Sustainable Intensification Strategies for GHG Mitigation Among Heterogeneous Dairy Farms in Paraná, Brazil

by Everton Vogel and Caetano Luiz Beber

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Abstract

Rearing dairy cattle leads to greenhouse gases (GHG) emissions which may contribute to global warming and consequently climate change. The remarkably heterogeneity among dairy farms as well as the lack of representative research, poses constraints to the development of effective actions to reduce GHG emissions in low- and middle-income countries. This study explores a large farm survey in order to identify dairy farm types and derive their carbon footprint (CF). Cluster analysis and life cycle assessment are applied to sample a of 895 farms. Results show a significant difference on the CF between three farm types. The type T1 was composed of less specialized producers, owning mixed herds and displaying low productivity and a higher CF (3.12 kg CO_2 eq. (kg FPCM)$^{-1}$). Slightly more specialized and productive, farms in T2 presented lower CF (1.79 kg CO_2 eq. (kg FPCM)$^{-1}$). However, the lowest CF was identified in T3 (1.30 kg CO_2 eq. (kg FPCM)$^{-1}$), which was composed of the largest and most specialized farms. Strategies to improve CF should be tailored to each type of farm respectively. Research and policy should strive to accelerate farmers' adoption of intensification technologies and practices, though following sustainable intensification practices that also account for regional socio-economic development.

Keywords: farm typology, life cycle analysis, farm management, milk production, environmental management.

JEL: Q51; Q54; Q56

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1 Introduction

Milk production in Brazil has grown significantly in the last decades. The Brazilian production has increased from 15.8 Mt in 1990 to 34.5 Mt in 2019, engaging approximately 1.18 million farmers in the activity (Embrapa, 2020; IBGE, 2018). These numbers place the country among the top five milk producers in the world. National and global demand for dairy products is expected to continue expanding in the coming decades (OECD-FAO, 2020). Concurrently, the concerns regarding the sustainability of milk production have been increasing at a rapid pace. Milk production is often associated with greenhouse gas emissions (GHG), one of the main factors responsible for the global warming. Worldwide the dairy cattle herd is responsible for about 30% of all GHG emissions from the livestock sector (~ 2.1 Gt CO_2 eq. yr^{-1}) (Gerber et al., 2013; Herrero et al., 2016). Thus, improving the environmental efficiency of dairy supply chains became a key strategy to tackle climate change (IPCC, 2019a; Roe et al., 2019; Willett et al., 2019). In order to achieve this goal, measuring CF in dairy production becomes paramount as a first step for developing appropriate strategies to reduce emissions. While this might be trivial in the dairy sector of high-income countries, the task reveals itself extremely complex in low- and middle-income countries (LMIC).

Sustainable intensification of farming systems in LMIC has been suggested as a strategy to increase food supplies while improving the environmental performance of the agri-food sector (IPCC, 2019a; Roe et al., 2019; Willett et al., 2019). This approach is also recommended for dairy farms, once less specialized dairy farms with low productivity display significantly larger GHG emissions per milk produced (Gerber et al., 2011; Herrero et al., 2016). In LMIC, however, dairy systems and management practices among dairy farmers are highly heterogeneous. In Brazil, for example, farmers operating highly specialized farms, with confined herds, coexist with small-holders owning only a few cows reared on pastures. Considering this diversity in the development of national and regional intensification strategies is central to reach mitigation targets, while avoiding harmful socioeconomic prejudice (Gerber et al., 2013; Ortiz-Gonzalo et al., 2017). Moreover, the presence of specialized dairy farms in developing countries suggests that, besides intensification, other approaches targeting specialized herds must also be considered (Herrero et al., 2016).

A central step to improve the environmental efficiency of the dairy sector is to understand the origins and fate of the GHG along the production chain. The Life Cycle Assessment (LCA) approach has been suggested as the standard technique to inventory GHG and calculate the Carbon Footprint (CF) of dairy products (FAO, 2017, 2016). LCA has been applied to quantify and understand the sources of GHG emissions from dairy systems in several countries. It was adopted, for example, to compare conventional and organic milk production in Europe (Kristensen et al., 2011; Thomassen et al., 2008) or for comparing the performance of milk produced among small-holders in Peru (Bartl et al., 2011). LCA was also applied to investigate the differences between confined and pasture-based systems in Ireland (O'Brien et al., 2014) and Canada (Arsenault et al., 2009). The studies conducted in Brazil evaluated pasture based, semi-confined, and confined production systems (de Léis et al., 2015), and the addition of grazing in the diet of cows fed with total mix ration (Ribeiro-Filho et al., 2020). Both case studies were conducted in southern Brazil and evaluated high-yield production modes, thus, representing only a small share of milk producers in the country (de Léis et al., 2015).

Generally, LCAs studies are very data demanding, requiring a significant amount of financial resources and labor to be completed. This feature, normally, leads researchers to rely on small samples from selected farming systems to conduct case studies. Such studies are very important for understanding the CF of specific production modes. However, they fail to capture the heterogeneity among dairy systems operating in a region, therefore, leading to the development of imprecise and incomplete mitigation policies and actions (de Léis et al., 2015; Yan et al., 2013). Therefore, with access to an extensive database we construct typologies of heterogeneous dairy farms and calculate their carbon footprint. This allows us to derive farm-type specific policy and management recommendations to reduce emissions. Clustering techniques, expert knowledge, and life cycle assessment are applied in a joint approach to study a sample of 895 dairy farms from Paraná, Brazil. In particular, we intend to categorize farm types that represent the wide range of producers operating in the region by characteristics such as their structure, practices, socioeconomics characteristics and CF intensities. We then discuss how sustainable intensification and other mitigation strategies can be applied to these different farm types, providing insights to improve the dairy sector of LMICs. Our study therefore, contributes to the literature by broadening the analysis of CF to less specialized dairy farms from a LMIC, where to our knowledge very few studies have been conducted. We expect this approach can support researchers and extension workers. More specifically, those engaged in implementing climate protection actions in developing countries but face a lack of resources to conduct proper field surveys to understand the heterogeneity among farming systems in their region.

2 Materials and methods

This study relates to milk producers from Paraná state, Southern Brazil Fig. 1. The state is located in a temperate region covered by two climate classifications Cfa[2] and Cfb, with annual rainfall ranging from 1300 to 2500 mm (Alvares et al., 2013).

