Carbon and fossil resource depletion footprints of milk production from Canterbury dairy farms

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Abstract

Among the different sustainability metrics, the carbon footprint is the most commonly reported, but the depletion of non-renewable resources such as fossil fuels, is also important. This study aimed to calculate the "cradle to farm-gate" carbon and fossil resource depletion footprint of milk production in Canterbury, New Zealand, comparing two different farm systems: one pasture-based with a relatively small amount of brought-in feed (Lincoln University Dairy Farm, LUDF) and an average Canterbury farm. The estimate of the carbon footprint of milk production was 0.68 and 0.80 kg CO_2-eq/kg of fat and protein-corrected milk (FPCM) for the LUDF and Canterbury average, respectively. The main contributor to the carbon footprint for both farms was enteric fermentation, but differences were found mainly in the emissions from the supplementary feed. Conversely, the Canterbury average farm showed lower fossil resource depletion footprint (1.05 MJ/kg FPCM) when compared with the LUDF farm (1.13 MJ/kg FPCM). The differences were mainly related to fertiliser use. However, this difference is small if compared with farms overseas. The study shows that it is important to look at more than one environmental metric when proposing mitigation practices.

Keywords: Life Cycle Assessment, mitigation, LUDF, cradle to farm-gate

Introduction

Milk is an important product for human nutrition. Recently, some consumers in developed countries have become more 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). Greenhouse gas emissions and their effects on climate change are key environmental issues for New Zealand (NZ, MfE 2020). Greenhouse gas reduction targets set by the NZ government (Climate Change Comission 2021) mean that large decreases are required from all sectors, including agriculture, since agriculture 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 (C) footprint of milk. The C 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 the understanding of the impact that farm practices have on GHG emissions and the identification of priorities for improvement.

Another important factor to consider is the efficiency of use of resources, especially fossil fuels. Their use is also a contributor to GHG emissions, mainly long-lived carbon dioxide (CO_2). As fossil fuels represent a limited non-renewable resource, the fossil resource depletion (RD) footprint is also an important factor to be analysed when evaluating dairy system sustainability. Thus, it is important to examine options for achieving high resource use efficiency, while minimising environmental impacts.

The C and RD footprints are calculated using a life cycle assessment (LCA) approach, a standardised (ISO 14040 standard, ISO 2006) methodology used to assess the impacts associated with all the activities contributing to the production, use and disposal of a product. For milk production, most studies use the "cradle to farm-gate" boundary, that accounts for the production of all inputs (including production of inputs such as fertilisers and brought-in feeds) and the on-farm stage (Baldini et al. 2017). Recently, Mazzetto et al. (2021) found that NZ milk has a low C footprint relative to many other countries, but there is also considerable variation between farms in emissions within NZ (Ledgard et al. 2020) and therefore opportunities for increasing environmental efficiency. There have been no evaluations of NZ research farms to understand where they sit in the distribution of variance in environmental footprints. The Lincoln University Dairy Farm (LUDF) has recently embarked on a drive for production efficiency (Pellow 2017), but it is not clear whether this aligns with low footprint values.

The objectives of this study were to calculate the cradle to farm-gate C footprint and the resource depletion (fossil) footprint of milk production from LUDF, compared with an average Canterbury dairy farm for the 2018/2019 production season, using

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attributional LCA methodology (ISO 14040:2006 and 14044:2006 standards; ISO 2006).

Material and Methods

The LUDF is a commercial demonstration farm owned by Lincoln University and managed by the South Island Dairy Development Centre (SIDDC, http://www.siddc.org.nz/). The LUDF has been changing its farm management over the last 10 years, participating in the local Pastoral 21 Phase 2 project (https://www.dairynz.co.nz/about-us/research/pastoral-21/). The farm is 160 ha (effective area), with targeted fertiliser application and a low amount of brought-in feed. The average Canterbury dairy farm used for comparison was described by Ledgard et al. (2020). Summary metrics for the two farms are shown in Table 1.

Functional unit and System Boundary

The functional unit was 1 kg of fat-and-protein-corrected-milk (FPCM; IDF 2015). The boundary of this study (cradle to farm-gate) covered all the relevant activities for milk production, including farm areas used for grazing replacement animals and wintering-off cows. Figure 1 summarises the key elements of the system boundary. All transportation steps and their associated emissions and energy use (including the production and combustion of fuel) within the system boundary were fully accounted for. It included transportation of feeds and chemicals (including fertilisers and pesticides) to the farm and the fuel use within the farm system. It also included the transport of the animals to/from the replacements and wintering-off farms and the farm activities at both.

