



## Mapping the carbon footprint of milk production from cattle: A systematic review

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### ABSTRACT

Recently, many studies have assessed the carbon footprint of bovine milk production. However, due to the complexity of life cycle assessment, most studies have analyzed research farms or “representative” farms, which do not capture farm variability. Furthermore, the lack of consistency in most studies means that we can seldom compare the footprint between different countries. To address this issue, we performed a systematic review of the literature, removing inconsistencies in life cycle assessment papers, namely the functional unit, allocation to milk, and global warming potential. We analyzed papers that accounted for many farms to address the variability of production systems within the countries. We found 21 papers from 19 countries; footprint recalculations were necessary for 16 papers. New Zealand, Uruguay, the United Kingdom, Australia, and the United States had a footprint <1 kg of carbon dioxide equivalents (CO<sub>2</sub>e) per kilogram of fat- and protein-corrected milk, whereas 5 countries had a footprint >2 kg CO<sub>2</sub>e·kg<sup>-1</sup> fat- and protein-corrected milk. The change in functional unit resulted in a small effect on the final footprint, whereas the global warming potential change was dependent on the greenhouse gas profile for each country. Countries where milk is produced mainly as a pasture-based system had most of their footprint (>50%) associated with the emission of methane from enteric fermentation, whereas other countries (especially from Europe and North America) had a significant share of emissions from manure management, feed production, and fertilizer use. This different greenhouse gas profile allows decision makers to tailor mitigation options specific for each country. The choice of the allocation method had a strong influence in the final footprint. We suggest that for future studies, authors adhere to the International Dairy Federation guidelines. When this is not possible, we suggest a set

of extra information to be reported, allowing recalculations as done in this review.

**Key words:** life cycle assessment, dairy, allocation, functional unit, global warming potential

### INTRODUCTION

Greenhouse gas (GHG) emissions and their effects on climate change are key environmental issues. Agriculture represents a substantial share of national GHG inventories, especially in agricultural economies such as New Zealand (MfE, 2019). Milk is an important source of nutrition, and the increase in demand (30% increase in milk production from 2005 to 2015) resulted in an 18% increase of the GHG emissions from the dairy sector (FAO and GDP, 2018). It is important for the livestock and dairy sectors to reduce emissions in the future. Greenhouse gas emissions can vary with different milk production systems, practices, and site conditions, and their contributions need to be fully accounted for using consistent methodologies.

Researchers in different countries have been calculating the carbon footprint of milk using life cycle assessment (LCA) to assess the efficiency of their milk production systems. Although LCA is the recommended methodology to calculate the carbon footprint, several factors can influence the ability of decision makers to make comparisons between different policy plans and about improved management or mitigation practices. Most LCA of milk production typically consist of an analysis of a “representative” (usually efficient) dairy farm or a research farm, which may not provide insights at the broader regional or national scale. Furthermore, the lack of consistency in the treatment of important factors in determining the carbon footprint results in discrepancies that limit the comparability of the studies (Baldini et al., 2017). Most studies include a comment in the results or discussion section pointing out the difficulty of comparing the footprints with other published research and identifying mitigation options because different studies used different details in the LCA methodology, such as boundaries, allocation methods,

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functional units (**FU**), and global warming potential (**GWP**) metrics. This challenge is not new. Bertrand and Barnett (2011) have pointed to the importance of keeping consistency to reduce confusion and allow fair comparisons. Baldini et al. (2017) also highlighted the same problem more recently. However, both studies cited above did not explore the differences on a deeper level, providing recommendations but not showing the effect of different methods or choices made by the LCA practitioners.

Dairy systems produce a mix of goods (mainly milk and meat) that cannot be easily disaggregated. In attributional LCA, this disaggregation can be done using allocation methods. The International Organization for Standardization (ISO) recommends avoiding allocation when possible. Still, complex systems (such as dairy production) usually depend on allocation practices to identify the environmental burdens among the assorted products. Different allocation methods have been proposed and used over the last years, including economic, mass, and protein allocation (Baldini et al., 2017). The decision of which allocation method to use depends on the goal and scope of the project, but the International Dairy Federation (IDF) has recommended the biophysical approach (IDF, 2015). This approach allocates the emissions according to the amount of energy used for growth (meat production) and lactation (milk production). The FU and GWP are 2 other key factors when calculating the carbon footprint of milk. The most common FU is 1 kg of fat- and protein-corrected milk (**FPCM**), although milk volume (in L) or mass of ECM are other FU commonly used. The GWP is a standard metric for comparing emissions of different greenhouse gases and it has been evolving and, consequently, values have been changing over the last 30 years.

Given the challenges mentioned above, it is complicated to analyze the carbon footprint of milk production in different countries and check the possible management practices and mitigation options to be implemented in each specific country. To do so, an LCA study would need to have a harmonized approach. However, most studies are “top-down” (i.e., seek to identify the big picture) and do not capture the details necessary to provide specific information for each country. To provide a broader insight into the carbon footprint of milk production at the country level that also considers the inherent variability of dairy farms, a review of the carbon footprint of dairy cattle milk was conducted, based on studies that accounted for a large number of farms (to account for on-farm variability) and were representative of the region or country studied. 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. This study aims to address most of the inconsistencies between studies in calculating the carbon footprint of cattle milk production, enabling decision makers to map the main sources of GHG in different countries and allow them to choose tailored management and mitigation practices.

