Mapping the carbon footprint of milk for dairy cows

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Abbreviations used

CH_4	Methane
CO_2	Carbon dioxide
dLUC	Direct land use change
DMI	Dry Matter Intake
FAO	Food and Agriculture Organisation of the United Nations
FPCM	Fat and Protein Corrected Milk
FU	Functional Unit
GHG	Greenhouse gas
GWP	Global Warming Potential
IDF	International Dairy Federation
IPCC	International Panel on Climate Change
LCA	Life Cycle Assessment
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_3^-	Nitrate
NZ	New Zealand

1. Executive Summary

The aim of this study was to compare the carbon footprint (i.e. total greenhouse [GHG] emissions per kg of product) of dairy cow milk from New Zealand (NZ) with that from different countries or major regions globally, while taking account of differences in methodologies used to calculate the footprint. To do this, we performed a systematic review of published studies analysing milk production from the “cradle to farm-gate”. Our search resulted in 86 papers that were screened for applicability to four selection criteria that focussed on: number of farms, the Global Warming Potential (GWP) metric used, fat-and-protein corrected milk (FPCM) as the functional unit (FU), and allocation method (partitioning of the inputs and/or outputs between the main product, i.e. milk, and co-product, i.e. liveweight sold for meat). Twenty-five papers from 18 countries were selected for this review, representing 55% of the milk produced in the world. The main factor for excluding papers was that they analysed only one or a limited number of farms or specific management / mitigation practices. Some papers did not meet the GWP, FU or allocation criterion, but did have sufficient data available (either in the paper or from personal communication with the authors) to recalculate the footprints. We performed these recalculations to keep the number of studies as high as possible and with comparable results.

The global average from this study was 1.47 kg CO_2e kg FPCM^{-1}, ranging from 0.77 (New Zealand – NZ or 0.91 if direct land use change is considered) to 3.34 (Peru) kg CO_2e kg FPCM^{-1}. There was a moderate negative correlation between the carbon footprint of milk and the milk yield per cow (more milk per cow = lower footprint - $r^2 = 0.33$, $p < 0.01$) between countries. Several countries were outside the confidence interval for this relationship, including NZ. The GHG profile (i.e. the share of each GHG in the carbon footprint) was different among countries. Developed countries with high milk yield per cow showed a bigger contribution from carbon dioxide (CO_2) and nitrous oxide (N_2O) to the footprint than other countries with lower milk yields, that had a higher contribution from methane (CH_4). This is especially important given recent focus on metrics that more accurately reflect the effects of a time-series of emissions of GHG, such as the new GWP* metric. Countries like NZ, Ireland, Australia and Uruguay, that are known for their pasture-based systems with good pasture management, could appear more efficient, with lower carbon footprints if a GWP* approach is used, as CH_4 contributes over 65% of the footprint of milk from these countries. In contrast, in countries with significant cow housing and crop-based feeding (e.g., USA, Canada and other European countries) CH_4 has a smaller share of the milk footprint (30 to 50%).

Reported results were influenced by methodology. No other studies referred to direct land use change (dLUC) on the milking farm (although it is unlikely to have occurred in most developed countries), but most studies appeared to account for dLUC for imported soybean feed. Accounting for dLUC from plantation forest to pasture for dairying in NZ increased the carbon footprint of NZ milk from 0.77 to 0.91 kg CO_2e kg FPCM^{-1}. The allocation method had a significant impact when recalculating the footprints using a common method, but there was little effect when the recalculations were performed for a common GWP or FU. The other important factor is the methodology used for calculating the emissions. Countries like NZ, Ireland and Australia use a national inventory approach and (mostly) regional/national specific emission factors, which is different from other countries that use the IPCC methodology with default factors. When recalculating New Zealand’s most recent carbon footprint (Ledgard et al., 2020) using the IPCC methodology with default factors, the footprint

for milk increased from 0.74 to 1.17 kg CO_2e kg $FPCM^{-1}$. However, the country-specific methodology is based on detailed research within the specific countries and is therefore the most valid approach to use where it is available.

2. Background

Greenhouse gas (GHG) emissions and their effects on climate change are a key environmental issue, and agriculture represents an important share of national inventories, especially in agricultural economies such as New Zealand (MfE 2019). Milk is one of the important products from cattle, and different countries have been calculating its carbon footprint (total GHG emissions associated with production of a product) using Life Cycle Assessment (LCA) to assess the efficiency of their milk production systems.

Dairy systems produce a mix of goods (mainly milk and meat) that cannot be easily disaggregated. In LCA, this disaggregation can be done using allocation methods. The International Organisation for Standarisation (ISO) recommends avoiding allocation when possible, but complex systems (as dairy production) usually depend on allocation practices to identify the environmental burdens among the different products. The decision of which allocation method to use depends on the goal and scope of the project, but recently the International Dairy Federation (IDF) has recommended the biophysical approach. The functional unit (FU) and Global Warming Potential (GWP) are two other important factors when calculating the carbon footprint of milk. The most common FU is one kg of fat-and-protein-corrected-milk (FPCM), although milk volume (in L) or mass of energy-corrected-milk (ECM) are other FU used. The GWP is a standard metric for comparing emissions of different greenhouse gases and it has been evolving (and in consequence changing values) over the last 20 years.

LCA studies of dairy cattle milk production usually consist of an analysis of an “average” or “representative” dairy farm, that doesn’t provide insights on the broader regional/national scale. Furthermore, the lack of consistency in the treatment of important factors (such as allocation, GWP and FU) (Baldini et al., 2017), results in discrepancies that limit the comparability of the studies.

To provide a broader insight into the carbon footprint of milk production at the country level, a review of the carbon footprint of dairy cattle milk was conducted, based on studies that accounted for a large number of farms (thus being representative of the country/region). To address the methodological inconsistencies between the studies, we used a systematic approach to evaluate and (when necessary) recalculate the footprint of the studies to allow comparisons.

