100 AR5 + Mass Allocation	GWP*+ C Sequestration	GWP*+Mass Allocation	GWP100 AR5 + C sequestration + Mass allocation	GWP*+ C sequestration + Mass Allocation
	kg CO_2e / kg meat							
Beef								
Farm	20.90	13.11	16.44	9.02	8.64	5.66	7.09	3.73
Processing	0.52	0.52	0.52	0.23	0.52	0.23	0.23	0.23
Post-processing	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
Total (average)	**21.94**	**14.15**	**17.47**	**9.76**	**9.67**	**6.40**	**7.83**	**4.47**
Sheep								
Farm	13.32	2.13	9.44	6.11	-1.75	0.98	4.33	-0.80
Processing	0.53	0.53	0.53	0.24	0.53	0.24	0.24	0.24
Post-processing	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
Total (average)	**14.73**	**3.54**	**10.85**	**7.23**	**-0.34**	**2.10**	**5.45**	**0.32**

5. Conclusions

This life cycle assessment study showed that the main emission of GHGs for both beef and sheep product systems occurred within the “cradle-to-farm gate” boundary (90 to 95% of total life cycle emissions). The farm stage was dominated by animal-related enteric methane and excreta nitrous oxide emissions (69-76% and 6-10% of the life-cycle total, respectively). Meat processing contributed 2-4% of the carbon footprint, while post-processing was 2-6%.

For NZ beef, the GHG emissions for the on-farm stage were at the low end of the published range. The results were influenced by the contribution of dairy beef, that showed a lower footprint than traditional beef. Sheep meat had lower emissions compared with beef for the on-farm stage, due in part to the fact that 30% of the emissions were allocated to the co-product wool. However, sheep meat had a greater bone component in the exported meat than for beef which was largely boneless. The carbon footprint of sheep meat was less than in other studies that have been published.

A number of additional sensitivity analyses were performed on cradle-to-farm gate data, including evaluation of the effects of including carbon sequestration associated with trees on farm and the use of the GWP* metric. Both of the analyses showed a strong effect on the emissions for the on-farm stage, but this result should be treated carefully, since as yet there is no international agreement on how to use these factors in footprint calculations. Nevertheless, the net carbon sequestration estimates indicate that trees/shrubs within sheep and beef farms could equate to a reduction in carbon footprint of traditional beef and sheep equivalent to about 30%.

National sheep and beef data over the past 20-years indicate that sheep methane emissions have declined by one-third while traditional beef have shown little change. When this data was used in the GWP* approach the dominant animal methane component of the “standard carbon footprint” declined greatly for sheep. Further research internationally is required to get an agreement on how this can be integrated into carbon footprint estimates.

The meat processing stage represented only 2-4% of the total carbon footprint of beef and sheep meat. This may be an underestimate for sheep plants (where only four plants provided primary data), but the effect on the total carbon footprint of sheep meat would be small (<1%). However, the use of mass allocation at the processing stage led to a significantly lower footprint (by 51-56%) compared to that estimated using the currently recommended economic allocation method.

Shipping represented 1-4% of the total carbon footprint. Thus, despite the long shipping distances sometimes involved, this study indicated that NZ beef and sheep meat supplied to widespread international markets have a full life-cycle carbon footprint at the lower end of the range of other published estimates.

It is important to note that when comparisons are made between different types of food, the functional unit should reflect the nutritional aspect of the food. In this case, nutritional indexes (instead of kg weight) would be preferable. However, based on consultation with nutrition experts from the Riddet Institute and AgResearch, it was concluded that the use of nutritional indices that don’t acknowledge the nutrient bioavailability and/or protein quality are not recommended for the comparison between different categories of food (e.g. meat versus vegetables). More extensive nutrient profiling needs to be conducted to assess the relationship between a nutritional index and the footprint associated with different protein alternatives.

6. Acknowledgements

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8. APPENDIX 1. Detailed GHG Methodology

The life cycle was divided into two steps: on-farm (cradle to farm-gate) and post-farm (processing to end-of-life).

8.1 On-farm model:

An important and typically dominant part of the life cycle is the cradle-to-farm-gate, common across all product systems (see Figure A1). This typically involves a number of components, and sometimes animals are reared on one farm but may be purchased and finished on another farm. Additionally, for beef, there is an important contribution from dairy farms from cull cows, heifers and surplus calves. At the farm-gate, the reference unit leaving the farm is one kg live-weight (LW), and for sheep, a co-product is one kg greasy wool.

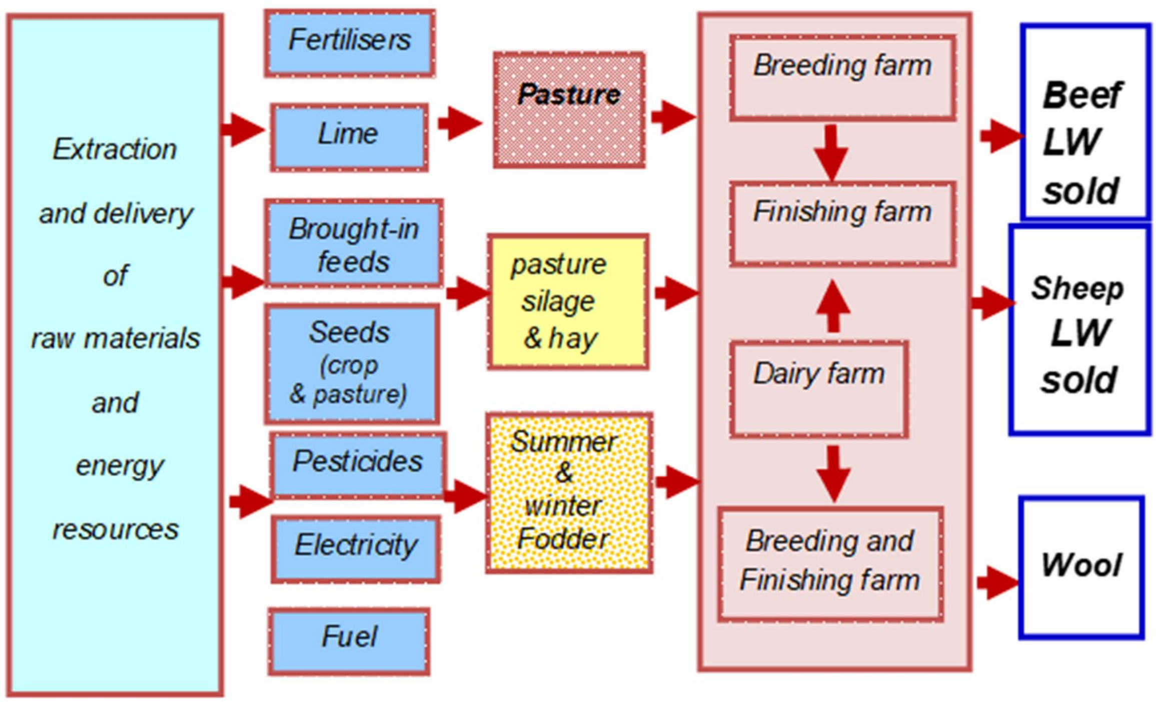

Figure A1. System boundary of the cradle-to-farm-gate life cycle stage

8.1.1 Processes for the cradle-to-farm-gate life cycle stage

The main inputs and outputs related to the production of sheep and cattle for meat processing that leaves the farm gate (see Figure A1) can be summarised as follows:

Inputs:

Feed (pasture and supplementary feeds)

Agrichemicals (mineral fertilisers and pesticides) for feed production

Animals for meat production

Energy (fuel and electricity)

Outputs:

Sheep or cattle sold for meat processing

Wool from sheep

Emissions

8.1.2 Processes excluded from the system boundary

Minor agri-chemicals, such as for treating for intestinal and external parasites, were not accounted for in the carbon footprint assessments.

