Updating the carbon footprint for selected New Zealand agricultural products: an update for milk

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Executive Summary

Recently, consumers have been concerned about the environmental impacts associated with the production of food. Milk plays an important role in human nutrition, and the greenhouse gas (GHG) emissions associated with milk production is a common way to evaluate its environmental efficiency. This study aims to update the carbon footprint of milk production in New Zealand (NZ) and is composed of:

- a brief literature review of published studies using life cycle assessment (LCA) methodology to assess the environmental impacts of milk production,
- A “cradle to retailer-gate” LCA for two dairy products from an average NZ dairy farm for the 2019-2020 year, exported to China. A comparison is also made with milk produced within China.

The average value published for dairy cow milk globally was 1.28 kg CO_{2eq}/kg of FPCM (fat and protein corrected milk) for the cradle to farm-gate boundary. Most countries had their cow milk carbon footprint values in the range of 1 to 1.5 kg CO_{2eq} /kg FPCM. Across all studies, there were large differences in completeness, methodologies used and quality of data. Thus, care is needed when comparing results in this report with other studies. A recent report (Mazzetto et al., 2021) accounted for the differences in methodologies, showing that NZ is placed in the low-range group of countries, with one of the lowest carbon footprints for milk production. The cradle to farm-gate carbon footprint using 2007 Global Warming Potential (GWP) values without including the direct land-use change (LUC) (most common approach found in the literature) was 0.76 kg CO_{2eq}/kg FPCM. The ISO14067 and the European Commission Product Environmental Footprinting guidelines recommend the use of the latest 2013 Assessment Report values for GWP for 100 years (AR5 GWP100) accounting for the climate-carbon cycle feedback (CCF) and including direct LUC (land converted from forest to pasture for dairying within the previous 20-years). When accounting for all of these recommendations, the carbon footprint of milk from an average dairy farm in NZ (i.e. cradle to farm-gate stage) was 1.09 kg CO_{2eq}/kg FPCM. However, no recent publications have used LCA methods with CCF, and therefore it is not possible to compare this estimate with other published estimates. The only direct comparison possible is the carbon footprint of milk produced in China (calculated by this study) that was 1.76 kg CO_{2eq}/kg FPCM.

In the literature review, only two studies covered a full "cradle to grave" life cycle assessment (i.e., considering all the value chain stages for milk production). Both studies showed that the farm stage has a significant impact (72% to 80%) on the total footprint. Nine other studies analysed different parts of the post-farm stage, with four studies focusing only on milk packaging. Those latter four studies showed that (generally) carton packages had a lower carbon footprint than plastic (PET and HDPE) or glass (single-use and returnable). This was mainly due to the

production of bottles that demand a large amount of energy. In the processing plant studies, the main sources of emissions were energy, fuel, and packaging.

A detailed LCA examined the carbon footprint of NZ milk for 2019-2020 processed to either whole milk powder (WMP) or ultra-high temperature (UHT) milk and shipped to a retailer in Beijing, China. The UHT milk produced in NZ and exported to China had a lower carbon footprint than the UHT milk produced in China (1.37 and 1.92 kg CO_{2eq}/L of milk, respectively). This was mainly related to the high on-farm efficiency of the milk production from NZ dairy farms, that represented 77% of the final footprint for UHT milk produced in NZ and exported to China. Shipping milk to China represented 9% of the total emissions for the UHT milk. The final footprint for WMP exported to China was 1.19 kg CO_{2eq}/L of milk (on a liquid-equivalent basis), lower than the footprint for UHT milk (on the same liquid-equivalent basis). The shipping stage to China represented only 1.5% of the WMP footprint.

In order to test the effect of the market distance on the final footprint, we performed a sensitivity analysis, where WMP produced in NZ was exported to Europe. Shipping to Europe represented only 3% of the total emissions, with the final footprint being similar to that for WMP exported to China (1.21 and 1.19 kg CO_{2eq}/L of milk, for Europe and China, respectively).

It is recommended that LCA studies analyse more than one environmental burden to avoid pollution swapping. It is important to stress that the carbon footprint is only one of the indicators for environmental sustainability. A complete picture of sustainability should also include other important factors, such as fossil fuel demand, water, land use and eutrophication.

1. Introduction

In looking at the sustainability of products, it is important to consider all contributing stages to their production, including the effects of the transportation, retail, consumer and end-of-life stages. The most appropriate tool to evaluate these aspects is Life Cycle Assessment (LCA). LCA provides a holistic approach to evaluate the environmental performance of a production system. It achieves this by considering the potential impacts from all life cycle stages of a product or system. An LCA of the whole product life cycle is called a "cradle-to-grave" LCA. However, some studies only focus on critical stages or stages over which the user of the analysis has an influence. For example, many analyses have only been carried out for the "cradle-to-farm-gate" boundary for livestock systems and products. For milk production, most studies use the "cradle to farm-gate" boundary, which is the stage that contributes to over 70% of the total "cradle to grave" footprint (e.g. Thoma et al., 2013).

Milk is an important product for human nutrition. Recently, consumers have been concerned about the environmental impacts associated with the production of food. Greenhouse gas (GHG) emissions from dairy production have been a common way to evaluate the environmental efficiency of milk production across the globe (Mazzetto et al., 2021). GHG emissions and their effects on climate change are key environmental issues for New Zealand (NZ) (MfE, 2021). GHG reduction targets set by the NZ government (Climate Change Commission, 2021) mean that large decreases are required from all sectors, including agriculture since it produces about one-half of NZ’s total GHG emissions (MfE, 2019). The total GHG emissions associated with producing a product such as milk are termed the carbon footprint. The carbon footprint is the total emission from the system (excluding sequestration) divided by the functional unit (in the case of dairy, kg or litres of milk). This assessment enables understanding the impact that inputs and practices have on GHG emissions and identifying priorities for improvement.

This study summarises information from published studies to compare the carbon footprint of milk (from dairy cattle) between different countries and stages of production. It also estimated the “cradle to retailer-gate” carbon footprint of NZ milk for 2019-2020 processed to either whole milk powder (WMP) or ultra-high temperature (UHT) milk and shipped to China.

2. Literature review

This section summarises a detailed literature review involving a library search in various databases, including BIOSIS, CAB Abstracts, Food Science and Technology Abstracts and SCOPUS. The search was carried out using all combinations of the following keywords: milk, cow, life cycle assessment (or LCA), footprint, carbon and greenhouse gas emission.

For each publication used, a specific study code was assigned, and the following characteristics were recorded in the database: authors, year, country, allocation type, study boundaries, farm typology, footprint results (in different functional units), % of fat and % of protein (when available). More details of the methodology for each boundary are presented in the sections below.

2.1 Cradle to farm-gate

The list of papers was screened, and the papers were retained if they met the following criteria: (1) cradle to farm-gate LCA; (2) using real farm data (not farm modelled or top-down studies); and peer-reviewed studies (published in scientific journals). All 62 studies provided estimates of GHG emissions (i.e. the carbon footprint of the products). Relatively few studies extended the estimation to other indicators of resource use or environmental impacts. However, even for the carbon footprint indicator, there were considerable differences in the methodologies used between the studies. This included the use of different allocation methods (between milk and co-products, e.g. meat) and different equations for the correction from litres of milk to fat and protein corrected milk (FPCM).

All the footprints were converted to a common functional unit (FPCM – using the International Dairy Federation [IDF] 2015 methodology). The most common missing gap in the reviewed papers/reports was the milk nutritional composition (especially the % of fat and protein). When not available, an average of 4% fat and 3.3% protein (weight:weight basis, IDF, 2015) was used to convert kg (or L) of milk to FPCM. The papers used two different equations for calculating FPCM (Gerber et al., 2011 and IDF, 2015). The IDF methodology was chosen as standard for this study. Furthermore, some papers calculated the carbon footprint based on an energy corrected milk (ECM) basis using two different equations (Sjaunja et al., 1990 and ALP, 2011). The different approaches were investigated, and the FPCM/ECM and footprint results were similar, independent of the method used (Appendix 1). In this study, we generated specific factors for converting all the results to the IDF methodology. Details of the different formulas used in the reviewed papers are in Appendix 1.

The global average carbon footprint of milk across all studies was 1.28 kg CO_{2eq}/kg FPCM (ranging from 0.49 to 13.72 kg CO_{2eq}/kg FPCM – unadjusted for differences in Global Warming Potentials or allocation method). The dairy farms were classified into three different categories: "Conventional" dairy farming (includes pasture-based), "Confined" farms (animals housed all day) and "Organic" farms. Figure 1 shows no significant difference in the footprint of milk production between the three types of dairy farms.