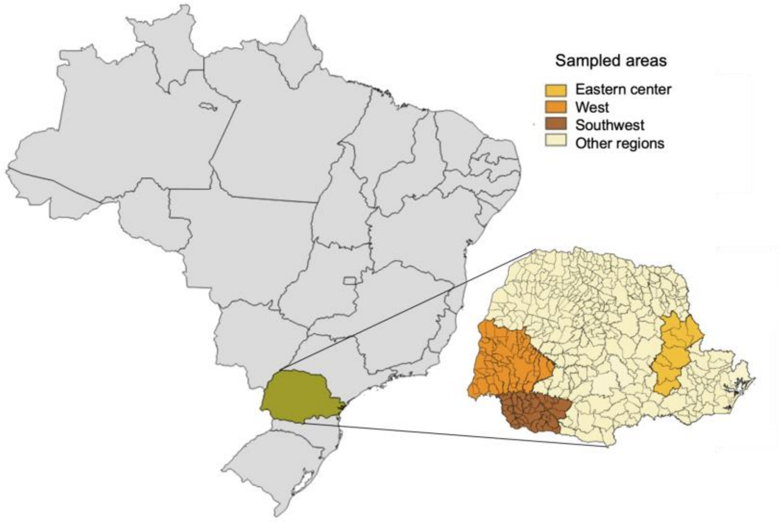

Figure 1 Location of Paraná in Brazil and Paraná with the sampled regions highlighted. Adapted from (IPARDES, 2009).

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[2] Cfa: humid subtropical oceanic climate, without dry season, with hot summers; Cfb: humid subtropical oceanic climate, without dry season, with temperate summer (Alvares et al., 2013).

Paraná is the third-largest milk producer in the country, with 87 063 dairy farms and an annual production of ~ 3.2 Mt in 2017 (IBGE, 2018). Data were collected in a general farm survey conducted by the Institute of Economic and Social Development of Paraná (IPARDES) in 2007. In total 1,043 farmers that declared producing milk were interviewed in the state subregions of Eastern center, West, Southwest, and other regions (IPARDES, 2009). The first three regions are considered the main dairy basins in the State, accounting for 62% of the total milk production in Paraná (IBGE, 2006). The other regions with a smaller share in the state's production were grouped into a single large region, called the Other Regions of the State.

The main objective of the survey was the elaboration of a diagnosis of the dairy sector in Paraná, addressing the several aspects that involve primary production and highlighting the technology used in production (IPARDES, 2009). To group the farms and calculate the CF we followed the steps depicted in Fig. 2. The details of our approach are described in the next subsections.

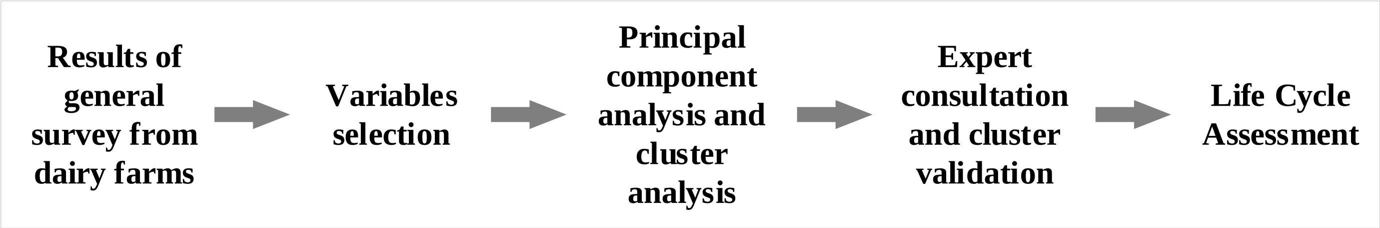

Fig. 2 Framework of analysis.

2.1 Multivariate analysis

Data were first inspected for outliers and filtered to remove farmers that did not commercialize any milk or milk products in the period. The selection of variables followed the premise that farm and herd characteristics will generate groups with contrasting carbon footprint. The variables considered were: farm area, pasture area, number of lactating cows, total number of animals in the herd, herd composition, percentage of specialized breeds in the herd, milk production per cow, annual milk production of the farm, machinery, equipment, and buildings used in the dairy farm. To conduct the multivariate analysis we followed the steps described by Alvarez et al. (2014) and Hair et al. (2017). The selected variables were submitted to the Kaiser-Maier-Olkin (KMO) measure of sampling adequacy and Bartlett test of sphericity (Hair et al., 2017). Only variables that presented an individual KMO $\geq$ 0.5 were maintained for analysis (Hair et al., 2017). Finally, we reached an overall KMO value score of 0.81. The suitability of the analysis was confirmed by applying the Bartlett test, which presented $p = 0.000$, confirming that the data set was suitable to PCA. The number of factors retained in the PCA was based on the Kaiser criterion (i.e., eigenvalues > 1) (Hair et al., 2017). We maintained four principal components which explained 65% of the variability in the data. Factor loadings from the PCA were used to conduct the clustering. The optimal number of clusters was obtained based on the gap statistics and scree plot ($k = 3$). With the predefined number of clusters, we applied the K-means algorithm to perform the clustering. Final validation of the results has been conducted by comparing the farm types, considering the variables' characteristics, as described by Subirana et al. (2014). We conduct the analysis with the R Core Team version 3.6.3, (2020), and packages 'ade4' v.1.7-16 (Dray and Dufour, 2007).

Following the definition of clusters, we interviewed an expert working as researcher on dairy production systems from Paraná. The interview was conducted to validate clustering results, identify important changes in the sector since the survey was conducted, and complement information on key parameters necessary to perform the CF calculations (e.g., manure management and concentrate feeding strategies). The interview was conducted in February 2021 and lasted around 1h30.