8.1.3 Modelling approach

This carbon footprint analysis used an attributional approach and average data for all processes.

8.1.3.1 Allocation at the farm

The allocation of GHG emissions between sheep and cattle were based on the relative feed DM intake by each animal type, according to recommendations in the Livestock Environmental Assessment and Performance (LEAP) partnership guidelines (FAO, 2015a,b). However, prior to this allocation, specific activities clearly associated with only one animal type (e.g. for shearing and chemicals for fly-strike treatment of sheep) were explicitly assigned to that animal type.

The impacts of GHG emissions between the sheep co-products of LW sold for meat and wool were allocated according to a biological causality, based on the physiological feed requirements of the protein production. The LEAP partnership guidelines method of protein mass allocation was used based on the relative amounts of LW and wool sold from the sheep farm system (FAO, 2015a). This resulted in allocation values for meat relative to the total of meat+wool of between 64% and 69%, varying with analysis scenario and production year.

8.1.3.2 Data Quality

The technical description of sheep and beef farm systems and outputs studied here relied mainly on two independent and reliable sources of information; the Beef + Lamb New Zealand Economic Service farm class survey data (Beef+LambNZ, 2019) and StatsNZ (2020) data on national animal slaughter statistics. DairyNZ/LIC annual statistics (DairyNZ/LIC, 2019) were also used for dairy cattle data.

Beef + Lamb New Zealand statistics covers an annual survey of over 500 NZ sheep and beef farms (540 farms for 2017/18) and provide a comprehensive summary of animal productivity and all farm practices and inputs. Data relating to dairy farm systems in NZ and the carbon footprint of milk and LW sold for meat (from cull cows and surplus calves) has been studied in detail for about a decade and was recently published (Ledgard et al., 2020).

The calculation of GHG emissions covering methane (CH_4) from enteric fermentation, CH_4 and nitrous oxide (N_2O) from excreta deposited on pasture, N_2O from N fertiliser, and carbon dioxide (CO_2) emissions from lime and urea application were based on IPCC and NZ GHG Inventory methodologies (MfE, 2020).

Secondary data from the international ecoinvent database (Wernet et al., 2016) was used in cases where primary data was unavailable and adapted as much as possible to the NZ situation for the carbon footprint of various minor inputs as pesticides, electricity and fuel.

8.1.4 Life Cycle Inventory Data

The first key requirement was determining the output of products from NZ-average farm production systems, including from over 23,000 sheep and beef farms across NZ (Beef+LambNZ, 2019), i.e. sheep LW sold for meat processing, wool and beef cattle LW sold for meat processing. For beef processing, it also needed to account for cattle LW sold for meat processing from over 11,000 dairy farms in NZ, i.e. cull dairy cows and heifers, as well as surplus calves (DairyNZ/LIC, 2019).

8.1.4.1 Description of NZ average sheep and beef farm systems

The estimation of the NZ-average production of sheep LW, wool and cattle LW sold for processing was carried out using two main approaches. The first involved producing a reconciliation of all sheep and cattle on NZ sheep and beef farms for 2017/18 (and for 1998/99 and an average of 2016-2020) linked to the number of sheep and cattle sold for meat processing and accounting for animal deaths. The second approach involved using Beef + Lamb New Zealand farm survey data (Beef + Lamb New Zealand Economic Service 2019, covering 530 farms) for their farm class 9. This represents a weighted average of data for the eight different farm class categories from across NZ (South Island high country, South Island hill country, South Island finishing/breeding, South Island intensive finishing, North Island hard hill country, North Island hill country, North Island intensive finishing).

8.1.4.2 National stock reconciliation for sheep

The base set of animal numbers were obtained from StatsNZ Animal Production Statistics (StatsNZ 2020), i.e. total number of breeding ewes and total lambs marked/tailed. The number of sheep from different types (i.e. cull ewes, rams, wethers, hoggets and lambs) that were slaughtered by meat processors was also obtained from StatsNZ. The proportion of sheep deaths for each type was based on typical values from Beef + Lamb New Zealand Economic Service data, with minor changes as required to ensure balancing of numbers using the base StatsNZ data noted above. This data was used to construct a monthly stock reconciliation with year-start (1 July 2017) to year-end (30 June 2018), with total numbers balancing (Table A1). For simplicity, sheep deaths within each type were assumed to occur at one time in the middle of the year, rather than spreading them throughout the year.

Table A1. Summary of sheep data for New Zealand sheep and beef farms based on StatsNZ data for 2017/18 and B+LNZ data for typical death rate.

	Numbers at 1 July plus lambs	Number slaughtered	Deaths (%)	Slaughter weight (kg/head)
Breeding ewes	17,541,053	3,594,752	3.5	25.7
Ewe hogget replacements	4,342,316	-	3.1	-
Total lambs (marked/tailed)	24,707,163	19,883,728	2.5	19.0
Wethers	214,972	214,972	-	25.9
Wether hogget replacements	221,282	-	2.9	-
Hoggets	239,541	239,541	-	25.3
Rams	274,231	28,963	5.0	34.2
Ram hogget replacements	65,599	-	3.6	-

Average sheep slaughter weights were also obtained from StatsNZ data, with average LWs for mature ewes (66 kg) and rams (79 kg) from the same data adjusted for killing-out percentage and compared against Beef + Lamb New Zealand data. Three different sale dates for the slaughter of lambs were used (30% after weaning at end January, 50% at end-of-April and 20% as late lambs in end-August at one-year-old). A sensitivity analysis was also carried out using a single average (based on NZ slaughter statistics) of end-April, as well as data from the AbacusBio model with a pattern of slaughter spread over all months. A single slaughter date (end-December) was used for other sheep based on the weighted average of slaughter statistics from StatsNZ.

For 1998/99, the same data sources were used. Some of the main differences relative to 2017/18 were the much larger sheep numbers, particularly for ewes (lambing % was lower), and the lower slaughter weights (Table A2). For 2016-2020, the data was similar to that for 2017/18, with slaughter weights being the same (Table A3).

Wool production was based on average data from Beef + Lamb New Zealand Economic Service for Farm class 9 and scaled up according to sheep numbers.

Table A2. Summary of sheep data for New Zealand sheep and beef farms based on StatsNZ data for 1998/99 and Beef + Lamb New Zealand data for typical death rate.

