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REGULAR ARTICLES

Milk carbon footprint of silvopastoral dairy systems in the Northern Peruvian Amazon

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Abstract
The objective of this study was to estimate the carbon footprint (CF) of milk production (in kg of CO_2 equivalents (CO_2e) per kg of fat and protein corrected milk (FPCM)) in dairy farms of the San Martín region, in the Peruvian Amazon. A cradle-to-farm gate characterization and analysis were carried out on eight representative dairy farms. Greenhouse gas (GHG) emissions were estimated using equations, following the 2019 refinement of the 2006 IPCC Guidelines. The results showed an average milk production of 9.7 ± 0.82 L milk/cow/day, Gyr x Holstein crosses as the predominant breed, use of cultivated grasses such as *Brachiaria brizantha*, living fences (*Guazuma ulmifolia* Lam) as the predominant silvopastoral arrangement, and low level of external inputs such as feed or grain additives. In relation to CF, an average value of 2.26 ± 0.49 kg CO_2e/kg FPCM was obtained, with enteric fermentation being the most important source (1.81 ± 0.51 kg CO_2e/kg FPCM), followed by manure management, land use, and energy/transport (0.26 ± 0.06, 0.14 ± 0.04, and 0.05 ± 0.04 kg CO_2e/kg FPCM, respectively). Differences were found between farmers, obtaining lower CF values (1.76 vs 3.09 kg CO_2e/kg FPCM) on farms with better feed quality, higher production levels, and a higher percentage of lactating animals compared to dry cows. It is concluded that dairy farms in the Peruvian Amazon region can reduce their emissions if they improve their current feeding practices.

Keywords Carbon dioxide · Dairy cattle · Grazing systems · Life cycle assessment · Methane · Nitrous oxide

Introduction

Globally, beef and milk production from cattle contributes 41% and 29% of greenhouse gas (GHG) emissions from the livestock sector, respectively (Gerber et al. 2013). In Latin America, the main sources of GHG emissions are from land use, land use change, and forestry (35%) and agriculture (23%) (Wellenstein and Hickey 2021). In this context, one sustainable production alternative is the implementation and expansion of silvopastoral systems (SPS). GHG emissions can be reduced in SPS versus conventional grazing systems; hence, lower environmental burdens per product are generated (Rivera et al. 2016; Murgueitio et al. 2012).

Silvopastoral systems contribute to reduce deforestation, furnish a diversified source of income to farmers, provide ecosystem services (water, carbon sequestration, nutrient recycling, biodiversity), increase welfare and animal production, as well as quality of pastures, and contribute to mitigate GHG emissions (Alonso 2011; Fernández 2008; Alegre et al. 2012; Fluker et al. 2016; Montagnini et al. 2013; Pérez et al. 2005; Pezo et al. 2019; Pizarro et al. 2019).

Livestock in Peru is characterized by small-scale productions (< 10 head of cattle), which represent 85.9% of the total nationally. Additionally, 39.4% of the national milk production comes from these cattle herds (MINAGRI 2017). In the same way, the Peruvian Amazon is characterized by dairy cattle productions under SPS as "living fences" and "scattered trees in pastures" (Pizarro et al. 2019). However, the environmental impact from this type of system is unknown.

Carbon footprint (CF) is an environmental impact indicator, which estimates direct and indirect GHG emissions generated and emitted into the atmosphere during the life cycle of a product along the production chain (Vistoso et al. 2015). It is normally expressed in kg of CO_2 equivalent (CO_2e) per kg of product (IPCC 2019a). Some methodologies used for its evaluation are as follows: ISO 14040, 14044, 14067, PAS 2050, GHG Protocol, IDF Common Carbon Footprint

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methodology (IDF 2015). It is crucial to know the CF value for the implementation of mitigation strategies (Mainar 2019).

Therefore, the objective of this study was to estimate the CF of milk production (kg CO_2e/kg of FPCM) on silvopastoral dairy systems in the Peruvian Amazon.