2.2 Life cycle assessment

The International Organization for Standardization (ISO) 14040 and 14044 guidelines suggest that an LCA study should follow a four-phase approach, namely, i) goal and scope definition, ii) Life Cycle Inventory (LCI), iii) Life Cycle Impact Assessment (LCIA), and iv) Interpretation (ISO, 2006a, 2006b).

i) The goal of the LCA in this study was to inventory and calculate the carbon footprint (CF) of heterogeneous dairy farms in Paraná, BR. To accomplish this goal, we adopted a time scope of one-year, accounting for the production of milk and liveweight gain at the farm. This cradle-to-farmgate approach is common when the focus of the study is to improve farm-level environmental management practices (Bartl et al., 2011; De Boer, 2003; de Léis et al., 2015). Dairy farms are multifunctional production units, and allocation of the burdens among the outputs is normally required (e.g., production of milk, cull animals). We adopted a biophysical approach, based on energy consumption by animals (Nemecek and Thoma, 2020). This allocation procedure was applied to allocate burdens between Fat and Protein Corrected Milk (FPCM) and liveweight gain at each farm. The system boundary included the production of feed (pasture, silage, hay, and concentrates) and the farming stage, including all animal categories declared by the producers. Due to the lack of information on the fate of manure produced in the farms, and to be conservative in our calculations, we allocated emissions from manure spread in agricultural soils to the dairy farms. Emissions associated with the production of medicines and construction of buildings were not accounted for due to their expected annual low impact.

The ii) life cycle inventory analysis is the stage in which data regarding input and outputs for the product system under analysis is collected (Klöpffer and Grahl, 2014). Thus, we conducted an inventory for the farming stage, as well as, for the production and transport of feed and farm inputs for the production of milk and animal liveweight (see FAO 2016). On-farm life cycle inventory of GHG emissions followed the refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019b). Based on the IPCC guidelines, we developed a stochastic model to calculate the emissions, including uncertainty associated with activity data and emission factors (EF). Probability distribution functions selected to perform the calculations were based on Sykes et al. (2019). The inventory regarding feed consumption included pasture, silage, hay, and concentrates. The share of each feed ingredient in the diet was calculated based on animal category and animal productivity, this step was conducted with support from an expert. Feed characteristics required to perform the calculations were retrieved from Feedipedia (2020) and Valadares Filho et al. (2020). Manure management strategies were derived from default values for Latin America (IPCC, 2019c). Furthermore, the LCI for the production and transport processes of fertilizers, agrochemicals, feed, mineral salt, seeds, and electricity were retrieved from the ecoinvent® v.3.06 database (Ecoinvent, 2019). We adjusted the mentioned processes to the Brazilian electricity mix. The processes of transportation of the inputs were adjusted to represent the EURO 3 technology.

The iii) life cycle impact assessment phase is dedicated to scaling the results of the LCI into the selected impact categories (Klöpffer and Grahl, 2014). Our study follows the single issue LCA where only the carbon footprint is evaluated. To this end, we calculated the standard impact category Global Warming Potential (100-year time horizon) (GWP_{100} kg CO_2 equivalent (eq.)) (Guinée, 2002). Characterization factors applied were 28 and 30 for biogenic methane (CH_4) and fossil methane, respectively, and 265 for nitrous oxide (N_2O) (Myhre et al., 2013). Moreover, due to the uncertainties associated with long term prediction of climate change some authors have suggested the adoption of shorter time span for calculating GWP (Bartl et al., 2011). Thus, we also report our results of GWP for a 20-year time horizon (GWP_{20}). The characterization factors used for this purpose were 264, 84, 85 for N_2O, biogenic CH_4, and fossil CH_4, respectively (Myhre et al., 2013).

The iv) interpretation of the LCA results was conducted by comparing the GWP from the different farm types by conducting the Kruskal-Wallis rank sum test followed by Dunn's Kruskal-Wallis multiple comparisons. In order to verify the relationship between productivity and the CF of milk, we calculated the Spearman's rank correlation coefficient of the variable cow productivity on CF of milk.

3 Results

3.1 Farm types

The results revealed three farm typologies that were identified by applying Principal Component Analysis (PCA) and K-means clustering. Table 1 presents general characteristics for the sample and the three farm types. In total, a sample of 895 farms was analyzed and clustered. The number of lactating cows owned by the farmers in the sample was 20,411 heads, with an annual production of ~131,501 tons of FPCM. Generally, the grouping followed an ascendant pattern regarding farm structure, herd composition and milk productivity. Type 1 (T1) was composed of 520 farms, representing 58 % of the sample. T1 is mainly represented by small dairy farms of the sample. The mean number of lactating cows in T1 was 8.5 animals. Type 2 (T2) was composed of the second largest number of farms (324), representing 36 % of the sample. T2 is mainly characterized by farmers owning medium to relatively large herds, operating with a slightly higher degree of specialization when compared to T1 farmers. Type 3 (T3) clustered 53 farms, representing 6% of the sample. T3 is mostly represented by high productive farms with large herds. Despite the low number of farms in T3, they were responsible for about 51% of the milk output among the farms in the sample. T3 was followed by T2 and T1 with 39%, and 10% of the production, respectively.

Table 1. Farm characteristics for the sample and three farm types.

Variable	Unit	Sample N=895	T1 N=520	T2 N=323	T3 N=51	p.overall
Farm area	ha	58.2 (149)	38.6 (83.8)	61.0 (108)	240 (461)	<0.001
Pasture area	ha	30.6 (70.2)	23.5 (55.5)	33.8 (84.4)	83.0 (82.0)	<0.001
Lactating cows	head	22.6 (36.7)	8.56 (8.30)	26.5 (21.2)	142 (62.2)	<0.001
Lactating + dry cows	head	29.8 (44.4)	13.5 (14.9)	34.4 (28.3)	167 (74.7)	<0.001
Total animals	head	59.4 (81.5)	31.9 (40.0)	65.5 (56.1)	301 (118)	<0.001
Animal units	head (450 kg)	53.3 (79.2)	25.3 (30.6)	59.6 (49.1)	299 (130)	<0.001
Lactating cow	%	75 (19)	71 (21)	79 (0.13)	85 (9)	<0.001
Holstein	% of the herd	39 (0.41)	18 (29)	65 (38)	91 (25)	<0.001
Jersey	% of the herd	17 (0.28)	20 (31)	14 (24)	4 (15)	<0.001
Girolanda[a]	% of the herd	8 (23)	10 (26)	5 (19)	3 (15)	0.005
Swiss brown	% of the herd	1 (7)	1 (8)	1 (8)	0 (0)	0.542
Other breeds	% of the herd	35 (43)	51 (45)	14 (30)	2 (13)	<0.001
Daily production per cow	kg FPCM	12.0 (6.50)	8.44 (3.51)	15.8 (5.50)	24.8 (6.38)	<0.001
Farm production	(tonne FPCM) yr^{-1}	146.65(346.41)	24.80 (22.49)	159.52 (152.13)	1,307.59 (677.30)	<0.001
Farm liveweight gain	tonne yr^{-1}	4.39 (6.44)	2.38 (3.43)	4.68 (4.28)	23.08 (10.06)	<0.001
Price received	BR Reais (kg FPCM)$^{-1}$	0.55 (0.12)	0.54 (0.13)	0.56 (0.09)	0.67 (0.09)	<0.001
Farm income from milk[b]	%	61 (32)	56(33.5)	65(29)	78 (23)	<0.001
Farm income from animals	%	6 (17)	8 (19)	4 (13)	1 (8)	0.001

[a] Dairy cow breed developed in Brazil by cross breeding Holstein x Gir (*Bos indicus*).