	Numbers at 1 July plus lambs	Number slaughtered	Deaths (%)	Slaughter weight (kg/head)
Breeding ewes	30,364,253	4,582,295	3.5	22.6
Ewe hogget replacements	5,823,034	-	3.1	-
Total lambs (marked/tailed)	31,161,111	24,600,131	2.5	15.6
Wethers	273,889	273,889	-	22.6
Wether hogget replacements	281,923	-	2.9	-
Hoggets	231,451	231,451	-	21.2
Rams	485,052	34,122	5.0	29.6
Ram hogget replacements	60,548	-	3.6	-

Table A3. Summary of sheep data for New Zealand sheep and beef farms based on StatsNZ data for 2006-2020 and B+LNZ data for typical death rate.

	Numbers at 1 July plus lambs	Number slaughtered	Deaths (%)	Slaughter weight (kg/head)
Breeding ewes	17,644,306	3,553,435	3.5	25.7
Ewe hogget replacements	4,304,785	-	3.1	-
Total lambs (marked/tailed)	31,161,111	24,376,032	2.5	19.0
Wethers	212,392	212,392	-	25.9
Wether hogget replacements	218,702	-	2.9	-
Hoggets	235,182	235,182	-	25.3
Rams	268,144	31,031	5.0	34.2
Ram hogget replacements	46,050	-	3.6	-

The Beef + Lamb New Zealand Class 9 data represented an alternative dataset to estimate national sheep data on total feed intake and GHG emissions. Detailed data from Class 9 were obtained from Beef + Lamb New Zealand Economic Service. The Beef + Lamb New Zealand statistics represent a survey of farms for each of the main farm types across NZ, with surveyed farm numbers in 2017/18 representing over 500 commercial sheep and beef properties in NZ.

The survey sheep data was modified to exclude any minor numbers of purchased store sheep so that it represented a “self-contained” system, thereby better representing the national flock. Small variation between year-start and year-end total numbers was overcome by determining the average and balancing for the same start and end total numbers. The lambing % values were adjusted to align to Beef + Lamb New Zealand Economic Service average data. Estimates of wool production and wool sales were based on achieving the same per-animal type data as in the original farm files.

Sheep slaughter weights were derived directly from the Class 9 summary, while the age of slaughter animals was based on the use of Farmax modelling of the system to fit with expected growth rates, except that late-season lambs were based on actual data for hoggets and wethers.

8.1.4.3 National stock reconciliation for beef cattle

The approach used was the same as described for sheep. Cattle numbers for breeding cows + heifers and the calves born alive to cows + heifers (equating to 87% calving) were derived from StatsNZ Animal Production Statistics (StatsNZ 2020) (Table A4). Numbers of cattle slaughtered for different cattle types were also based on StatsNZ data, except for the category ‘cows’ where numbers could not be reconciled thereby resulting in a lower proportion slaughtered than apparent from StatsNZ data. The proportion of cattle deaths for each type was based on typical values from Beef + Lamb New Zealand Economic Service data, with minor changes as required for balancing numbers.

A key assumed productivity parameter was a 20% replacement rate for breeding cows (based on industry experts and considered to be within the range of 17-23% (Sise et al., 2020). The total number of calves from beef breeding cows, as noted above, was used to define the numbers available for finishing, after subtraction of the number of replacement heifers required to account for the cow replacement rate. Then, by difference (and adjusting for typical death rates from Beef + Lamb New Zealand Economic Service data), the number of heifers and steers from the dairy sector was calculated as required to achieve the defined total number of finishing heifers and steers slaughtered. These dairy-derived cattle were assumed to be from surplus dairy calves (some of which will have been from dairy cows mated to beef-breed bulls) that were reared (details defined later) to 100 kg weaning weight and brought into sheep and beef farm systems on 1st December. Similarly, surplus dairy bull calves (e.g. many as Friesians) were assumed to be sourced from the dairy sector and reared to 100 kg before being taken to finishing on sheep and beef farms. It was assumed that all bulls slaughtered were from dairy-derived cattle, except for the mature breeding bulls slaughtered, thereby constituting 95% of all bulls slaughtered.

Table A4. Summary of cattle data for New Zealand sheep and beef farms based on StatsNZ data for 2017/18 and Beef + Lamb New Zealand data for typical death rate.

	Numbers at 1 July plus calves	Number slaughtered	Deaths (%)	Slaughter weight (kg/head)
Breeding cows (2yr+)	1,029,149	169,810	3.5	228
Heifer replacements	212,958	-	3.3	-
Farm-born heifer calves	449,119	-	1.9	-
Purchased dairy heifer calves	237,869	-	3.0	-
Heifers 1yr	458,360	-	2.0	-
Heifers 2yr	449,193	444,701	1.0	247
Farm-born steer calves	427,406	-	1.0	-
Purchased dairy steer calves	136,793	-	2.2	-
Steers 1yr	556,202	-	1.9	-
Steers 2yr	545,635	535,268	1.9	314
Purchased dairy bull calves	543,078	-	3.0	-
Bulls 1yr	526,786	-	2.0	-
Bulls 2yr	516,250	516,250	1.0	305
Breeding bulls	43,318	20,858	1.5	378
Bull replacements 1yr	21,498	-	1.5	-
Bull replacements 2yr	21,176	-	1.5	-
Farm-born bull calves	22,385	-	3.0	-

Average cattle slaughter weights were also obtained from StatsNZ data, with average LWs for mature cows (450 kg) and bulls (700 kg) from the same data adjusted for killing-out percentage and rounded up to align to Beef + Lamb New Zealand data. A single average sale date for the slaughter of each cattle type was assumed based on the monthly pattern of cattle slaughtered from StatsNZ data to derive the weighted-average mid-point date. This resulted in average age at slaughter for heifers, bulls and steers of 28, 29 and 32 months, respectively. Sensitivity analysis of these ages was also examined and compared with ages used in the NZ GHG Inventory (24 months for all cattle classes) and by Sise et al. (2020) which covered a spread of ages.

National data on total cattle carcass weight was used from StatsNZ (2020), and also being used to define the number of cull cows, cull heifers and surplus calves ('bobby' calves) derived from the dairy sector.

For 1998/99, the same data sources were used. Some of the main differences relative to 2017/18 were the larger numbers of traditional cattle but a smaller number of calves purchased from dairy farms (associated with the smaller dairy cattle population), and the lower slaughter weights (Table A5). For 2016-2020, the data was similar to that for 2017/18 with 4% lower number of breeding cows (2+years) and slaughter weights being the same (data not presented).

Table A5. Summary of cattle data for New Zealand sheep and beef farms based on StatsNZ data for 1998/99 and Beef + Lamb New Zealand data for typical death rate.

