The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-023-02157-x

CARBON FOOTPRINTING

# Milk production from family agro-industries in São Paulo state: Carbon balance accounting

**Maiara Campos Silva**[1] · **Anna Lúcia Mourad**[1] · **Adriana Torres Silva Alves**[1]

Received: 3 June 2022 / Accepted: 9 March 2023


## Abstract

**Purpose** The objective of this work was to evaluate the environmental profile of milk production from family agro-industries in the State of São Paulo Brazil, in order to characterize them and identify opportunities to reduce their environmental footprint. Given the complexity, variability in the form of calculations and the importance of carbon balance accounting, this article discusses only this impact category.

**Methods** The data used in this project were collected through visits to 14 dairy farms. The life cycle assessment tool was used considering the stages of production of feed and maintenance of the cattle, considering heifer, lactating and non-lactating cows, the milking process, and milk cooling. A model to estimate the emissions resulting from enteric fermentation from the composition of the feed given to the animals was used. The inclusion and exclusion of carbon capturated during photosynthesis, as well as the biophysical allocation of part of the impacts to livestock co-production, were considered.

**Results and discussion** The simple average carbon footprints of the 14 farms were 2408 and 2189 kg CO2 eq. per 1000 kg FPCM, without and with, respectively, biophysical allocation of inputs and emissions between milk and cattle. The step with the greatest contribution to these emissions is that of enteric fermentation, which represented 60% of greenhouse gas emissions. The amount of feed offered varied greatly from 1118 to 2484 kg of DM (dry matter)/1000 kg FPCM. For cattle obtained from this herd, the calculated impact of climate change was 15,117 kg $CO_2$ eq. per 1000 kg live weight of animals, using the same methodological approach. The carbon capturated during the photosynthesis process occurred in the production of feed was 1677 kg $CO_2$ eq. per 1000 kg FPCM for milk and 15,003 kg $CO_2$ eq. per 1000 kg live weight of animals, values that represent 76% and 99% of the calculated carbon footprint.

**Conclusions** Production units that combine smaller amounts of feed offered (in dry mass) by the functional unit, with little dependence on its external acquisition and good milk yield, tend to generate more environmentally efficient units. The authors consider that the carbon balance, including carbon captured during photosynthesis, is of great importance and should be accounted for and disclosed together with traditional calculations. Recent studies show that agriculture, which is part of this chain, when carried out with good cultivation practices, can be one of the most efficient ways of stocking carbon.

**Keywords** Milk · Feed · Cows · Carbon balance · Smallholder

## 1 Introduction

According to the FAO (Food and Agriculture Organization), family farming produces around 80% of food and employs 30% of the world's population. Representing around 600 million farms, 84% are less than 2 ha, accounting for 12% of arable land. About 70% of agricultural land is occupied by only 1% of total farms. Although family farmers are fundamental in the sustainable transformation of food production, they are among those most affected by poverty and vulnerability (FAO 2020, 2022).

Climate change is among the most noticeable environmental impacts currently on all continents. In the 6th Report (IPCC 2022), the authors state that the balance of average annual global emissions (difference between gases of anthropogenic origin emitted and captured) continued to grow in the decade between 2010 and 2019 but the annual growth rate declined by 2.1 to 1.3% over the previous

Communicated by Tim McAllister

✉ Anna Lúcia Mourad
annalumourad@gmail.com

1 Institute of Food Technology, Ital, Campinas, Brasil

decade. The balance of global average emissions in 2019 was 59 ± 6.6Gt$CO_2$-eq for gases evaluated within the UNFCCC (United Nations Framework Convention on Climate Change).

In 2019, the biggest contributors to these emissions were $CO_2$-FFI (64%) from fossil sources and from industrial processes, $CH_4$ (18%) methane, and $CO_2$-LULUCF (11%) land use and land use change forestry. Emissions resulting from changes in land use are those that present the greatest variations in their estimates due to the difficulty of accounting. Carbon balances, which are directly linked to the emission or removal of greenhouse gases, which cause climate change, however, have been carried out in different ways, as described in the following paragraphs.

According to PAS2050 (BSI 2011), all emissions and removals of biogenic carbon must be accounted for with the exception of food and feed. The carbon that becomes part of the product must be excluded; emissions other than $CO_2$ from food waste degradation and from enteric fermentation must, in turn, be accounted for. This approach aims to make a carbon balance over a 100-year time horizon and account for what remains stored in this period; however, emissions other than $CO_2$ but originating from sequestered carbon, such as methane, must be corrected by discounting the amount captured. The GHG protocol document (WRI/WBCSD 2011) considers similar boundaries such as life cycle assessment method. Regarding carbon removals, for an example of processes such as paper production, the tool recommends that only the amount of carbon that enters the papermaking process in the form of wood be counted as biogenic carbon removal. The allocation application follows the same principles of the LCA tool, which recommends non-allocation whenever possible with subdivision into subprocesses and when this is not possible, the use of allocation by physical relationships, by mass or volume, and in the last case, the use of economic allocation.

The IDF (International Dairy Association) has developed a method for calculating the carbon footprint (IDF 2015) to be used to evaluate the production of milk and dairy products, based on international standards such as ISO 14040 (ISO 2006), PAS2050 (BSI 2011), and the GHG protocol (WBSD 2011). In this approach, all emissions arising from the use of fertilizers, soil amendments, use of diesel, change in land use, animal feed production, enteric digestion, and waste management are accounted for; however, this approach does not account for the carbon stored during the photosynthesis process in crops that are later consumed as feed. The allocation of inputs and emissions between milk and cattle is considered.

Cows belong to the group of ruminant animals that have an expansive chamber known as the rumen, located in the anterior part of the digestive tract. In the rumen, an intensive microbial enteric fermentation takes place, capable of digesting the cellulose stored in cattle feed (IPCC 2019). Volatile fatty acids, carbon dioxide, and methane gas are formed during enteric fermentation; the first group is used as an energy source, the other two are eliminated by eructation. There are studies that show the relationship between $CH_4$ emission and animal feed, and suggest the introduction of lipid in the feed to reduce the production of this gas (Codognoto et al. 2014; Zott and Paulino 2009).

Several milk LCA studies can be found in the scientific literature, but the methodological differences employed in each one make the comparison between the results extremely difficult. In addition, the carbon footprint calculation carried out through the use of data external to the study itself, which brings little specificity regarding the region where it was conducted.

Most recent studies have already adopted the functional unit related to the nutritional quality of milk, "Fat Protein Corrected Milk"—FPCM (Feyissa et al. 2022; Vogel and Beber 2022; Carvalho et al. 2022; González-Quintero et al. 2021). Another widely used functional unit is the "Energy Corrected Milk – ECM" (Drews et al. 2020; Léis et al. 2015), Gollnow et al. 2014). The allocation among farm products is mainly carried out between milk and live weight of cattle by biophysical principles (Feyissa et al. 2022; Vogel and Beber 2022; Pirlo and Lolli 2019; EDA 2018; Bacenetti et al. 2016), but also the allocation by economic values has been widely used (Feyissa et al. 2022; González-Quintero et al. 2021). These two methods were also identified as the main allocation methods practiced in the scientific literature in a review study published by Kyttä et al. (2022). In the study conducted for a large farm in the Bahia region of Brazil, small allocation differences were found between the two methods (Carvalho et al. 2022). The Colombian study, on the other hand, shows significant differences in the burden allocation factors for meat between the economic allocation methods (36%), followed by energy content (30%) and by mass allocation (13%).