Table 2 presents manager characteristics and labor information for the sample and the three farm types. Most farmers in the sample had five years or more of experience as managers. However, the T1 clustered most farmers having four years or less of experience as a milk producer, with 27% of the managers in that farm type. In contrast, these figures represent only 8% and 4% of T2 and T3 managers, respectively. Women represented less than 10% of the managers in the among farm types. Although the mean age of the managers in the sample was similar, the education level varied considerably. About 96% of the managers within T1 and T2 worked on the farm and had 4.7 and 5.9 years of formal education, respectively. For the T3, 90% of the managers also worked in the farm, and the level of education was higher 10 years. Furthermore, the average number of farmworkers among the farm types were 2.4, 3.0 and 3.2 workers for T1, T2, and T3, respectively. The T1 farms relied mostly on family labor, hiring on average only 6% of the work force, while for the T2 and T3 hired labor represented 13% and 31% of the workforce, respectively.

Table 2 Manager information, labor structure, technical assistance, and financial access.

Variable	unit	Sample N=895	T1 N=520	T2 N=323	T3 N=51	p.overall
Age of farm manager	year	50.8 (12.7)	51.3 (13.4)	49.6 (11.3)	52.1 (13.4)	0.125
Sex of the farm manager	female	69 (7.72%)	46 (8.85%)	18 (5.57%)	5 (9.80%)	0.153
	male	825 (92.3%)	474 (91.2%)	305 (94.4%)	46 (90.2%)	
Level of education of the manager	year	5.46 (3.62)	4.72 (3.07)	5.94 (3.78)	10.0 (3.98)	<0.001
Number of family workers	unit	2.41 (1.14)	2.30 (0.96)	2.62 (1.27)	2.25 (1.64)	<0.001
Number of hired workers	unit	0.28 (0.45)	0.14 (0.35)	0.39 (0.49)	0.98 (0.14)	<0.001
Total number of workers	unit	2.69 (1.14)	2.44 (0.96)	3.01 (1.21)	3.24 (1.61)	<0.001
Manager worked in the farm	no	35 (3.91%)	18 (3.46%)	12 (3.72%)	5 (9.80%)	0.097
	yes	859 (96.1%)	502 (96.5%)	311 (96.3%)	46 (90.2%)	
Received technical support	no	357 (39.9%)	288 (55.4%)	65 (20.1%)	4 (7.84%)	<0.001
	yes	537 (60.1%)	232 (44.6%)	258 (79.9%)	47 (92.2%)	
Associated at cooperative or association	no	196 (21.9%)	148 (28.5%)	46 (14.2%)	2 (3.92%)	<0.001
	yes	698 (78.1%)	372 (71.5%)	277 (85.8%)	49 (96.1%)	
Acquired external financing	no	584 (65.3%)	398 (76.5%)	172 (53.3%)	14 (27.5%)	<0.001
	yes	310 (34.7%)	122 (23.5%)	151 (46.7%)	37 (72.5%)	

The expert consultation confirmed the existence distinct farm types as indicated by our results. However, as expected some changes in the sector have occurred since the survey was conducted. Two major changes were identified. First, a series of federal regulations that came into force providing novel standards regarding milk quality, storage, and transportation (de Mendonça et al., 2020). Another aspect that has changed over past years concerns the requirement of environmental license by farms with large herds. These issues are further discussed in section (4 discussion).

3.2 Carbon footprint

Results of the Global Warming Potential, calculated based on the Life Cycle Assessment approach, displayed a significant difference (P = 0.05) between the three farm types (Fig. 3). Our results, therefore, confirmed that clustering dairy farms enable one to identify farm types producing milk with distinct carbon footprints. The T1 was characterized by a mean GWP_{100} of 3.12 kg CO_2 eq. (kg FPCM)$^{-1}$. The T2 and T3 presented mean GWP_{100} of 1.79 and 1.30 kg CO_2 eq. (kg FPCM)$^{-1}$ (Fig. 3a).

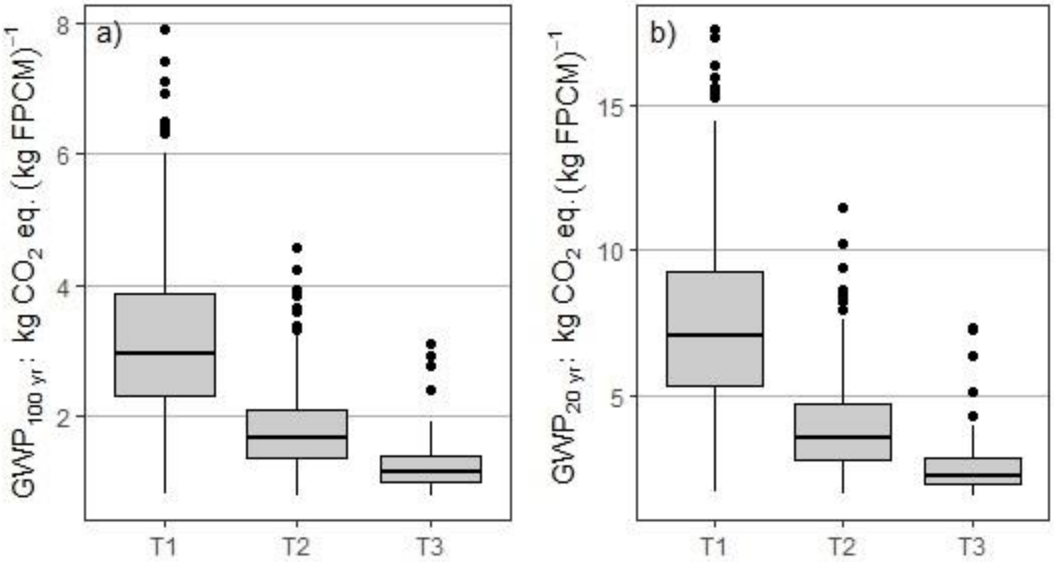

Figure 3. a): Global Warming potential 100-year time horizon (GWP_{100}); b): (GWP_{20}) for the production of one kg of Fat and Protein Corrected Milk (FPCM).