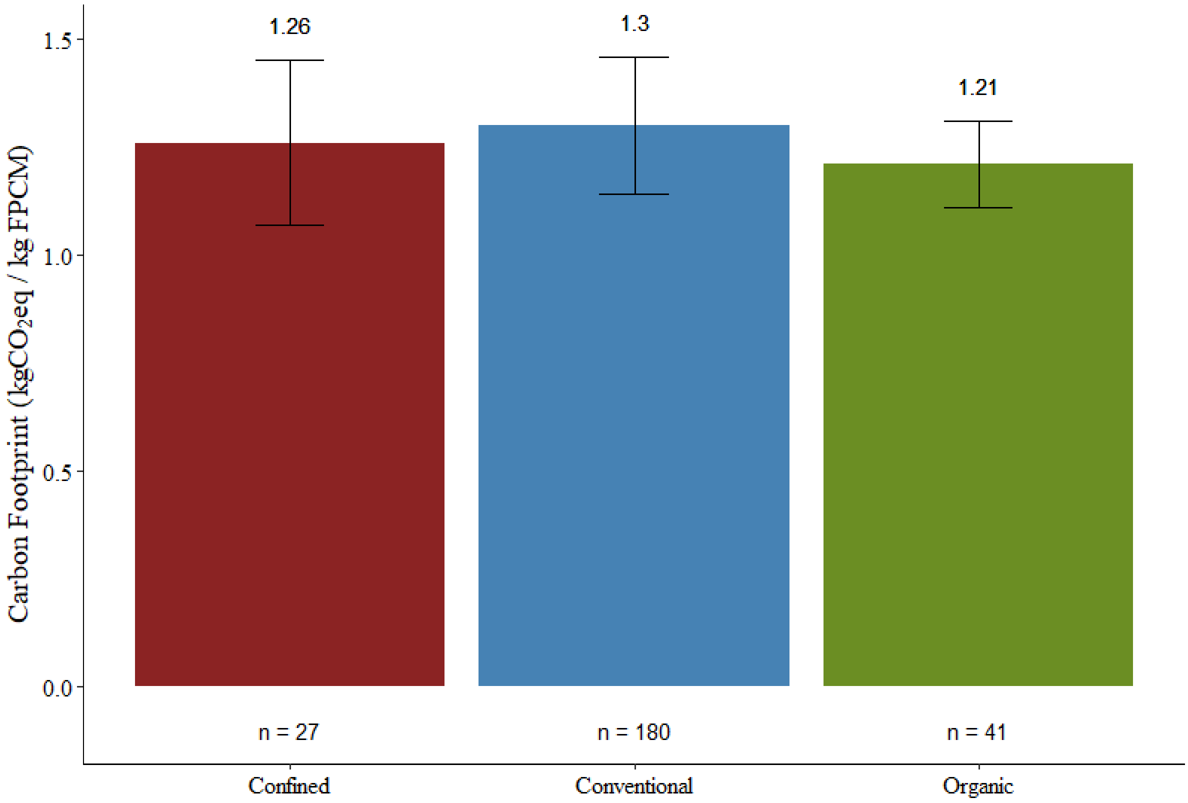

Figure 1 – Carbon footprint (in kg CO_{2eq}/kg FPCM) for milk production at the farm gate for the three types of dairy farms in the database ('confined' refers to cows confined in housing systems). The error bars represent the 95% confidence interval. The "n" marks the number of footprint analyses (note that some papers studied more than one type of farm and/or had multiple farms of the same type).

The New Zealand average across four published studies was 0.77 kg CO_{2eq}/kg FPCM. This excluded land-use change [LUC], i.e. land converted from trees to pasture for dairying) (Figure 2). Most of the studies didn’t consider LUC in their calculations. Most countries had their cow milk carbon footprint values in the range of 1 to 1.5 kg CO_{2eq}/kg FPCM (Figure 2). The country with the most studies was Italy (18), followed by the USA, Ireland (6) and UK (5). New Zealand had four studies, while many countries had only one or two studies.

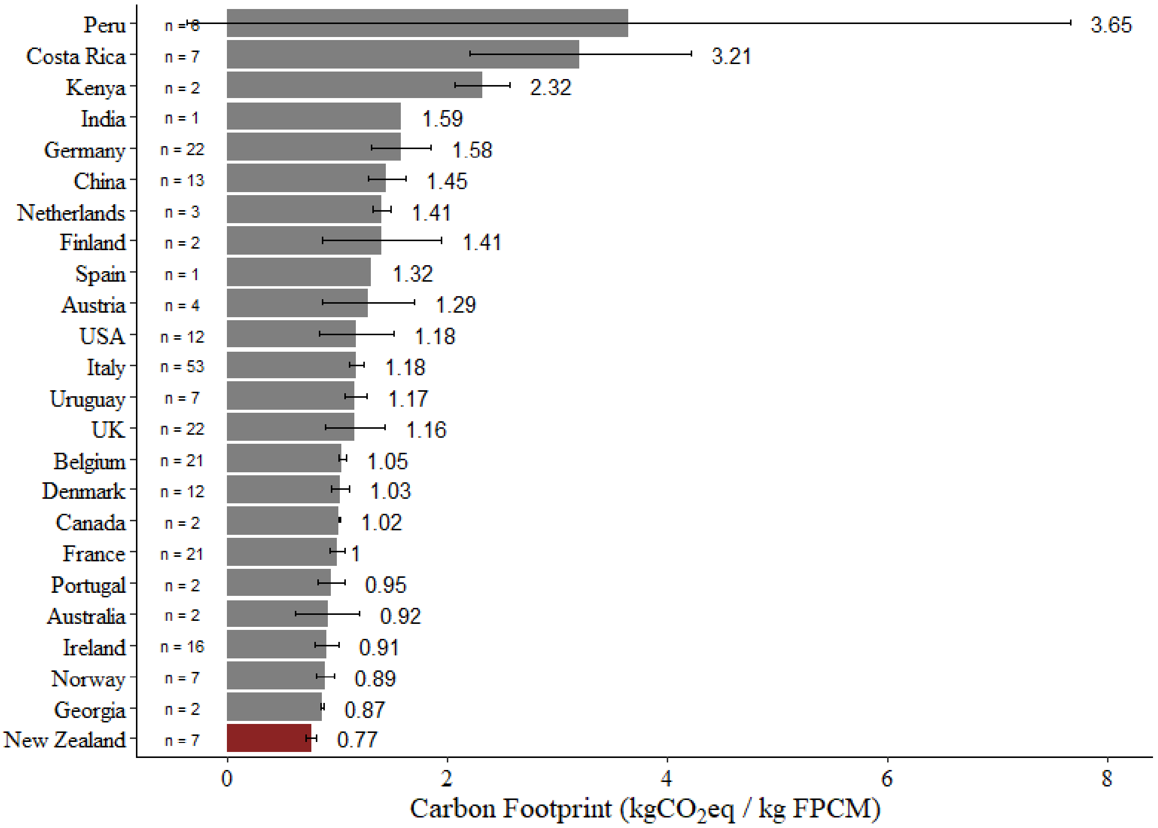

Figure 2 – Carbon footprint (kg CO_{2eq}/kg FPCM) of milk production at the farm gate for the countries recorded in the database. The error bars represent the 95% confidence interval. The "n" marks the number of footprints (note that some papers studied farms in more than one country and/or multiple farm types in the same country). The NZ studies excluded direct land-use change (forest to pasture for dairying), while most other studies made no comment about LUC.

Dairy systems produce a mix of goods (mainly milk and meat) that cannot be easily disaggregated. In LCA, this disaggregation is commonly done using allocation methods. The decision of which allocation method to use depends on the goal and scope of the project, which makes the task of comparing different studies challenging. Ten different allocation methods were recorded in the database, the most common being the economic method (suggested by PAS2015 (BSI, 2011) and one allocation method identified in ISO 14040), followed by the biophysical method (recommended by the IDF, 2015). Generally, when the study did not apply any allocation method, the average footprint was higher than the other methods. Gilardino et al. (2020) introduced the "farmer's perception" allocation method, which can be highly subjective but relevant for smallholder farms. In this approach, the authors expanded the system to include alternative production systems to the co-products meat (for market or self-consumption), milk (for market or self-consumption or calves), milk for calves, manure (as fertiliser), livestock (as saving asset or workforce) and cultural aspects. The farmer perceptions were ranked by the farmers, and shares of allocation were calculated for all co-products. In this Peruvian study, the milk for market had the largest allocation, with 30% of the total emissions. Since the authors studied smallholder farms in Peru, the co-products listed above can play an important role in the farm that are usually not relevant in large commercial farms.

Apart from the allocation methods, other factors can also influence the final result, such as the different Global Warming Potentials (GWP). The GWP is a standard metric for aggregating emissions of different GHGs, and it has been evolving over the last 20 years (therefore, values have changed). In order to perform a "fair" comparison between studies, factors such as GWP and allocation must be standardised. Recently, Mazzetto et al. (2021) conducted a structured review of the literature to compare the carbon footprint of cattle milk from different countries (Figure 3). The authors selected studies with a representative number of farms for each country and standardised the most important factors for an LCA study (functional unit, GWP and allocation – more details in Mazzetto et al., 2021). The results show that NZ was in the group with the lowest carbon footprint.