3. Method

3.1 Review

We conducted a structured review focusing on the carbon footprint of cow’s milk from different countries. The literature search was performed using “Web of Science”, “Science Direct” and “Google Scholar” search engines. The search was carried out using all combinations of the following keywords: “life cycle assessment”; “LCA”; “carbon footprint”; “carbon accounting”; “milk”; “cattle”. We also screened the references of studies retrieved. There were no restrictions regarding the year of the publication.

Papers were selected based on the following criteria (summarised in Figure 1):

1) The system boundary was “cradle to farm-gate” and more than 100 farms were included or it was claimed that the sample was representative of the country/region. When more than one paper from the same country covering important country-regions were found, we assessed the dairy production of the regions to check if the composite sample represented a good average of the country. Most papers were eliminated in this first step since the majority of cattle milk LCA studies covered only one “typical” farm or a small number of farms comparing different management practices;

2) The study used the GWP100 values from the IPCC 4th assessment report (IPCC, 2007 – carbon dioxide [CO_2] = 1; methane [CH_4] = 25; nitrous oxide [N_2O] = 298) as the global warming potential, or had data available that could be easily recalculated. This approach was selected instead of the latest values (IPCC, 2013 – 5th assessment report) because only a small number of papers used the 2013 method. The footprint had to be re-calculated for five papers (Thomassen et al. 2009; O'Brien et al. 2015; O'Brien et al. 2016; Darré et al. 2020; Gilardino et al. 2020);

3) The study used biological allocation between milk and liveweight sold for meat (i.e. based on the relative energy requirements for production of these co-products) as recommended by International Dairy Federation (IDF, 2010, 2015) or had the data available that could be allocated correctly. The allocation had to be recalculated (and was set to a typical value of 85% allocation to milk – IDF, 2015) for 16 papers (Thomassen et al. 2009; van der Werf et al. 2009; Bartl et al. 2011; Flysjö et al. 2011; Kristensen et al. 2011; Thoma et al. 2013; Garg et al. 2016; O'Brien et al. 2016; Chen & Holden 2018; Christie et al. 2018; Morais et al. 2018; Wang et al. 2019; Darré et al. 2020; Gilardino et al. 2020; Wilkes et al. 2020; Mazzetto et al. 2020);

4) The study used FPCM as a functional unit or had the fat and protein data available to allow the functional unit to be changed. The functional unit had to be recalculated for six papers (Bartl et al. 2011; Flysjö et al. 2011; Kristensen et al. 2011; Thoma et al. 2013; Darré et al. 2020; Gilardino et al. 2020).

Our initial search resulted in 86 papers, of which 25 (Table 1) from 18 different countries (Figure 2) fulfilled the selection criteria (Figure 1). The countries with more than one study selected were New Zealand, Ireland and Italy (all with three studies), followed by Australia and Peru (two studies each), while the other countries had only one study each (Figure 2). In every step mentioned, we scanned the papers to find data that would allow the recalculation of the footprints. If data were not available, we contacted the authors and asked for supplementary data. If the author didn’t have the data or didn’t answer, we excluded the paper from the database (Figure 1). Table 1 summarises the recalculations performed.

Figure 1: Flow diagram showing how the papers were included or excluded from the review. GWP: Global Warming Potential; FU: Functional Unit

Table 1: Papers selected for the review. The red circles represent where the recalculation was necessary and the green ticks show where the original data were extracted from the paper.

Author	**Country**	**Number of farms**	**Allocation**	**GWP**	**FU**
Ledgard et al., 2020	New Zealand	268	✓	✓	✓
Gilardino et al., 2020	Peru	34	●	●	●
Wilkes et al., 2020	Kenya	382	●	✓	✓
Lovarelli et al., 2020	Italy	84	✓	✓	✓
Darre et al., 2020	Uruguay	277	●	●	●
Mazzetto et al., 2020	Costa Rica	253	●	✓	✓
Wang et al., 2019	China	36	●	✓	✓
Jayasundara et al., 2019	Canada	142	✓	✓	✓
Chen et al., 2018	Ireland	262	●	✓	✓
Morais et al., 2018	Portugal	25	●	✓	✓
Reisinger et al., 2017	New Zealand	244	✓	✓	✓
Garc et al., 2016	India	60	●	✓	✓
O'Brien et al., 2016	Ireland	65	●	●	✓

Author	**Country**	**Number of farms**	**Allocation**	**GWP**	**FU**
O'Brien et al., 2015	Ireland	221	✓	●	✓
Kiefer et al., 2015	Germany	113	✓	✓	✓
Christie et al., 2015	Australia	41	●	✓	✓
Guerci et al., 2014	Italy	32	✓	✓	✓
Gollnow et al., 2014	Australia	139	✓	✓	✓
Bava et al., 2014	Italy	28	✓	✓	✓
Thoma et al., 2013	USA	536	✓	✓	●
Kristensen et al., 2011	Denmark	67	✓	✓	●
Bartl et al., 2011	Peru	52	●	✓	●
Flysjo et al., 2011	New Zealand	268	●	✓	●
Flysjo et al., 2011	Sweden	National data	●	✓	●
van der Werf et al., 2009	France	47	●	✓	✓
Thomassen et al., 2009	Netherlands	119	●	●	✓