When evaluating the results based on a 20-year time horizon, the results for T1, T2, and T3 were 7.41, 3.92, and 2.69 kg CO_2 eq. (kg FPCM)$^{-1}$, respectively (Fig. 3b). The differences between GWP_{100} and GWP_{20} were driven by the higher methane conversion factors applied for calculating the GWP_{20}. Furthermore, the overall correlation between productivity and GWP was r= -0.86, confirming that the CF of milk decreases as yields increases.

The relative contribution, displayed in Fig. 4, shows that enteric methane and feed are the main contributors to the CF of milk. For the three farm types these sources represented about 87% of all emissions (Fig 4). However, it was possible to identify a reduction in the contribution of methane from 67% to 48% when moving from the less specialized farms (T1) towards more specialized ones (T3). Conversely, the contribution of feed increased from 19% to 40% of the total GWP. This shift is commonly observed in LCA of livestock and, is linked to several factors such as share of roughage in the animal’s diet, feed quality, and animal genetics (De Boer, 2003; de Léis et al., 2015; Gerber et al., 2011).

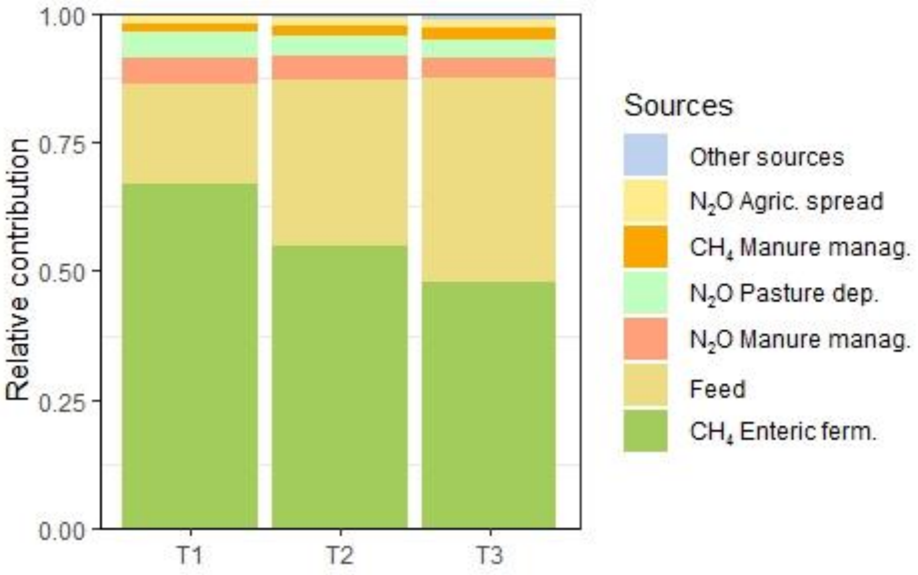

Figure 4. Relative contribution to GWP 100-year time horizon according to the origin of the emissions.

4 Discussions

4.1 Recent developments in the dairy sector in Paraná

The new regulations that came into force after the survey was conducted triggered some changes in the dairy sector in Brazil. More specifically the Normative Instructions IN 51 from 2002, the IN 62 from 2011 and the IN 76 and IN 77 from 2018 defined more stringent SCC and TBC[3] parameters at national level. These normative required that farmers adjusted themselves by adopting new production practices and improved farm infrastructure. Consequently, due to the lack of financing and managerial skills, many farmers could not comply with the requirements and deadlines and exit the activity. According to IBGE (2018), between 2006 and 2016 the total number of dairy farmers in Paraná reduced by 27%. Farms with less than 10 dairy cows decreased by 27%, while farms with 21 to 50 dairy cows decreased by 22% and farms with 101 to 200 dairy cows decreased by 20%. Nevertheless, other factors than the new regulations may have affected farmers' decision to abandon the activity, e.g., market constraints (Beber et al., 2018) and lack of a successor (Bánkuti et al., 2018).

Furthermore, farmers that informally processed their milk into dairy products (e.g., cheese, butter, and *requeijão*[4]) also had to adapt. The informal market in Paraná corresponded to 16% of the volumes produced in 2016, while in 2006 it represented 23% of the volumes produced (IBGE, 2017). Intensification of inspections on milk manufacturing increased in recent years putting pressure on farmers operating without a formal license, which had to formalize their business in order to remain operative. In addition to pay for inspection services, many farmers had to improve their manufacturing facilities to comply with quality and sanitary standards. Such improvements required financing and technical supervision, which in most cases were not available. Consequently, farmers in this situation either abandoned the activity or remained working clandestinely, subject to the risk of being penalized.

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[3] Since 2018 these figures are 300.000 CFU/ml for total bacterial count (TBC) and 500.000 SC/ml for somatic cell count (SCC).

[4] A sort of cream-cheese widely consumed in Brazil

Regulations regarding manure management came into force in 2018 in Paraná. Farmers operating intensive systems with herds larger than 80 animals, and semi-intensive with herds larger than 180 animals, must apply for an environmental license in order to operate (IAP, 2018). To be eligible to receive this license, the farm must comply with practices and parameters for proper waste storage and destination (e.g., use coated storage systems if manure is handled in liquid form). The regulation covers issues related to manure leaching, runoff, and discharge in water bodies; but it makes no mention of actions to reduce GHG emissions during waste management. Moreover, by setting these numbers of animals as the threshold for demanding an environmental license, the regulation does not cover the great majority of dairy farms in Paraná. Even small dairy farms can accumulate a significant amount of waste over time (e.g., washing-water, feed waste, bedding material, and manure). Besides the non-obligation to comply with this regulation, such farmers may be unaware of the problems manure can generate; and generally, do not receive any training on managing farm waste. This licensing obligation to large farms might have had the effect of reducing the CF of farms categorized in the T3, consequently increasing its CF gap in respect to T1 and T2 from the time the data was collected to nowadays.