Most studies carried out indicate that enteric fermentation is the biggest contributor to the carbon footprint (Carvalho et al. 2022; González-Quintero et al. 2021; Asem-Hiablie et al. 2019; Ruviaro et al. 2015). Estimates of emissions from animal growth and maintenance, including the enteric fermentation step, can be made using the IPCC Eqs. (2019), with estimates that use herd characteristic data such as average cattle weight, estimated net energy concentration of diet, and digestibility values (Carvalho et al. 2022; Ruviaro et al. 2015; González-Quintero et al. 2021). Given the difficulty of measuring, the biogenic carbon captured during photosynthesis and the biogenic carbon emitted back to the soil, through feces, urine, and that contained in food products, such as meat, milk, and bones, are not normally accounted for, which makes this balance, in practice, incomplete.

Food production is vital for feeding the population, but huge environmental impacts have been associated with it. So, the objective of this work is initially to measure the impact of milk production by small farms related mainly to climate change impact and to identify opportunities to minimize this impact.

## 2 Methods

### 2.1 Boundaries

Considering that the dairy sector has a significant participation in the state of São Paulo, as identified in the study by Pazinato (2017), this study focused on the survey of milk production coming mainly from the family agroindustry. The participating properties are located in the State of São Paulo. Farms managed by families were selected, mostly with milk processing on the farm to produce derivatives such as cheese and yogurt among others, within the perspective of evaluating properties characterized as "family agro-industries."

The adopted frontier is shown in Fig. 1 below, which includes the stages of animal feed production, the stages of raising the animals through heifer, lactating, and dry cows, up to the milk production inside the farm gate. The stages of food production, whether on or off the farm, were included, considering all inputs such as fertilizers (synthetic or organic manure), herbicides, pesticides, fuel use for agricultural machinery, and land use, in addition to consumption of water and electricity. Energy and water costs for cleaning the animals during milking were included in the boundaries.

Only the amounts of mineral salts and vitamin supplements were recorded, without considering their production from the extraction of raw materials. The production of agricultural equipment, veterinary products, and fertilizer packaging materials were not included in the study boundary.

### 2.2 Functional unit

In this work, 1000 kg of FPCM milk was adopted as the main functional unit, according to the equation developed by the International Dairy Federation (IDF 2015), in which the milk is corrected for the protein and fat content, since there is variation in the quality of the milk among different producers.

$$\mathrm{FPCM(kg)} = M_{\mathrm{milk}}(\mathrm{kg}) \times ((0.1226 \times \%G) + (0.0776 \times \%P) + 0.2534)$$

where FPCM (fat and protein corrected milk, kg) = the mass of milk corrected for the amount of fat and protein, expressed in kg

$$M_{milk}(kg) = the\ total\ mass\ of\ milk\ produced$$

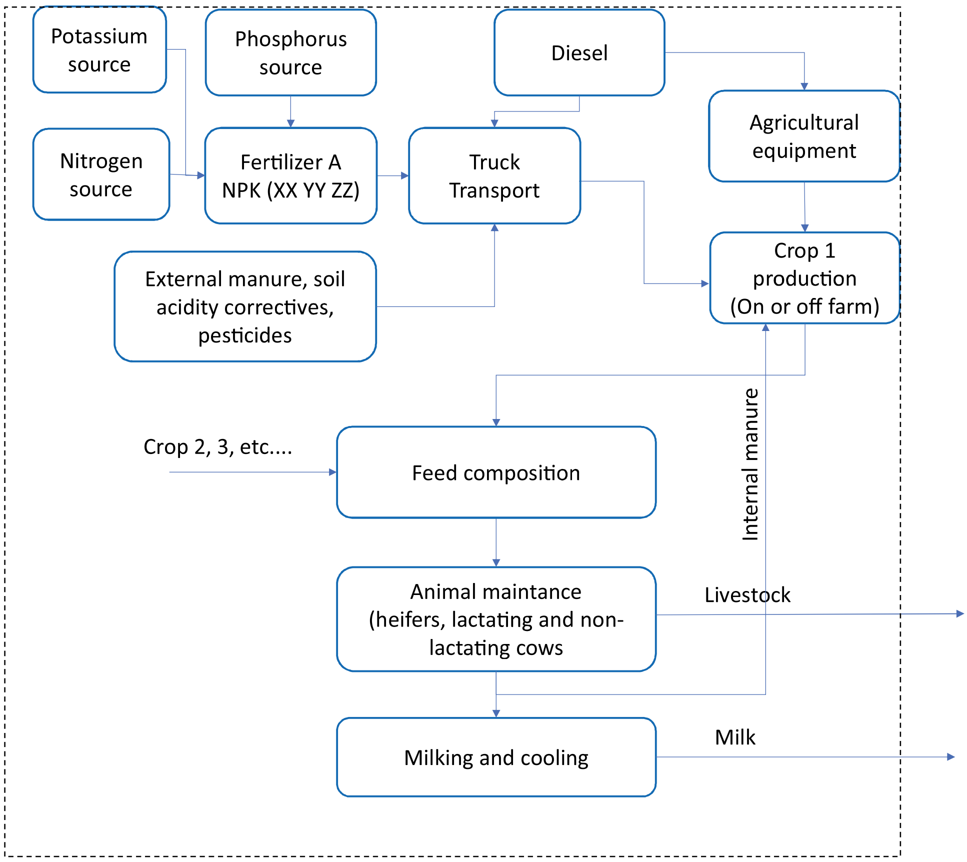



**Fig. 1** Boundaries of the study of milk production

*%G = percentage of fat contained in milk*

*%P = percentage of protein contained in milk*

Approaches were carried out with and without consideration of input allocation and impacts that are also associated with subsequent meat production. In the calculation using biophysical allocation, Eq. 4 of IDF method (2015) was used:

$$AF = 1 - 6.04 \times \frac{M_{meat}}{M_{milk}}$$

where AF = allocation factor

$M_{meat}$ is the mass of live weight of all animals sold including bull calves and culled mature animals per year.

$M_{milk}$ is the mass of fat and protein corrected milk (FPCM) sold per year.

The live weights of the animals divided by the average life times were counted and associated with the values of milk produced. Given that the farms form a dynamic system where calves/heifers, cows producing milk, and non-lactating cows coexist, all inputs added to the system and their outputs were accounted for on an annual basis, creating inventories that represent the annual averages of the farms.

## 2.3 Data collection

In partnership with the Coordination of Sustainable Rural Development (Cati/Campinas), a list of milk-producing properties in São Paulo was made available. All were previously invited to participate in the project through telephone and electronic contact. During the development period of this project, the adhesion of 14 production units (PU) was achieved, which were visited and identified as PU1 to PU14.

The PUs sampled are located in cities located in the state of São Paulo, southeastern Brazil, between the years 2019 and 2021. During the visits, the participants provided information about the characteristics of the herd, the agricultural property, the composition of the animals' diet, from the milking process to milk production. During farm visits, samples of milk produced on the same day were collected from the entire herd, from cows at different stages of lactations and ages. The collected milk was stored in a 500-ml sterile glass bottle, transported under refrigeration and sent for characterization in the laboratory.

The milk was submitted to fat determination by the butyrometric method (IAL 2005), which consists of the use of sulfuric acid and isoamyl alcohol to separate and quantify the fat, including those bound to the protein in the lipoprotein structure. The total protein content was determined by the official Kjeldahl method by multiplying the total nitrogen value by the correction factor equal to 6.38. This determination was carried out in accordance with IDF (1993, 1962).

## 2.4 Study modeling

All data are modeled using the software Gabi Professional (Sphera Solutions 2019). The composition of the rations given to the animals was differentiated by the growth phases: for heifers, lactating, and dry cows**.** The boundaries of the study considered the production of feed from the preparation of the land, planting the seeds until the harvest of agricultural products.

The carbon captured during the growing process of agricultural products was accounted for in the approach that includes carbon captured during photosynthesis. The values used refer to the carbon content in each ingredient of feed, considering their dry mass. For cases where this content is not known, the value of 47.5% of dry mass in carbon was taken as a reference (Nemecek et al. 2014). All farms participating in this project are located in the State of São Paulo, where there has been no change in land use in cultivated pasture areas in the last 20 years (Novaes et al. 2017).