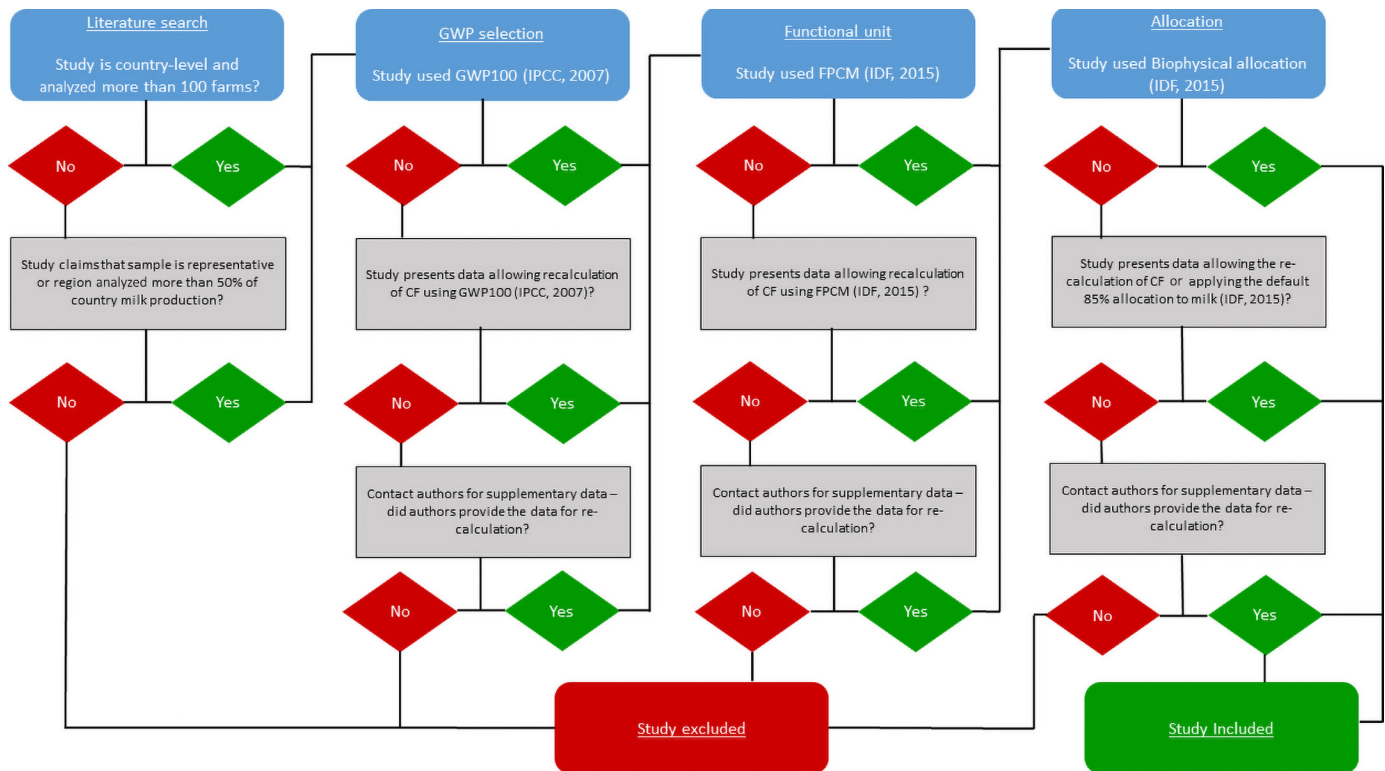
## MATERIALS AND METHODS

Because no live human or animal subjects were used, this analysis did not require approval by an Institutional Animal Care and Use Committee or Institutional Review Board.

We conducted a systematic review focusing on the carbon footprint of cow milk. A literature search of scientific papers published in English was performed using Web of Science (<https://clarivate.com/webofsciencelibrary/solutions/web-of-science/>), Science Direct (<https://www.sciencedirect.com/>), and Google Scholar (<https://scholar.google.com/>) search engines. The search was carried out using all combinations of the following keywords: life cycle assessment; LCA; carbon footprint; carbon accounting; milk, and cattle. White papers or “grey literature” were excluded. We also screened the references of studies retrieved. All studies found were screened for relevance based on the title. Relevant titles were then screened by abstract, and the full text was then reviewed. The review was finished in October 2021, and papers published after this date are not included.

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

- (1) The study was described as an attributional LCA, and the system boundary was “cradle to farm-gate.” We aimed to select papers that were representative (i.e., represents the characteristics of a large number of farms in the specific country) and included a substantial number of farms in their analysis. By doing so, they accounted for the inherent variation of dairy systems. Papers that claimed selecting few (less than 10) representative farms were excluded.
- (2) The paper used the GWP100 values from the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report [AR4; IPCC, 2007; carbon dioxide ( $\text{CO}_2$ ) = 1; methane ( $\text{CH}_4$ ) = 25; nitrous oxide ( $\text{N}_2\text{O}$ ) = 298] or had data available allowing recalculation for AR4 GWP100 (i.e., breakdown of the footprint between the different GHG). These values were chosen to maximize the number of papers assessed in the review. The GWP had to be recalculated for 11 papers (Styles et al., 2018; Darré et al., 2020;



**Figure 1.** Flow diagram showing how the papers were included or excluded from the review. CF: carbon footprint; GWP: global warming potential; FPCM: fat- and protein-corrected milk.

- Gilardino et al., 2020; Berton et al., 2021; Cortés et al., 2021; González-Quintero et al., 2021; Hawkins et al., 2021; Huang et al., 2021; Lambotte et al., 2021; Rotz et al., 2021; van Boxmeer et al., 2021).
- (3) The study used biophysical allocation between milk and live weight sold for meat (i.e., based on the relative energy requirements for the production of these co-products) as recommended by the International Dairy Federation (IDF, 2015) or had the data available allowing the recalculation of the allocation factor. The basic data necessary for the recalculation was a description of the method used and the % of the footprint allocated to milk. The allocation had to be recalculated (and was set to a typical value of 85% allocation to milk; IDF, 2015) for 13 papers (Bartl et al., 2011; Christie et al., 2016; Garg et al., 2016; Styles et al., 2018; Darré et al., 2020; Gilardino et al., 2020; Mazzetto et al., 2020; Wilkes et al., 2020; González-Quintero et al., 2021; Hawkins et al., 2021; Huang et al., 2021; Lambotte et al., 2021; van Boxmeer et al., 2021). When the data were available, the total production of milk and total production of meat was

used to re-calculate the footprint using the IDF methodology (only for Styles et al., 2018).

- (4) The study used FPCM as a FU or had the fat and protein data available to allow the FU to be changed. The FU had to be recalculated for 5 papers (Bartl et al., 2011; Styles et al., 2018; Darré et al., 2020; Gilardino et al., 2020; Lambotte et al., 2021). The data necessary was the % of fat and % of protein in the milk.

In every step of the studies selection, 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 did not have the data available or did not answer, we excluded the paper from the database (Figure 1). Only 5 papers presented data in the suggested format described above (steps 1 to 4; Figure 1, blue boxes) where recalculations were unnecessary (Kiefer et al., 2015; Rice et al., 2017; Jayasundara et al., 2019; Ledgard et al., 2020; Lovarelli et al., 2019).