Despite the above-mentioned changes, on average, farm and herd structures across farms have not suffered considerable changes compared to our sample. Farms with high productivity and low CF, as those characterizing T3, are still the exception in the Brazilian dairy sector (de Léis et al., 2015; IBGE, 2019). Most dairy farms in Paraná, as those characterizing T1 and T2, still operate with a low or medium technological level and display low productivity compared to the potential that can be reached in the region (Bánkuti et al., 2018; IBGE, 2018). For example, the average annual milk production per cow in this state was around 3.7 t in 2017 (IBGE, 2018). This value was below the average of the T2 (4.78 t) [5], and nearly a half of the amount produced by T3 (7.35 t) in our sample from 2007, indicating the persistence of low productivity in this state. Furthermore, given the actual annual milk production per cow at national level (~ 2.6 t), we can deduce that the other states of the country are in a

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[5] Estimated annual production was calculated assuming a lactation period of 305 days.

similar or even worse situation than Paraná. With this, despite the year of the data collection, our analysis provides relevant insights into the structure and CF of dairy farms in Paraná and Brazil, which was also confirmed by the interviewed expert. Furthermore, it is important to stress that the heterogeneity of farms from such a large sample also indicates the existence of farms in different stages of structural and managerial development. Today, in Paraná and in Brazil, it is still possible to find producing farms from the most rudimental to the most high-tech, which is a typical characteristic of an emerging economy. Therefore, the farm types resulted from the clustering and their attributed CF, brings valid and insightful reflections for the dairy farming of several other countries where farms and farmers are found in similar development stages to the ones in our sample.

4.2 Carbon Footprint and mitigation strategies

The LCA results unveiled the CF of two types of farms that have been underexplored in Brazilian conditions. Namely, the T1 and T2, which are the most representative types for dairy producers in Paraná and Brazil (Bánkuti et al., 2018; IBGE, 2018). By comparing our results with other studies, we identified that the mean CF found for the T1 (3.12 kg CO_2 eq. (kg FPCM)$^{-1}$) was above the global average of 2.7 kg CO_2 eq. (kg Milk)$^{-1}$ reported by Gerber et al. (2013). However, it was below the values for milk production in Asia (5.5 kg CO_2 eq. (kg Milk)$^{-1}$) (Gerber et al., 2013); and in the Peruvian highlands (5.42 kg CO_2 eq. (kg energy corrected milk-ECM[6])$^{-1}$) (Bartl et al., 2011). The results for the T2 (1.79 kg CO_2 eq. (kg FPCM)-1) were slightly above the values identified for costal systems in Peru (1.74 kg CO_2 eq. (kg ECM)$^{-1}$) (Bartl et al., 2011). T2 also presented values above the upper range limits found for pasture based systems in Ireland (1.74 kg CO_2 eq. (kg ECM)$^{-1}$) (O'Brien et al., 2016). Most farms belonging to the T3 could be compared to dairy farms from developed countries. Thus, not surprisingly, the average CF for the T3 (1.30 kg CO_2 eq. (kg FPCM)$^{-}$1) was also within the range of several OECD countries (Gerber et al., 2013; O'Brien et al., 2016; Thomassen et al., 2008). However,

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[6] kg of energy corrected milk (ECM) is another common functional unit applied in milk LCAs. For our general discussion we did not scale the results, however, significative differences may emerge in detailed comparisons, see (Schüler and Paulsen, 2019).

our results are still higher than previously CF reported for very intensive systems in developed countries and southern Brazil. In a case study in Brazil, de Léis et al. (2015) reported mean values of 0.776, 1.065, and 1.013 kg CO_2 eq. (kg ECM)$^{-1}$ when comparing milk production in confined, semi-confined and pasture-based systems respectively. Likewise, Ribeiro-Filho et al. (2020) reported average values of 1.06 kg CO_2 eq. (kg ECM)$^{-1}$ for high productive systems in southern Brazil.

The diversity of structure and practices among the three types of farms identified in our study indicates the necessity of different approaches to mitigate GHG emissions from dairy cattle. The fact that farms operating with high productivity display lower CF suggests that increasing the productivity of low-yield farms has a great potential to mitigate emissions in Paraná. Increasing the productivity while reducing GHG intensity of dairy farms depends on a series of strategies which should be applied under a sustainable intensification framework (Gerber et al., 2013; Herrero et al., 2016; IPCC, 2019a). More especially, these strategies focus on actions to increase animal and herd performance, improve feed production and feeding management, optimize waste management, and to increase energy efficiency (Gerber et al., 2011; Herrero et al., 2016). The range of mitigation options available for specialized farms operating with already low GHG intensity is evidently more limited. However, due to the size of such operations, small improvements can result in high absolute reductions. Conversely, options to improve the CF of smaller and less specialized farms operating with higher CF intensity are wider. In the following, we present such strategies and discuss their practical implementation among the three farm types.

4.2.1 Herd management

The adoption of appropriate dairy breeds and herd management is an important step to increase the productivity of the herd and reduce GHG emissions. However, despite producing less milk, less specialized animals may bring advantages to small-holders belonging to T1. Many farmers opt for mixed breed herds to produce milk and beef in order to diversify their sources of income and reduce the risks of running a specialized dairy farm. Even in this structure, strategies to speed up backgrounding and fattening of beef animals can reduce the overall CF of the farm (Gerber et al., 2013). Other advantages of owning mixed breed animals are the resistance against diseases, better response to low-quality pastures and co-products feedstuffs, and lower immobilization of capital in animals. In turn, owning non-specialized mixed breed animals also demands less operation management capacity from farmers.

In addition to a suitable breed, optimizing herd structure and reproductive performance of the dairy cows and heifers is a key strategy to the improve the efficiency of dairy farms and consequently reducing GHG. The most important actions in this field are the reduction of calving interval, enhancement of fecundity, and expanding the productive life of the cows. Additionally, the use of Artificial Insemination (AI) is an effective strategy to improve productivity and reduce GHG intensity of dairy farms (Gerber et al., 2013; Herrero et al., 2016). Herds with a small number of cows normally have underutilized bulls that require feed, space, and health care; which increases the GHG emissions of the herd. The adoption of natural mating is a common practice among less specialized farms in Paraná. By owning a bull, farmers do not need to detect the best moment to inseminate the cows (i.e., no need for estrus detection), which requires specific training. Farmers also do not need to rely on professionals to perform the AI. Large distances and the scarcity of dairy specialized technicians may difficult for the available technicians to schedule their visits with the best moment to apply the AI. In some cases, the IA shot may also have a charge that can be seen as costly by farmers. Furthermore, proper health management is indispensable to reduce mortality rates, undesirable culling, and consequently GHG intensity of dairy herds (Gerber et al., 2013; O’Brien et al., 2014).