All inputs used for forage formation, such as fertilizers and soil correctives (limestone and gypsum), were accounted for within the feed production stage within the farm. The main forages used were elephant grass, Napier grass, ryegrass, and oats. The use of diesel for use in agricultural equipment was also accounted for. corn and sorghum silages are also among the production inside the farm, but they are also acquired from third parties. The inputs declared by the owners for the production of feed were included.

All feeds obtained outside the farm had their inventories obtained either from a national database or estimated from scientific literature, considering agricultural inputs such as fertilizers, soil correctives, pesticides, and the use of diesel, as shown schematically in Fig. 1. Dataset from soybean grains (Folegatti Matsuura 2019a), maize grains (Folegatti Matsuura 2019b), maize silage (Dias 2019), and sugarcane (Cavalett 2019) representing some regional or national conditions of Brazilian data were extracted from Ecoinvent database version 3 (Wernet et al. 2016). The main components of animal feed used on farms include corn, soybean and sorghum grains, sugar cane, and soybean meal. The cottonseed inventory was estimated using average herbaceous cotton yield data for the state of São Paulo of 3675 kg/ha (IBGE 2018), the average cottonseed yield of 55% according to the Brazilian Association of Cotton Producers (ABRAPA 2016), and agricultural inputs from the Embrapa publication (Costa et al 2016).

For waste from industrial processes such as brewer's waste and citrus pulp, only the emissions resulting from their transport were considered, since they are considered co-products and their impacts are associated with their chains of origin. Transport distances of inputs from places of purchase to farms were recorded and transport emissions were accounted for. As trucks generally return empty, the distance has been doubled.

Using the value of water consumption by cows from Alves et al. (2011) and variation of urine volumes as a function of the temperature of the day, for simplicity, the volume of urine generated was regarded as 50% of the difference between the volume of water consumed and the production of milk for lactating cows and 50% of the volume of water ingested for heifers and dry.

Methane emission due to enteric fermentation was performed according to the average values found for Holstein cows, in an experiment in which this gas was measured using the sulfur hexafluoride (SF6) tracer gas method (Pedreira et al. 2009). According to Pereira and his collaborators, the methane emission factors are dependent of the total digestible organic matter contained in the feed. The factors found in this work of 32.9/37.4 and 35.7 g of $CH_4$ per kg of digestible organic matter for heifers, lactating, and dry cows, respectively, were adopted in the present model to estimate the amount of enteric methane.

The total nitrogen content ingested was estimated from the crude protein content of each feed ingredient. The crude protein value was divided by 6.25 to obtain the total nitrogen content (Zhongming et al. 2019). Nitrogen excretion parameters in feces and urine were used as 31.1% and 38.2% of the total nitrogen contained in the feed, as determined in an experiment with 12 Holstein cows carried out by Freitas et al. (2001). Direct emissions of ammonia ($NH_3$) from added synthetic fertilizers were calculated according to Table 5 and emissions from animal management according to Table 6, both from WFLDB (Nemecek et al. 2014). The emission of nitrogen oxides ($NO_x$) was estimated to be 2.6% in relation to the total nitrogen added, whether of organic or synthetic origin, after reduction of volatilized nitrogen as ammonia (Nemecek et al. 2014).

The emission of nitrous oxide ($N_2O$) considered was 8% of the total ammoniacal nitrogen content of the manure. The ammonia content of the manure was considered to be 60% of the total nitrogen. The estimation of the emission due to the crops was carried out according to WFLDB (Nemecek et al. 2014). The estimation of nitrate leached to water bodies was performed according to the SQCB (Sustainability Quick Check for Biofuels) model reported in Faist Emmenegger et al. (2009).

The emission of carbon dioxide of fossil origin was considered after the application of limestone and urea according to the IPCC (2019). The amounts of pesticide actives added to the crops were also considered as emissions to agricultural soil, in the same amount as recommended by the WFLDB for the estimated inventories (Nemecek et al. 2014).

The midpoint Recipe 2016 method has characterization factors that are representative on a global scale. The hierarchical perspective (*H*) for the 100-year horizon was selected for the assessment of the impacts of this work, considered an approach closer to the likely one with the inclusion and exclusion of biogenic carbon (Huijbregts et al 2016).

### 2.5 Statistical treatment

Statistical analysis was performed using the RStudio Software Version 1.4.1106 (2020) to study the relationship between the effect of climate change and the quantities of feed offered, milk yield per cow, digestible organic matter, and roughage, all calculated by the functional unit of 1000 kg FPCM. The statistical tool used was the Pearson's "rcorr" correlation.

## 3 Results/discussions

### 3.1 Production unit (PU) characteristics

The main characteristics of PUs are shown in Table 1.

The research sampling was focused on inviting family farmers to participate, which resulted in the inclusion of 14 production units. Seven PUs have a total area of less than 8 ha, 5 PUs between 14 and 44 ha, and 4 PUs with an area greater than 50 ha. Most allocate part of their area to planting fodder on their own property. One PU adopts the organic system and all the other units adopt conventional crops with the use of agrochemicals. The number of animals per property had the following distribution: 7 PUs between 9 and 62, 5 PUs between 90 and 110, and 2 PUs above 200 animals. Milk productivity varied between 9 and 28 FPCM per cow per day.

### 3.2 Sector characterization

The present work was carried out in a similar way to those found in the scientific literature for the dairy chain, as the aim is also to study other categories of environmental impact, results that will be presented in a sequential article. The results discussed here relate only to the carbon balance.

The evaluation of the results in Table 2 shows that the average emission obtained by the simple average of the production units is 2408 kg $CO_2$ eq./1000 kg FPCM and that there is a reduction of 6.6% in the total emission of equivalent carbon dioxide units when considering the unit of 1000 kg of milk without nutritional correction and a reduction of 9.1% when partially allocating emissions related to cattle production. This small reduction when considering the partial allocation for meat is due to the annual mass ratio: the amount of milk produced is about 77 times the amount

**Table 1** Main characteristics of the evaluated production units

| Main parameters | Productive unit (PU) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Total farm área (ha) | 44.0 | 3.0 | 14.0 | 3.5 | 4.8 | 3.4 | 280.0 | 7.3 | 23.0 | 5.0 | 205.7 | 50.0 | 15.8 | 16.9 |
| Forrage area (Ha) | 25.0 | 2.0 | 12.0 | 2.0 | 4.8 | 2.4 | 80 | 6.1 | 0 | 1.5 | 12.1 | 50 | 3.3 | 9.68 |
| Pasture area (Ha) | 19.0 | 1.0 | 2.0 | 1.5 | 0 | 1 | 200 | 1.2 | 23 | 3.5 | 193.6 | 0 | 12.5 | 7.26 |
| Planting and animal management | org | conv | conv | conv | conv | conv | conv | conv | conv | conv | conv | conv | conv | conv |
| Stocking rate (livestock unit (LU) per ha of pasture area) | 5.3 | 104 | 20 | 10 | - | 42 | 2.5 | 7.5 | 5.2 | 5.1 | 1.1 | - | 2.3 | 8.5 |
| Milk yield (FPCM per day/lactating cow) | 17 | 20 | 19 | 13 | 23 | 20 | 11 | 15 | 11 | 17 | 9.3 | 28.0 | 9.5 | 15 |
| Annual milk production (1000 L) | 471 | 438 | 263 | 41 | 675 | 270 | 1825 | 36 | 360 | 90 | 548 | 839 | 73 | 215 |
| Transport distance of inputs (km) | 5–10 | 20–80 | 30 | 30 | 2–10 | 10–20 | 5–80 | 6–30 | 2–40 | 40 | 10–100 | 20–130 | 20–120 | 40–150 |
| Feed (dry matter) (kg) | 1470 | 1440 | 1120 | 1790 | 1160 | 1170 | 2480 | 2360 | 2200 | 1140 | 1650 | 1200 | 2250 | 2070 |
| Feed (roughage) (kg) | 1020 | 847 | 768 | 1410 | 873 | 751 | 1240 | 1700 | 1140 | 675 | 1200 | 747 | 2020 | 1110 |
| Feed (digestible organic matter) kg | 949 | 1070 | 809 | 681 | 787 | 853 | 1870 | 1530 | 1280 | 643 | 1040 | 908 | 1240 | 1330 |
| Share of roughage, (%) | 69 | 59 | 69 | 79 | 75 | 64 | 50 | 72 | 52 | 59 | 73 | 62 | 90 | 54 |
| Share of digestible organic matter (%) | 65 | 74 | 72 | 38 | 68 | 73 | 75 | 65 | 58 | 56 | 63 | 76 | 55 | 64 |