GWP: Global Warming Potential; FU: Functional Unit

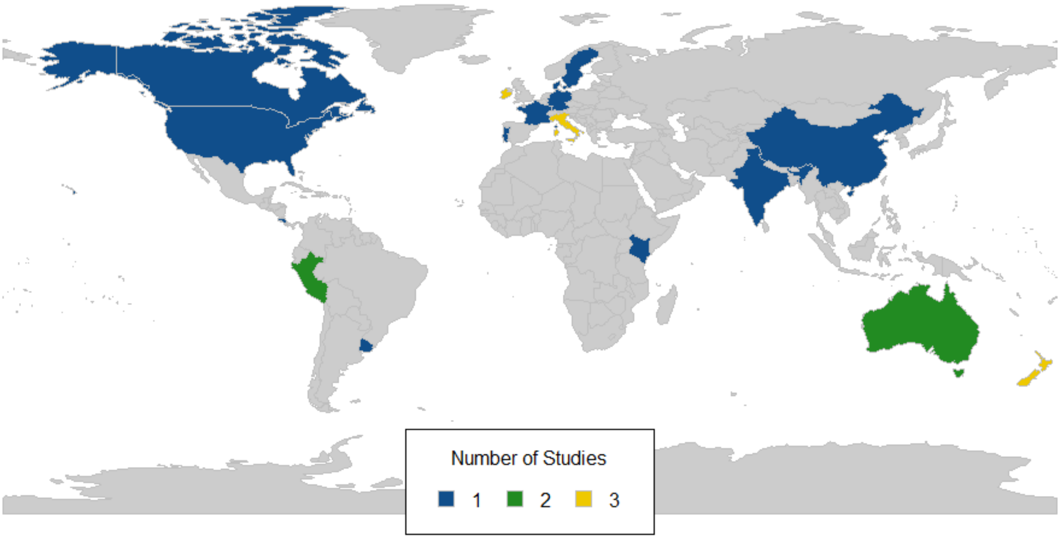

Figure 2: Map of the countries selected and number of studies per country reviewed

For each publication, a specific study code was assigned. The following characteristics were recorded in the database: author, year, country, region, number of farms studied, average farm area (ha), allocation method, allocation percentage (%), GWP method, functional unit, carbon footprint (kg CO_2e FU^{-1}), GHG breakdown (% of total footprint related to CH_4, CO_2 and N_2O), milk production (and unit), milk fat (%), milk protein (%), number of cows, live weight of cows (kg), dry matter intake (DMI) for cows (and unit) and replacement rate (%). Where possible, statistical data (standard deviation, coefficient of variation, quartiles, etc.) were collected for each of the characteristics mentioned above.

When more than one study was found for a specific country (e.g. 3 studies for NZ), a weighted average based on the number of farms in each study was calculated.

Apart from the methodological differences described above, LCA studies have different levels of sophistication (or “Tiers”), depending on the emission factors available for each country/region. In our review, we also compiled the methodology (equations and/or models) used in the studies to calculate the emissions for the following sources: enteric CH_4, CH_4 from manure; direct N_2O from nitrogen application (fertiliser, urine and faeces); indirect N_2O via nitrate (NO_3^-), leaching; indirect N_2O via NH_3 volatilisation; and background processes (production of inputs, fuel, electricity, etc.).

3.2 Footprint recalculation for NZ using different methodologies

In order to test the effect of the methodology used, we used the NZ study of Ledgard et al. (2020) and performed an LCA using both country-specific and default (IPCC, 2006) emission factors for N_2O. We chose to use the default factors from 2006 to keep the results consistent in comparison with the other reviewed studies. In this study, we expanded the analysis by also recalculating the emission from CH_4 (enteric fermentation and manure) using the IPCC emission factors. We selected the GWP from IPCC (2007) to keep the results consistent with the other papers evaluated in this review. Effects of including dLUC were also assessed using national inventory data and PAS2050 (2011) methodology.

4. Results and Discussion

4.1 Effect of the re-calculations performed

The recalculations performed in this study were based on limited data obtained from the papers or personal communication with the authors. As shown in Table 1, we had to recalculate the footprint for 18 of the 25 papers. The effects of the recalculations are shown in Figure 3. For 14 studies the recalculation resulted in relatively small changes (<15% of the original footprint), while the change for the other studies were moderate (between 20 and 30% for 2 studies) or larger (around 50% of original footprint for the remaining 2 studies).