To represent the most up-to-date farm management practices in the country as possible, we selected the most recent paper from each country and excluded older papers. For example, both Reisinger et al. (2017)

**Table 1.** Articles selected for the review; check marks show where data had to be recalculated, and dashes where original data were extracted from the paper<sup>1</sup>

Article	Country	Number of farms	GWP	FU	Allocation
van Boxmeer et al. (2021)	Netherlands	1,946	✓	—	✓
Rotz et al. (2021)	USA	120	✓	—	—
Lambotte et al. (2021)	France	95	✓	✓	✓
Huang et al. (2021)	China	189	✓	—	✓
Hawkins et al. (2021)	Tanzania	1,199	✓	—	✓
González-Quintero et al. (2021)	Colombia	1,313	✓	—	✓
Cortés et al. (2021)	Spain	96	✓	—	—
Berton et al. (2021)	Italy	75	✓	—	—
Wilkes et al. (2020)	Kenya	382	—	—	✓
Mazzetto et al. (2020)	Costa Rica	253	—	—	✓
Ledgard et al. (2020)	New Zealand	268	—	—	—
Gilardino et al. (2020)	Peru	34	✓	✓	✓
Darré et al. (2020)	Uruguay	277	✓	✓	✓
Lovarelli et al. (2019)	Italy	84	—	—	—
Jayansundara et al. (2019)	Canada	142	—	—	—
Styles et al. (2018)	UK	738	✓	✓	✓
Rice et al. (2017)	Ireland	221	—	—	—
Garg et al. (2016)	India	60	—	—	✓
Kiefer et al. (2015)	Germany	113	—	—	—
Christie et al. (2016)	Australia	41	—	—	✓
Bartl et al. (2011)	Peru	77	—	✓	✓

<sup>1</sup>GWP = global warming potential; FU = functional unit.

and Ledgard et al. (2020) filled the selection criteria for New Zealand, but Ledgard et al. (2020) was selected because it had more recent data. This was done to avoid the use of papers that do not represent the most recent management systems for each country. The same rationale was applied to all papers.

When papers studied fewer than 50 farms or did not claim that the sample was representative of the country's management, we recorded the number of farms and the regions studied. If different papers studied regions that produce a substantial amount of the total milk production for the country, we calculated a weighted average (based on the number of farms) for the country. This was done for Italy (total of 159 farms: Lovarelli et al., 2020, 84 farms; and Berton et al., 2021, 75 farms) and Peru (a total of 111 farms: Bartl et al., 2011, 77 farms; and Gilardino et al., 2020, 34 farms).

For each publication selected, a specific study code was assigned. The following characteristics were recorded in the database: author, year, country, region, number of farms studied, number of cows per farm, allocation method, allocation percentage (%), GWP method, FU, carbon footprint [kilograms of carbon dioxide equivalents (**CO<sub>2</sub>e**) per kilogram of FU], breakdown of the footprint by GHG (% of total footprint related to CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O) and source (percentage of the total footprint associated with enteric fermentation, manure management, and so on), and milk production (kg of FPCM per cow). Where possible, statistical data (standard deviation, coefficient of variation, quartiles,

and so on) were collected for each characteristic mentioned above.

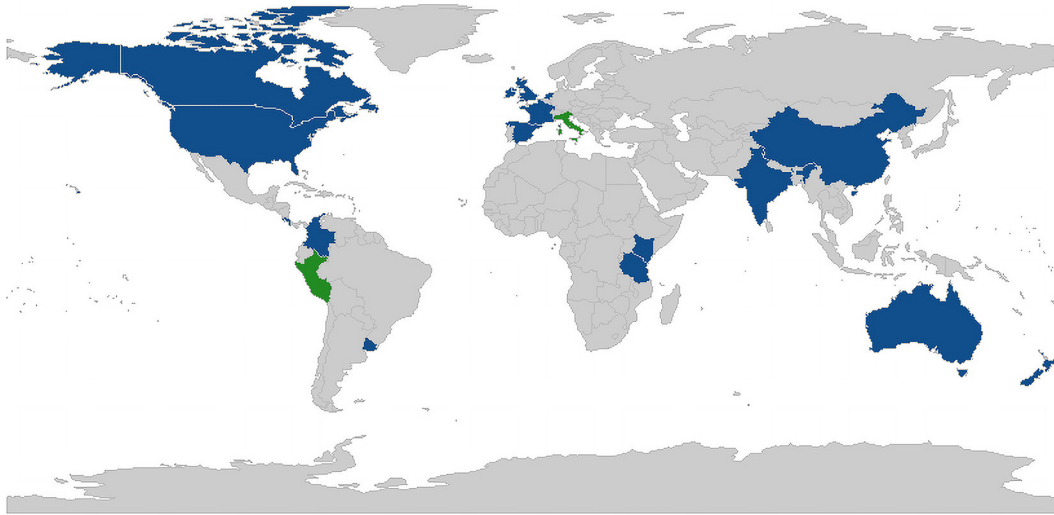
## RESULTS AND DISCUSSION

### Papers Selection

Our initial search resulted in 127 papers, of which 21 (Table 1) from 19 different countries (Figure 2) were selected. Most papers were eliminated in the first step of the selection criteria because the majority of cattle milk LCA studies covered only one “typical” farm or a small number of farms comparing different management practices. Only one paper was excluded due to lack of communication from the authors.

Most papers were “cradle to farm-gate” LCA, except one (Berton et al., 2021) that was a “cradle to processing-gate” study. We excluded the emissions related to processing the milk to compare this study with others. All papers presented a good description (and diagrams) of the emission sources considered. Only one paper (Darré et al., 2020) did not clearly state the inclusion of emissions from the production of fertilizers, although it is included in their system's diagram. All studies included the main sources of emission [enteric fermentation, manure management, fertilizers (production and soil), feed production, and upstream data (electricity, fuel, and so on)]. Usually, emissions that are ignored represent less than 1% of the total (as per the LCA cut-off criteria) and are related to minor sources, such as refrigerants (included in papers such as Rice et al.,





**Figure 2.** Map of the countries selected. Countries highlighted in blue had 1 study, whereas countries highlighted in green had 2 studies.

2017, and Ledgard et al., 2020) and veterinary products (not accounted for in the papers selected). When these minor emissions are included, they do not affect the footprint significantly (Ledgard et al., 2020).

The 19 countries covered by the review represent 58% of the total milk produced globally (FAOSTAT, 2019). Among some of the top 10 milk producers not included in the review are Brazil, Russia, and Turkey. Among the top 20 milk producers not included are Pakistan, Poland, Mexico, Argentina, Uzbekistan, and Ukraine.