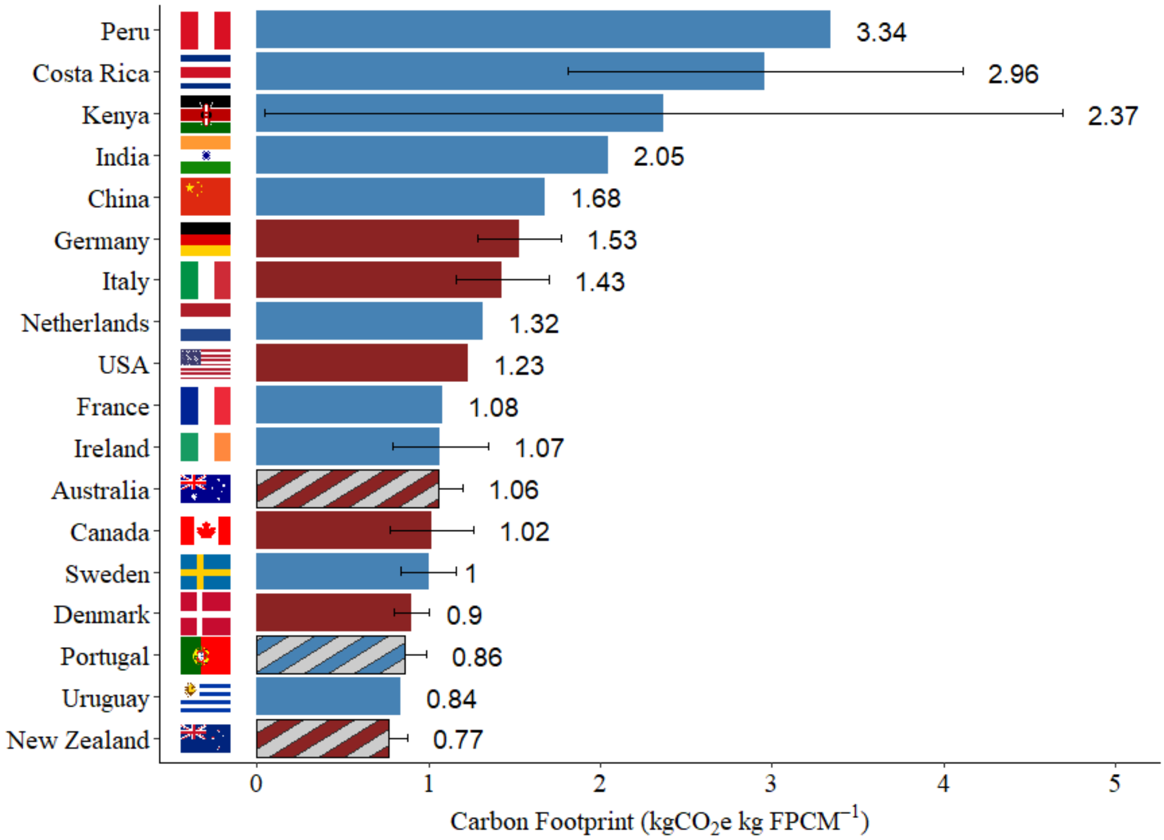

Figure 3 (adapted from Mazzetto et al., 2021): Carbon footprint of milk production (kg CO_{2eq}/kg FPCM) in different countries (after correction to common GWP, functional unit and allocation methodology). Red bars represent studies that used the IDF (biophysical) allocation, blue bars represent studies that used different types of allocation and had their footprint recalculated. Bars with diagonal grey patterns represent studies that used region-specific emission factors. Error bars denote the standard deviation, calculated as a weighted standard deviation when more than one study was selected per country or extracted from the study when only one study was considered. Studies from Peru, India, China, Netherlands, USA and France didn't report standard deviations. The NZ studies excluded direct land-use change (forest to pasture for dairying) while most other studies made no comment about LUC.

As noted by Mazzetto et al. (2021), LCA studies also have different levels of sophistication (or "Tiers"), depending on the emission factors (EFs) available for each country/region. This creates an additional challenge when comparing the footprint of different countries. For example, countries where region-specific EFs are available (e.g. NZ) showed lower footprints, while countries that used the Intergovernmental Panel on Climate Change (IPCC) 2006 default factors generally showed the largest footprints.

A recent review by Lorenz et al. (2019) showed that the carbon footprint value generally decreased with increased milk production per cow and with an increased proportion of the diet from pasture. Dairy farms relying on pasture as the main feed component usually show a low contribution of carbon dioxide (CO_2), linked to low fossil fuel consumption and the low use of bought-in feed. The same pastoral farms have a high contribution of methane (CH_4) (e.g. 70% of the total CO_{2eq} for NZ - Ledgard et al., 2020). In countries where animals need to be housed due to climatic conditions, the profile of emissions is different. The emissions from the use of fuel and crop feeds can constitute over 10% of the carbon footprint of milk (O'Brien et al., 2014), and CH_4 can represent less than 50% of the total CO_2-equivalent, especially in confinement dairy systems (Thoma et al., 2013). Another important source of emission for the on-farm stage is the use of synthetic fertiliser, especially for the pasture-based systems, with significant impacts related to the emission of nitrous oxide (N_2O) from nitrogen fertilisers.

2.2 Cradle to grave

We follow the same rationale as described above (section 2.1). For this boundary, studies that analysed specific stages (e.g. comparison between different types of packaging) were included.

We identified 11 papers that studied more than just the milk production on-farm. Some of them were related to different parts of the processing stage, from studies dedicated only to the packaging (Meneses et al., 2012; Bertolini et al., 2016; Boesen et al., 2019; Stefanini et al., 2020) to others considering only the processing plant stage (Heller and Keolian, 2011; Nutter et al., 2013). In addition, some papers studied the "cradle to processing gate" boundary (Gonzalez-Garcia et al., 2013; Hospido et al., 2013; Jungbluth et al., 2018), and only two studied the "cradle to grave" boundary (Fantin et al., 2012; Thoma et al., 2013). In the following sections, we review the main results for each stage described above. A summary of the different stages can be found in Table 1.

2.2.1 Processing

According to Gonzalez-Garcia et al. (2013), 69% of emissions for the processing stage are from the energy used in the processing plant, followed by packaging, mainly related to CO_2 emissions. A study performed in the USA (Nutter et al., 2013) showed that fuel and electricity had similar importance for the processing plant (29% and 26% of the total, respectively), followed by packaging (17%). Jungbluth et al. (2018) studied different types of milk products and noticed that, due to the allocation applied (based on the amount of milk solids in each co-product at the processing stage – IDF, 2015), concentrated milk had a lower impact than cream (Table 1). The steam (i.e. heat) for preheating and evaporating the milk had the main impact on unpacked concentrated milk (Jungbluth et al., 2018).

2.2.2 Packaging

As mentioned above, the packaging is usually the second or third most important source of emissions at the processing stage. Four studies described the different carbon footprint for packaging options.

Meneses et al. (2012) showed that larger aseptic carton packages had a lower carbon footprint than smaller ones for the same amount of liquid content when compared to Polyethylene Terephthalate (PET) and High-Density Polyethylene (HDPE). A similar conclusion was found by Bertolini et al. (2016). For PET and HDPE, the bottle is the leading cause of the environmental burden for the packaging stage. In particular, their impact is generated by the raw materials (granulate) and the high energy consumption and emissions related to their manufacturing. Instead, the lower environmental impacts of multilayer cartons depend mainly on the low energy consumption and emissions associated with the packaging production phase and the use of paperboard instead of polymeric materials.

Boesen et al. (2019) studied the gap between consumer's perception and LCA results. The authors concluded that consumers assess the environmental sustainability of different packages primarily based on the material type and what they can personally do at the disposal stage, not considering the impacts of production and transport. Generally, bio-based and glass bottles are perceived as the most sustainable, while plastic is perceived as the least sustainable. However, the LCA performed by the authors showed that plastic (especially for laminated cartons) could be a better option, even though they are harder to recycle.

Similar LCA results were found by Stefanini et al. (2020), who studied four different packaging systems (PET, PET 50% recyclable [R-PET], non-returnable glass bottle and returnable glass bottle [eight cycles]) for 1 L of pasteurised milk. The authors showed that non-returnable glass bottles had the highest carbon footprint, mainly due to its production, with furnaces needing high temperature to melt the raw material, consuming a large amount of energy. The returnable glass bottle had a lower carbon footprint than the single-use glass bottle, even after considering the transport and washing of the glass. This is because most of the emissions from production are divided over eight cycles. PET and R-PET had the lowest footprints, with R-PET having a footprint 18% lower, mainly because the recyclable PET bottle avoids the use of virgin material. It is important to note that those studies are related to the carbon footprint only. Other environmental burdens (water footprint, eutrophication, acidification, etc.) can show different patterns depending on the packaging option.

2.2.3 Full life cycle

According to a review by Üçtuğ et al. (2019), the on-farm stage represents 75% of the “cradle to retailer-gate” for milk production, with 22% related to the processing stage and 3% to the transportation stage (note the authors didn't include Thoma et al. 2013 in their review). As pointed out above, Thoma et al. (2013) is one of the two papers that covered "cradle to grave". The main contributing stage of the value chain for GHG emissions was the farm (72% and 83% of the total for Thoma et al. [2013] and Fantin et al. [2012], respectively).

Table 1 – Description of studies that analysed post-farm emissions (processing stage, cradle to processing-gate and cradle to grave).

			% for each stage of the LCA					
	Functional Unit (FU)	Footprint (kg CO_{2eq}/FU)	Cradle to farm gate	Transport*	Processing plant	Transport$^{\#}$	Retail	Consumer
Gate to gate (processing stage only):								
Nutter et al., 2013	1 kg packaged milk	0.20	-	-	100%		-	-
Heller & Keolian (2011)	1 kg packaged milk	0.46	-	8%	51%	41%	-	-
Cradle to processing-gate:								
Gonzalez-Garcia et al., 2013	1 kg ECM	1.74	55%	-	45%	-	-	-
Jungbluth et al., 2018	1 kg UHT	0.92	78%	-	22%	-	-	-
Jungbluth et al., 2018	1 kg Cream	2.74	78%	-	22%	-	-	-
Jungbluth et al., 2018	1 kg concentrated milk	2.40	82%	-	22%	-	-	-
Hospido et al., 2013	1 kg of milk	1.05	80%	-	20%	-	-	-
Cradle to grave:								
Fantin et al., 2012	1L	1.30	82%	1%	14%	3%	-	-
Thoma et al., 2013	1 kg consumed milk	2.05	72%	-	17%	-	6%	5%

*transport to processing plant

#transport to retailer

3. Updated carbon footprint of NZ dairy products

3.1 Methods

This study covered the cradle to retailer-gate of two NZ produced milk products (whole milk powder [WMP] and ultra-high temperature [UHT] milk) to China (a 'typical' retail outlet in Beijing) (Figure 4). We also calculated the carbon footprint of an average Chinese farm in the Hebei region, based on data from collective (Wang et al., 2018) and industrial (Lu et al., 2018) farms. The following sections are separated into the cradle to farm-gate and post-farm gate stages.