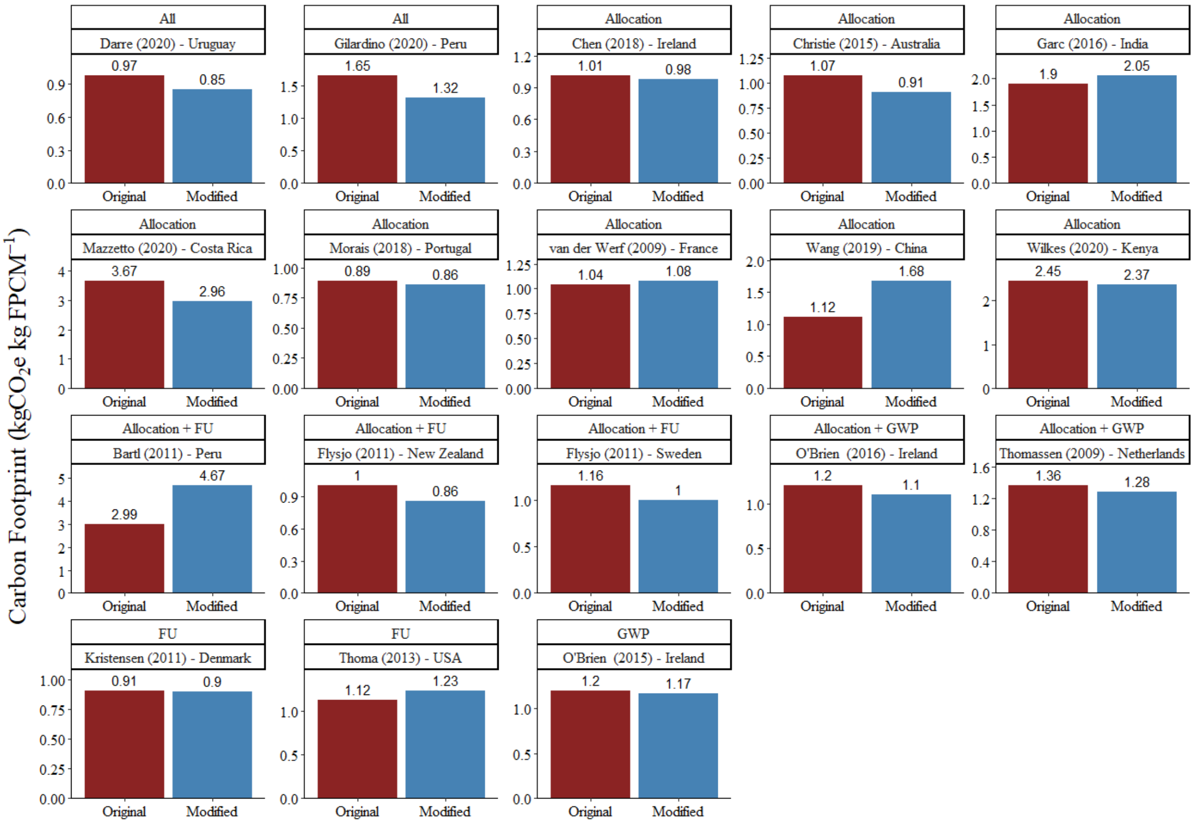

Figure 3: Effect of recalculations on the original footprint for the 18 studies, depending on the allocation, Global Warming Potential (GWP) and Functional Unit (FU) factors (or the combination of them – All).

The change in FU (for (Kristensen et al. 2011)) resulted in only a small change in the final footprint (Figure 3). The equations for FPCM and energy corrected milk (ECM) are similar, not having a significant impact on the final footprint (Baldini et al., 2017) (Figure 3).

The change in GWP in O'Brien et al. (2015) resulted in little change in the final carbon footprint (Figure 3). O'Brien et al. (2015) used the GWP values from IPCC (2013) but our recalculation used GWP values from IPCC (2007). Thus the CH_4 GWP decreased from 27.75 to 25 (IPCC 2013 and 2007, respectively) while the N_2O GWP increased from 265 to 298 (IPCC 2013 and 2007, respectively). Therefore, the magnitude of the effect of the GWP change will depend on the GHG profile of the study. Reisinger et al. (2017) showed that the carbon footprint of NZ farms is robust against changes in values used for GWP. Still, there are instances when a change in the metric would change the conclusions of the LCA (e.g. comparison between higher and lower input systems).

The allocation methods are particularly important and lead to significant differences in the footprint (Figure 3). The effect of this recalculation can be two-sided. For some studies, it led to lower footprints than the original (Chen & Holden 2018; Christie et al. 2018; Morais et al. 2018; Darré et al. 2020; Gilardino et al. 2020; Mazzetto et al. 2020), while others had higher footprints (van der Werf et al. 2009; Garg et al. 2016; Wang et al. 2019; Wilkes et al. 2020).

According to IDF (2015), the biological allocation (considering the amount of milk and live weight produced by the dairy farm) is the most appropriate allocation approach. We didn’t find data in most papers that allowed us to recalculate the allocation using the IDF (2015) method, leading us to apply the default factor of 85% allocation to milk in these studies. This recalculation may have reduced the footprint for farms/countries where the dairy farms don’t export many animals (culled cows and calves) and/or have very high milk production per cow, resulting in a true allocation factor for milk that would be higher than 85%. On the other hand, the recalculation may have increased the footprint of farms that export many animals, and where the true allocation factor would be lower than 85%. Thus, it will likely have led to a small under-estimation of the real carbon footprint of milk for farms with high milk per cow production such as for Canada, USA and Sweden, while leading to a small overestimation for low milk production farms such as for India, Kenya and Peru.

4.2 Carbon footprint review

The 18 countries covered by the review represent 55% of the total milk produced in the world (FAOSTAT, 2018). The carbon footprint of milk (after the recalculations) ranged from 0.77 (New Zealand; excluding dLUC or 0.91 including dLUC) to 3.29 (Peru) kg CO_2e kg FPCM^{-1} (Figure 4). Of the 25 studies, only 14 reported the standard deviation (or data that allowed the calculation of the standard deviation – Figure 4). Given the significant impact of the recalculation due to different allocation practices in the final footprint (section 4.1), the studies that used the IDF allocation (biological) are represented as red bars on Figure 4. The average across all countries for this study was 1.47 kg CO_2e kg FPCM^{-1}, smaller than the global average estimated by FAO (2010) (2.4 kg CO_2e kg FPCM^{-1}). This could be because our review included fewer developing countries, that tend to have relatively high carbon footprint values. Another important factor was the allocation method used by the FAO study, based on the amount of protein for milk and meat. As highlighted above (section 4.1), the allocation method plays an important role in the final footprint.