of meat, measured in live weight of animals. The average allocation factor found for the 14 production units, calculated by Eq. 4 of the IDF (2015) for milk was 0.91 and, consequently, 0.09 for the live weight of the animals (the weight of the animals is divided by the mean lifetime). For each 1000 kg FPCM, an average of 14.3 kg of animal live weight was produced annually.

The FPCM unit is the functional unit considered the most correct, as it brings nutritional equivalence in relation to the levels of protein and fat. It is observed that for the simple unit of production of 1000 kg of milk, the emissions are lower, which indicates that, on average, the milk produced is below the nutritional level established by the unit. The step with the greatest contribution to this emission is due to the generation of methane during the digestive process that involves enteric fermentation, representing an average of 60% of emissions. The emission of carbon dioxide, resulting mainly from the stages of transport and use of agricultural machinery, represents 25% of these emissions. The high coefficients of variation of the flows of $CO_2$, $N_2O$, and $CH_4$ from non-enteric fermentation from each PU indicate possibilities of reducing these contributions. If the weighted average of the farms is considered, the average value reaches 2417 kg $CO_2$ eq./1000 kg FPCM, since the production units with higher production volumes presented lower environmental efficiencies.

### 3.3 Inclusion of capturated carbon in photosynthesis

Food production has always been associated with major environmental impacts. To simplify calculations, in general the carbon absorbed during photosynthesis is not accounted for in life cycle assessment studies, as it is known that this same absorbed carbon will return to the atmosphere in a relatively short time horizon. On the other hand, the emission of methane comes from this same carbon absorbed in photosynthesis. Therefore, the authors understand that at least the absorbed portion should be expressed together with emissions.

Table 3 shows very different results among the different production units. The differences between the quantities stored by the units are quite large. If it was possible to add the amount of biogenic carbon stored to the balance, it is likely that some of these units could be considered carbon storage farms, such as PUs 1, 4, 5, 11, and 13, which have higher credits than emissions, in relation to parameters that can be calculated. However, due to the difficulty of estimating the share of biogenic carbon that remains in the soil and continues in the chain, this balance is generally not complete.

Another factor that makes the carbon balance difficult to carry out is the time window considered for the calculations. Part of the biogenic carbon is temporarily stored as meat, milk,

**Table 2** Comparison of the climate change (CC) impact of the 14 PUs measured by Recipe 2016, v1.1, estimated for different functional units

| Flow | Simple averages (kg $CO_2$ eq. by) | | | Coefficient of variation, CV(%) | | |
|---|---|---|---|---|---|---|
| Function units | 1000 kg milk | 1000 kg FPCM | 1000 kg FPCM | 1000 kg milk | 1000 kg FPCM | 1000 kg FPCM |
| Allocation (*) | no | no | yes | no | no | yes |
| Flow | | | | | | |
| $CO_2$ emitted | 558 | 597 | 542 | 119 | 123 | 122 |
| $N_2O$ | 141 | 148 | 136 | 107 | 100 | 103 |
| $CH_4$ others | 205 | 222 | 201 | 99 | 99 | 99 |
| $CH_4$ enteric fermentation | 1344 | 1441 | 1309 | 30 | 32 | 30 |
| Total (exclu biogen carbon) | 2249 | 2408 | 2189 | 39 | 40 | 39 |

$CH_4$ others = $CH_4$ from non-enteric fermentation source

CV(%) = standard deviation/average×100

(*) = Allocation between milk and live weight of cattle according to IDF (2015)

bones, and solid products that are likely to be degraded in an annual time window. Methane emission factors are calculated based on the average lifetime of methane in the atmosphere, which varies between 8.4 and 12 years (IPCC 2001). Part of the carbon is stored in the form of roots and organic compounds that enrich the soil, but its residence time in these forms is quite dependent on agricultural practices and climatic conditions and there are few studies regarding this residence time.

Therefore, the time window in which the impact of climate change is considered is of great importance and the approach of 20, 50, or 100 years may not be the most adequate to represent these balances that change in shorter time intervals. All of these factors show that agriculture and livestock sectors must be evaluated differently in relation to climate change impact.

The change in land use has been one of the main factors responsible for the increase in GHG emissions in the world, when native lands are converted into pastures. However, in the evaluated region of São Paulo, the farms are old and there has been no variation in the type of land use in the last 20 years and, consequently, no carbon variation was associated with this factor, according to a study done by Embrapa (Novaes et al 2017). The biggest concerns are in relation to pastures. Depending on the type of animal management and agricultural practices, these properties can be considered accumulators or emitters of carbon.

Recent work on carbon balance carried out on 40 coffee farms in the region of Minas Gerais/Brazil, with analysis of the carbon content captured by plants (in trunks, leaves, roots, fruits) and organic carbon content in soil depths of 10 to 100 cm, for traditional planting practices a carbon stock of 1.63 Mg $CO_2$eq $ha^{-1}$ $year^{-1}$ was measured. For areas where good practices were adopted, this stock rose to 10.5 Mg $CO_2$eq $ha^{-1}$ $year^{-1}$ (Imaflora 2022).

An experiment carried out with soybeans intercropped with wheat in India, demonstrated that there is an increase in the amount of carbon stored in the soil by roots and nodules due to plantings. The average annual contribution of carbon to the soil was 24% of the aboveground harvestable biomass yield due to soybean planting. In addition, the use of manure, associated with the use of NPK-type fertilizer, increased the amount of organic carbon in the soil (SOC) by 40% in relation to the amount retained without the use of manure (Kundu et al. 2007). Therefore, depending on the agricultural practices adopted, farms have enormous potential to become carbon stores.