4.2.2 Feed and pasture management

Feed management is a cornerstone of dairy farms and has a large potential to reduce GHG emissions. Feeding animals all year-round with balanced diets based on high digestibility ingredients is important to explore the maximum production potential of dairy cows and reduce methane emissions from enteric fermentation (Herrero et al., 2016). However, feeding a dairy herd with a balanced diet is not an easy task and is among the challenges to be faced by small dairy producers in Paraná. It depends on several factors such as knowledge of nutrition, financial capital, production system, and the farm's feed production capacity in terms of area, soil, topography, and weather conditions. The majority of dairy farms in the region rely partially or entirely on grazing to provide animals with the necessary roughage. Thus, improving pasture management is an important strategy to be implemented in among low-performance dairy farms (Gerber et al., 2013; IPCC, 2019a). Sowing pastures with good nutritional quality grasses and the adoption of rotational grazing are among the simplest practices that can be implemented by less specialized producers.

Furthermore, farmers owning natural pastures can significantly improve their productivity and quality by sowing leguminous plants and winter grazes (Ruviaro et al., 2015). More recently, the modernization of crop-livestock-forestry integration systems in Brazil has also provided an excellent alternative to improve pasture and consequently the productivity and income of dairy farms (Bungenstab et al., 2019). Beyond providing good quality forage for animals, well-managed pastures can store carbon and preserve regional biodiversity (IPCC, 2019a). However, in regions where a dry season occurs, which in Paraná is from May to July, maintaining good pastures year-round is difficult without the support of irrigation and fertilization. Thus, the production of conserved forages such as silage and hay is relevant to complement the diet of the animals during the dry season.

The inclusion of concentrated and feed supplements in the ration is crucial to fulfil the nutritional requirements of dairy cows, increasing milk productivity and reducing methane emissions from enteric fermentation (Gerber et al., 2013). Nevertheless, this strategy depends on land availability to produce feedstuffs or financial resources to purchase it, which might difficult the adoption by small-farmers. In addition, the use of co-products in the ration of dairy cattle has advantages to farmers and the environment. It has favorable cost-effectiveness for farmers and normally presents low CF. The use of co-products also reduces the demand for land to produce feed, and contributes to the circular economy (Van Zanten et al., 2019). When using co-products, however, farmers must adjust the diet of the animals accordingly. Besides, if the co-product has low-digestibility, e.g., straw, on-farm emissions from enteric fermentation are likely to increase. Avoiding wastage of feedstuffs is another strategy to reduce emissions from dairy systems. Wastage should be avoided across all the supply chain, e.g., production, transportation, storage, and feeding. Depending on the level of management and feed storage systems, forage loses can reach up to 30% (FAO, 2017).

Farmers operating intensive systems tend to have adequate feed management strategies. In these cases, animals stay housed year-round and all feed must be provided in-house in the form of roughages, concentrates, protein supplements, minerals, and vitamins. Feeding can then be optimized for each animal according to its physiological and productive stage (e.g., calves, heifers, lactating cows, and dry cows). Problems often associated with zero-grazing systems are the high GHG intensity for the production and transportation of feedstuffs (O'Brien et al., 2015; Ruviaro et al., 2020), and the high capital costs of facilities and machinery. The integration of grazing in the diet of high productive animals could be a feasible option to reduce this problem in southern Brazil, a region that can produce high quality pasture all year-round (Ribeiro-Filho et al., 2020). Further feed management strategies that specialized farmers can apply includes the development of precision-feeding and the use of feed additives to reduce enteric methane production (Gerber et al., 2013).

4.2.3 Waste management

In pasture-based farms an expressive share of the manure is deposited directly on pastures, but it can also accumulate on the collecting yard and milking area. If not properly handled this effluent can leach and runoff into water bodies during the rainy season. Thus, regardless of the herd size or production system, selecting an appropriate storage system can reduce substantially absolute on-farm emissions from waste (IPCC, 2019c). Farmers that already own waste storage systems can adopt a series of practices to reduce emissions, for example, by decreasing storage time, covering piles in solid storage systems, or applying aeration in liquid storage systems (Gerber et al., 2013; Herrero et al., 2016). The adoption of anaerobic digestion systems is an effective technology to treat waste and recover energy in dairy farms. The implementation of this technology has been supported by the Low Carbon Agriculture Plan (ABC)[7], but adoption is still low among dairy farms in Paraná because of the high costs and restricted access to information and trained personnel. The State registered 66 digesters in 2019, most of them installed in pig farms (CiBiogas, 2021).

5 Policy implications and future research

Future development and expansion of the dairy sector in Brazil will inevitably pass through the path of production intensification. Thus, developing a framework based on sustainable intensification of the dairy farms in the country will be essential for achieving mitigation targets in the livestock sector. However, sustainable intensification based only on actions to reduce GHG intensity, by increasing yields with less inputs, are often criticized for being narrow framed (Clay et al., 2020; Garrett et al., 2018). Similar to traditional intensification programs, it may also lead to non-inclusive socioeconomic development and animal welfare issues (Clay et al., 2020; IPCC, 2019a). The Low Carbon Agriculture Plan (ABC) from the Brazilian Government has yielded some astonishing results in the development of integrated production systems, such as crop-livestock, crop-livestock-forestry integration, and agroforestry (Bungenstab et al., 2019; Costa et al., 2018; de Moraes et al., 2014; Martinelli et al., 2019). Most actions sponsored by the ABC plan can provide farmers with environmental and economic benefits (Costa et al., 2018; Pashaei Kamali et al., 2016). Yet, the low rate of adoption among farmers indicates that the next generation of Low Carbon Agriculture in Brazil should go beyond credit subsidies and actions at farm-plot level (Cortner et al., 2019). Given the heterogeneity of farming systems in Brazil and the concentration of small-holders farmers in some sectors, climate policies in the country should consider a transition within a broader process of socio-environmental change in rural areas (Clay et al., 2020; IPCC, 2019a).