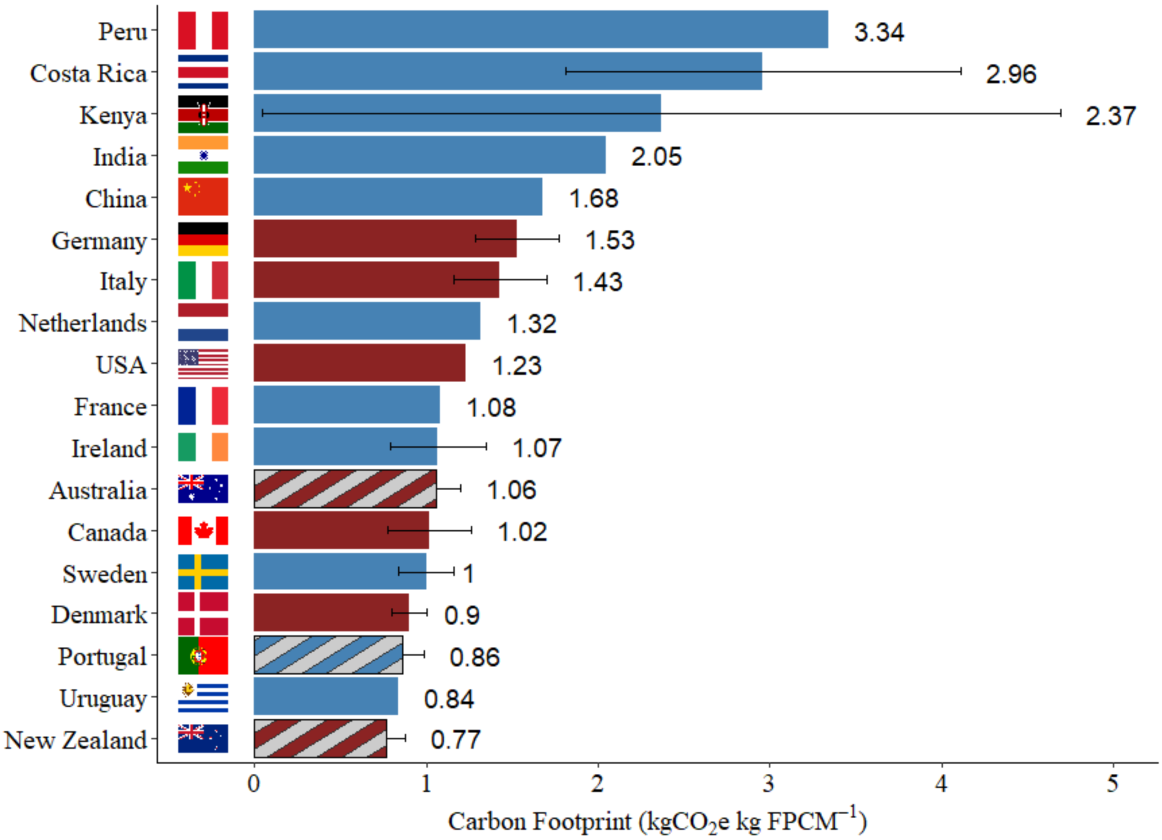

Figure 4: Carbon footprint of milk production (kg CO_2e kg FPCM^{-1}) in different countries (after correction to common GWP, functional unit and allocation methodology) – NZ data excludes dLUC and would be 0.91 if it was included. Red bars represent studies that used the IDF (biophysical) allocation. Bars with diagonal grey pattern represent studies that used region-specific emission factors (more details in section 4.3). 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 linear regression model based on the national data showed that an increase in milk yield per cow significantly reduces the carbon footprint (Figure 5 – $r^2 = 0.33$, *$p<0.01$*), confirming results from other studies that reported the same relationship (Baldini et al. 2017; Lorenz et al. 2019). A few countries lie outside of the confidence interval (Figure 5), among them NZ. Those countries had mid-range milk yields per cow (between 4,000 and 6,000 kg FPCM per cow) and either a high footprint (Peru and Costa Rica) or a low footprint (NZ, Ireland, Uruguay, Australia and Denmark). The GHG profile (i.e. the share of each GHG in the carbon footprint) also tended to change with increased milk yield per cow; countries with a lower milk yield per cow generally had a larger contribution of CH_4 in their milk footprint (Figure 5).

Figure 5 shows that the GHG profile varies depending on the region of the world and livestock management. Two developing countries (Kenya and India) have low milk production per head (2,000 to 4,000 kg FPCM cow^{-1}) and a high carbon footprint. However, most of their footprint is related to the emission of CH_4, a short-lived GHG (Allen et al. 2018)

(Figure 5). The most important source of emissions in these countries is the CH_4 from enteric fermentation.

Many of the developed countries showed a high milk production per cow, from 7,000 to 10,000 kg FPCM cow^{-1} (Figure 5). The footprint for those countries (mainly European countries plus the USA and Canada) is in the lower half of the overall range These countries also tended to have a different GHG profile, with the contribution of CH_4 being lower. This is mainly due to the differences in management practices (e.g. keeping animals indoors during the winter, thereby increasing emissions from manure management and feeding) and the high milk production per head (associated with increased use of concentrate/supplements leading to more emissions from production of the brought-in feed). As a result, the CH_4 contributes less to the final footprint, increasing the share of N_2O and CO_2 .

The carbon footprint of milk for mid-yielding cows (from 4,000 to 7,000 kg FPCM cow^{-1}) can be divided into three areas (Figure 5). The higher footprint values are found in developing countries, where milk production is mostly pasture-based (Costa Rica and Peru), but with lower feed conversion efficiency(e.g. due to low quality feed and poor animal management practices) than the other developed countries with similar milk yield per cow. These latter developed countries (i.e. with low footprint values) are known for having pasture-based milk production, with good pasture and animal management ensuring high pasture quality and high feed conversion efficiency, with relatively low external inputs (New Zealand, Ireland, Uruguay and Australia). Between the top and bottom of this range is China (with significant cow housing and crop-based feeding), but lower milk yield per cow than in European and North American countries with cow-housing and crop-based systems.

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 when CH_4 emissions are rising, and a smaller effect with CH_4 emissions are stable or falling. This reflects the actual physical effects on surface temperatures, whereas GWP100 does not. This effect is also noted using the Global Temperature Potential (GTP) metric (Reisinger et al. 2017). This is especially relevant for countries where most of the milk footprint is related to the emission of CH_4 from enteric fermentation. Using current GWP values, more milk production per cow is related to a smaller footprint (Figure 5), but due to the difference in GHG profile this apparent advantage needs to be re-interpreted when using the GTP or GWP* metrics.