	Numbers at 1 July plus calves	Number slaughtered	Deaths (%)	Slaughter weight (kg/head)
Breeding cows (2yr+)	1,457,413	240,473	3.5	192
Heifer replacements	298,611	-	2.4	-
Farm-born heifer calves	582,965	-	1.9	-
Purchased dairy heifer calves	165,190	-	3.0	-
Heifers 1yr	433,512	-	2.0	-
Heifers 2yr	424,842	420,594	1.0	219
Farm-born steer calves	552,922	-	1.0	-
Purchased dairy steer calves	87,900	-	2.2	-
Steers 1yr	634,293	-	1.9	-
Steers 2yr	622,242	610,419	1.9	299
Purchased dairy bull calves	358,118	-	3.0	-
Bulls 1yr	347,374	-	2.0	-
Bulls 2yr	340,427	340,427	1.0	294
Breeding bulls	60,726	28,237	1.5	294
Bull replacements 1yr	30,043	-	1.5	-
Bull replacements 2yr	29,592	-	1.5	-
Farm-born bull calves	30,972	-	3.0	-

The same source of Beef + Lamb New Zealand Class 9 data as described for sheep was used for cattle. The survey cattle data was modified to represent a “self-contained” system by excluding purchased store cattle, and total cattle numbers were balanced at year-start and year-end.

Cattle slaughter weights were derived directly from the Class 9 summary, while the age of slaughter animals was based on the use of Farmax modelling of the system to fit with expected growth rates. A component (10%) of early-sale steers (before winter at 21 months) was used according to Class 9 data, with the remaining 90% sold at 30 months age. The average age at slaughter for heifers and bulls was 26 and 32 months, respectively. These ages were based on estimated growth rates (from Farmax) to achieve the national-average slaughter weight and achieving similar average ages to that for the national slaughter data (StatsNZ 2020).

One limitation of farm survey data is that it represents animal population numbers for different animal types that may not reflect a stable/balanced system, e.g. some farms may be decreasing or increasing numbers, changing stock policy, and/or adjusting for variation in feed supply by selling or buying animals. For evaluation of national average data, it is preferable that animal populations reflect a balanced system, e.g. with replacement breeding animals aligning to the average replacement rate of mature ewes/cows (determined by culling rate and deaths) (e.g. FAO, 2015a,b). Consequently, for the two approaches where national data were used, the numbers were adjusted where required to achieve a balance between year-start and year-end numbers and so that the increasing age groups led to the final expected numbers for mature replacements or for finishing animals (e.g. 2-3 year-old steers, bulls and heifers). Thus, it fully accounted for all breeding animals required to produce finishing animals for meat processing, with the latter matching national slaughter statistics (StatsNZ 2020).

8.1.4.4 NZ-average farm system and farm input data

Beef + Lamb New Zealand Class 9 farm information from the survey farms was used to define the average NZ farm system and inputs to that system. The total farm area was adjusted down to account for a small area for cash crop and for areas used for grazing dairy cattle, deer and goats. The intake from these animal types was estimated to equate to 6.9% of total feed intake on farm. For simplicity, it was assumed that these animals would be grazed on a particular part of the farm and therefore the assumed effective farm area was decreased by 6.9% to represent the land used for beef and sheep production. This resulted in an effective farm area of 626 ha for sheep and beef cattle (Table A6). Data on fertiliser inputs are also given in Table A6. Note that inputs of additional sulphur (4 kg/ha/year) and magnesium (0.6 kg/ha/year) were also accounted for. Data were obtained on the relative areas of fertilisers and lime applied by aeroplane, and the fuel requirements for aerial application were accounted for. Survey data indicated that 1.6% of the land area had pasture renewal and analyses accounted for the residue-N_2O, new pasture seed production, and energy emissions associated with pasture renewal.

Direct fuel use data based on expenditure was used, and with data from the average price per litre over the year was used to calculate fuel use. In addition, the fuel associated with specific activities for pasture conservation, crop establishment and harvest were accounted for. Data on the proportion of fertiliser spread by contractors was obtained from Class 9 data and included in estimates of total fuel use. Pesticide applications were assumed to be carried out by contractors. Indirect fuel use for pasture seed production for pasture renovation was included based on data from a separate LCA study on total energy use and emissions from grass and clover seed production.

Similarly, electricity use was estimated based on expenditure on electricity use, which includes electricity for general home use and therefore will be an overestimate. Annual or biennial shearing will account for an important part, but no attempt was made to differentially allocate it since it was a relatively small overall contributor to total GHG emissions. Fuel requirements for contract shearers was accounted for and assigned specifically to sheep.

Table A6. Farm system data for the NZ average Class 9 farm for 2017/18, as a weighted average for NZ sheep and beef cattle farms (Beef + Lamb New Zealand Economic Service 2020).

Farm system parameter	Units
Effective area (ha; for sheep and beef cattle)	626
Area in summer crop (ha; assumed as brassica)	5
Area in winter crop (ha; assumed as brassica)	18
Area used for silage/hay making (ha)	22
Sheep stock units	2,475
Cattle stock units	1,578
Fertiliser nitrogen (kg N/ha/year; assumed as urea, or DAP to crops)	12.1
Fertiliser phosphorus (kg P/ha/year; assumed as superphosphate)	11.4
Fertiliser potassium (kg K/ha/year; assumed as KCl)	4.9
Lime (kg/ha/year)	42
Electricity use (kWh)	11,197
Direct diesel use (L)	4,240
Direct petrol use (L)	1,520
Aviation fuel use (L)	850

Data on total use of herbicides and pesticides were obtained from a 2005 national summary (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 areas treated. 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).

Indirect emissions from background processes were accounted for. For example, this included the emissions from the production and transport of inputs to the farm, such as fertilisers, lime, pesticides, pasture and crop seed production. Emissions from fertiliser production and transportation (including from country where raw constituents were obtained) were based on data from NZ fertiliser manufacturers and reported in Ledgard and Falconer (2019).

8.1.5 Animal feed intake model

8.1.5.1 Dry Matter Intake

The dry matter intake by animals was estimated using the NZ GHG Inventory model (MfE 2020). 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. Dry matter intake was estimated by calculating the energy required for maintenance, growth, gestation, lactation, and grazing (MJ metabolisable energy [ME] per day) and dividing this value by the energy concentration of the diet consumed (MJ ME per kg dry matter) based on monthly average values (MfE, 2020).

The intake model from the NZ GHG Inventory described above was used for each farm class or national dataset by entering monthly data on animal numbers (split into different animal types and ages), production status/type (e.g. mature versus growing, pregnant, lactating, male or female), animal LWs and by adjusting the feed quality (ME, digestibility and N concentrations), on a monthly basis to account for all feed supplements or forage crops used in addition to pasture. Apportioning of supplementary feeds between months was based on expertise within AgResearch (but would have a negligible impact on GHG estimates).

8.1.5.2 N excreted

The N excreted by animals was calculated using the NZ inventory methodology, which was based on principles in the OVERSEER® nutrient budget model (Wheeler et al., 2003). Dry matter intake was determined based on the method outlined previously. This was then multiplied by the average NZ diet-N concentration (from a review of data for the NZ inventory) to calculate N intake. Average values for pasture of 3.0% N were used based on the NZ GHG Inventory (MfE, 2020), while specific average values for forage crops were based on NZ average data from samples submitted to a major NZ laboratory. The N in the net gain in meat and wool (based on the NZ inventory) was subtracted from the total N intake to calculate the amount of N excreted.

8.1.5.3 Methane and nitrous oxide emissions

Methane emissions from enteric fermentation were calculated from the product of energy and dry matter intake by animals using the NZ Inventory model and the IPCC-NZ emission factors (MfE, 2020).