**Table 3** Comparison of inputs and outputs of the evaluated systems for climate change impact without allocating part of the impacts to meat (Functional unit: kg $CO_2$ eq./1000 kg FPCM)

| Climate change (kg $CO_2$ eq.) | PU1 | PU2 | PU3 | PU4 | PU5 | PU6 | PU7 | PU8 |
|---|---|---|---|---|---|---|---|---|
| Capture (*) | 2376 | 1722 | 838 | 2900 | 1968 | 472 | 2228 | 938 |
| Emission (**) | 2074 | 1925 | 1983 | 2113 | 1584 | 1308 | 3198 | 3587 |
| Difference | -302 | 202 | 1145 | -788 | -384 | 836 | 969 | 2649 |
| **Climate change (kg $CO_2$ eq.)** | **PU9** | **PU10** | **PU11** | **PU12** | **PU13** | **PU14** | **SA** | **WA** |
| Capture (*) | 2797 | 1308 | 2623 | 533 | 6090 | 2582 | 2098 | 1846 |
| Emission (**) | 5212 | 1353 | 1796 | 2806 | 2277 | 2503 | 2408 | 2417 |
| Difference | 2415 | 44 | -826 | 2273 | -3814 | -79 | 310 | 571 |

*PU* = production unit, *SA* = simple average, *WA* = weighted average

(*)Biogenic carbon storaged during photosynthesis of feed production considering only edible parts of the plants that feed the herds

(**)Mainly composed of fossil $CO_2$, $N_2O$, $CH_4$ enteric, and $CH_4$ other equivalents. Value does not include biogenic emission of $CO_2$

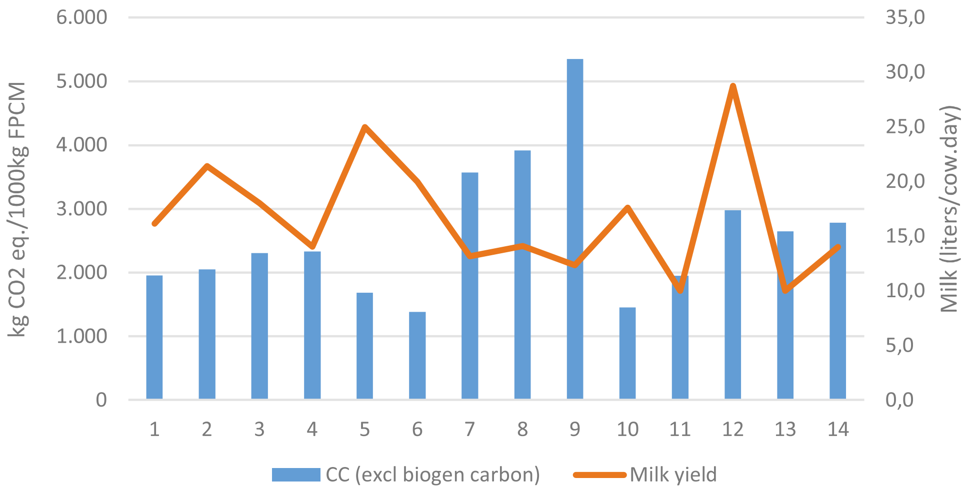



**Fig. 2** Variation of the climate change impact (CC) with the milk productivity of the properties

### 3.4 Assessments of individual environmental impact profiles

The production units have differences in relation to the handling and treatment systems of the animals, which lead to environmental efficiencies, as shown in Figs. 2 and 3. The emission values ranged from 1381 (PU6) to 5350 (PU9) kg $CO_2$ eq./1000 kg FPCM, that is, a variation of 3.9 times among the farms evaluated, which shows the possibility of optimizing the performance of the units with higher emissions.

In Fig. 2, it can be seen that the daily milk productivity per cow varied between 9.3 and 9.5 FPCM/cow.day, values obtained in production units 11 and 13, respectively, to 28.0 FPCM/cow.day in PU 12. The average productivity was 16.8 L per day per animal. Although a reduction in climate change impact is theoretically expected for higher milk yields, this is not the only parameter that influences the measured impact. The PU12's high milk yield does not make it a unit with low greenhouse gas emissions.

The analysis of the possible factors that can influence the measured parameters shows that the amount of dry matter offered as animal feed can also be one of the parameters that influence the environmental performance. In Fig. 3, there is a difference of 2.2 times in the amounts of feed offered, which vary from 1118 (PU3) to 2484 (PU7) kg DM/1000 kg FPCM. The production units that offered the highest amounts of feed by the functional unit (PU 7, 8, and 9) are the same that presented the highest values of climate change impact.

The analysis of Figs. 2 and 3 seem to indicate that good milk productivity associated with a balanced diet, without feed excesses, can be a guideline for obtaining better environmental performance.

### 3.5 Contribution analysis

For a better understanding of the factors that generate the results presented, a contribution analysis was performed, as shown in Figs. 4 and 5.

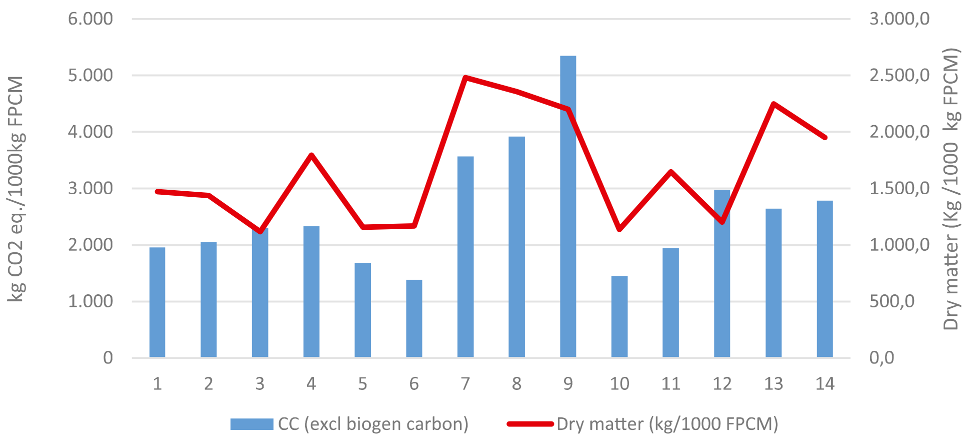



**Fig. 3** Variation of climate change impact (CC) with the amount of dry matter offered in animal feed

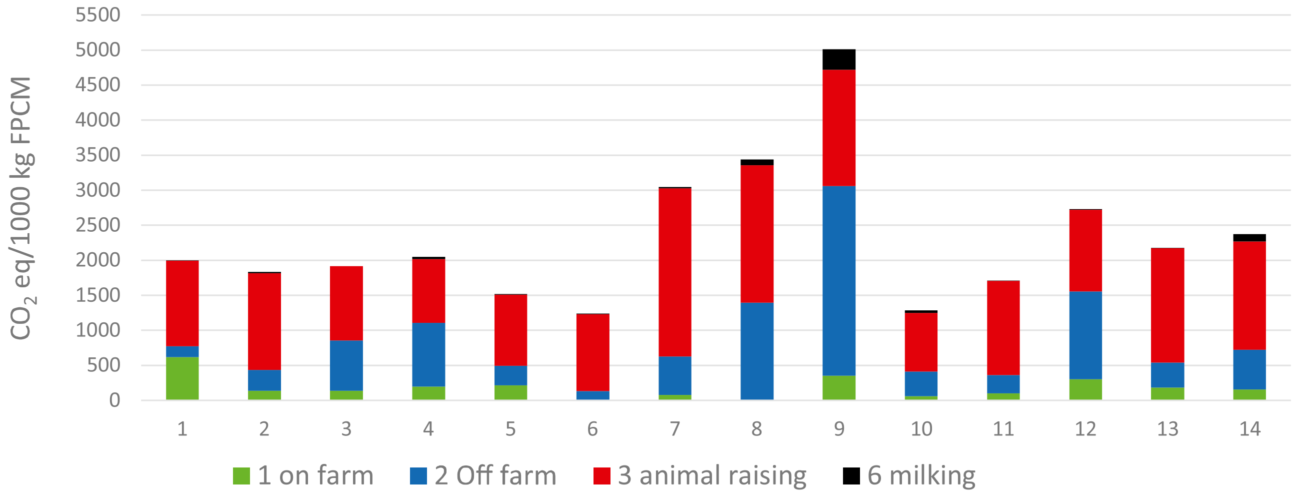



**Fig. 4** Main contribution steps for the calculation of climate change impact, without the inclusion of biogenic carbon and without allocating part of the impacts to meat (Recipe 2016, v1.1)