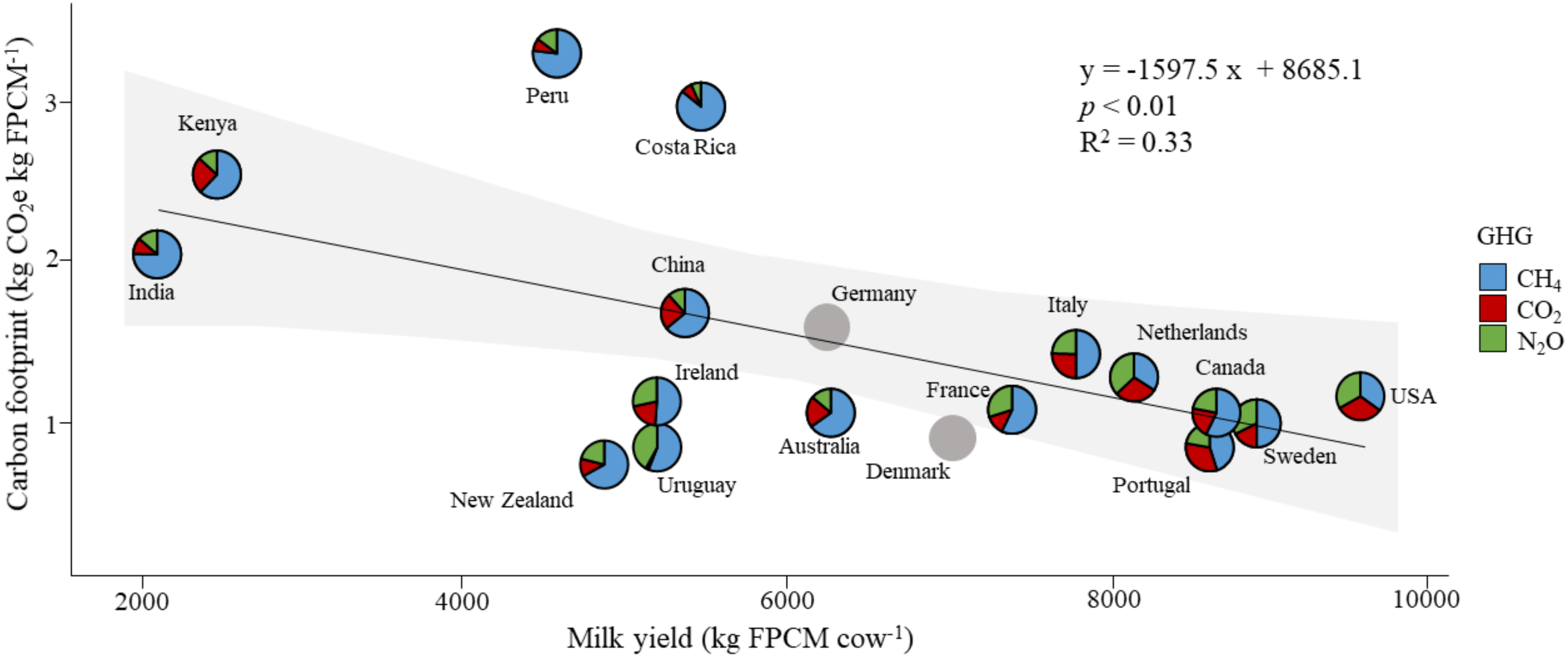

Figure 5: Carbon footprint (kg CO_2e kg FPCM^{-1}) as a function of milk yield (kg FPCM cow^{-1}) in different countries. The pie chart represents the GHG breakdown for each country. The shaded area represents the 95% confidence interval for the linear regression. Data for calculating the GHG breakdown for Denmark and Germany were not available.

4.3 Methodologies

Some countries (New Zealand, Portugal and Australia) use specific methodologies based on national inventories and national/regional emission factors (NI – Figure 6). Other countries are using a mixed IPCC / regional factors approach (IPCC + Specific or IPCC + Lit Review, Figure 6), while others rely on the IPCC approach with default emission factors (IPCC - Figure 6). One caveat of this analysis is that most papers mentioned the methodology used, but didn't describe whether the factors used (e.g. digestibility of the feeds) were country/region-specific or if they used the IPCC default. Country-specific emission factors are usually lower than the default factors recommended by the IPCC, being an important factor to consider when evaluating the footprints. Countries with specific emission factors may have an advantage in comparison with others that are using the IPCC default approach.