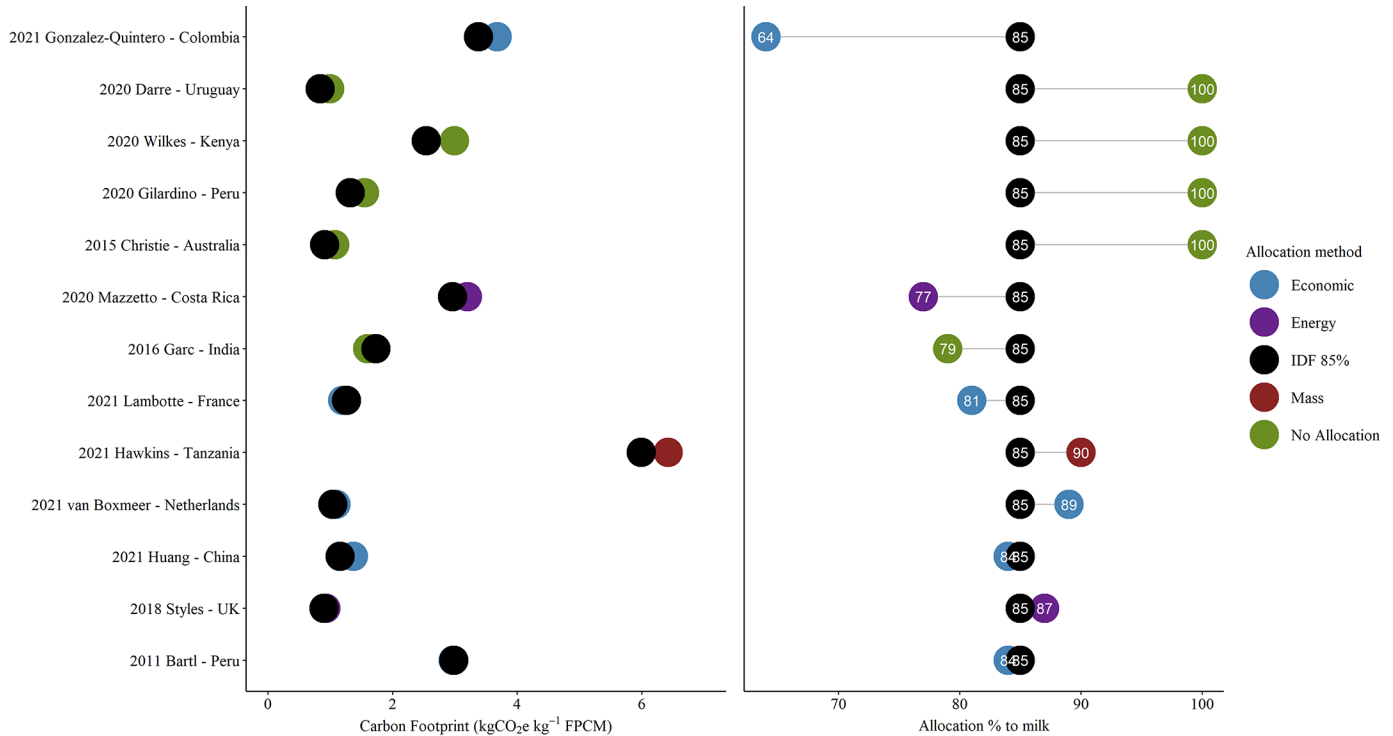
### Effect of Recalculations

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 16 of the 21 papers. The effects of the recalculations are shown in Table 2. For 9 studies, the recalculation resulted in relatively small changes (<10% of the original footprint), although the change for other 7 studies was moderate (between 13 and 22% of original footprint).

**Table 2.** Original footprint extracted from the articles and the results after recalculating the values for 3 different factors (in isolation or combined): allocation, functional unit (FU), and global warming potential (GWP)<sup>1</sup>

Article	Original value	Allocation	GWP	FU	Allocation + GWP	Allocation + FU	GWP + FU	Final value
van Boxmeer et al. (2021)	1.14	1.09	1.09	—	1.04	—	—	1.04
Rotz et al. (2021)	1.01	—	0.96	—	—	—	—	0.96
Lambotte et al. (2021)	1.21	1.26	1.16	1.25	1.22	1.31	1.20	1.26
Huang et al. (2021)	1.48	1.26	1.37	—	1.16	—	—	1.16
Hawkins et al. (2021)	6.52	6.16	6.42	—	5.99	—	—	5.99
González-Quintero et al. (2021)	2.77	3.68	2.55	—	3.38	—	—	3.38
Cortés et al. (2021)	1.33	—	1.30	—	—	—	—	1.30
Berton et al. (2021)	1.19	—	1.13	—	—	—	—	1.13
Wilkes et al. (2020)	2.99	2.54	—	—	—	—	—	2.54
Mazzetto et al. (2020)	3.20	2.96	—	—	—	—	—	2.96
Ledgard et al. (2020)	0.74	—	—	—	—	—	—	0.74
Gilardino et al. (2020)	1.65	1.40	1.57	1.64	1.33	1.39	1.55	1.32
Darré et al. (2020)	0.97	0.82	0.96	1.00	0.81	0.85	0.99	0.84
Lovarelli et al. (2019)	1.42	—	—	—	—	—	—	1.42
Jayansundara et al. (2019)	1.02	—	—	—	—	—	—	1.02
Styles et al. (2018)	1.02	0.99	—	0.93	—	0.90	—	0.90
Rice et al. (2017)	1.05	—	—	—	—	—	—	1.05
Garg et al. (2016)	1.60	1.73	—	—	—	—	—	1.73
Kiefer et al. (2015)	1.53	—	—	—	—	—	—	1.53
Christie et al. (2016)	1.07	0.91	—	—	—	—	—	0.91
Bartl et al. (2011)	2.99	2.99	—	2.97	—	2.98	—	2.98

<sup>1</sup>Values are in kilograms of carbon dioxide equivalents per kilogram of fat- and protein-corrected milk.