Direct N_2O emissions were calculated by multiplying N inputs from excreta-N and fertiliser-N by specific NZ emission factors corresponding to the fraction emitted to the atmosphere as

N_2O based on values from national research and used in the NZ GHG Inventory. Direct N_2O emissions from forage crop residues and pasture residues associated with pasture renewal were calculated using the default methodology from IPCC (2006). Indirect N_2O emissions from excreta-N and fertiliser-N were calculated using the IPCC-NZ N source and emission factors (MfE, 2020).

8.1.5.4 CO_2 emissions from lime and urea application

Direct CO_2 emissions from lime and urea application to soils were calculated according to the default IPCC emission factor (IPCC, 2006). The carbon dioxide absorbed by plants was not considered since we assumed that it is in equilibrium with losses from the grazing cycle and plant respiration.

8.2 Processing plant model

A processing model was developed to integrate all inputs and estimate GHG emissions from the meat processing plants. The activities modelled included processing energy, use of consumables, packaging and waste treatment (solid and water).

8.2.1 Allocation at the processing plant

For cattle and sheep, data was obtained from Beef + Lamb New Zealand on the average economic returns for meat, hides, renderable material and other co-products based on a five-year average (2106-2020) of Free on Board (FoB) NZ prices exported (Tables A7 and A8). While tallow and meat meal prices were available for rendered material, the rendering stage involves further processing and energy use. Therefore, a relative price based on that received by meat processing companies was used since all processors surveyed sent their renderable material off-site to secondary processors. For sheep meat, it was difficult to differentiate minor co-products of rendered material, inedible offal and others and so a single estimate only was made. A weighted average for beef was estimated based on the relative weights of traditional and dairy beef based on the relative LW processed (65:35). Weighted-average sheep meat was estimated based on the relative weights of lamb and mutton processed (from NZ slaughter statistics for 2016-2020) of 0.786 and 0.214, respectively.

Table A7. Average five-year (2016-2020) data on the mass and economic returns for co-products from beef based on Free-on-Board NZ export prices (source: Beef + Lamb New Zealand), except for renderable material which was based on estimated abattoir return. A weighted-average refers to the relative weights of traditional and dairy beef LW of 0.65 and 0.35, respectively.

	Traditional beef		Dairy beef		Weighted-average	
	Economic	Mass	Economic	Mass	Economic	Mass
	%					
Meat	91.4	40.5	89.1	36.0	90.6	39.0
Hide	5.1	6.0	6.5	7.0	5.6	6.3
Rendered material	1.0	32.0	1.3	35.0	1.1	33.0
Other co-products	2.5	21.5	3.1	22.0	2.7	21.7

Table A8. Average five-year (2016-2020) data on the mass and economic returns for co-products from lamb and mutton based on Free-on-Board NZ export prices (source: Beef + Lamb New Zealand). A weighted average refers to the relative weights of lamb and other sheep LW processed of 0.77 and 0.23, respectively.

	Lamb		Mutton		Weighted-average	
	Economic	Mass	Economic	Mass	Economic	Mass
	%					
Meat	92.7	41.5	87.4	40.8	91.5	41.3
Hide	2.1	6.9	4.5	6.2	2.6	6.7
Slipe wool	0.9	1.7	0.9	1.4	0.9	1.6
Rendered material	0.9	36.1	1.1	39.3	0.9	36.8
Other co-products	3.4	13.8	6.1	12.3	4.0	13.5

[1] includes mix of rendered material and inability to split between mutton and lamb

8.2.2 Data Quality

Survey template forms were sent to multiple processors across NZ by MIA to obtain data on inputs, wastewater, wastes and animals processed. Completed forms were received back from seven beef cattle processors and four sheep processors. Most data received was complete, with some having to be confirmed, which appeared to be at extremes relative to data from other companies. In several cases, no data was received and, in that case, the average across all other processing plants per kg carcass weight was assumed.

8.2.3 Inventory data

Energy use in processing the live animal to a finished product was determined from the meat processing plant survey data. The forms of energy (and their emission factors) are described in Table A9.

Table A9. Emission factors for different sources of energy (from Ecoinvent processes using NZ-specific data)

Energy source	Unit	EF (kg CO_2 / Unit)
Electricity	kWh	0.14
Natural Gas	kWh	0.60
Fuel	kWh	0.91
Coal / Lignite	kWh	1.29
Coal / Lignite	kg	2.59
LPG	kg	0.54
LPG	kWh	3.14

The emissions associated with the manufacture and disposal of consumables such as aprons, gloves, paper towels, weasand clips, bungs and cleaning chemicals were calculated based on detailed lists provided by a number of processing plants. It was assumed that all the disposable gloves used were nitrile and aprons made from PVC (supported PVC coated nylon). Weasand clips and bungs are both made of plastic (polypropylene - PP). The sanitiser material was divided for each different task (water treatment, processing). It was assumed that all the consumables were transported from a manufacturing plant 30 km away by truck (EF: 0.092 kg CO_2e per tkm). Emission factors for each consumable were estimated using modified Ecoinvent processes (data not presented). Data on use of fuels (petrol, diesel, oils) at the plants were also obtained by the processing plant survey. The EFs for production and combustion of each fuel type is described in Table A10.

Table A10. Emission factors for different fuels (from Ecoinvent processes using NZ-specific data)

Fuel	Unit	EF (kg CO_2 / Unit)
Petrol	L	2.76
Diesel	L	3.14
Oil	L	0.74

The consumables related to the packaging stage were mainly cardboard, plastic, strappings and cling film. The energy consumed for the packaging stage was assumed to be reported as total energy from the processing plant.

The GHG emissions associated with processing wastewater treatment were calculated based on the NZ Inventory, following the EF from Cardno (2015) (44.7 kg CO_2e per CW for CH_4 and 2.8 kg CO_2e per CW for N_2O).

The survey also collected data for solid waste treatment. Each waste was classified by its final destination (recycling, landfilling or composting), and specific emission factors were used for each strategy and composition of the waste (Table A11 – MfE, 2020). In the case of the landfilling, it was also considered if the landfill recovered gas (CH_4). It was assumed that the waste was sent to the nearest landfill or recycling unit (data obtained from the NZ Inventory and Google Maps). If the waste was composted, it was assumed that the composting was made in the site, with no transportation associated.

Table A11. Emission factors for solid waste, depending on the destination (MfE, 2020)

Material	Gas Recovery	Unit	EF (kg CO_2 / Unit)
Landfill - Food	Yes	kg	0.299
Landfill – Paper	Yes	kg	0.797
Landfill – Wood	Yes	kg	0.856
Landfill – Other	Yes	kg	0
Landfill - General	Yes	kg	0.311
Landfill - Food	No	kg	1.125
Landfill – Paper	No	kg	3
Landfill – Wood	No	kg	3.225
Landfill – Other	No	kg	0
Landfill - General	No	kg	1.17
Composted	-	kg	0.172
Recycling	-	kg	0

The processing plant survey also requested data on the use of refrigerants. However, not all plants provided data. When data was provided, it was used to estimate average refrigerant emissions for a plant per kg CW processed and this average was applied across plants with no data.