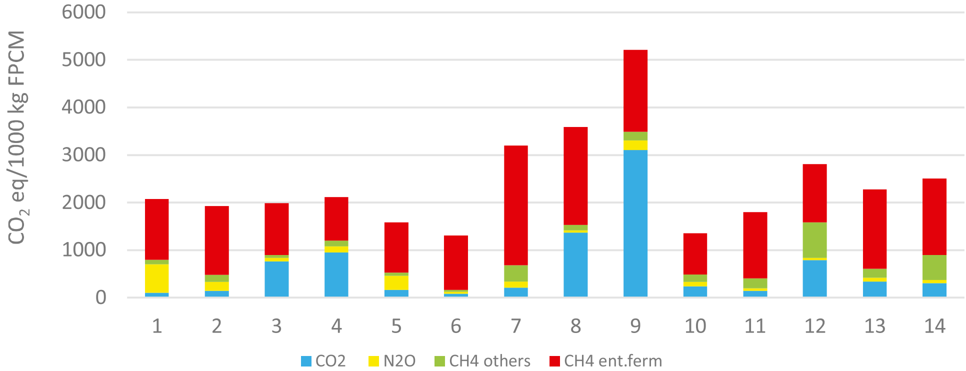
The analysis of Fig. 4 shows that the stages of greatest contribution to the effects studied are the off-farm production stages and the animal growth stage, the latter basically represented by emissions from enteric fermentation. This digestive stage represents between 33 and 89% of emissions from each PU. Feed imports, on the other hand, tend to increase emissions, depending on the need for transport and represent between 8 and 54% of total emissions.

A more detailed analysis of the main components that contribute to the impact of climate change in Fig. 5 reveals how the differences in the management practices carried out by each PU influence the results obtained. PU9 combines supply of a high amount of feed in dry mass with a high external dependence on these components, which makes the amounts of $CO_2$ for transporting inputs (2 to 40 km) and enteric $CH_4$ emissions the main contributors to the calculated impact.

The transport distances of inputs ranged from 2 to 150 km. Figure 5 shows that the emission of $CO_2$ due to the transport of inputs starts to have a significant impact on properties where there is also a high consumption of dry mass per unit of milk produced. Longer transport distances, between 100 and 150 km for the inputs of PUs 11, 12, 13, and 14 did not, however, result in the same $CO_2$ emission levels, showing that other factors must have influenced this emission.

Statistical analysis performed using Pearson's correlation, "rcorr" identified a statistically significant correlation at the 95% confidence level between Climate change (kg $CO_2$ eq) and feed (dry matter, correlation = 0.65, *p*_value = 0.008 and feed (digestible organic matter, correlation = 0.62, *p*_value = 0.62). The correlation values obtained (0.62–0.65) show influence on the measured impact, but also show that they are not the only parameters. These results are consistent with Fig. 3 and with the fact that enteric fermentation, the main component of the measured impact, is dependent on the amount of digestible organic matter, according to Pedreira and colleagues (2009).

**Fig. 5** Contribution analysis of the main components of climate change impact calculated, without the inclusion of biogenic carbon and without allocating part of the impacts to meat (Recipe 2016, v1.1)



### 3.6 Impacts of the main products: milk and cattle

Although the dairy chain is not the main supplier of the meat sold in the country, as there is a differentiation of breeds between the beef herds and in the treatments given to the animals, the dairy chain also generates meat, after the period of production of the cows when they are slaughtered. In 2021, female meat represented 43.5% of the total value of cattle slaughtered in the country (ABIEC 2022). The production of meat, for this reason, was not the focus of the work, but it was possible to calculate the impacts of its production, through the use of the allocation between the two main products generated, using the allocation factors calculated according to the IDF of 2015, as explained in the description of the functional units.

Figure 6 shows emissions relative to weighted averages for milk production and live weight of animals, without considering the carbon captured during photosynthesis. The analysis of Fig. 6 shows that emissions from livestock production, 15,117 $CO_2$ eq/1000 kg live weight of animals, is about 7 times higher than that from milk production, 2189 $CO_2$ eq/1000 kg FPCM of milk in the traditional approach.

In the work carried out with average data from slaughterhouses in the USA, of the live weight of cows, about 25% of it is used to obtain edible beef by the consumer, after the losses resulting from the removal of the carcasses, removal of fat and bone, shrinkage and spoilage losses, consumer losses due to steak preparation, meat spoilage, and cleaning (Asem-Hiablie et al. 2019). According to the Brazilian Meat Exporters Association, 20.9% of the live weight of animals can be appreciated by the consumer (ABIEC 2022). Consequently, it is estimated that emissions of 72,329 $CO_2$ eq/1000 kg of beef steak are used by the consumer. The value of the beef steak is only an estimate, since the values for using live cattle for the supply of steak refer to national averages and there was no specific survey of these data from individual slaughterhouses.

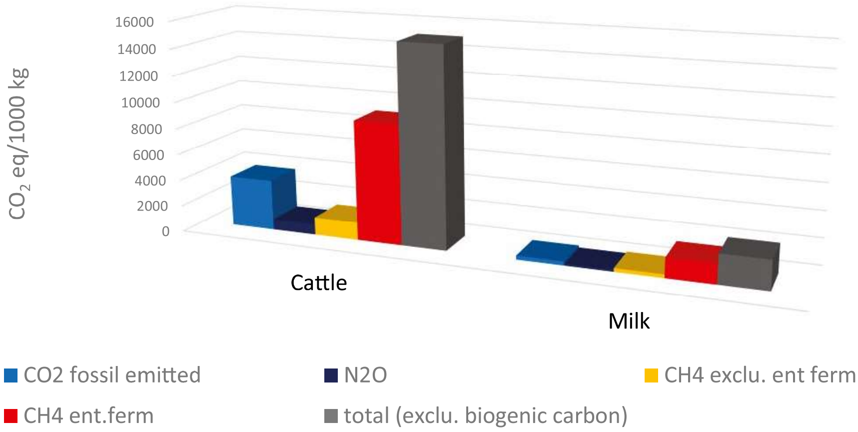
### 3.7 Comparison of data obtained with other studies

Comparison with other studies carried out is always important, but the differences in boundaries and specificities of modeling methods in each study also turn extremely difficult to compare results.

Recent work carried out on a farm in the state of Bahia with a herd of 128 Girolando animals and mixed breeds with Holstein (Carvalho et al. 2022) published a milk life cycle assessment study. Since the soil analysis did not reveal the need to add potassium fertilizer, it was not included. The result of this farm shows a low greenhouse gas emission of 1.41 kg $CO_2$-eq kg FPCM, probably because it is representative of a single efficient farm, where the predominant feeding was from pasture, with little supplementation of concentrates. The weighted average obtained in the present study was 2.19 kg $CO_2$-eq kg FPCM with allocation to meat. The very difference in profiles between the farms evaluated, which ranges from 1.38 to 5.35 $CO_2$-eq kg FPCM, shows that emissions are highly dependent on the practices of each production unit. However, as the total amount of feed in dry mass was not declared, it is not possible to compare directly with the main conclusion of the present work.

A study involving 911 dairy farms in the southern region, in the state of Paraná/Brazil, identified through statistical analysis 4 groups with footprints ranging from 1.75 kg $CO_2$ eq (group 1) to 3.27 kg $CO_2$ eq. (group 4). The lowest emissions occurred on large farms with highly productive cows of 21.4 kg FPCM per day, with 77% of the herd composed by breed Holstein and access to higher levels of technology assistance (Vogel and Beber 2022). This study estimates the amounts of cattle feed based on the composition of the breeds of each herd, the owners' declaration regarding the supply or not of concentrates and feed supplements, and correlations between milk yield declared by farmers and diets recommended by Embrapa. For this reason, the results referring to emissions are valid, but quite dependent on the

**Fig. 6** Main contributors to the calculation of climate change impact, without the inclusion of biogenic carbon for the 2 products: milk ($CO_2$ eq/1000 kg FPCM and cattle ($CO_2$ eq/1000 kg live weight of animals) (Recipe 2016, v1.1)



modeling used in the study and may not exactly represent the practices actually adopted by each farm.