Allocation

A dairy farm produces two main co-products of milk and live-weight sold for meat. Thus, total calculated emissions and energy use were allocated between the co-products based on the physiological feed requirements of the animal to produce milk and meat (surplus calves, culled cows) using the IDF (2015) methodology. Surplus calves are defined as male calves and surplus female calves that are slaughtered or sold for rearing for beef production. For other processes generating more than one product such as some brought-in feeds, an economic allocation was used (IDF 2015).

Table 1 Summary of farm characteristics for the Lincoln University Dairy Farm (LUDF) and the average Canterbury dairy farm for the 2018/19 production season (July-June).

	Units	LUDF	Canterbury average
Farm effective area	ha	160	221
Milk production	kg FPCM[1]	3,556,426	4,020,461
Milking cows	number	550	733
Surplus cattle sold	kg LW	72,160	126,471
Allocation to milk[2]	%	88	81
Nitrogen (N) fertiliser	kg N/ha	179	204
Brought-in feed	kg DM/ha	574	1337

[1] fat- and protein-corrected milk
[2] based on relative feed requirements for milk production to milk plus meat

Data source

A dairy cattle population summary was extracted for a 12-month period, including milking cows and all replacements. For the LUDF, the data were extracted from their database and interviews with the farm manager. The Canterbury average data were extracted from DairyBase (62 farms - https://www.dairynz.co.nz/business/dairybase/). Table 1 gives a summary of the main characteristics for each farm. The number of animals, their average live-weights and sales of surplus animals, were used to determine the total live-weight of surplus cattle sold from the farm (cull cows, cull heifers and surplus calves) over the 12 months.

The farms also provided data on the quantities (dry weight) of the range of feeds fed to all animal classes (including pasture silage). Footprint models were developed for each of the feeds, covering all life cycle emissions and energy use to the point of harvested/stored product or processed product (for concentrate feeds). This included all background emissions associated with the production and use of inputs such as fertilisers, fuel and brought-in feeds (Figure 1).

The farms provided primary data on the fuel and electricity use associated with the dairy farm, and all the contractor's activities performed on-farm. Fuel use for all aspects of the production of crops and transportation of crop feeds to the farm was calculated as part of the footprint of feeds, as described above.

An "average" pastoral farm was assumed to be used for grazing replacements for both the LUDF and Canterbury average farm. This was based on data for a typical beef and sheep intensive-finishing farm (generic class 7 from Beef + Lamb New Zealand), which also graze dairy replacements (Ledgard et al. 2020). The wintering-off information was obtained from the LUDF managers for the LUDF case study. For the Canterbury average, it was assumed that the wintering-off was done on pasture following the same approach as Ledgard et al. (2020).

Carbon footprint calculation

The dry matter intake (DMI) by animals was estimated using the NZ GHG Inventory model (MfE 2020). Methane (CH_4) emissions from enteric fermentation were calculated from the product of energy and DMI by animals using the NZ GHG Inventory model and the NZ-specific emission factors (EFs, MfE 2020).

The nitrogen (N) excreted by animals was calculated using the NZ GHG Inventory methodology, based on estimated DMI. Nitrous oxide (N_2O) emissions from cattle excreta were calculated assuming that the amount of N in excreta was the difference between the N in feed intake minus the N in the milk and meat using the Intergovernmental Panel on Climate Change (IPCC 2006) methodology. Methane and N_2O emissions from cattle excreta were also calculated, based on EFs from the NZ GHG Inventory. Methane emissions from dung were calculated by multiplying faecal DM proportion (1 - digestibility of feed) by specific EFs according to MfE (2020) for faecal DM deposited on pastures. Methane and N_2O emissions from farm dairy effluent were also estimated based on NZ Inventory methodology.

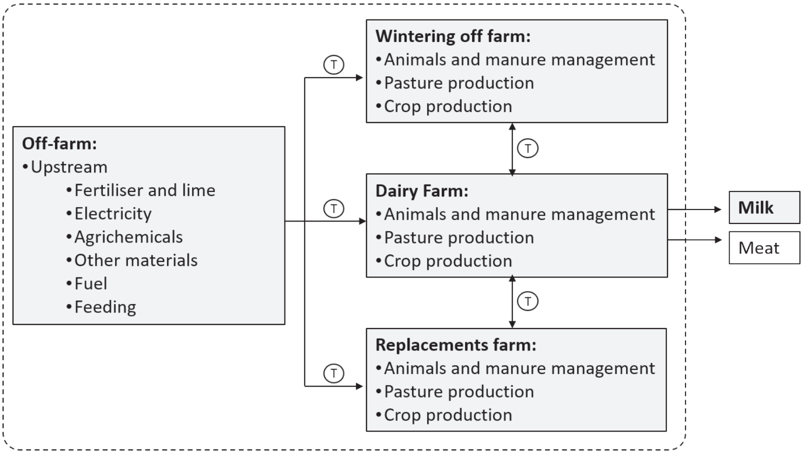

Figure 1 System boundary for the cradle to farm-gate life cycle assessment of milk production, including the off-farm land for wintering of cows off-farm and the grazing of replacement animals. "T" stands for transportation.