8.3 Other life cycle stages

The integrative modelling of stages other than the cradle-to-farm-gate and processing consisted of (Figures 1 and 2): 1) the transport of animals from farm to the processing plant; 2) the transport from the processing plant to the NZ port, from the NZ port to the overseas port and intermediate storage, 3) transport from the overseas port to retail; and 4) the consumption and processing of waste associated with consumption.

8.3.1 Transport and storage:

8.3.1.1 Transport

The first transport stage was for animals from the farm to the abattoir. The distance from farm to abattoir was the average cartage distance (65 km for cattle and 64 km for sheep) obtained from the Beef + Lamb New Zealand survey weighted by farm class contribution. The NZ-specific emission factor used for the transport was 0.089 kg CO_2e per tkm based on using a 28 t truck.

The second main transport stage was from abattoir to NZ port prior to shipping. All of the surveyed meat processing plants were between 60 and 120 km from the most likely export port. In the absence of a calculated weighted average distance for NZ export beef or sheep meat, we used a distance of 100 km in the base analysis.

For both the frozen and chilled chains, it was assumed that the product was packed into cardboard boxes and loaded into intermodal 20-foot refrigerated containers (reefers). The maximum weight of meat in each container was 12,000 kg for chilled product and 19,000 kg for frozen product. A summary of this data and other post-processing data is given at the end of this report in Table A13. The container was trucked from the processor to the NZ port using a 38-tonne articulated truck, where it was assumed to sit in storage for three days (estimated average from industry experts), then placed on a container ship until the overseas destination, off-loaded at the port where it was assumed to sit in storage for an additional three days. From the overseas port, the reefer was trucked or railed to a retail distribution centre (RDC). It was assumed that the reefers were unpacked at the RDC and the product was stored for 14 days before being distributed to a supermarket or restaurant using refrigerated trucks.

No primary data was collected on transport in the overseas components of the supply chains. For each country or region, it was assumed that the port was that nearest the main city, except for the USA frozen beef where it was assumed that the ports were Long Beach and Philadelphia (half product to each port). The oceanic distances were calculated using www.seadistances.org. For transoceanic shipping, two different emission factors from ecoinvent were used, i.e. 0.018 and 0.016 kg CO_2e/tkm for chilled and frozen containers, respectively.

Distances to the RDCs were based on distances from port to main cities and subsequent distances to retailer were based on upper rounded estimates according to size of country (Table A13). For example, the total transport within the UK was 300 km, which was more than that (c. 275 km) from the early report of Smith et al. (2005). Transport at these steps was assumed to be in refrigerated trucks.

8.3.1.2 Storage

Times of storage at the overseas port, RDC and retailer were based on average estimates from industry experts. Energy use during storage at the RDC was estimated using specific energy consumption (SEC) values from Evans et al. (2011) for chilled cold storage and frozen cold storage. The SEC for chilled cold storage was 44.3 kWh/m^3/year and the SEC for frozen cold storage was 61.9 kWh/m^3/year. The calculation to determine how much electricity was used per kg of product per hour was modified from a published UK report on GHG emissions from food transport and storage (DEFRA, 2009). This number was then multiplied by the appropriate country-specific electricity emission factor (Table A12).

Table A12. Country Specific Electricity Emission factors

Country	Unit	EF (kg CO_2 / Unit)
NZ	kWh	0.090
USA	kWh	0.576
China	kWh	1.051
Japan	kWh	0.647
UK	kWh	0.367

There was no repacking of the product at the international RDC except for the frozen beef to the USA. This went to a processing facility where it was minced and repacked before being transported to the RDC. Energy for mincing was estimated from the technical specifications of a commercial meat grinding machine: the “Butcher Boy (Frozen Meat Blocks) Meat Grinder” from MPBS Industries (http://www.mpbs.com/catalog/product/meat-grinders-meat-choppers-butcher-boy-meat-grind) based on a capacity of about 6300 kg per hr with a power requirement of 75 kW. This equates to a specific mincing energy requirement of 0.012 kWh per kg. At the processing facility, the emissions accounted for the energy required for mincing and the production of the packaging material (assuming mince patties in a 25 kg box with an inner plastic bag liner.

8.3.2 Consumer use

This part of the model encompassed the storage of the product at the food service enterprise (supermarket or restaurant) and cooking of the product either at home or at the restaurant.

Storage at the restaurant or fast food outlet was assumed to be two days in a walk-in chiller, and the energy consumption was taken from a published UK report on GHG emissions from food transport and storage (DEFRA, 2009) and multiplied by the country-specific electricity emission factor (Table A12).

If the product was consumed at home, then it was assumed to be stored in a refrigerator for seven days, using an energy consumption of 0.0037 kWh/kg of meat (PEFCR, 2018).

For the frozen beef to the USA, it was assumed that the food service enterprise was a fast-food outlet. For chilled beef to Japan, it was assumed to be fried and served in a restaurant. Chilled lamb exported to the UK was assumed to be roasted at home, whilst frozen sheep meat to China was assumed to be cooked at home using a hot-pot. Chilled sheep meat to California was assumed to be roasted in a restaurant. A cooking factor of 1 kWh/h was used to estimate the amount of electricity used for cooking (PERCR, 2018). The cooking times used for each scenario can be found in Table A13.

8.3.3 End-of-Life

The end-of-life (EOL) model considered all packaging disposal throughout the post-processing stage of the life cycle, namely the shipping cardboard box and the plastic shrink wrap around each product. For the frozen beef to the USA it was assumed that the patties were repacked into a similar-sized cardboard box and bagged used for shipping. All bags were assumed to be made of PE.

Each country was assumed to have different waste management systems. The USA was assumed to dispose 82% of its waste to landfills, with 18% incinerated (Asem-Hiablie et al., 2019). It was assumed that Japan incinerated all its waste, while China sent it all to landfill. Table A13 shows specific emission factors for each country and the country-specific waste management process for the UK.

Table A13. Summary of data used in this study for post-processing stages in the LCA of beef or sheep meat covering five product systems

Data	unit	Description	Frozen beef to the USA	Chilled beef to Japan	Chilled lamb to the UK	Frozen sheep meat to China	Chilled sheep meat to California
Amount of meat in reefer	kg	chilled		12000	12000		12000
	kg	frozen	19000			19000	
Processing plant to NZ Port	km	Mode of transport (truck)	100	100	100	100	100
Storage at NZ Port	days	-	3	3	3	3	3
Shipping distance	km	Average from 4 NZ ports*	16706	9250	22465	10701	10809
International Port	-	-	Long Beach and Philadelphia	Tokyo	Southampton	Tianjin	Long Beach
Storage at International Port	days	-	3	3	3	3	3
Transport to Processing facility	km	-	20	N/A	N/A	N/A	N/A
Mincing and Repacking	-	-	√	×	×	×	×
Transport to distribution centre	km	-	20 (Truck)	28 (Train)	130 (Truck)	173 (Truck)	46 (Truck)
Distribution centre	-	-	Long Beach and Philadelphia	Tokyo	London	Beijing	Los Angeles
Storage at distribution centre	days	-	14	14	14	14	14
Supermarket/Restaurant	-	-	Takeaway	Restaurant	Supermarket	Supermarket	Restaurant
Transport to retailer	km	truck	300	50	200	50	300
Storage at retailer	days		2	2	2	2	2
Consumer use	days	Refrigeration at home	N/A	N/A	7	7	N/A
	Mode	Cooking	Frying	Frying	Roast	Hot-Pot	Roast
	min	Cooking Time	10	10	60	30	60
EOL method	-	-	82% landfill 18% incineration	100% incineration	Ecoinvent process specific to UK	100% landfill	82% landfill 18% incineration