A large representative study of 1313 farms in Colombia, with data collected between 2014 and 2015, quantified the average emission of 4.3 $CO_2$-eq per kg FPCM, using mass allocation (González-Quintero 2021). This study suggests that these emissions can be reduced by improving pastures, adopting better agricultural practices, using fertilizers efficiently and optimizing the stocking rate.

A milk life cycle assessment study carried out in Italy with four farms identified emissions of 1.47, 1.35, 1.49, and 1.50 kg $CO_2$ eq. per kg FPCM, considering allocation by mass, with values reduced to 1.02, 1.11, 1.26, and 1.20 when excluding land use change and soil carbon storage (Battini et al. 2016).

A study performed for beef production in the southern region of Brazil (Dick et al. 2015) estimates the emission of 22.52 and 9.16 kg $CO_2$ eq. per 1 kg live weight of animals for extensive system and improved system. Compared to the values of the present study, expressed on the same basis, emissions are 30.2 kg $CO_2$ eq per 1 kg of live weight, considering the same percentage of 50% for carcass weight, the value used in the reference study. The data obtained seem to be very coherent, considering that the beef, the object of this study, has included in the boundaries the production of nutritional concentrates necessary for the production of milk. This was not included in the production of meat obtained in a herd with 50% of participation of males, which also have higher productivity in meat, because on average, they are heavier than cows.

Another Brazilian study was carried out for meat production in the southern region of Brazil considering the production of steak from Aberdeen Angus cattle in different farming systems, from natural pasture with only grass, improved natural pasture, pastures with ryegrass, and/or sorghum (Ruviaro et al. 2015). The carbon footprints varied between 18.3 and 42.6 kg $CO_2$ eq./kg LWG considering the contribution of cows, calves, and steers, which shows that the results of the present study, expressed on the same basis (15.1 $CO_2$ eq./kg LWG) are about 17% lower than that obtained in the previous study.

## 4 Conclusions

The data obtained in this work bring important results related to the environmental aspects of milk production by the family agribusinesses participating in this project.

The climate change category, calculated by the Recipe 2016 methodology (*H*), resulted in values of 2408 and 2189 $CO_2$ eq/1000 kg FPCM, referring to the simple averages obtained among the 14 agro-industries, calculated without allocation and with biophysical allocation according IDF method, respectively, of inputs and products between milk and live cattle weight.

The carbon footprints normally calculated in LCA studies in this sector are incomplete, due to the difficulty of estimating the amounts of captured and emitted carbon. The authors suggest that the amounts of carbon captured during photosynthesis can be expressed together with the other sources. Recent studies show that agriculture, carried out with good cultivation practices, can be one of the most efficient ways of storing carbon.

Five of the evaluated farms had higher captures than emissions and have the potential to be considered carbon stores. This classification, however, should be confirmed through continuous monitoring of the carbon content stored in plants and soil.

The data obtained show that the amounts of feed offered (in dry mass) by the functional unit differ by 2.2 times between the PUs. In addition to the well-known optimization of the use of agrochemicals, climate change impact values calculated indicate that units that combine, by the functional unit, smaller amounts of feed provided, with little external dependence and good milk yield tend to generate more environmentally efficient units.

Considering the weighted average, the highest emissions occur during the growth of the animals, with the emission of methane during the enteric fermentation, responsible for 67% of the equivalent emissions and the emission of carbon dioxide, responsible for 14%, emitted during stages of transport and agricultural production. Statistical analysis showed a significant correlation between the measured impact and the amounts of feed consumed per 1000 kg of FPCM milk, expressed in total dry matter and digestible organic matter. These conclusions reinforce the need to make feeding more efficient from a nutritional point of view, that is, to feed cattle more efficiently, supplying them with nutrients that are really necessary both for a good milk productivity and for the maintenance of their life, in order to make diets more efficient, without shortages or waste.

Analysis of beef co-production shows an estimated emission of 30,234 kg $CO_2$ eq per 1000 kg of beef, if considering that 50% of the live weight of the animals is used, or 72,329 kg $CO_2$ eq per 1000 kg of beef, if considering the use of 20.9% (ABIEC 2022) in relation to the live weight of the animals.

**Acknowledgements** We would like to thank Stephen Shaw for his careful review of the English and Daisy Moitinho for her data statistical treatment carried out.

**Funding** The authors are grateful for the financial support received from the São Paulo State Research Support Foundation (Processes Fapesp 2018/10896–5 and 2018/24730) and Fundepag—Agribusiness Research Development Foundation (Process No. 000153–000197/2018) and the support of the owners of the collaborating data farms.

**Data availability** Most of the data collected is already available in the article itself. Additional data that do not compromise the confidentiality of the participating agro-industries can be requested to the corresponding author.

## Declarations

**Conflict of interest** The authors declare no competing interests.

## References


Alves AA, Sales RO, Azevedo MMR, Azevedo AR, Arruda AV (2011) Exigências Nutricionais de Ruminantes em Ambiente Climático Tropical. Federação da Agricultura e Pecuária do Estado do Ceará - FAEC, Fortaleza

Asem-Hiablie S, Battagliese T, Stackhouse-Lawson KR et al (2019) A life cycle assessment of the environmental impacts of a beef system in the USA. Int J Life Cycle Assess 24:441–455. https://doi.org/10.1007/s11367-018-1464-6

Associação Brasileira de Exportadores de Carne – ABIEC (2022) Beef report. Perfil da pecuária no Brasil. http://abiec.com.br/publicacoes/beef-report-2020/ . Accessed 31 March 2022

Associação Brasileira de Produtores de Algodão – ABRAPA (2016) Custos de produção de algodão. https://www.abrapa.com.br . Accessed 16 June 2021

European Dairy Association - EDA (2018) Product environmental footprint category rules for dairy products. EDA, Brussels, p 168

Bacenetti J, Bava L, Zucali M, Lovarelli D, Sandrucci A, Tamburini A, Fiala M (2016) Anaerobic digestion and milking frequency as mitigation strategies of the environmental burden in the milk production system. Sci Total Environ 539(1):450–459.https://doi.org/10.1016/j.scitotenv.2015.09.015

Battini F, Agostini A, Tabaglio V, Amaducci S (2016) Environmental impacts of different dairy farming systems in the Po Valley. J Clean Prod 112:91–102 Part 1 ISSN 0959–6526. https://doi.org/10.1016/j.jclepro.2015.09.062

BSI (2011) PAS 2050:2011—specification for the assessment of life cycle greenhouse gas emissions of goods and services. British Standards Institute, London

Carvalho LS, Willers CD, Soares BB et al (2022) Environmental life cycle assessment of cow milk in a conventional semi-intensive Brazilian production system. Environ Sci Pollut Res 29:21259–21274. https://doi.org/10.1007/s11356-021-17317-5

Cavalett O (2019) Sugarcane, BR-SP (Brazil, São Paulo) Ecoinvent database version 3.7.1. Laboratório Nacional de Ciência e Tecnologia do Bioetanol- Campinas

Codognoto LC, Porto MO, Cavali J, Ferreira E, Stachiw R (2014) Alternativas de mitigação de emissão de metano entérico na pecuária. Rev Bras Ciênc Amazônia 3(1):81–92

Costa KR, Picoli JF, Hilara LGS, Scachetti MT, Donke ACG, Suassuna ND, Mmrandi MAB, Folegatti-Matsuura MIS (2016) Avaliação do ciclo de vida da produção de algodão no cerrado brasileiro. https://www.bdpa.cnptia.embrapa.br . Accessed on 16 June 2021

Dias F (2019) Maize silage production, BR (Brazil) ecoinvent database version 3.6. Embrapa Pantanal, Corumbá