Direct N_2O emissions from excreta and N fertiliser application were calculated by multiplying N inputs by NZ-specific EFs corresponding to the fraction emitted to the atmosphere as N_2O. Indirect N_2O emissions were calculated using the NZ Inventory N source and EFs, which were developed from research and reviews carried out by NZ scientists (MfE 2020).

Direct CO_2 emissions from lime and urea application to soils were calculated according to the default IPCC EFs (IPCC 2006). The CO_2 absorbed by plants was not taken into account since it is assumed to be in equilibrium with losses from the grazing cycle and plant/soil respiration (i.e., zero net ecosystem production).

The C footprint calculations for the manufacturing and delivery of fertilisers were based on the NZ study of Ledgard & Falconer (2019b). The C footprint of the different brought-in feed sources was based on research in a Ministry for Primary Industries (MPI) project on GHG emissions associated with feed sources (Ledgard & Falconer 2015). When not available, the C footprint of the feed was retrieved from databases such as AgriFootprint (Durlinger et al. 2014) and Ecoinvent (Wernet et al. 2016), considering the appropriate country of origin with some modifications to include transport to NZ. The C footprint to produce pesticides was obtained using the same databases mentioned above (AgriFootprint and Ecoinvent).

The GHG EF for electricity use was based on the NZ average grid mix and use of Ecoinvent 3.5 (Wernet et al. 2016).

The C footprint (equivalent to Global Warming Potential) for a 100-year time horizon (GWP100) was calculated according to the IPCC 2013 method (Stocker et al. 2013) in kg CO_2-equivalent (subsequently expressed as kg CO_2-eq). This has CO_2-eq multiplication factors of $CO_2 = 1$, $N_2O = 265$ and enteric fermentation $CH_4 = 27.75$.

Fossil resource depletion footprint calculation

Fossil resource use associated with the production and use of all inputs was determined, including pesticides, lime, fertilisers and brought-in feeds. Other sources were the fuel directly used on-farm; fuel derived from the transportation of the inputs to the farm and fuel used for the contractor's activities (estimated using specific factors). Specific energy factors were used, with most estimates derived using country-specific adjustment in Ecoinvent version 3.5 (Wernet et al. 2016).

Results and Discussion

Carbon footprint

The estimate of the C footprint (cradle to farm-gate) of milk production was 0.68 and 0.80 kg CO_2-eq/kg FPCM for the LUDF and Canterbury average farm, respectively (Table 2). The result for the Canterbury average is in the middle of the range for the NZ average C footprint of milk calculated in the 2018/2019 production season, 0.72-0.86 kg CO_2-eq/kg FPCM (Ledgard et al. 2020). A recent review of international studies (Lorenz et al. 2019) showed that the C footprint value generally decreased with increased milk production per cow and with an increased proportion of the diet from pasture. The LUDF value is lower than the NZ range for the

2019/19 production year, and much lower than average values found in different regions of the world (0.77 to 3.34 kg CO_2-eq/kg FPCM, Mazzetto et al. 2021).

The main contributor to the C footprint of milk was CH_4 from enteric fermentation (73% and 72% of the total for the LUDF and Canterbury average farm, respectively), as typically found in most dairy and beef cattle studies (Baldini et al. 2017).

The emission from the manure management on both farms was low (Tables 2, 3), reflecting the effect of the year-round grazing, especially when compared with studies in temperate countries where animals are housed for a greater proportion of the year, and manure emissions have a more substantial impact on the final footprint (Mazzetto et al. 2021).

The emission of CO_2 from the inputs and production of supplementary feeds contributed 6% of the C footprint of milk for the Canterbury average farm, relative to less than 1% for the LUDF (Table 2). The main brought-in feed on Canterbury farms was palm-kernel expeller (PKE) that has a relatively high C footprint associated with its production and import (Ledgard et al. 2020). Farms relying on grazing of pasture show less CO_2 emissions from fossil fuel due to efficient feed utilisation via grazing compared to housed systems where crops must be established, harvested, transported and fed to animals. Other sources with a smaller contribution to the C footprint were CO_2 from fuel and electricity and on-farm crop residues, both accounting for less than 5% of the total emission.