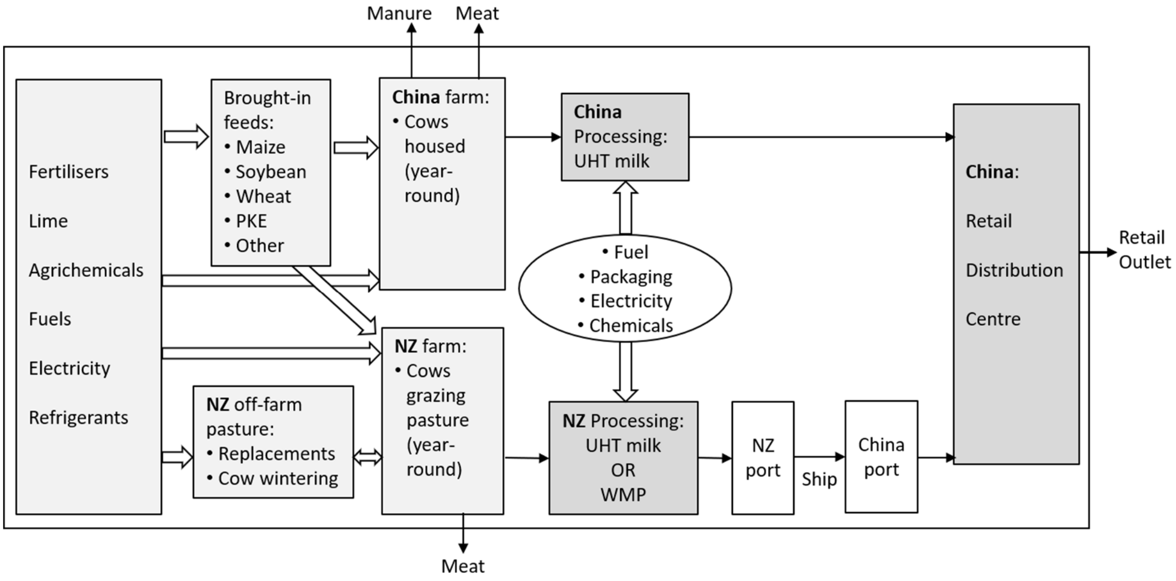

Figure 4 - System boundary of the life cycle stages for milk produced in NZ or China, processed to whole milk powder (WMP) or ultra-high temperature (UHT) milk, and transported to a retailer in Beijing, China.

3.1.1 Cradle to farm-gate

The scope of the cradle to farm-gate stage of the current study covered estimation of the carbon footprint of milk from an average NZ farm. For greater detail on data and calculation methods, see Appendix 2.

New Zealand regional average dairy farm systems were analysed in this study for the 2019/20 season. Farm information was mainly based on DairyNZ/LIC (2020) statistics (for animal-based data) and a DairyNZ DairyBase 2019/20 survey of 352 farms (regionally-based random survey; used mainly for fertiliser and supplementary feed data). An average NZ farm (Table 2) was determined based on a weighted average of regional data (based on milk production per region).

For the average Chinese farm, data was collected from collective (with multiple small-farm ownership of animals - Wang et al. (2018)) and larger industrialized (Lu et al., 2018) farms (see

Zhang et al. (2017) for a general description of farm systems in China) in the main dairying region of Hebei. These represented the two main farming systems and contribute more than 98% of milk production from the Hebei region (MOA, 2016). A weighted average was calculated based on relative milk production from these systems (MOA, 2016). Both farm systems involved year-round housing of animals, with all feed brought into the farm.

An LCA methodology was used (e.g. IDF (2015); Chobtang et al. (2017)), with the system boundary for this life-cycle stage of the study being the "cradle-to-farm-gate" for both NZ and Chinese average farms (Figure 5). The reference unit was one kg of fat-and-protein-corrected-milk (FPCM). FPCM is recommended internationally for dairy LCA to enable comparisons of milk at a common level of fat and protein content (IDF 2015, FAO 2015).

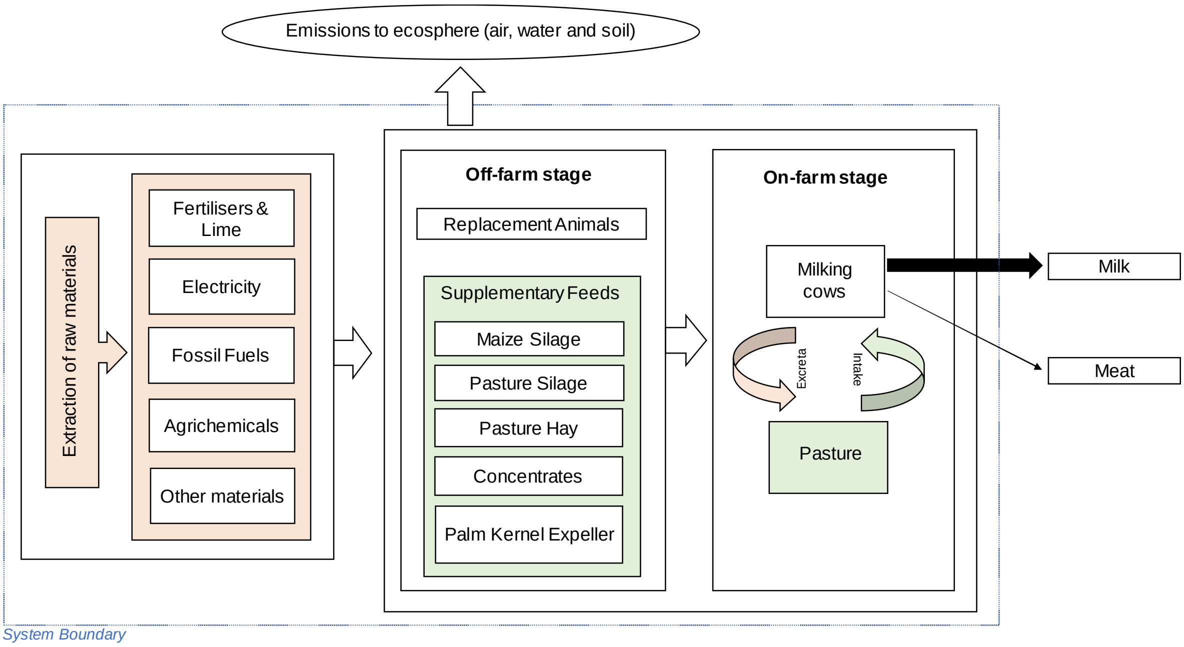

Figure 5 - System boundary of the raw milk life cycle stage (Chobtang et al. (2017)).

Table 2 - Technical description for the on-farm data for a weighted average dairy farm in New Zealand and China (based on the proportion of milk obtained from each region in NZ or type of farm in the Hebei region in China).

	NZ weighted average	China weighted average
Dairy cows	506	358
Replacement rate (%)	21	25
Milk (t FPCM per cow)	4990	7493
Butterfat (%)	4.85	3.89
Protein (%)	3.83	3.27
Allocation to milk (%)	85	84
Fertiliser N (kg/ha)*	136	0
Fertiliser P (kg/ha)*	22	0
Brought-in feed (in t DM / cow / year)		
Maize silage	0.09	6.03
Maize grain	-	0.15
Steam-pressed maize grain	-	1.98
Soybean meal	0.00	1.10
Wheat bran	-	0.10
Leymus chinensis	-	1.14
Alfafa	-	0.65
Pasture silage	0.12	-
Barley grain	0.06	-
Concentrate	0.04	-
PKE	0.32	-
Other feeds	0.07	0.52
Total brought-in feed	***0.70***	***11.67***

*DM = dry matter; * fertiliser for pasture production*

The GHG emissions were allocated between the co-products milk and meat based on the physiological feed requirements of the animal to produce milk and meat (calf, culled cows) using the IDF (2015) methodology. The average annual value for percentage allocation to milk was 85% for NZ and 84% for China.

The calculation of GHG emissions covering methane (CH_4) from enteric fermentation by dairy cattle, CH_4 and N_2O from excreta deposited on pasture and from farm dairy effluent (FDE), N_2O from N fertiliser, and CO_2 emissions from lime and urea application were based on IPCC and NZ GHG Inventory methodologies (Clark (2001); IPCC (2006); MfE (2021)). See Appendix 2 for details.

In this report (as recommended in PAS2050 (BSI 2011)), capital was excluded from all calculations. The use of refrigerants (mainly associated with vats for chilling milk on-farm prior to collection) was summarised after discussion with an NZ refrigeration expert (D. Grey). The estimate of emissions associated with the refrigerants represented only 0.1% of the total carbon footprint but was included in all estimates for completeness.

The effects of including direct LUC were also estimated. In this case, it refers to land previously in forest (commonly pine plantation) converted to pasture and currently used for dairy farming. The methodology from PAS2050 (BSI 2011) and FAO (2015) was used whereby LUC over the previous 20-years was estimated (based on deforestation data provided by MPI and an assumption that 70% of the total deforested land was used for conversion to dairying) and amortized to derive an annual average estimate.

3.1.2 Post-farm gate (to retailer-gate)

The post-farm stages covered transport of milk from farms to an average milk processor, processing to WMP or UHT milk, packaging, transport to an NZ port, shipping to China (assumed to be Tjjian), transport to a Regional Distribution Centre (RDC), storage at the RDC and transport to a retail outlet.

Transportation of milk from farms to factory in NZ is by articulated tankers and data on the average actual fuel use for milk collection by Fonterra (pers comm, 2019) equated to 2.3 L diesel per t of FPCM. For the Hebei region of China, average milk transportation distance from farm to factory of 100 km (from local expert judgement and reduced to be the same as the NZ average) and assuming similar fuel use efficiency to NZ collection.