Materials and methods

Study location

The study was carried out on eight farms in Juan Guerra, San Martín, Peru. Juan Guerra is located at 230 m above sea level, latitude 6° 35′ West, longitude 76° 19′ South. San Martin region is characterized by farms dedicated to milk production (32,697 t/year) and beef (5443 t/year) (MIDAGRI 2020). The Juan Guerra district has a semi-dry and warm climate, a tropical dry forest ecosystem, an average temperature of 26.2 °C, and an annual rainfall of 1213 mm (IDERSAM 2016).

Carbon footprint analysis

The methodology used was described by the methodological guide of the International Dairy Federation (IDF) 479/2015, which uses the methodological structure of ISO 14040, 14044, 14067 standards, PAS 2050, and GHG Protocol (IDF 2015). This study used the life cycle analysis (LCA) methodology from "cradle to farm gate" to estimate and describe the carbon footprint of milk production for each of the 8 farms evaluated. The LCA steps followed for its calculation are detailed below.

Goal and scope

System limits Figure 1 shows the incomes and outcomes from the system. GHG emissions such as methane, nitrous oxide, and carbon dioxide produced from "cradle to farm gate" were estimated.

Functional unit A total of 1 kg FPCM and 1 kg of beef were used as functional units. For these estimates, equations provided by the IDF (2015) were used.

$$\text{FPCM (kg/year)} = \text{production (kg/year)} \times \left[0.1226 \times \text{milk fat \%} + 0.0776 \times \text{milk protein \%} + 0.2534\right]$$

Allocation The economic allocation was carried out following the equation given by Thoma et al. (2013), considering 4% fat and 3.5% protein. The mass allocation was based on FPCM (kg) and beef (kg) from surplus animals produced per year.

Data collection and feed samples

The data collected came from surveys conducted on eight farms located in the Juan Guerra district. The province and district were selected following the Qualitative Factors Assessment Methodology. It was a non-probabilistic selection. Also, the principal criteria to include farms was the farmer's availability to work with the researchers, with at least 10 to 20% trees in the grazing area, milk production as the leading activity (60% milking cows), similar edaphic and environmental characteristics, and accessibility to make easer the sampling.

The survey consisted of questions at the farm level: landowner name, farm name, area (for crops, pastures (native