Table 2 Carbon footprint for the Lincoln University Dairy Farm (LUDF) and the average Canterbury dairy farm for the 2018/2019 year, divided into greenhouse gas sources. Data units are kg CO_2-eq/kg FPCM.

	LUDF	Canterbury average
	kg CO_2-eq/kg FPCM	
Enteric CH_4	0.50	0.58
Urine, Dung and FDE[1] N_2O	0.03	0.06
CO_2 from supplementary feed production	<0.01	0.05
CO_2 from fertiliser application and production	0.03	0.04
Nitrogen fertiliser N_2O	0.03	0.03
CO_2 from fuel and electricity	0.03	0.02
CO_2 from other activities[2]	0.04	0.01
Dung and FDE CH_4	0.02	0.01
Total	**0.68**	**0.80**

[1] FDE: farm dairy effluent

[2] Other activities: upstream emissions from wintering-off and replacement farms

For the C footprint of milk production, the relative contributions from CH_4, N_2O and CO_2 were 76%, 15% and 9%, respectively for the LUDF farm and 74%, 14% and 12%, respectively for the Canterbury average farm (Table 3). Dairy farms that rely on grazing of pasture usually show a proportionally high contribution of enteric CH_4 in the total footprint (Mazzetto et al. 2020; Ledgard et al. 2020). For both farms, enteric CH_4 represents over 70% of the total emission. This contrasts with the footprint in some other temperate countries, where the manure management and brought-in feed represents an important share of the final footprint. In such cases the enteric CH_4 can account for <50% (Jayasundara et al. 2019; Wang et al. 2019).

The LUDF farm showed a higher percentage of CH_4 and lower percentage of CO_2 contribution to total footprint when compared with the Canterbury average farm, due largely to differences in the level of brought-in feed (Tables 1, 3). This is especially relevant given the new GHG metrics that are being proposed. Recently, a group of researchers proposed a new methodology (GWP*) to account for the surface temperature effects of gases with different lifetimes (Allen et al. 2018). Because it accurately reflects the surface warming of a time-series of gases, GWP* gives a stronger warming effect than GWP100

Table 3 Percentage contribution from various gases and sources to the carbon footprint of milk from the Lincoln University Dairy Farm (LUDF) and the Canterbury average dairy farm for the 2018/2019 year.

Source	LUDF	Canterbury average
Methane (CH_4)	76	74
Nitrous oxide (N_2O)	15	14
Carbon dioxide (CO_2)	9	12
Sources of CH_4:		
Enteric fermentation	96	98
Manure/FDE[1]/dung	4	2
Sources of N_2O:		
Excreta on pasture	50	67
Nitrogen fertiliser on pasture	48	30
On-farm residues	2	3
Sources of CO_2:		
Feeds	0	43
Nitrogen fertiliser on pasture	28	35
Other[2]	51	9
Fuel and electricity	21	13

[1] FDE: farm dairy effluent

[2] Other: production of fertiliser, production and use of fuel

when CH_4 emissions are rising, and a smaller impact when CH_4 emissions are stable or falling.

As CH_4 from enteric fermentation is the main source of emissions, future mitigation practices should focus on reducing this source. These could focus on breeding animals with low-CH_4 emission, as already demonstrated with small ruminants (Goopy 2019; Rowe et al. 2019). The use of additives, such as seaweed or other inhibitors (Vijn et al. 2020), are also promising alternatives to reduce CH_4 emissions.

It is important to note that these footprints account for all the emissions on- and off-farm, including the inputs and CH_4 emissions from animals in the wintering-off and farms breeding the replacement animals. Most farm management software that calculates GHG emissions usually does not account for the off-farm emissions, and the calculation can not be considered a "full-LCA" approach. The use of such calculations could lead to wrong interpretation of suitable mitigations. For example, the use of low-N feeds (as maize silage) would decrease the on-farm calculated footprint but may actually increase it when all off-farm contributions are included.