Raw milk collected from dairy farms was assumed to be processed into WMP or UHT milk without elements of processing to other products, except for adjustment to a defined FPCM concentration, as recommended by IDF (2015). Energy use for milk processing was derived from the literature and using country-specific adjustment in the ecoinvent database (Wernet et al., 2016). For WMP, it was based on electrical and thermal energy use of 0.35 and 2.5 kWh kg^{-1} product (Feitz et al., 2007, Xu and Flapper, 2011, Finnegan et al., 2017). It was assumed that 7.39 L of milk was used to produce 1 kg WMP, based on average NZ processing data of 13 kg WMP per 100 L (Pearce, 2017). Main cleaning chemicals of acid and alkali were assumed based on amounts and types from Finnegan et al. (2017), i.e. 14.4 and 4.5 g $(\text{kg WMP})^{-1}$ sodium hydroxide and nitric acid, respectively.

For UHT milk, the energy use for processing (0.25 and 0.46 MJ / kg for electrical and thermal energy, respectively) and packaging were based on an average of published data (Chandarana et al., 1984; Hospido et al., 2003; Fantin et al., 2012; González-García et al., 2013; Djekic et al., 2014). Cleaning chemicals associated with UHT milk production were based on an average of published data (Fantin et al., 2012; González-García et al., 2013; Djekic et al., 2014; Jungbluth et al., 2018), i.e. 7.0 and 2.3 g / kg UHT milk for sodium hydroxide and nitric acid, respectively.

Detailed packaging data (weights and materials) were obtained from Fonterra, with energy use and GHG emissions for constituent components and production based on ecoinvent and NZ-specific energy factors. For WMP, it was based on 250 g WMP in a laminated foil sachet and in a cardboard box, with 24 sachets in a cardboard box and 70 boxes stretch-wrapped on a pallet (total of 222 g packaging/kg WMP, including cardboard boxing but excluding the pallet). Packaged product was assumed to be 250 mL UHT milk in a carton (of layered paper, aluminium, polyethylene and polypropylene), with 24 cartons/cardboard box and 140 boxes stretch-wrapped on a pallet (total of 75 g packaging / kg UHT milk, including cardboard boxing but excluding the pallet). Specific packaging constituent weights were provided by Fonterra.

Transportation stages for NZ milk products involved moving the packaged product 166 km from the processing plant to a port based on location data for regional milk production (DairyNZ/LIC, 2020) and using 80% transport by rail and 20% by truck (G. Philip, pers. comm.). The following stages were shipping 10,360 km from Ports of Auckland to Tijian, transporting 170 km from the Tijian port to an RDC in Beijing by rail and then trucking a further 20 km to a retail outlet. In China, UHT milk produced in factories in the Hebei region was assumed to be transported 170 km by rail to the RDC in Beijing and trucked 20 km to a retail store (distances and transport mode based on local dairy industry knowledge). We assumed that WMP was stored at the RDC for three months, while UHT milk was stored for one month.

For the milk produced in China, milk was assumed to be collected from farms in tankers, transported to a milk processing plant and processed to UHT milk. It was assumed that all inputs, cleaning chemicals, packaging and energy use for processing milk in China were the same as that for NZ. Exceptions were for packaging, where the aluminium component in NZ was from hydroelectricity, thereby giving slightly lower GHG impacts, and for processing energy use to account for the higher fat and protein content of NZ milk.

3.1.3 Carbon footprint calculation

We followed the ISO14067 and the European Commission Product Environmental Footprinting guidelines that recommend using Global Warming Potential (GWP) factors for a 100-year time horizon (GWP100), including climate-carbon cycle feedbacks (CCF). This has GWP100 multiplication factors of 1, 34, 36 and 298 for CO_2, biogenic CH_4, fossil CH_4 and N_2O, respectively (Reisinger et al. (2017). A sensitivity analysis was also performed using GWP100 values without CCF (Stocker et al., 2013), with factors of 1, 27.75 and 265 for CO_2, biogenic CH_4, and N_2O, respectively. A further analysis was performed at the "cradle to farm-gate" boundary using the 4th Assessment Report (2007 AR4) with GWP100 factors of 1, 25 and 298 for CO_2, biogenic CH_4, and N_2O, respectively, to allow comparison with other studies found in the literature review.

3.1.4 Sensitivity analysis

In order to test the impact of a more distant market on the final footprint, we calculated the emissions for the WMP produced in NZ and exported to Europe. The only changes made were to the post-processing stage (described in section 3.1.2), with the end-port for shipping being Zeebrugge and use of a Europe-specific emission factor for electricity use for the RDC.

3.2 Results and Discussion

3.2.1 Cradle to farm-gate

The total annual carbon footprint (based on GWP100 AR5 and including CCF) for 2019/20 was 0.95 kg CO_{2eq}/kg FPCM, without accounting for any net GHG emissions due to direct LUC associated with dairying (Table 3). Direct LUC contribution was equivalent to 0.14 kg CO_{2eq}/kg FPCM (based on amortisation over 20 years from 1999-2019) and would result in a total carbon footprint for milk (including LUC) of 1.09 kg CO_{2eq}/kg FPCM (including CCF) (Table 3). The corresponding estimate for milk produced in China was 1.76 kg CO_{2eq}/kg FPCM (which had no LUC). A carbon footprint estimate is also presented in Table 3, excluding CCF for both AR4 and AR5 values. The AR4 values in Table 3 excluding LUC are similar to the NZ values found in the literature review (Figure 2) and by Mazzetto et al. (2021) (Figure 3). As noted before (section 2.1), the values found in those literature reviews are largely based on GWP100 AR4 values and without including GHG emissions from direct LUC. In this case, a direct comparison should be made using the GWP100 AR4 value (0.76 kg CO_{2eq}/kg FPCM), which places NZ at the lowest range of the milk carbon footprint when compared with other countries (Figures 2 and 3).

Table 3 - Cradle-to-farm-gate carbon footprint estimates (with or without an estimate of direct land-use change (LUC)) for New Zealand and China. Results are expressed in fat and protein corrected milk (FPCM) and are based on GWP100 excluding or including CCF.

	NZ AR4 without CCF	NZ AR5 without CCF	NZ AR5 with CCF	China AR5 with CCF
	kg CO_{2eq} / kg FPCM			
Excluding LUC	0.76	0.81	0.95	1.76
Including LUC	0.90	0.95	1.09	1.76

3.2.1.1 Sources contributing to the carbon footprint

The carbon footprint of the Chinese farms was nearly twice that of the average NZ farm when excluding the direct LUC or around 1.6 times the NZ footprint when including the direct LUC (Table 4). This difference is due to several contributing factors. For the comparisons below, we will use the NZ carbon footprint including direct LUC (1.09 kg CO_{2eq} / kg FPCM). Animal enteric CH_4 dominated emissions at 60% of the total on the NZ farm and 51% on the Chinese farms, but with absolute emissions highest on the Chinese farms. The latter was mainly associated with a lower feed conversion efficiency (higher feed dry matter intake per kg FPCM) on Chinese farms, presumably reflecting lower quality feeds and animal efficiency, as well as some differences in animal energy requirement calculations (based on NZ-specific and China-specific models separately), since all estimates were based on the IPCC (2006) factor of 6.5% energy from feeds lost as methane. The total GHG emissions per kg FPCM for these average farm systems were similar to those reported in other studies using LCA for China (Wang et al., 2018) and NZ (Ledgard et al., 2020).

Manure CH_4 emissions were higher from Chinese farms, representing 14% of the total footprint (Table 4) because of losses from collected and stored manure. In contrast, most animal excreta on NZ farms is directly deposited on soil and is not subject to anaerobic conditions that favour lower emissions. N_2O emissions from manure were similar in magnitude but from different sources. Most of the manure N_2O emissions for NZ are from urine/dung deposited on pasture, while for China, most of the N_2O emissions are indirect from ammonia loss from manure during cow housing and manure storage.

The other main contributor to higher GHG emissions on Chinese farms was feed production (13% of the total footprint). All feeds used on Chinese farms were produced off-site and were based on crop production with energy requirements for establishing and harvesting crops. This was associated with greater fuel use for the production and processing of crop feeds, as well as greater overall use of N fertilisers in the production of feeds. In contrast, most feeds by NZ dairy cattle was from perennial pastures consumed by animal grazing. In addition, a significant component of the animal feed used in China was from concentrates which had an energy requirement associated with processing them.

Table 4 - Contribution of various on-farm and off-farm sources to the total carbon footprint of milk (kg CO_{2eq} / kg FPCM; based on GWP100 AR5 values including CCF) for the average NZ and Chinese farm systems.

	New Zealand	China
	kg CO_{2eq} / kg FPCM	
Animal enteric CH_4	0.65	0.89
Manure CH_4	0.01	0.24
Manure N_2O	0.10	0.12
N fertiliser N_2O	0.03	0.10
Feed production, transport and crop residue N_2O	0.11	0.22
Fertiliser production and transport	0.03	0.10
Fuel use (direct on-farm)	<0.01	0.01
Electricity use	0.01	0.07
Other	0.01	<0.01
TOTAL	**0.95**	**1.76**
Land-use change (LUC)*	0.14	-
TOTAL (including LUC)	**1.09**	**1.76**

*direct land-use change from forestry to dairying

3.2.1.2 Sensitivity Analysis – climate-carbon cycle feedback

The inclusion of climate-carbon cycle feedbacks in the carbon footprint estimation is recommended in the ISO14067 carbon footprint guidelines. Likewise, the European Commission Product Environmental Footprinting guidelines also require inclusion of climate-carbon cycle feedbacks (see PEFCR guidance version 6.3). However, there are no studies available using those metrics, making it difficult to compare the numbers.

The effect of excluding the CCF is a reduction in the calculated CH_4 and N_2O emissions, with the percentage contribution of methane reducing from 62% to 58% of the total carbon footprint (Table 5). The estimate of the carbon footprint of milk excluding CCF decreases by 16% to 0.95 kg CO_{2eq}/kg FPCM (Table 5). Similarly, for the Chinese farm, the exclusion of CCF reduced the carbon footprint of milk by 16% (from 1.76 to 1.51 kg CO_{2eq}/kg FPCM).