The provision of adequate extension services and training to all farmers is an initial fundamental step to implement sustainable intensification strategies (Gerber et al., 2013). Extension services can facilitate the

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[7] GHG reduction strategies in the Brazilian agricultural sector have been guided by the Low Carbon Agriculture Plan (ABC) (Brasil, 2012; Bungenstab et al., 2019).

diffusion of knowledge and technologies at the farm level. Thus, qualifying extensionists in sustainable production practices is a key action to promote the development of the dairy sector in Paraná and Brazil. Extensionists should be trained and provided with tools to support farmers that are willing to implement changes. For instance, extensionists should be able to support farmers in selecting sustainable production systems that are in accordance with farmer's beliefs and intentions (e.g., traditional, integrated, multifunctional, or agroecological systems). Systems which are the best adapted to their socioeconomic and pedoclimatic conditions. Although decisions must be taken by farmers themselves, extensionists must also be able to guide farmers through the production process, for example in adjusting the scale of their operations, in selecting appropriate breeds, in drawing the feeding management strategy and in the development of sanitary and reproductive controls. Embrapa[8] has developed a successful program (Full Bucket project) that focuses on the creation of demonstration dairy farms and in training extensionists and technicians across the country (Novo et al., 2013). Expanding this program and making it accessible to a larger number of extensionists and farmers is crucial for developing the dairy industry in Brazil.

Production technologies and technical knowledge available in Brazil already allow the ambitious and financially capable producer to build intensive dairy operations similar to those in the developed countries, with high productivity and low carbon footprint (de Léis et al., 2015; Ribeiro-Filho et al., 2020). Nevertheless, research in Brazil should strive to determine which systems and level of intensification are more sustainable for the country's condition. Such studies should take a broader view of the farming systems, accounting for issues such as animal welfare, farm ecosystem services as well as economic development and climate change adaptation strategies. Improving production based on the circularity concept is another emerging field in the livestock sector that also desires more research in the Brazilian context (Van Zanten et al., 2019). Integrated crop-livestock, crop-livestock-forestry systems and agroecological systems could offer improvements in this direction. Optimizing

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[8] Brazilian Agricultural Research Corporation

semi-intensive systems in southern Brazil might offer an interesting strategy to reduce the CF of milk while avoiding problems from the super-intensive systems (e.g., animal welfare issues, reliance on off-farm sources of feed, and consumer acceptance) (Hennessy et al., 2020; Ruviaro et al., 2020).

Moreover, southern Brazil has a great potential to develop sustainable intensified pasture-based systems. The region lies in a subtropical climatic zone with favorable conditions to grow annual tropical and temperate pastures as well as perennial pastures with good nutritional quality (Alvares et al., 2013; Ribeiro-Filho et al., 2020). Adoption of a intensified pasture-based system can reduce costs of feed and improve the profitability of dairy farms while promoting a reduction in GHG intensity (O'Brien et al., 2015; Ruviaro et al., 2020). Stanley et al. (2018) also show that pasture-based systems can provide significant reduction of GHG emission through soil carbon sequestration, which is generally not accounted in LCA studies. In Brazil, Embrapa is also conducting studies in this direction (Embrapa, 2018). The development of certified pasture-based milk production in Brazil can support this strategy. Research institutes and processing companies should foster such project, which could be especially interesting for cooperatives that attend small and medium-size farms as a market strategy of product differentiation. Similar to the developments achieved by the Carbon Neutral Brazilian Beef project (see, Alves et al., 2017) dairy farmers would, in this case, receive a premium price to produce milk within a sustainable framework. Besides, the dairy industry could benefit by adding value to their products and promoting fair social and green marketing.

Regardless of the size of the operation in commercial dairy farms, profitability is one of the most relevant determinants for the adoption of new technologies and management practices. Most intensification technologies can also promote higher returns in the short to mid-term. Thus, expanding financial credit to a wider range of dairy farmers, and promoting a business environment in which farmers are keen on taking the initial risks is also necessary to expand the adoption of new technologies (Gerber et al., 2013). Improving education, training and access to quality information makes producers feel more confident and willing to take higher risks. The provision of credit is one of the main strategies of the ABC plan (Brasil, 2012), for which the low rate of adoption is one of the factors responsible for the moderate success of the program. Increasing awareness of farmers to the options available is necessary; especially farmers that do not receive any technical assistance are less likely to be aware of governmental programs and credit possibilities.

The milk sector is in constant development in Brazil and Paraná, but it is generally not considered competitive if compared to other agricultural supply chains in the country (e.g., beef and grains) (Beber et al., 2019). Private processing companies and cooperatives operating in Southern Brazil are facing several challenges in order to maintain their business operations. While new international companies started operations in the region, others less competitive were merged or dissolved (Beber et al., 2018). This rather unstable market environment may hinder farmers' decision to invest in new technologies and thus, spoiling any attempt to promote climate friendly practices and policies. Consequently, this is also delaying the socioeconomic development in the region, where more than 87 thousand farms produce milk, corresponding to approximately 28,5% of the farms in Paraná. Developing regional environmental governance frameworks may be required to develop the supply chain in Paraná and grant access to international markets and global value chains. Government, business, and civil society need to provide a clear direction (and the necessary resources) to farmers on which pathways to follow in order to develop a sustainable agri-food system. In this regard, it is paramount to recognize the heterogeneity among farms and farmers and the provision of an adequate socioeconomic environment, where each dairy farmer could thrive. This can be achieved through stable market conditions and fair prices, as well as resources to farmers willing to process and market their own milk. Public research and extension/advisory services should be expanded in the region, since technicians supported by the processing sector tend to focus only on issues related to productivity and milk quality. Lastly, the country should be prepared to provide meaningful alternatives to farmers and businesses that will not cope with challenges ahead and, eventually, leave the production chain.

6 Concluding remarks

Tackling climate change is a matter of priority in the livestock sector. Nevertheless, guiding best management strategies in practice are sometimes blurred by the lack of information regarding regional characteristics of heterogeneous farming systems. In the present study, we integrate multivariate statistical analysis and expert knowledge to create a typology of dairy farms and explore their carbon footprint. Our approach identified three farm types showing distinct characteristics and as expected, the farms also displayed significant differences in the Global Warming Potential comparison. Detailed analysis of the results indicated that farms operating with higher CF represented the majority of the dairy farms in Paraná. On average, they were likely to have less specialized herds with lower productivity, received less technical support, and owned less farm machinery and infrastructure when compared to farms that displayed lower CF. This suggests that high CF is only one of the problems of most farmers operating in the region. The reduction of CF in the dairy sector in this region will largely depend on sustainable intensification of the production. This must, however, be integrated into a broader framework of regional environmental governance and socioeconomic development of the entire agricultural sector.

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