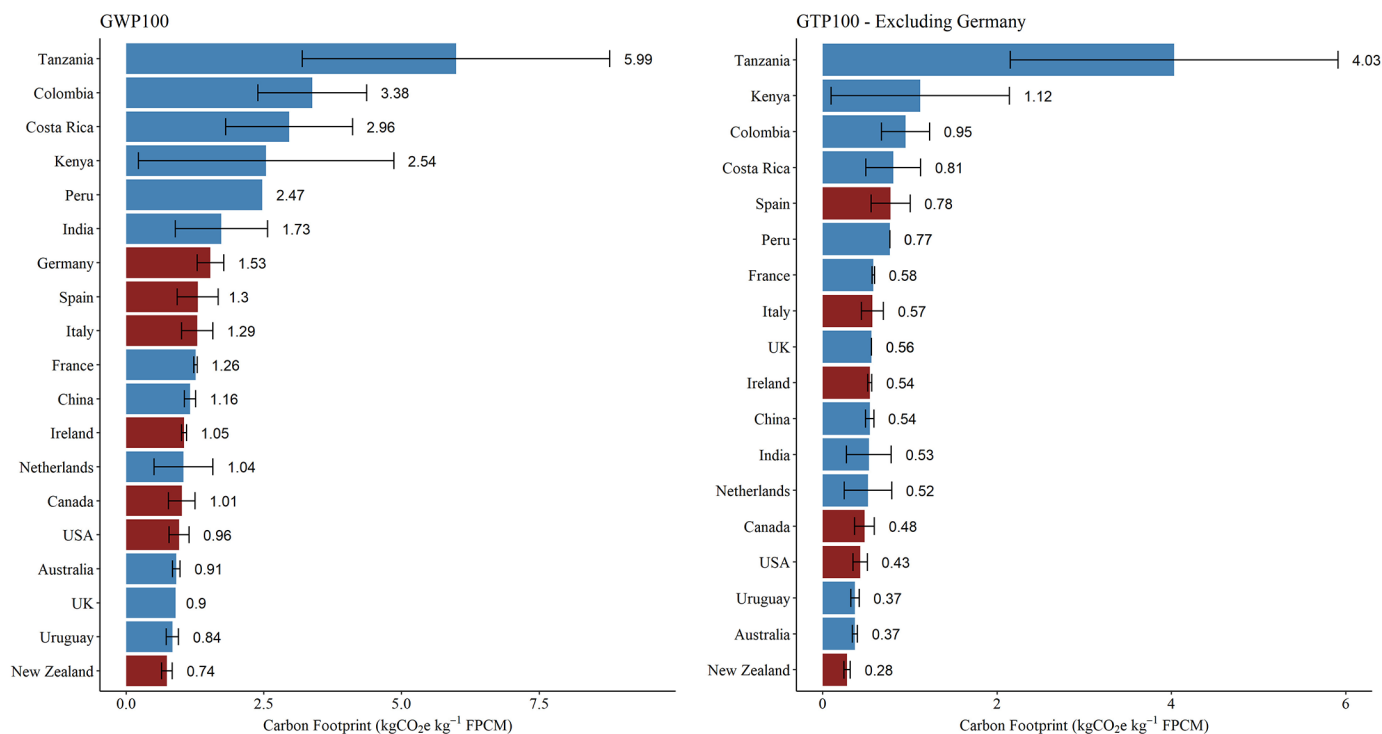
**Figure 3.** Carbon footprint of milk [kg of CO<sub>2</sub> equivalents (CO<sub>2</sub>e) per kg of fat- and protein-corrected milk (FPCM)] and allocation to milk (%) for the countries where the allocation factor had to be recalculated. The carbon footprint numbers in the original allocation (economic, energy, mass, or no allocation) are recalculated for the same functional unit and global warming potential (Table 2).

The change in FU results in small changes in the final footprint (Table 2), mainly because the equations for FPCM and ECM are similar (Baldini et al., 2017). Only 3 papers had used liters (L) as the FU (Styles et al., 2018; Darré et al., 2020; Lambotte et al., 2021), although 2 others used ECM (Bartl et al., 2011; Gilardino et al., 2020).

The magnitude of the effect of the GWP change will depend on the GHG profile of the study (described in the Recalculated Footprint section). For studies that applied IPCC (2013) factors, the CH<sub>4</sub> GWP factor decreased from 27.75 to 25 kg CO<sub>2</sub>e·kg<sup>-1</sup> CH<sub>4</sub> (IPCC 2013, 2007, respectively; Stocker et al., 2013), whereas the N<sub>2</sub>O GWP factor increased from 265 to 298 kg CO<sub>2</sub>e·kg<sup>-1</sup> N<sub>2</sub>O (IPCC 2013, 2007, respectively). Reisinger et al. (2017) showed that the relative carbon footprint between different mitigations showed little change with changes in values used for GWP. Still, in some instances 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 important differences in the footprint (Table 2 and Figure 3). The effect of this recalculation can be 2-sided. For some studies, it led to lower calculated footprints than the original (Christie et al.,

2016; Garg et al., 2016; Darré et al., 2020; Gilardino et al., 2020; Mazzetto et al., 2020; Hawkins et al., 2021; Huang et al., 2021; van Boxmeer et al., 2021; Table 2 and Figure 3), whereas others had higher footprints (Bartl et al., 2011; Styles et al., 2018; Wilkes et al., 2020; González-Quintero et al., 2021; Lambotte et al., 2021; Table 2 and Figure 3). According to IDF (2015), the biophysical allocation (considering the amount of milk and live weight produced by the dairy farm) is the most appropriate allocation approach. Only one paper had data that allowed us to recalculate the allocation using the IDF (2015) method (Styles et al., 2018). This led us having to apply the default factor of 85% allocation to milk in most studies. This recalculation may have reduced the footprint for farms/countries where the dairy farms do not export many animals (culled cows and calves) or have very high milk production per cow, resulting in a true allocation factor for milk that would be higher than 85%. In contrast, the recalculation may have increased the footprint of farms that export many animals, and where the allocation factor would be lower than 85%. Thus, it will likely have led to a slight underestimation of the carbon footprint of milk for farms with high milk per-cow production while leading to a slight overestimation for farms with low milk production per cow (Figure 3).