Table 5 - Contribution from the various gases to the carbon footprint of milk produced in New Zealand for 2019/20 year in kg CO_{2eq} / kg FPCM (including LUC) excluding climate-carbon feedback (CCF) compared to analysis including CCF. Percentage contributions are in brackets. A disaggregated footprint is also provided for the main specific greenhouse gases with no GWP factor (in kg GHG/kg FPCM) .

	No metrics	AR4 Without CCF	AR5 Without CCF	AR5 With CCF
	kg GHG/kg FPCM	kg CO_{2eq}/kg FPCM		
Methane (CH_4)	0.01982	0.50 (55%)	0.55 (58%)	0.68 (62%)
Nitrous Oxide (N_2O)	0.00045	0.13 (16%)	0.12 (13%)	0.14 (13%)
Carbon dioxide (CO_2)	0.27000	0.27 (30%)	0.27 (28%)	0.27 (25%)
Other (e.g. HCFC134a)*	-	< 0.01 (0.2%)	< 0.01 (0.1%)	< 0.01 (0.1%)
Total	**-**	**0.90**	**0.95**	**1.09**

* Includes refrigerants, sulphur hexafluoride, etc.

3.2.2 Post-farm gate (to retailer-gate)

Detailed data on fuel use for milk collection from dairy farms and transport to factories across NZ was used to estimate GHG emissions equivalent to 0.0077 kg CO_{2eq}/kg FPCM. The corresponding estimate for milk collection in China was similar at 0.009 kg CO_{2eq}/kg FPCM. Packaging had the largest contribution in the processing stage for UHT milk (54% and 42% for milk produced in NZ and China, respectively (Table 6). This was also noted in several studies (Hospido et al., 2003; Nutter et al., 2013; Jungbluth et al., 2018). For WMP, thermal energy was the larger contributor (76%) in the processing stage (Table 6). WMP has been widely used because of its flexibility for storage, non-refrigeration, transportation, and prolonged use after opening compared to fluid milk. However, this is associated with a larger energy requirement for drying at the processing stage.

Shipping of NZ milk to China was the main contributor among the various transportation stages. The shipping of WMP to China showed a footprint 6.4 times lower than the UHT milk per litre of milk (Table 7 – kg CO_{2eq}/L of milk). Drying removes most of the water and decreases the weight and volume for transportation. Thus, while GHG emissions for transportation from NZ to China were similar for WMP and UHT milk on a product weight basis, they were lower for WMP on a liquid milk equivalence basis.

Table 6 - Breakdown of GHG emissions per kg product for the milk processing stage for New Zealand (NZ) whole milk powder (WMP) or ultra-high temperature (UHT) milk to Beijing, China. Data are compared to UHT milk produced in China. All data are per kg actual product on a fat- and protein-milk equivalent basis and litres of milk (liquid-equivalent).

Per kg of milk product (kg CO_2eq / kg)	NZ WMP	NZ UHT milk	China UHT milk
Electrical energy	0.060	0.012	0.076
Thermal energy	0.984	0.050	0.050
Cleaning chemicals	0.032	0.016	0.016
Packaging	0.218	0.094	0.104
TOTAL	**1.294**	**0.172**	**0.246**
Per litre of milk liquid-equivalent (kg CO_2eq / L milk*)			
Electrical energy	0.008	0.012	0.074
Thermal energy	0.123	0.048	0.048
Cleaning chemicals	0.004	0.016	0.016
Packaging	0.027	0.091	0.101
TOTAL	**0.162**	**0.167**	**0.238**

*1 kg of Whole Milk Powder makes 8 L of milk

Table 7 - Breakdown of GHG emissions per kg product for the milk shipping stage for New Zealand (NZ) whole milk powder (WMP) or ultra-high temperature (UHT) milk to Beijing, China. Data are compared to UHT milk produced in China. All data are per kg actual product on a fat- and protein-milk equivalent basis and litres of milk (liquid-equivalent).

Per kg of milk product (kg CO_2eq / kg milk)	NZ WMP	NZ UHT milk	China UHT milk
NZ factory to port	0.009	0.007	-
NZ to China	0.136	0.120	-
Chinese port to RDC	0.006	0.005	-
Storage at RDC	0.014	0.005	0.005
RDC to retailer	0.007	0.004	0.004
Chinese processor to retailer	-	-	0.005
TOTAL	**0.172**	**0.141**	**0.014**
Per litre of milk liquid-equivalent (kg CO_2eq / L milk*)			
NZ factory to port	0.001	0.007	-
NZ to China	0.017	0.116	-
Chinese port to RDC	0.001	0.005	-
Storage at RDC	0.002	0.005	0.005
RDC to retailer	0.001	0.004	0.004
Chinese factory to retailer	-	-	0.005
TOTAL	**0.022**	**0.137**	**0.014**

*1 kg of Whole Milk Powder makes 8 L of milk; RDC: regional distribution centre

3.2.3 Cradle to retailer-gate carbon footprint

Table 8 and Figure 6 summarise the “cradle to retailer-gate” carbon footprint of milk produced in NZ and delivered to a retail store in China, compared to milk produced in China and delivered to the retail store. In order to provide a direct comparison, the results below are discussed in litres of milk, considering that 1 kg of WMP results in 8 L of milk (on an equivalent FPCM basis; Table 8).

The final footprint for the cradle to retailer UHT milk produced in NZ and delivered to a retail store in China was 1.37 kg CO_{2eq} / L of milk, lower than the UHT milk produced in China and distributed to the retail store (1.96 kg CO_{2eq} / L of milk) (Table 8 and Figure 6). The on-farm stage represented 77% and 70% of the total footprint for NZ and Chinese milk, respectively (Figure 6). Similar footprints were found in the processing stage for both countries. Shipping the UHT milk to China represented 9% of the final footprint for the milk produced in NZ.

The final footprint for the cradle to retailer-gate for WMP produced in NZ and exported to China was 1.19 kg CO_{2eq} / L of milk (on a liquid-equivalent FPCM basis), lower than UHT milk produced in NZ and exported to China or UHT milk produced in China (1.37 and 1.96 kg CO_{2eq}/L of milk, respectively) (Table 8 and Figure 6). The shipping to China represented only 1% of the final footprint for WMP. This led to an increase in the (relative) importance of the on-farm footprint (84% of the total) for the WMP milk exported to China when compared to the on-farm contribution for the UHT milk (77%) (Figure 6). The use of WMP requires that the consumer add water to reconstitute it, and there will be some energy requirement for reticulation of the water, but it is likely to be insignificant. Interestingly, the wider Beijing area has a high water scarcity factor, whereas NZ has a low water scarcity factor (by at least 3-fold; Payen et al., 2018). Therefore, the water scarcity footprint for WMP could be higher than that for UHT. However, a detailed LCA is required to determine whether it is significant or not.

3.2.4 Sensitivity analysis – WMP to Europe

Whole Milk Powder exported to Europe had a very similar final footprint to WMP exported to China (1.21 and 1.19 kg CO_{2eq} / L of milk, respectively – Table 8 and Figure 6). While the greater shipping distance to Europe doubled the shipping emissions, this stage represented only approximately 1.5% and 3% of the total footprint (Table 8). Changing the RDC electricity emission factor for Europe gave a small decrease in emissions but it was <1% of the total footprint overall. Since most of the emissions are related to the on-farm production and processing of milk, the distance to the market has only a minor impact. Similar results were found in studies for different countries (e.g. Weber and Mathews, 2008).

Table 8 – Effect on the carbon footprint of whole milk powder (WMP) or ultra-high temperature (UHT) milk produced in NZ and shipped to a retailer in China. Data are compared to UHT milk produced in China. All data are per kg actual product on a fat- and protein-milk equivalent basis and litres of milk (liquid-equivalent).

	NZ WMP to China	NZ UHT to China	Chinese UHT	NZ WMP to Europe
Per kg of milk product (kg CO_2eq / kg milk)				
Farm	8.03	1.09	1.76	8.03
Transport from farm to factory	0.06	0.01	0.01	0.06
Processing*	1.29	0.17	0.25	1.29
Transport from processor to NZ port	0.01	0.01	-	0.01
Shipping	0.14	0.12	-	0.30
Transport port to RDC	0.01	0.01	-	< 0.01
Transport Chinese processor to RDC**	-	-	0.01	-
Storage at RDC	0.01	<0.01	<0.01	<0.01
Transport to RDC and retailer	0.01	<0.01	<0.01	0.01
TOTAL	**9.56**	**1.41**	**2.02**	**9.71**
Per litre of milk (liquid-equivalent) (kg CO_2eq / L milk)***				
Farm	1.00	1.05	1.70	1.00
Transport from farm to factory	0.01	0.01	0.01	0.01
Processing	0.16	0.17	0.24	0.16
Transport from processor to NZ port	<0.01	0.01	-	<0.01
Shipping	0.02	0.12	-	0.04
Transport port to RDC	<0.01	0.01	-	<0.01
Transport Chinese processor to RDC*	-	-	0.01	-
Storage at RDC	<0.01	<0.01	<0.01	<0.01
Transport to RDC and retailer	<0.01	<0.01	<0.01	<0.01
TOTAL	**1.19**	**1.37**	**1.96**	**1.21**

* includes processing and packaging; ** for Chinese milk only; ***1 kg of Whole Milk Powder makes 8 L of milk, RDC: regional distribution centre