*Auckland, Lyttleton, Napier and New Plymouth; EOL: end-of-life;

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9. APPENDIX 2. Preliminary estimation of effects of net carbon sequestration from trees on sheep and beef farms in New Zealand

A preliminary estimate of net carbon sequestration was carried out using information from Case and Ryan (2020) for carbon stocks and from MPI (2019) and MfE (2020) for harvesting, deforestation and soil carbon changes. The details of this are described below. However, the recent more comprehensive report on this net carbon sequestration by MfE (2021) is considered more accurate than estimates in this section and is used as the basis for estimation in the main report. Nevertheless, this study resulted in similar overall estimates of net carbon sequestration as in the MfE (2021) report.

Estimates of net carbon (C) sequestration associated with woody vegetation on sheep and beef farms across NZ depends on the extent to which various influencing factors are included in their calculation. The report by Case and Ryan (2020) provided an estimation of the carbon sequestration in vegetation (with no consideration of contributions from harvesting and deforestation that also occurs on sheep and beef farms) ranging from 10.4 to 19.7 million t CO_2/year, and an average for these C stocks of 15 million t CO_2/year (Figure A2).

This preliminary assessment used data for gross carbon sequestration in trees on-farm from Case and Ryan (2020) and added generic NZ estimates for CO_2e emissions from harvesting and deforestation based on MPI statistics (MPI, 2019). Standard NZ factors for CO_2e emissions from tree harvesting were applied based on a simple average emission for pre-1990 and post 1989 plantings of 720 t CO_2/ha/year (MfE, 2020). Additionally, it recognised that approximately 2,000 ha of exotic forest land on farms across NZ were deforested (i.e. representing land-use change, as opposed to the previously mentioned harvested land where reforestation is assumed) (MPI, 2019). It was assumed that 20% of this deforested land occurred on sheep and beef farms based on MPI annual deforestation and intention surveys, with results accounting for an amortised average over the past 20 years (with 10% on other land uses and 70% on dairy farms; Ledgard et al., 2020). The estimates of CO_2 emissions for 2018 for harvesting and deforestation were subtracted from gross carbon sequestration estimates from Case and Ryan (2020) to provide an approximate net estimate of carbon sequestration on sheep and beef farms. An additional assessment was made considering potential changes in soil carbon in land where exotic trees were planted (344,800 ha from Case and Ryan, 2020), based on the average decrease in soil carbon from the conversion of productive pasture to exotic forest (c. 12.9 t C/ha from average soil C stocks in MfE, 2020; amortized over 20 years).

The harvesting of trees (and associated replanting) on sheep and beef farms was estimated to emit 7.1 million t CO_2/year using national-average data. If this is subtracted from C stocks, then the estimated net C sequestration would decrease to 7.9 million t CO_2/year (Figure A2). Additionally, some deforestation on sheep and beef farms associated with land use change from trees to pasture was estimated at 1.2 million t CO_2/year using national-average data. If this is also subtracted, then the estimated net C sequestration would decrease further to 6.7 million t CO_2/year (Figure A2).

The harvesting and deforestation estimates were based on simple NZ average estimates and did not account for site-specific estimates using GIS, unlike the estimates in the MfE (2021) report.

Estimates of net C sequestration should also account for potential changes in soil C. The estimate for deforestation did account for change in soil C (via a small increase in soil C using the average factor from the NZ Inventory). If the national average change associated with harvesting and forest planting was accounted for, it would equate to a net decrease of approximately 0.815 million t CO_2/year (based on an increase of 344,800 ha exotic forest). This would change the simple average net C sequestration value to 5.9 million t CO_2/year.

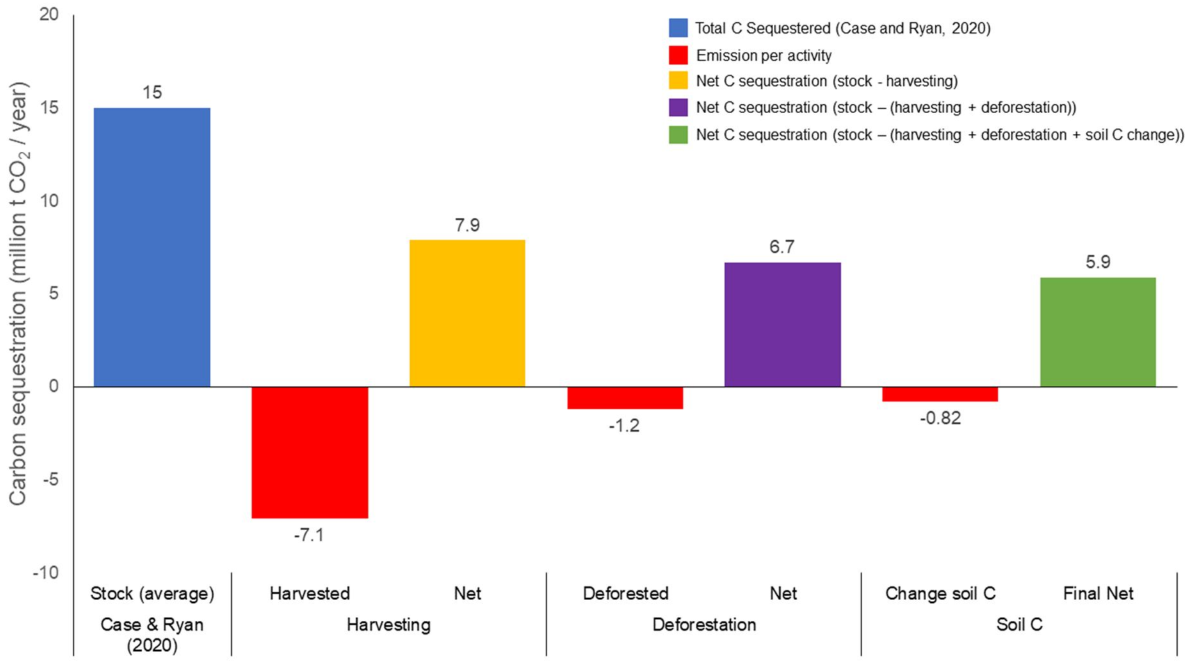

Figure A2. Estimated net carbon sequestration associated with woody vegetation on sheep and beef farms in NZ. The average stocks of carbon in vegetation is from Case and Ryan (2020), while net values are adjusted for emissions of CO_2 from harvested forest and deforestation (i.e. change from forest to pasture) and from decease in soil carbon.