Dick M, da Silva MA, Dewes H (2015) Life cycle assessment of beef cattle production in two typical grassland systems of southern Brazil. J Clean Prod 96:426–434

Drews J, Czycholl I, Krieter J (2020) A life cycle assessment study of dairy farms in northern Germany: the influence of performance parameters on environmental efficiency. J Environ Manag 273:111127.https://doi.org/10.1016/j.jenvman.2020111127

Faist Emmenegger M, Reinhard J, Zah R (2009) Sustainability quick check for biofuels – intermediate background report. With contributions from Ziep T, Weichbrodt R, Prof. Dr. Wohlgemuth V et al. Agroscope Reckenholz-Tänikon. Dübendorf, Switzerland

FAO (2020) Coronavirus disease 2019 (COVID-19) and family farming. Rome, p 8

FAO (2022) Family farming. Legal brief 8, March 2022, p 10. https://www.fao.org/3/cb8227en/cb8227en.pdf

Feyissa AA, Senbeta F, Diriba D et al (2022) Understanding variability in carbon foot prints of smallholder dairy farm, in the Central Highlands of Ethiopia. https://doi.org/10.21203/rs.3.rs-1335143/v1

Folegatti Matsuura MIS (2019a) Soybean production, BR-PR (Brazil, Paraná) ecoinvent database version 3.6, Embrapa Meio Ambiente, Jaguariúna

Folegatti Matsuura MIS (2019b) Maize grains production, BR-MS (Brazil, Mato Grosso do Sul) ecoinvent database version 3.6, Embrapa Meio Ambiente, Jaguariúna

FREITAS SC de (2001) Metodologia analítica para determinação de adulteração em gordura de leite. 225 f. Tese (Doutor em Ciência e Tecnologia de Alimentos) - Faculdade de Engenharia de Alimentos, Universidade Estadual de Campinas, Campinas

Gollnow S, Lundie S, Moore AD, Mclaren J, Van Buuren N, Stahle P, Christie K, Thylmann D, Rehl T (2014) Carbon footprint of milk production from dairy cows in Australia. Int Dairy J 37(1):31–38. https://doi.org/10.1016/j.idairyj.2014.02.005

González-Quintero R, Kristensen, T, Sánchez-Pinzón MS et al (2021) Carbon footprint, non-renewable energy and land use of dual-purpose cattle systems in Colombia using a life cycle assessment approach. Livestock Sci 244:104330. https://doi.org/10.1016/j.livsci.2020.104330

Huijbregts MAJ et al (2016) ReCiPe 2016 A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization RIVM Report 2016–0104

Instituto Adolfo Lutz - IAL (2005) Métodos físico-químicos para análise de alimentos. 4th ed. Ministério da Saúde, Brasília, BR

Instituto Brasileiro de Geografia e Estatística – IBGE (2018) Tabela 1612 - Área plantada, área colhida, quantidade produzida, rendimento médio e valor da produção das lavouras temporárias. https://www.ibge.gov.br . Accessed 28 July 2020

Instituto de Manejo e Certificação Florestal e Agrícola - Imaflora (2022) Balanço de carbono na cafeicultura com boas práticas agrícolas CECAFÉ. https://www.cecafe.com.br

International Dairy Federation - IDF (2015) A common carbon footprint for the dairy sector. The IDF guide o standard the life cycle assessment methodology. Bulletin 479/2015, Brussels, p 70

International Dairy Federation (1993) Milk: determination of nitrogen content (FIL-IDF 20B). FIL/IDF, Brussels, p 11

International Dairy Federation (1962) Determination of the total nitrogen content of milk by Kjeldahl method. (FIL-IDF 20). FIL/IDF, Brussels, p 3

Intergovernment Panel of Climate Change – IPCC (2001) Chapter 4: Atmospheric chemistry and greenhouse gases In: TAR Climate Change 2001: The Scientific Basis

Intergovernment Panel of Climate Change – IPCC (2022) Climate change 2022: mitigation of climate change. Working Group III Contribution to the IPCC Sixth Assessment Report

Intergovernment Panel of Climate Change – IPCC (2019) Chapter 10: Emissions from livestock and manure management In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

International Organization for Standardization – ISO (2006) ISO 14040: Environmental management – life cycle assessment – principles and framework. Geneva

Kundu S, Bhattacharyya R, Prakash V, Ghosh BN, Gupta HS (2007) Carbon sequestration and relationship between carbon addition and storage under rainfed soybean-wheat rotation in a sandy loam soil of the Indian Himalayas. Soil & Tillage Research 92:87–95

Kyttä V, Roitto M, Astaptsev A, Saarinen M, Tuomisto HL (2022) Review and expert survey of allocation methods used in life cycle assessment of milk and beef. Int J Life Cycle Assess 27(2):191–204. https://doi.org/10.1007/s11367-021-02019-4

Léis CM, Cherubini E, Ruviaro CF, Silva VP, Lampert VN, Spies A, Soares SR (2015) Carbon footprint of milk production in Brazil: a comparative case study. Int J Life Cycle Assess 20:46–60. https://doi.org/10.1007/s11367-014-0813-3

Nemecek T, Bengoa X, Lansche J, Mouron P, Rossi V, Humbert S (2014) Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 2.0, July 2014. WorldFood LCA Database (WFLDB) Quantis and Agroscope, Lausanne and Zurich, Switzerland.

Novaes RM, Pazianotto RA, Brandao M, Alves BJ, May A, Folegatti-Matsuura MI (2017) Estimating 20-year land use change and derived $CO_2$ emissions associated to crops, pasture and forestry in Brazil and each of its 27 states. Glob Change Biol 00:1–13. https://doi.org/10.1111/gcb.13708

Pirlo G, Lolli S (2019) Environmental impact of milk production from samples of organic and conventional farms in Lombardy (Italy). J Clean Prod 211:962–971. https://doi.org/10.1016/j.jclepro.2018.11.070

Pazinato BC (2017) Macro caracterização das agroindústrias familiares do estado de São Paulo. Dissertation, Instituto de Tecnologia de Alimentos

Pedreira MDS, Primavesi O, Lima MA et al (2009) Ruminal methane emission by dairy cattle in Southeast Brazil. Sci Agric 66(6):742–750

RStudio Team (2020) RStudio: integrated development for R. RStudio, PBC, Boston, MA. http://www.rstudio.com

Ruviaro CF, Léis CM, Lampert VN et al (2015) Carbon footprint in different beef production systems on a southern Brazilian farm: a case study. J Clean Prod 96:435–443, ISSN 0959–6526. https://doi.org/10.1016/j.jclepro.2014.01.037.

Sphera Solutions (2019) Life cycle assessment product sustainability (GaBi) software Available online: https://sphera.com/life-cycle-assessment-lca-software/. Accessed on 13 October 2020

Vogel E, Beber CL (2022) Carbon footprint and mitigation strategies among heterogeneous dairy farms in Paraná, Brazil. J Clean Prod 349:131404. https://doi.org/10.1016/j.jclepro.2022.131404

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21(9):1218–1230. https://doi.org/10.1007/s11367-016-1087-8 . Accessed on 24 May 2021

World Resources Institute / World Business Council for Sustainable Development - WRI/WBCSD (2011) Greenhouse gas protocol. Product Life Cycle Accounting and Reporting Standard. Switzerland, p 148

Zhongming Z, Linong L, Xiaona Y, Wangqiang Z, Wei L (2019) Emissions from livestock and manure management. In: 2006 IPCC guidelines for national greenhouse gas inventories. Chapter 10. IPPC, pp 10.1–10.87

Zott CA, Paulino VT (2009) Metano na produção animal: emissão e minimização de seu impacto. Ecologia de Pastagens, Curso de Pós-graduação em Produção Animal Sustentável. Instituto de Zootecnia, APTA/SAA