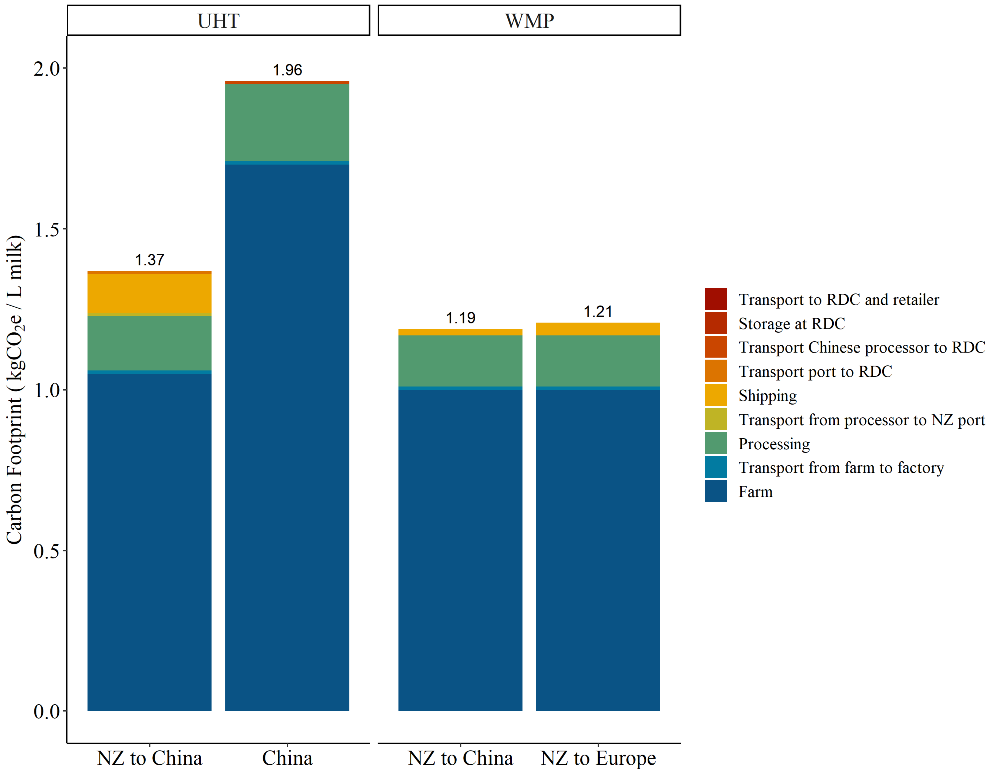

Figure 6 – Cradle to retailer-gate carbon footprint (in kg CO_{2eq}/L of milk) for Whole Milk Powder (WMP) produced in New Zealand exported to China or Europe; ultra-high temperature (UHT) milk produced in New Zealand and exported to China; and UHT milk produced in China.

Results from this study cannot be compared directly with those from the earlier MPI-supported dairy carbon footprint project due to various methodology differences (Lundie et al., 2008; Ledgard et al., 2008). However, the previous analysis was based on NZ dairy farm data for 2004/05 that was collected in the same way as the current study. When results for the previous study for the cradle to farm-gate were analysed using the same methodology as for the current study using GWP-2013 (without CCF), they resulted in similar estimates of the carbon footprint of milk of 0.80 and 0.81 kg CO_{2eq} / kg FPCM (excluding LUC) for 2004/05 and 2019/20, respectively. The corresponding estimates with LUC included were 0.85 and 0.95 kg CO_{2eq}/kg FPCM, respectively, with the latter being higher because it includes accounting for the relatively high LUC from plantation forest to pasture for dairying in 2006 and 2007 (since the LUC methodology is based on changes during the previous 20-years and there was no LUC prior to 2000). Thus, while there was little difference between 2004/05 and 2019/20 in GHG emissions per kg milk production based on farm GHG efficiency, it was higher for 2019/20 when LUC was included.

The earlier dairy carbon footprint study (Lundie et al., 2008) was based on an average mix of dairy products produced by Fonterra at that time and the system boundary for the study ended at an average overseas port. That study showed that the farm, processing and transport (largely shipping) stages made up 85%, 10% and 5% of the total carbon footprint of the dairy products to an average overseas port (Hutchings and Ledgard, 2009). These ratios are similar to those from the current study, but the methodology differences mean that it is not possible to make a direct comparison.

4. Future trends in dairy LCA

Recent literature has identified a fundamental issue associated with selecting functional units for food-based LCA studies. These studies typically utilise functional units based on mass or volume of a given product rather than the commodity's true function, which is to provide nutrition (Van Kernebeek et al., 2014). A recent review by McAuliffe et al. (2018) identified 16 papers that used the nutritional aspect as the functional unit. Nine studies estimated environmental impacts for functional units associated with nutrient density scores, and the others utilised alternative approaches to account for nutritional value, such as linear programming and end-point modelling combined with epidemiological data. Future research comparing multiple food categories (e.g. cattle milk versus plant-based alternatives) should acknowledge differences in nutritional composition and bioavailability between the final products and, ideally, the effects of these nutrients on overall dietary quality.

One other important topic of current discussion is the different impact categories evaluated in an LCA study. A recent review by McClelland et al. (2018) showed that the most frequently included impact category in livestock studies was climate change (i.e. carbon footprint), followed by resource depletion. The least frequently reviewed factors were particulate matter, ionising radiation, and biodiversity. Only a few studies examined more than six impact categories, and only four publications examined 12 categories. Simplified LCA is an important tool for highlighting the magnitude of one or a select set of environmental impacts, but because they ignore other potential impacts, they risk misinterpreting and misrepresenting the full extent of impacts on the environment. Specifically for NZ, impact categories such as eutrophication (from both nitrogen and phosphorus), resource depletion (especially fossil fuels) and stratospheric ozone depletion are relevant and should be included in the analysis.

Recently, researchers have developed a new GHG emission metric (GWP*) that more accurately represents the global warming impact of short-lived gases, such as CH_4, when estimating sector contributions to climate change targets. GWP100 averages the impact of short-lived gases over 100 years. In contrast, GWP* aims to more closely reflect short-term fluctuations in global warming impacts from short-lived gases by giving a stronger warming effect than GWP100 when CH_4 emissions are rising and a smaller effect when CH_4 emissions are stable or falling (Allen et al., 2018). This is especially relevant for ruminants, given that most of the emissions are related to enteric CH_4, and CH_4 is a short-lived GHG. GWP100 is relatively easy to use to calculate carbon footprints using current data and is the most common metric in use. To use GWP* to calculate total farm-level emissions, each farm would need to have access to accurate data on the farm's historical emissions – as GWP* requires baseline emissions information. The literature suggests this should be kept from 20 years prior to the current date of emissions calculation. While GWP* is largely untested for use in carbon footprinting by the wider scientific community, it is currently being examined by international groups alongside other potential options for more accurately representing the global warming impact of short-lived gases.

5. Conclusions

This study followed the most recent international guidelines (ISO 14067 and PEFCR) for calculating the “cradle to retailer-gate” carbon footprint of milk produced in New Zealand and exported to China. Following the guidelines, the emissions from direct LUC were included, and the latest 2013 GWP100 factors including CCF were used.

The UHT milk produced in NZ and exported to China had a lower carbon footprint than the UHT milk produced in China (1.37 and 1.96 kg CO_{2eq}/L of milk, respectively). This was mainly related to the high on-farm efficiency of the milk production in NZ, that represented 77% of the final footprint for UHT milk produced in NZ and exported to China. The carbon footprint for the on-farm stage in NZ was 38% lower than the on-farm stage in China (1.09 and 1.76 kg CO_{2eq}/ kg FPCM – including direct LUC and CCF). Shipping milk to China represented 9% of the total emissions for the UHT milk. The final footprint for WMP exported to China was 1.19 kg CO_{2eq}/L of milk (on a liquid FPCM equivalent basis), lower than the footprint for UHT milk. The shipping stage to China represented only 1% of the WMP footprint. A sensitivity analysis showed that exporting WMP to a more distant market (Europe) had little effect on the final footprint (1.21 kg CO_{2eq}/L of milk).

The studies found in the literature review had large differences in methodology and quality of the data used. Generally, studies focused on the “cradle to farm-gate” boundary and were based on GWP100 AR4 values, without CCF and excluding the direct LUC. For a direct comparison, values applying similar factors should be used. The carbon footprint for on-farm NZ milk using GWP100 AR4 values and excluding the direct LUC was 0.76 kg CO_{2eq}/kg FPCM, placing NZ in the lowest range of the carbon footprint estimates. A recent review addressing the different methodologies (Mazzetto et al., 2021) showed a similar result.

Most studies focused on the on-farm stage, with only two studies considering the whole value chain (cradle to grave) and the other nine studies focusing on both the on-farm and processing stage or only the processing stage or only packaging. Generally, the cradle to grave studies showed that most emissions (72% to 80% of the total) were associated with the on-farm stage, mainly due to animal CH_4 emissions. Carton packages showed a lower carbon footprint among the different packaging options, mainly due to the high energy demand for PET, HDPE, and glass bottles. In addition, comparative studies should use multiple environmental indicators (applying the latest accepted methods) to evaluate a range of potential environmental impacts associated with milk production and identify any burden-shifting between the impacts.