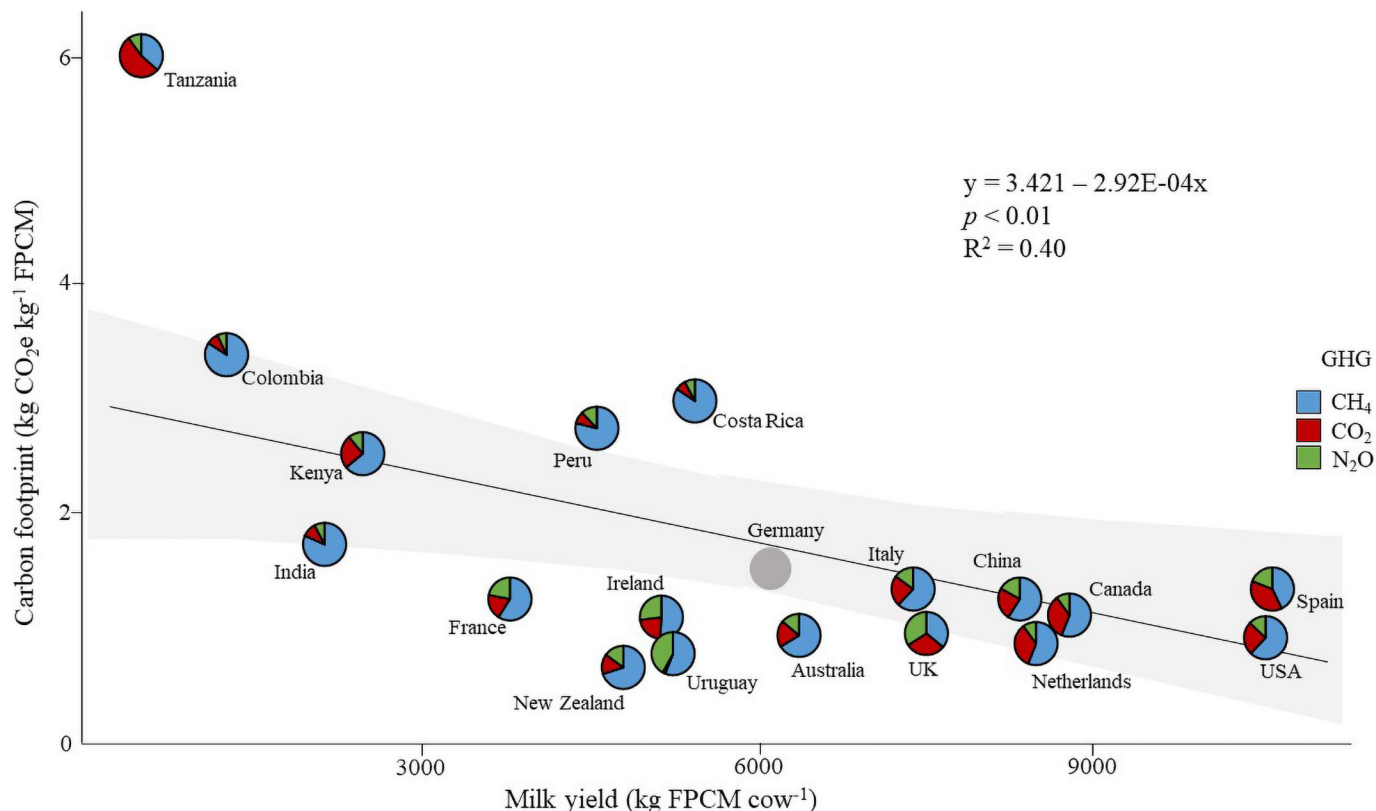


**Figure 4.** Carbon footprint of milk [kg of CO<sub>2</sub> equivalents (CO<sub>2</sub>e) per kg of fat- and protein-corrected milk (FPCM)] in different countries [after correction to common global warming potential (GWP), functional unit, and allocation methodology]. Red bars represent studies that used the International Dairy Federation (biophysical) allocation. Blue bars represent studies that used a different type of allocation than recommended by the International Dairy Federation. 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. GTP: global temperature potential.

### Recalculated Footprint

The carbon footprint of milk (after the recalculations) ranged from 0.74 (New Zealand) to 5.99 (Tanzania) kg CO<sub>2</sub>e·kg<sup>-1</sup> FPCM (Figure 4). Of the 21 studies, only 3 [Styles et al. (2018) the United Kingdom; Gilardino et al. (2020) and Bartl et al. (2011), Peru] did not report the standard deviation (or data that allowed calculation of the standard deviation; Figure 4). Given the strong effect of the recalculation due to different allocation practices in the final footprint (Effect of Recalculations section), the studies that used the IDF (2015) allocation (biophysical) are represented as red bars in Figure 4. The average across all countries for this study was 2.11 kg CO<sub>2</sub>e·kg<sup>-1</sup> FPCM, slightly lower than the FAO (2010) estimated global average (2.40 kg CO<sub>2</sub>e·kg<sup>-1</sup> FPCM). This could be because our review included fewer countries with relatively high carbon footprint values, especially from Asia and Africa. Another important factor was the allocation method used by the FAO (2010) study, based on the amount of protein for milk and meat. As highlighted above (section 3.2), the allocation method plays an important role in the final footprint.

Recently, a group of researchers proposed a new metric to account for the surface temperature effects of gases with different lifetimes (**GWP\***; 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<sub>4</sub> emissions rise over time, and a smaller effect with CH<sub>4</sub> emissions are stable or falling. There are no recommendations on using the GWP\* metric in LCA studies, and because it requires at least 2 emission pulses, it was not possible to recalculate the current footprints using GWP\*. A different metric that recognizes CH<sub>4</sub> as a short-lived GHG is the global temperature potential (**GTP**). The GTP is directly related to temperature changes, having the advantage to quantify temperature change compared with GWP (Fagodiya et al., 2017). We recalculated the footprints (except for Germany due to the lack of data on the GHG breakdown) using the GTP factors of 1, 4, and 234 for CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, respectively (Figure 4; Stocker et al., 2013). Very small changes were observed in the order of farms within Figure 4. In order from the lowest value, the most remarkable change was India's footprint, which was the 14th and changed to the 7th. This is linked to the GHG breakdown of India,



**Figure 5.** Carbon footprint [kg of CO<sub>2</sub> equivalents (CO<sub>2</sub>e) per kg of fat- and protein-corrected milk (FPCM)] as a function of milk yield (kg of FPCM per cow) in different countries. The pie chart represents the greenhouse gas (GHG) breakdown for each country. The shaded area represents the 95% confidence interval for the linear regression. Data for calculating the GHG breakdown for Germany were not available.

presenting a high contribution of CH<sub>4</sub>, especially from enteric fermentation (see discussion below and details on Figures 4 and 5).

Figure 5 shows that the GHG breakdown varies depending on the region of the world, with associated differences in livestock management. The GHG breakdown for these countries also tended to change with increased milk yield per cow: countries with a lower milk yield per cow generally had a larger relative contribution of CH<sub>4</sub> (largely from enteric fermentation) in their milk footprint (Figures 5 and 6). 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;  $R^2 = 0.40$ ,  $P < 0.01$ ), confirming results from other studies that reported a similar relationship (Baldini et al., 2017; Lorenz et al., 2019).