Fossil resource depletion footprint

The estimate of the fossil RD footprint (cradle to farm-gate) of milk production was 1.05 and 1.13 MJ/kg FPCM for the LUDF and Canterbury average farms, respectively (Table 4). There have been few studies examining the fossil energy use at the farm-gate boundary. The results obtained are much lower than studies performed in livestock housing systems in the Netherlands (5.1 MJ/kg FPCM, Thomassen et al. 2009), where the main energy use is related to the brought-in feed. Dual-purpose systems in tropical areas (4.06 MJ/kg FPCM, Mazzetto et al. 2020), mixed dairy systems (pasture grazing and partial housing) in Ireland (2.3 MJ/kg FPCM, O'Brien et al. 2012) and France (2.6 MJ/kg FPCM, van der Werf et al. 2009) also showed lower RD footprint than fully housed systems, but still higher than the footprint obtained in this study. These differences are largely due to the variation in the use of resources for feeding between the various temperate countries. Most feed consumed on NZ farms is from grazed perennial pasture. When brought-in feeds are included in the animal diet, the effect is noted in the RD footprint, as shown by the Canterbury average farm (Table 4). However, this effect on the total did not lead to an overall higher footprint than the LUDF farm where less brought-in feed was used (Tables 1, 4), due to the offsetting effect of other factors – fertiliser, fuel and electricity. The resource depletion footprint obtained for both farms in this study was also lower than the estimate for the NZ average of 1.32 MJ/kg FPCM (Ledgard & Falconer 2019a).

Table 4 Fossil resource depletion footprint for the Lincoln University Dairy Farm (LUDF) and the Canterbury average dairy farm for the 2018/2019 production season.

	LUDF	Canterbury average
	MJ/kg FPCM	
Fertiliser	0.90	0.79
Brought-in feed	0.01	0.14
Direct fuel	0.08	0.04
Electricity	0.14	0.08
Transport	0.01	0.01
Total	**1.13**	**1.05**

The main contributor to the RD footprint of milk was fertiliser (79% and 75% of the total for the LUDF and Canterbury average farms, respectively), which includes energy for manufacturing and fuel used for transport and spreading. It is important to note that, despite LUDF having a lower N fertiliser application rate (Table 1), this analysis included all types of fertilisers, not only N. The use of energy for the production and transport of brought-in feeds contributed to 13% of the RD footprint of milk for the Canterbury average farm. Other sources with a much smaller contribution to the RD footprint of milk were lime production/transport and application; electricity and fuel for the transportation of the animals to/from the run-off farm, all accounting for less than 5% of the total emission (Table 4).

Fossil fuel is a non-renewable resource that is being depleted and has increasingly higher price volatility (Liu et al. 2020). Thus, managing this resource can result in economic benefits as well as synergies with other environmental benefits, e.g., reduced CO_2 emission. The largest opportunities for reduction relate to reducing N fertiliser use and increasing N efficiency, as well as minimising use of brought-in feeds (especially from imported-to-NZ feeds). All the potential mitigation actions listed above would also contribute to a reduction in the C footprint of the dairy farm.

General Discussion

One other important topic of the current discussion is the different impact categories that should be evaluated in an LCA study, bringing a more holistic perspective into decision-making, not only focusing on one environmental burden (usually climate change). A recent review by McClelland et al. (2018) showed that the most frequently included impact category in livestock studies was climate change (i.e., C footprint), followed by resource depletion, the two impact categories studied in this paper. The least frequently reviewed factors were particulate matter, ionising radiation and biodiversity. Only a small number of studies examined more than six impact categories, and only four publications examined 12 categories. Simplified LCAs are important tools for highlighting the magnitude of one or a select set of environmental impacts. Still, they risk under-representing the full extent of impacts on the environment because they ignore other potential consequences. This study showed that LUDF has a C footprint 18% lower than the Canterbury average, but a resource footprint that was 8% higher. This is one example of the possible "pollution swapping" that can happen if mitigation practices are defined when assessing only one environmental burden.

One important factor to consider is the interaction between production systems, such as between dairy and beef farms. When the dairy farm's boundaries are expanded for considering the contribution of dairy cattle to beef systems, less intensive farming results in a smaller C footprint per kg of milk plus beef, but still shows a larger land occupation footprint (m^2) than intensive systems (Mazzetto et al. 2020). This also applies for increased dairy cow reproductive efficiency. One option for reducing the footprint of pasture-based systems is making greater use of surplus calves from the dairy herd, with a potential to reduce up to 22% of the final footprint due to less need for breeding beef cows with their associated lifetime emissions (van Selm et al. 2021).

Conclusion

This LCA study has illustrated differences in fossil resource demand and GHG emissions with the LUDF showing relatively high efficiency, especially for the C footprint. The pasture-based management had a strong influence on the result observed for the LUDF C footprint, mainly related to the low use of brought-in feed. However, analysis showed the enteric fermentation and N fertiliser emissions as areas for further reduction opportunity. Future work should look at changes over time from the LUDF to learn where the greatest environmental benefits have occurred. It should also consider other environmental impacts (such as water footprint, land footprint, etc.) to avoid trade-offs when imposing climate change mitigations.

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