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7. Appendix 1 - FPCM calculations

Accounting for differences in protein and fat concentrations

IDF Equation (FPCM)

$$FPCM = M * (0.1226 * F + 0.0776 * P + 0.2534)$$

Where:

FPCM = Fat and Protein Corrected Milk (in kg);
M = Milk production (in kg);
F = Fat content (in %);
P = Protein content (in %);

FAO (or Gerber et al., 2011) Equation (FPCM)

$$FPCM = M * (0.116 * F + 0.06 * P + 0.337)$$

Where:

FPCM = Fat and Protein Corrected Milk (in kg);
M = Milk production (in kg);
F = Fat content (in %);
P = Protein content (in %);

ALP Equation (ECM)

$$ECM = M * (0.038 * F) + (0.024 * P) + (0.017 * L)/3.14$$

Where:

ECM = Energy Corrected Milk (in kg);
M = Milk production (in kg);
F = Fat content (in g/kg);
P = Protein content (in g/kg);
L = Lactose content (in g/kg) – Assumed average of 48g of Lactose per kg of milk;

Sjaunja et al. (1990) Equation (ECM)

$$ECM = (0.25 * M) + (12.2 * \left(M * \frac{F}{100}\right) + (7.7 * (M * \frac{P}{100})$$

Where:

ECM = Energy Corrected Milk (in kg);
M = Milk production (in kg);
F = Fat content (%);
P = Protein content (%);

Comparison

In order to compare all equations, we simulated the FPCM/ECM and carbon footprint calculations of an average cow milk with 4% fat and 3.5% protein. We used 100 kg of milk, with an emission of 100 kg of CO_{2eq}. The results (Table A1) show that all methodologies reached similar results, and we selected the IDF method as the standard for calculating the FPCM, as recommended by IDF (2015).

Table A1 – Comparison of milk FPCM conversions and footprint calculations using different equations.

Method	**FAO 2011**	**IDF 2015**	**Sjaunja et al., 1990**	**ALP**
FU	FPCM	FPCM	ECM	ECM
Milk prod (kg)	100	100	100	100
Fat (%)	4	4	4	4
Protein (%)	3.5	3.5	3.5	3.5
GHG Emission (kg CO_2eq)	100	100	100	100
FPCM (kg)	101.1	101.5	100.8	101.1
Footprint (kg CO_{2eq}/kg FU)	0.99	0.98	0.99	0.99

Where Milk prod is milk production; FPCM is fat and protein corrected milk; GHG is greenhouse gas

8. Appendix 2 – LCA approach for the cradle to farm-gate boundary

A1 - Goal of the study

The primary goal of this study was to determine the carbon footprint of milk from the average NZ dairy farm system for the year 2019/20 using LCA methodology in accordance with ISO 14040:2006 and 14044:2006 standards.

A2 - Scope of the study

The scope of an LCA study is defined in ISO 14044:2006 section 4.2.3.1, and among other things outlines the functions, functional unit, system boundary and cut-off criteria of the study. These are outlined in the following sections for the current study.

A2.1 Functional unit

The function analysed was the milk production of dairy farms. The main functional unit is one kg of fat and protein corrected milk.

A2.2 System boundary

The life cycle from cradle to farm gate was assessed for NZ milk production. The main inputs and outputs related to the production of raw milk (see Figure 5 in the main text) can be summarised as follows:

Inputs:

1. Feed (pasture and supplementary feeds)
2. Agrichemicals (mineral fertilisers and pesticides) for feed production
3. Animals for dairy production
4. Fuel
5. Energy for milking

Outputs:

1. Raw milk
2. “Meat”, i.e. live surplus animals sold for meat processing or for sale to beef farmers to grow for subsequent meat processing
3. Emissions

Processes excluded from the system boundary

Minor agri-chemicals such as treatments for intestinal parasites, mastitis and shed cleaning chemicals were not accounted for in the carbon footprint assessments. Other research indicates that these are likely to be negligible contributors (e.g. <0.1% of total).

A3 - Modelling approach

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

A3.1 Allocation

For the dairy farm stage, the GHG emissions were allocated between the co-products milk and meat according to a biological causality, based on the physiological feed requirements of the animal to produce milk and meat (calf, culled cows). The IDF (2015) methodology for allocation was used based on the relative amounts of milk and meat produced from the dairy farm system. This resulted in an average allocation value of 85% for milk.

For other processes generating more than one product such as some of the brought-in feed sources e.g. PKE, an economic allocation was used (IDF 2015).

A3.2 Data Quality

The technical description of regional dairy farm systems studied here relied mainly on two independent and reliable sources of information: the DairyNZ/LIC annual statistics (DairyNZ/LIC 2020) and the Dairybase database (DairyBase 2021).

DairyNZ/LIC statistics incorporate all NZ dairy farms but provide information on only some of the parameters needed for our analysis (milk production and quality, cow population and farm size). The Dairybase database was based on a significant sample of farms for each region and it provided complementary data on the inputs used by each regional average system.

Complementary surveys in each region were used to get more detailed information about the practices on dairy farms in each region. The different aspects and distances of transportation for animals grazed-off farm were based on a survey of consulting officers from DairyNZ and experts from Westland Milk products and PGG Wrightson (PGGW). Data on the distances of fertiliser transportation for each region were provided by experts from fertiliser companies (Ballance® and Ravensdown®). Transportation distances for brought-in-feed supplements were obtained from experts from Pioneer, DairyNZ and PGGW.

Secondary data from the international ecoinvent database (Wernet et al. 2016) was adapted as much as possible to the NZ situation for the carbon footprint of all inputs such as fertilisers, electricity and fuel.

A4 - Life Cycle Impact Assessment method

The carbon footprint (equivalent to Global Warming Potential (GWP)) for a 100-year time horizon (GWP100) was calculated according to Stocker et al. (2013) using kg CO_2-equivalent (subsequently expressed as kg CO_{2eq}). This has multiplication factors of CO_2 1, N_2O 265 and biogenic CH_4 27.75. GWP corresponds to the impact of emissions on the heat radiation absorption of the atmosphere.

A sensitivity analysis was carried out to determine the effects of including the climate-carbon cycle feedbacks. This has GWP100 multiplication factors of CO_2 1, N_2O 298, CH_4-biogenic 34 and CH_4-fossil 36 (Reisinger et al. 2017).

A5 - Life Cycle Inventory Data

A5.1 Regional averages and New Zealand weighted average

DairyNZ/LIC statistics and regional Dairybase data provided by DairyNZ were the two main sources of data used to design a non-overlapping range of regional average estimates.

A5.2 Off-farm grazing of replacements and wintering-off

For all regions, an average beef farm was assumed to be used for grazing replacements, based on the MPI Intensive Beef Monitor Farm. Where wintering off occurred, it was assumed to be on pasture, except for Otago/Southland where it was assumed to be on a brassica crop.

A5.3 Production of brought-in supplementary feeds

The average use of supplementary feeds brought into the farm, based on DairyBase data, are given in Table 2 (main text). The carbon footprint of the different brought-in feed sources was based on research in an MPI project on GHG emissions associated with feed sources (Ledgard & Falconer 2015). For regions using maize silage, it was assumed to be produced on a “typical” forage cropping block off the farm. The technical data for maize silage production was provided by the NZ branch of an international seed company (Ian Williams, Pioneer, pers. comm.), while data for barley grain and cereal silage were based on De Ruiter and Hanson (2004). The pasture silage was assumed to come from the beef farm where replacement animals were grazed. For PKE and molasses, the carbon footprints from AgriFootprint (Durlinger et al. 2014) from the appropriate country of origin was used with some modifications to include transport to NZ. It accounted for relative importation from different supplying countries. Molasses was assumed to come from Australia and PKE from Malaysia and Indonesia. The category “other feeds” includes waste horticulture products such as carrots, potatoes, kiwifruit, sweetcorn silage. These feeds were assumed to be waste product and therefore no production emissions were accounted for. However, it did include transport of the other feeds to the farm.

A5.4 Intake model

The DM intake by animals was estimated by using the NZ GHG Inventory model (MfE 2021) for both dairy cow and replacement animals. 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). The feed quality (ME, digestibility and N concentrations) was adjusted on a monthly basis to account for all feed supplements used in addition to pasture.

A5.5 Inventory-based greenhouse gas emissions

The inventory of GHG emissions covering CH_4 from enteric fermentation by cows, CH_4 and N_2O from excreta deposited on pasture and from effluents, and CO_2 emissions from lime and urea application were based on use of the NZ GHG Inventory methodology MfE (2021). Similarly, emissions from peatland soils was estimated using the Tier-1 method from the NZ GHG Inventory.

A5.6 Indirect inventory data

Electricity consumption was calculated as a function of cow numbers based on an NZ study by Sims et al. (2005) and as a function of irrigation based on a summary of types of irrigation systems, mm irrigation water applied and typical depth of pumping. The NZ electricity inventory was based on the breakdown between different NZ electricity sources (thermal including coal, natural gas and oil, hydro, and geothermal) according to for all years analysed.

The fuel consumption for all agricultural components including cow management, pasture production, supplementary feed production and delivery, was calculated from the analysis of all single operations needed specifically for each scenario and parameterised in our LCA model (SimaPro Version 9.1.1.1).

The carbon footprint calculations for the manufacturing and delivery of fertilisers were based on the NZ study of Ledgard et al. (2019).

A5.7 Land use change

A5.7.1 Direct Land use change

Land Use Change (LUC) was calculated based on methodology in the PAS 2050:2011 (BSI 2011), which accounted for changes over a 20-year period. This required adjustment for land converted from forest to dairying over a 20-year period up to the year of estimation of the carbon footprint. This was based on satellite data from MfE on the change in total area of land conversion from forest, which is regularly updated and therefore can result in small changes. It was assumed that 70% of this conversion was to dairying, based on the average from deforestation surveys of intended land use that varied over time between 54% and 91% (Manley (2006-2016)). The NZ GHG Inventory factor for forestry-to-pasture was used, which accounted for an increase in soil C after conversion to pasture (data provided by MPI).

A5.7.2 Land use change for PKE

The IDF (2015) guidelines recommend that CO_2 emissions associated with direct land use change (LUC) should be included in LCA-based carbon footprint analyses. In this study, the contribution from LUC associated with palm kernel expeller (PKE) from Malaysia and Indonesia was included. The carbon footprint of PKE was accessed from the AgriFootrpint database (Durlinger et al. (2014)), which uses the Direct Land Use Change Assessment Tool (Blonk (2017)) created by Blonk consultants to help LCA practitioners determine the direct land use change value for a specific crop in a specific country based on FAOSTAT data.