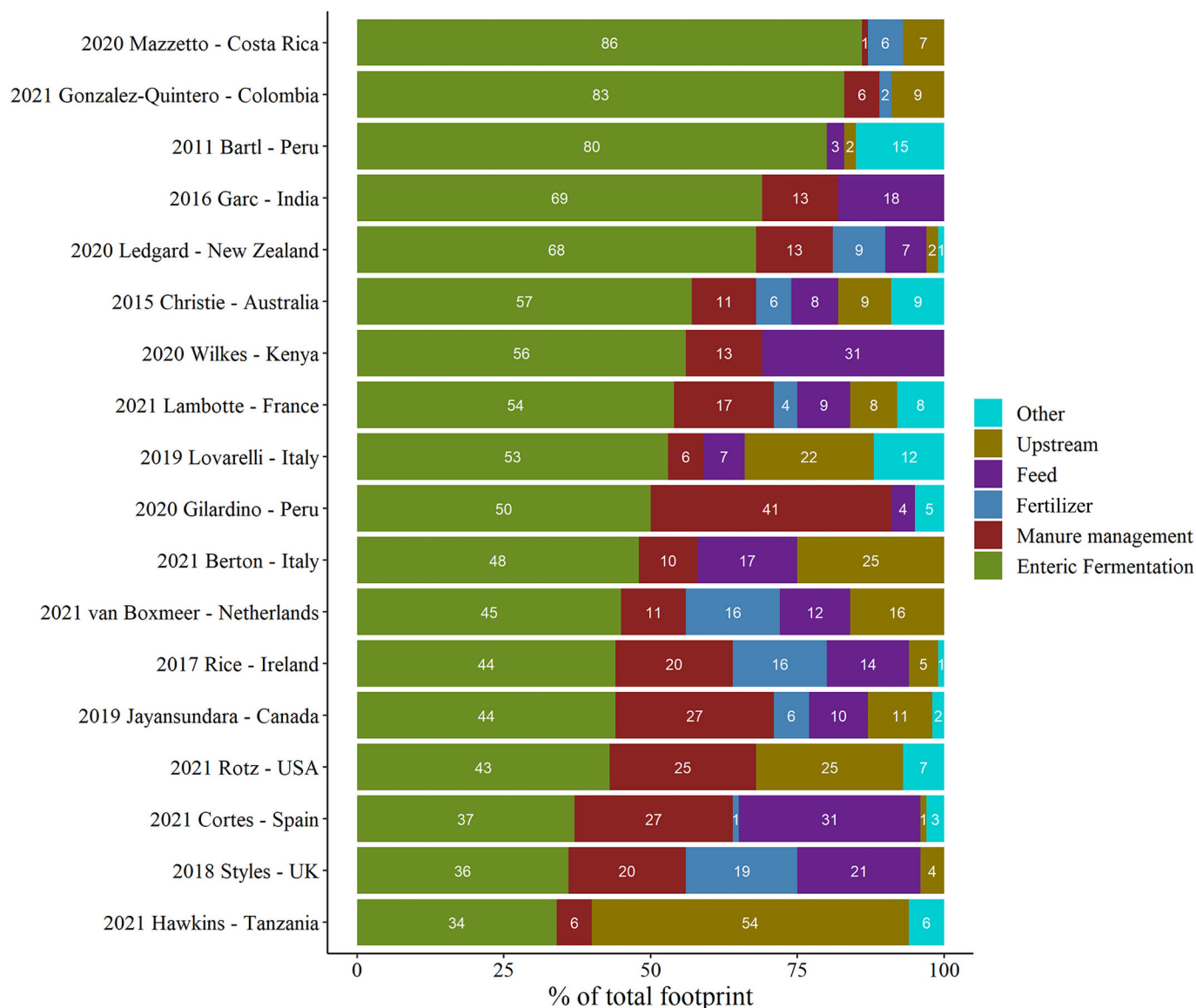
Three countries (Colombia, Kenya, and India) have low milk production per head (<3,000 kg of FPCM per cow) and a high carbon footprint. However, most of their footprint is related to the emission of CH<sub>4</sub>, a short-lived GHG (Allen et al., 2018) (Figure 5). The most important source of emissions in these countries is the CH<sub>4</sub> from enteric fermentation (Figure 6). Tanzania has low milk production per cow but a different

GHG breakdown than other countries. This is mainly related to the dry season effect. The rainfall pattern is unimodal in Tanzania, with a long dry season of 6 mo, resulting in lower quality and availability of forages and increased use of brought-in feed during this time, also associated with a reduction in the cow's productivity (Hawkins et al., 2021).

The countries with a milk yield per cow in the mid-range (between 3,000 and 7,000 kg of FPCM per cow) outside of the 95% confidence area in Figure 5 had either a high or low footprint. The higher footprint values are found in 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 animal management practices) than other countries with similar milk yield per cow. These latter countries (i.e., with low footprint values) have pasture-based milk production, with good pasture and animal management ensuring high pasture quality and high feed conversion efficiency, with relatively low external inputs (Australia, Ireland, New Zealand, and Uruguay).

Many of the European and North American countries showed a high milk production per cow, from 7,000 to 11,000 kg of FPCM per cow (Figure 5). The footprint





**Figure 6.** Breakdown of the carbon footprint of milk production per source (in %) in different papers or countries. Papers from Uruguay (Darré et al., 2020), China (Huang et al., 2021), and Germany (Kiefer et al., 2015) were excluded due to the lack of data. The upstream data for Tanzania include upstream + feed, due to the impossibility of separating the sources based on the available data.

for those countries (mainly European countries plus the United States, Canada, and China) is in the lower half of the overall range. These countries also tended to have a different GHG profile, with the relative contribution of  $\text{CH}_4$  being lower (Figures 5 and 6). 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 or supplements leading to more emissions from the production of the brought-in feed; Figure 6). As a result, the  $\text{CH}_4$

contributes less to the final footprint, increasing the share of  $\text{N}_2\text{O}$  and  $\text{CO}_2$  (Figure 5).

Methane from enteric fermentation represents more than 50% of the total footprint for 9 of the 18 studies (Figure 6; studies from Uruguay, China, and Germany excluded due to the lack of data). Different mitigation practices or technologies aiming to reduce methane emissions have been proposed recently, from breeding (Breider et al., 2019) to the use of methane inhibitors (Schilde et al., 2021) and vaccines (Zhang et al., 2015). However, mitigation practices need to be tailored specifically for each country or region to avoid unintended

consequences. For pasture-based systems, improved grazing management can be an effective strategy for reducing enteric CH<sub>4</sub> emission. Pastures under excessively high or low grazing intensities affect the animals dry matter intake (Kunrath et al., 2020) and, consequently, the enteric fermentation process. For indoors or confinement systems, additives (Honan et al., 2021) and supplements, such as red seaweed (Roque et al., 2021), are potential alternatives. However, the GHG emission from the production of such additives or supplements must be considered in the final LCA results.

Manure management is a substantial source of emission (>20% of total) in countries such as the United Kingdom, Spain, the United States, Canada, Ireland (due to keeping animals indoors during the winter), and Peru. Adghim et al. (2020) showed that anaerobic biodigesters reduced the emissions (in kg of CO<sub>2</sub>e) from manure management by 25% for large dairy farms. Guest et al. (2017) also showed comparable results using a liquid-manure separation composter in Canada. The use of such technologies can also reduce emissions by replacing synthetic fertilizers. The use of coated fertilizers and N inhibitors can reduce both N<sub>2</sub>O emissions and nitrate leaching (Di and Cameron, 2002). Da Costa et al. (2019) performed an LCA for the production of coated urea, from cradle to grave (i.e., including the production of the fertilizer and coated material, transport, and application to soil). The coated urea showed lower ammonia volatilization losses (by 11 to 50%) and had a lower final footprint (−35%) when compared with uncoated urea. Apart from the emissions on soil, the production of synthetic fertilizer results in substantial CO<sub>2</sub> emissions due to high energy requirements (Gaidajis and Kakanis, 2020). One strategy is using renewable energy, such as solar or other sources, as green hydrogen (Manna et al., 2021) and biomass (Ahlgren et al., 2008), to generate at least part of the required energy for the production of the fertilizer, reducing the total fertilizer footprint. The use of such treated fertilizers will be most relevant for reducing the carbon footprint of milk in countries such as the United Kingdom, Ireland, and the Netherlands, where N fertilizer is a major contributor to the footprint.