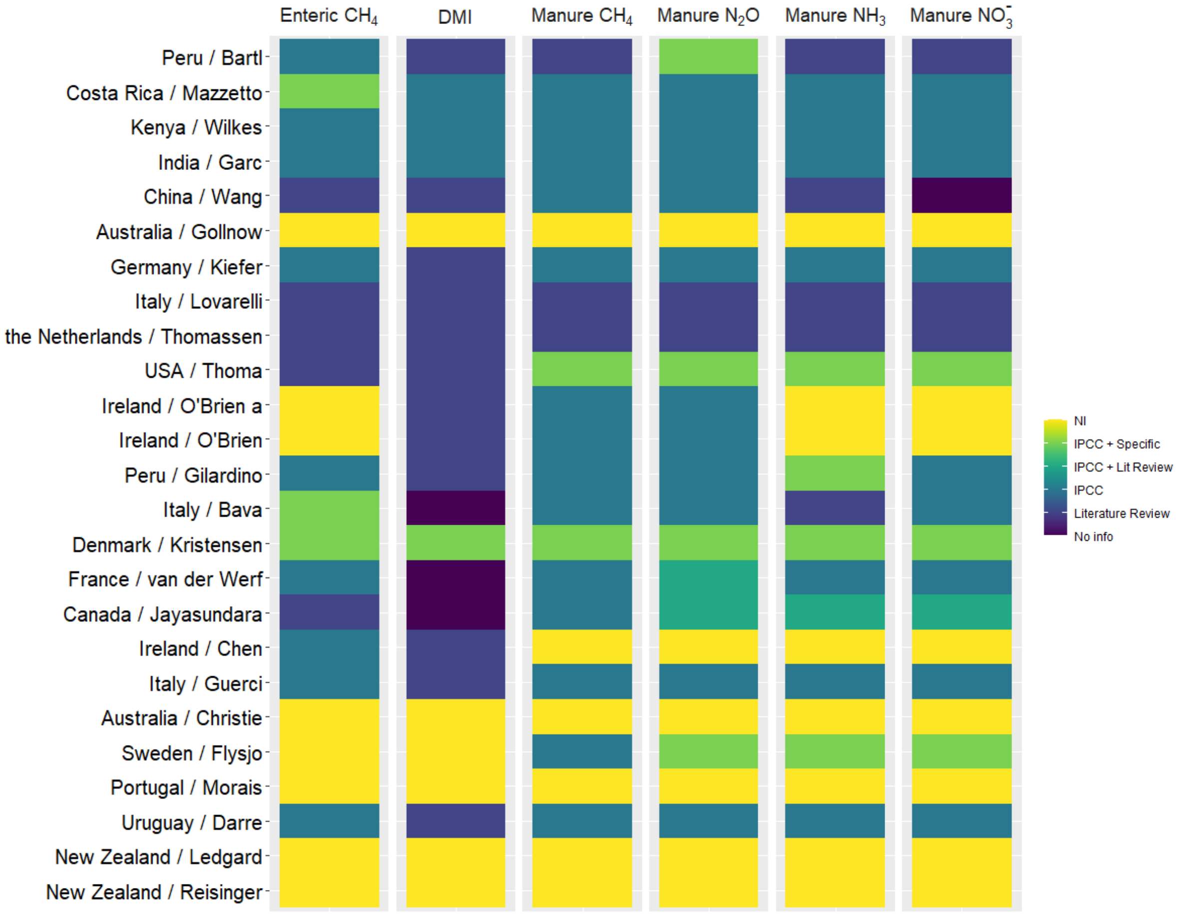

Figure 6: Methodologies used by the different studies (where IPCC refers to use of the default equations from IPCC, and NI refers to the use of National Inventories).

4.4 NZ footprint recalculation

New Zealand is one of the countries fully using national inventory and country-specific emission factors to calculate its carbon footprint (Figure 6). Recalculation of the footprint from Ledgard et al. (2020 - original footprint 0.74 $kgCO_2e$ kg $FPCM^{-1}$) showed that changing the methodology to the default IPCC method would lead to a 58% increase in the value for the footprint (Full IPCC - Figure 7). Changes in N_2O and CH_4 both resulted in significant effects on the final footprint (Figure 7).

It is likely that in future, other countries will develop country-specific emission factors that can potentially reduce their carbon footprint. For example, recent research in Ireland (Krol et al. 2016) has shown N_2O emission factors for excreta and fertiliser that are lower than the IPCC default values (with some even lower than NZ values), although more research followed by a thorough review by an international panel is necessary before they will get integrated into their National Inventory. Nevertheless, such a change might bring the Irish carbon footprint value in Fig. 4 down to below 1.0 kg CO_2e kg FPCM^{-1}. Provided the country-specific methodology is based on detailed research within the specific countries it is the most valid approach to use where it is available. The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) also includes some lower emission factors than the 2006 version.

Few studies have accounted for all components of direct land use change (dLUC) in determining the carbon footprint of milk, often assuming stable land use. The NZ study (Ledgard et al., 2020) included an analysis to estimate the potential contribution for land that had been converted from exotic forestry (mainly plantation pine) to pasture and used for dairying during the past 20-years. This contribution from dLUC was estimated at the equivalent of 0.14 kg CO_2eq kg FPCM^{-1} (Figure 7). In practice, most estimates of dLUC are based on changes in land use from national statistics. If the dLUC from forest to dairying had been based on NZ statistics on the areas under different land uses over the past two decades, it would have produced a nil dLUC value. This is because between 1990 and 2016 there was a national change in land use representing a decrease in grassland area of -3.7% (-566,000 ha) while there was an increase in the area under forest of +5.2% (native and planted; +490,000 ha) (MfE, 2018). While changes in LUC are important to be accounted for in national inventories, it is less relevant when assessing system efficiency and carbon footprints at the farm scale.