The estimated net C sequestration in woody vegetation (including adjustment for harvesting and deforestation) equates to 36% of the total calculated GHG emissions from agricultural production on NZ sheep and beef farms. This is based on using data in Tables 1 and 5 for cattle and sheep carbon footprints per kg LW with the national amounts of LW sent to abattoirs in 2017/18, giving a total of 18.7 million t CO_2e for the cradle-to-farm-gate emissions from total NZ meat and wool (excluding dairy beef). Animal biological emissions (i.e. enteric and excreta CH_4 and excreta N_2O only) from sheep and beef farms equated to 17.13 million t CO_2e in 2017/18. Therefore, the net C sequestration in vegetation (accounting for harvesting and deforestation) would equate to 39% of these animal biological emissions.

The stock C sequestration values from Case and Ryan (2020), based on their average, minimum and maximum estimates equate to 80%, 55% and 105% of total NZ (cradle-to-farm-gate) sheep and beef (excluding dairy beef) emissions, respectively. Therefore, in the case of the maximum stock C sequestration (and ignoring harvesting and deforestation), this suggests C-neutrality, as noted in the Case and Ryan (2020) report. However, when the net C sequestration (adjusted for harvesting and deforestation) was accounted for, the carbon footprints (cradle-to-farm-gate) of LW and wool sold from the sheep and beef farm (i.e. excluding beef from dairy farms) decreased by 36% (Table A14).

For beef, this applies only to the ‘traditional’ beef from sheep and beef farms and excludes beef from dairy farms, since the benefits from woody vegetation refer only to plantings on the sheep and beef farms. Assuming no net C sequestration on dairy farms, then the C sequestration on sheep and beef farms equates to a lower decrease in the carbon footprint of total weighted-average NZ beef (traditional + dairy beef) of 26%. Note that the carbon footprint for dairy-beef includes an adjustment for land-use change associated with GHG emissions from land converted from forest to pasture for dairying (including recognising soil C sequestration). Similarly, the carbon footprint of sheep and ‘traditional’ beef decreased by up to 105% for the maximum C-stocks-only scenario, while the corresponding reduction for all beef (traditional and dairy-beef) was up to 77% (Table A14).

If the soil C changes (amortized over 20 years) associated with vegetation are also included in the calculations for the estimated net C sequestration in woody vegetation (including harvesting and deforestation), it shows an overall decrease of 32% in carbon footprint of traditional beef or sheep in this study (Table A14). This smaller decrease in the carbon footprint of 32% (compared to the 36% reduction when soil C changes are not included) was due to the estimated decrease in soil C under exotic forest relative to that under pasture, i.e. CO_2 emissions occur from soil (MfE, 2019).

Table A14. Effect on the carbon footprint of sheep and beef (cradle-to-farm-gate) when accounting for carbon sequestration (Cseq) associated with woody vegetation on sheep and beef farms in NZ. Data for stocks of carbon in vegetation (for average, minimum and maximum estimates) are from Case and Ryan (2020), while net Cseq values accounted for emissions of CO_2 from harvested forest and deforestation (i.e. change from forest to pasture). Estimates of effects of including soil C changes are also given.

	Base (unadj. for Cseq)	+Net Cseq (stocks - harv.- defor.)	+Net Cseq (stocks -harv.)	+Cseq Stocks (average)	+Cseq Stocks (min.)	+Cseq Stocks (max.)
	kg CO_2e/kg live-weight					
Vegetation changes:						
Sheep	6.01	3.84	3.46	1.18	2.66	-0.30
Traditional beef	10.09	6.46	5.82	1.99	4.48	-0.50
All beef (incl. dairy)	8.97	6.61	6.19	3.69	5.31	2.07
Vegetation + soil C changes:						
Sheep	6.01	4.10	3.71			
Traditional beef	10.09	6.88	6.24			
All beef (incl. dairy)	8.97	6.88	6.46			

Cseq: carbon sequestration; harv: harvesting; defor: deforestation

An example of how carbon sequestration by trees can be linked with estimates of the carbon footprint of beef is illustrated in a report for an agroforestry system in Finland (Ripamonti and den Herder, 2020; see Figure A3). In this way, it is reported as a separate calculation and the extent of potential mitigation is evident from the difference between the estimates.

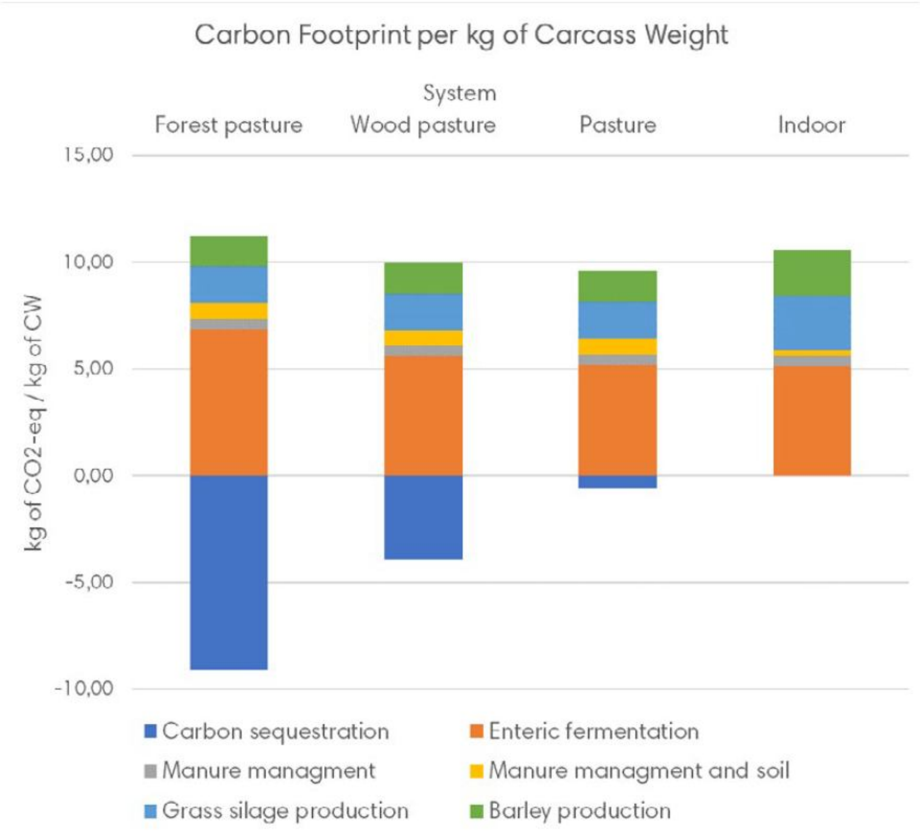

Figure A3. Carbon footprint per kg carcass weight in four beef cattle production systems in Finland: Forest pasture, wood pasture, open pasture and indoor production (Ripamonti and den Herder, 2020).

Reference:

Ripamonti A. and den Herder M. 2020. Potential of agroforestry in climate change mitigation: Assessment of greenhouse gas emissions in four different beef cattle production systems in Finland. Agroforestry Innovation Networks Technical Article. 4p.