Feed production is also a relevant source of emissions for countries such as Kenya and Tanzania due to the typical dry season and the lack of pasture and in Spain, Netherlands, Italy, and the United Kingdom where animals are indoors for much or all of the year (Figure 6). The use of a pasture-based diet as the only mitigation strategy is not necessarily connected with lower footprints, as noted from the footprint of Costa Rica and Peru, for example (Figure 4). This is mainly related to pasture management, lower pasture quality, and the use breeds not adapted to tropical climate, resulting in a

low production of milk per cow. However, when associated with other management best practices aiming to achieve optimal pasture utilization, the pasture-based diet can greatly influence the final emissions, as noted by New Zealand and Uruguay results and an increased proportion of the diet from pasture.

## General Discussion

Producing country-specific agricultural GHG emission factors (**EF**) that better reflect different management systems (e.g., animal diet and animal breed for CH<sub>4</sub> emission; fertilizer type, soil type and rainfall for N<sub>2</sub>O emission) is a growing interest, and to move from tier 1 to tier 2 national GHG inventories for the United Nations Framework Convention on Climate Change (UNFCCC) reporting requirements and also generate a more accurate baseline emission inventory. The development of regional or country-specific EF also offers the opportunity to account for changes in management practices and reflect specific mitigation strategies within national inventories. Most countries are currently using a hybrid approach combining the IPCC approach and country-specific EF (e.g., New Zealand and Ireland). In contrast, others rely only on the IPCC approach with default EF (e.g., Costa Rica, Tanzania, Peru, and Colombia). Country-specific EF are usually lower than the IPCC default tier 1 EF, being an important factor to consider when evaluating the footprints. Thus, countries with country-specific EF may have lower calculated footprints than others using the IPCC default EF. A recent update of the IPCC methodology guidelines (IPCC, 2019) saw several default EF being disaggregated by climatic zones. Although these are not regionally specific, it provides a more reliable set of values when compared with the default factors published in 2006 (IPCC, 2006). It is likely that in future, countries will develop country-specific EF that better reflect their climatic or soil or farm systems; this may also reduce their calculated carbon footprint. Country-specific EF that are used for national GHG inventory reporting and subjected to international peer review provides LCA practitioners with the most valid approach for calculating the carbon footprint of bovine milk production. 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.

One reason for the high footprint of the studies in Colombia (González-Quintero et al., 2021) and Costa Rica (Mazzetto et al., 2020) is the fact that the dairy systems analyzed in these countries are mainly dual-purpose instead of specialized dairy farms as found in most of the other countries. Dual-purpose systems often

**Table 3.** Additional information suggested for reporting in dairy life cycle assessment studies<sup>1</sup>

Item	Description
Allocation	Methods used and percent allocated to milk Amount of LW sold by the dairy farm Amount of milk sold in FPCM (or % of fat and protein in milk)
GWP	IPCC Assessment Report used and respective GWP for CO <sub>2</sub> , CH <sub>4</sub> , and N <sub>2</sub> O Breakdown of the final footprint between the GHG (% of CO <sub>2</sub> , CH <sub>4</sub> , and N <sub>2</sub> O) Disaggregated footprint (i.e., footprint for each GHG, e.g., kg of CH <sub>4</sub> per kg of FPCM)
FU	Percentage of fat and protein in milk

<sup>1</sup>LW = live weight, GWP = global warming potential; FPCM = fat- and protein-corrected milk; FU = functional unit.

have lower milk yield per cow and stocking rate, resulting in a higher carbon footprint. However, Mazzetto et al. (2020) showed that dual-purpose farms have lower carbon footprints when a combined FU that considers milk and meat production (no allocation) is used when compared with specialized dairy farms in the same country. Because dairy and beef farms are inherently interconnected, an expanded boundary approach could be considered when looking at the sustainable intensification of the cattle sector, rather than just at the dairy or beef sectors.

For countries such as Tanzania and Peru, most milk production is related to smallholder farms that are usually multipurpose. Weiler et al. (2014) studied the multifunctionality of smallholder systems and discussed different allocation practices. Gilardino et al. (2020) introduced the “smallholder 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), manure (as fertilizer for the farmer or sold), 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. These co-products can play an important role in farms that are usually not relevant to large commercial farms. In this Peruvian study using the perception allocation approach, the milk for market had the largest allocation, with 30% of the total emissions.

Direct land use change reporting (dLUC) is a controversial issue. Only New Zealand (Ledgard et al., 2020) and Tanzania (Hawkins et al., 2021) reported the emissions separately due to dLUC from dairy expansion. Other countries often assume stable land use. However, it is unlikely that New Zealand and Tanzania are the only countries where the dairy sector has expanded over the last 20 years. A more rigorous analysis of the dLUC in the dairy sector for all countries should be done, with results reported separately, as recommended in ISO14067. The main reason for the separate report-

ing is because the dLUC is a temporal source of GHG. For example, from 2027, the dLUC footprint from New Zealand will be minimal (given that no further expansion happens in the following years). The use of an appropriate methodology is also necessary. For example, for New Zealand, indirect data indicated dLUC from forestry to pasture, whereas national data has shown a decrease in pasture land and an increase in area under forest (MfE, 2018; Ledgard et al., 2020).

### General Recommendations for Future Dairy LCA

Keeping in mind the difficulty of comparing results when studies are not following the same guidelines, we provide a few recommendations for future studies (Table 3). We recommend the practitioners follow the IDF (2015) guidelines, or those of the 2022 update when it is released, when possible. However, the decisions around boundaries, allocation procedures and FU are connected to the goal and scope of each study. When it is the case that the goal and scope of the study requires a deviation from the IDF (2015) guidelines, we suggest the authors report the extra information in the main text or in the supplemental material of their papers. These extra points are important to allow other practitioners or readers to convert the published values to a common approach when necessary, allowing (fairer) comparisons as done in this study.

## CONCLUSIONS

The systematic approach performed in this study allowed the comparison of milk production at a national level from a range of countries. The variability in GHG profiles among countries means that mitigation options must be tailored for each specific region and management strategy. Although the emission of CH<sub>4</sub> from enteric fermentation is an important source for all countries, different mitigation practices should also target manure management, feed, and fertilizer production, particularly in countries with intensive production and high inputs. To compare emissions between coun-

tries, we encourage future studies to adopt a consistent methodology to report LCA studies from dairy farms or report extra data to allow recalculations. Changes in emissions metrics that more accurately reflect the surface temperature effects of CH<sub>4</sub> such as GWP\* may change the current ranking. Countries with high per-cow milk production have a proportionally greater contribution from CO<sub>2</sub> and N<sub>2</sub>O, reducing the relative share from CH<sub>4</sub>.

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