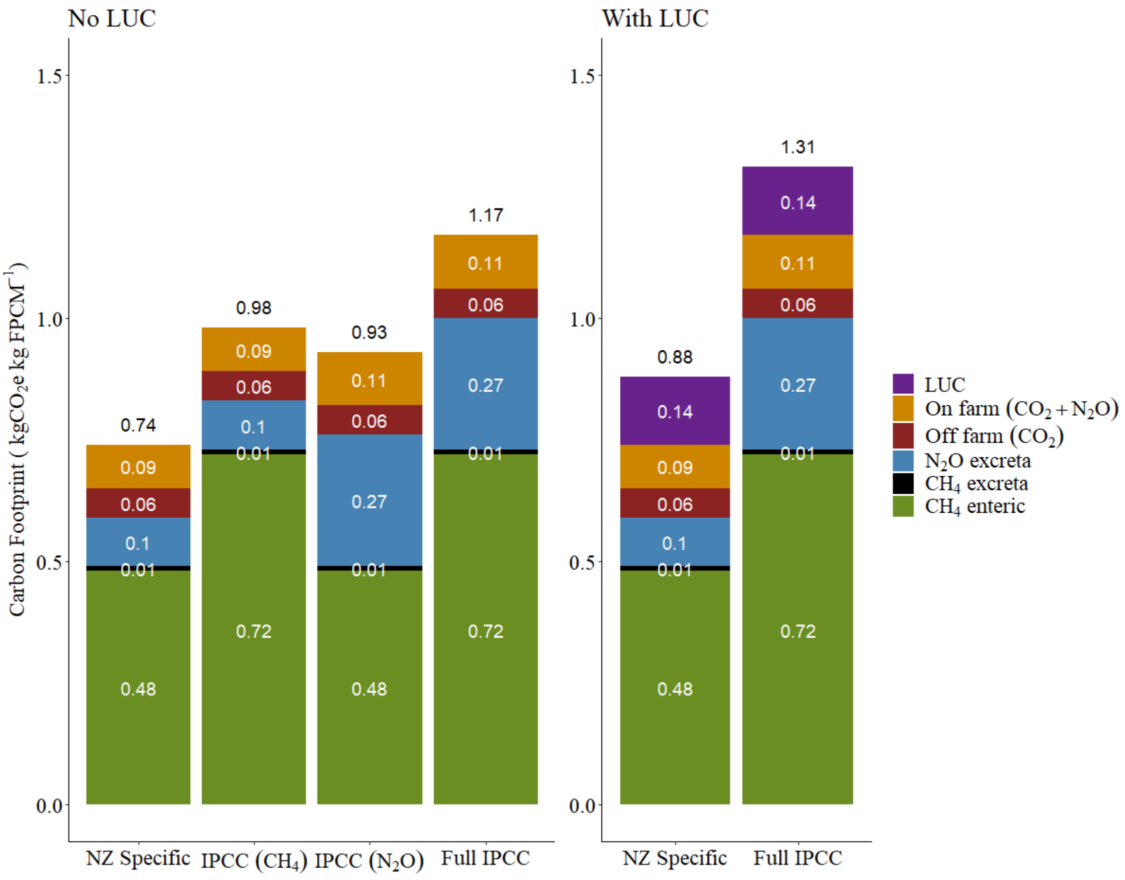

Figure 7: Carbon footprint (kg CO_2e kg FPCM^{-1}) for New Zealand milk calculated using different methodologies. IPCC refers to the use of IPCC default emission factors for individual gases (CH_4 and N_2O) or in total (Full IPCCC).

4.5 Limitations of this study

Apart from the limitations related to the recalculations (described in section 4.1), the paper from Darre et al. (2020 - Uruguay) showed an unusual GHG profile, with only 2% of the total GHG being attributed to CO_2. We've contacted the authors to clarify if upstream emissions (e.g. production of fertilisers and brought-in feeds) were included in their calculations but didn't get confirmation. It is very likely that the current footprint for Uruguay (0.84 kg CO_2e kg FPCM^{-1}) is not from a "full LCA" and will increase due to the inclusion of the upstream processes.

Another methodological challenge of the comparison of the studies was the fact that most adequately described the equations used for each GHG source but didn't specify if the emission factors used were region/country specific or defaults recommended by the IPCC. This is an important piece of information that is not described in many papers. For example, when recalculating the NZ footprint (Figure 6) using the IPCC equations (instead of the NZ National Inventory) for enteric CH_4 would result in an increase from 0.48 to 0.49 kg CO_2e kg FPCM^{-1} (both based on the NZ specific feed digestibility of 77%). However, the use of the default DE from IPCC 2019 (60% for Oceania) led to a 50% increase in the estimated enteric emissions (from 0.48 to 0.72 kg CO_2e kg FPCM^{-1}).

Very limited data about direct land use change (e.g. conversion of forestry to pasture) was available on papers, being mentioned (and calculated) only by the Irish and NZ papers.

An important point to mention is that some countries (as Denmark, Sweden, the Netherlands, France and the USA) were represented in this study by papers published before 2015. If all papers before 2015 were excluded from the database, only 15 studies would be included in the analysis. In order to have a more updated and complete comparison considering important countries that were left out (e.g. UK and Brazil), countries need to update their research in dairy LCA.

5. Conclusions

The systematic approach performed in this study allowed the comparison of milk production at regional/national level from across a range of countries. NZ showed the lowest average carbon footprint (if dLUC was excluded), although the standard deviation shown by the error bars indicate overlap with the range for several countries (NZ, Uruguay, Portugal, Denmark, Sweden and Canada). The fact that NZ uses country-specific emission factors may be an advantage. These specific emission factors were developed over many years of research, and it is expected that in the future other countries will improve their emission factors, potentially resulting in a reduction of their current footprint values. Recent LCA studies have been following closely the recommendations for harmonisation, especially related to the allocation methodology. This study showed that allocation of GHG emission between milk and meat had a large effect on the calculation of the footprints.

Changes in emissions metrics that more accurately reflect the surface temperature effects of CH_4, such as GWP* and GTP, may change the current ranking. The developed countries with high per-cow milk production have a proportionally greater contribution from CO_2 and N_2O, reducing the share from CH_4. If the footprints are recalculated using the GWP*, these countries may show higher footprints, while others may have the footprint reduced due to the large share of CH_4. NZ is well-positioned in this context, with 67% of its footprint consisting of CH_4 emissions.

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9. Appendix 2 – Table with average values

Table A2: Carbon footprint (average and standard deviation) for the different countries studied.

Country	**CF**	**S.D.**
	kg CO_2e $FPCM^{-1}$	
New Zealand	0.77	0.11
Uruguay	0.84	-
Portugal	0.86	0.13
Denmark	0.90	0.10
Sweden	1.00	0.16
Canada	1.02	0.24
Australia	1.06	0.14
Ireland	1.07	0.28
France	1.08	-
USA	1.23	-
Netherlands	1.32	-
Italy	1.43	0.27
Germany	1.53	0.24
China	1.68	-
India	2.05	-
Kenya	2.37	2.32
Costa Rica	2.96	1.15
Peru	3.34	-

CF: carbon footprint; S.D.: standard deviation; FPCM: fat and protein corrected milk