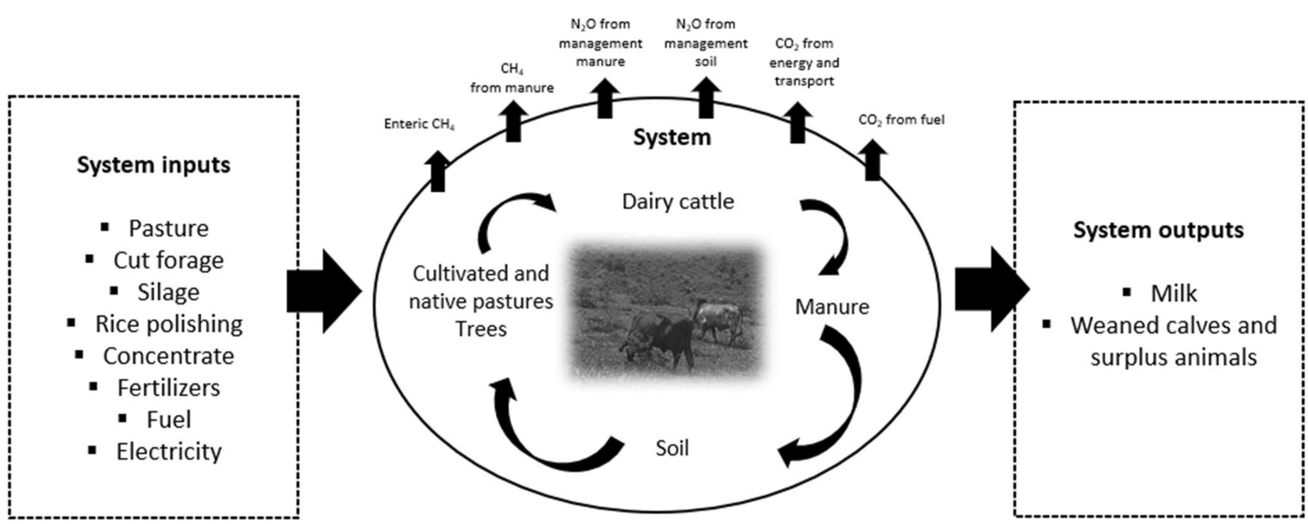

Fig. 1 Limits of milk production system for each dairy farm in a "cradle to farm gate" approach in the San Martín region

and/or cultivated), forage bank, primary forest, secondary forest, and infrastructure), type of silvopastoral arrangements, and predominant tree species. At the livestock level: herd composition (number of animals per category), predominant genotype (%), milk production (kg/cow/day), feed inputs, fertilizers, machinery, fuel, energy, manure management, and hours of grazing.

Subsequently, pasture and feed samples provided to animals were taken from each farm for each period of the year (rainy and dry season). The grass samples consisted mainly of *Brachiaria brizantha*, using the "hand sampling" methodology (Flores 1983; Austin et al. 1983).

Greenhouse gas estimation

The CF estimation was performed using the refined equations given by the Intergovernmental Panel on Climate Change (IPCC 2019b, c). The global warming potentials (GWP) used were the following: 28 for methane, 265 for nitrous oxide, and 1 for carbon dioxide for a time horizon of 100 years (IPCC 2014). Microsoft Excel 2019 was used for the calculations. Table 1 details emission sources and equations used for their estimation.

Data analysis

This study used a descriptive statistical analysis such as medium and standard error.

Results

Characterization of the farms

The main characteristics of the eight farms (F1–F8) are in Table 2. The average area was 51.5 ± 26 ha, and 30.1 ha of these was used for grazing. The average tree cover was 22.5%. The total size of dairy cows was 32 ± 6.3, of which

Table 1 Emission sources and equations used to calculate carbon footprint from each farm evaluated in the San Martín region

Source	Equations	Result	GWP[a]
Enteric methane	10.3, 10.4, 10.6, 10.8, 10.13, 10.14, 10.15, 10.16, 10.21 (IPCC 2019b, c)	kg CH_4/year	28 (IPCC 2014)
Manure methane	10.23, 10.24 (IPCC 2019b, c)	kg CH_4/year	28 (IPCC 2014)
Nitrous oxide from manure management	10.25, 10.28, 10.29, 10.31, 10.32, 10.33 (IPCC 2019b, c)	kg N_2O/year	265 (IPCC 2014)
Nitrous oxide from soil management	11.1, 11.9, 11.10, (IPCC 2019b, c)	kg N_2O/year	265 (IPCC 2014)
Carbon dioxide from energy, fuel, and transport	3.2.1 (IPCC 2006), Ecoinvent (2010)	kg CO_2/year	1 (IPCC 2014)

[a]*GWP* global warming potential

Table 2 Overall characteristics from each farm evaluated in the San Martín region

Items	Farms							
	F1[a]	F2[b]	F3[c]	F4[d]	F5[e]	F6[f]	F7[g]	F8[h]
Surface, ha	54.0	44.0	88.6	22.5	22.5	29.0	90.0	53.5
Silvopastoralism (trees), %	31.4	33.2	24.3	37.2	37.2	12.9	15.2	16.3
Crops, ha	2.0	6.0	2.0	0.4	0.4	0.3	1.5	1.0
Pasture, ha	23.0	25.0	60.0	19.0	19.0	24.0	35.0	33.0
Average milk production, L/cow/day	10.1	9.3	9.5	9.8	9.8	11.3	10.0	8.6
Average production FPCM, kg/cow/day	10.6	9.7	9.9	10.2	10.2	11.8	10.5	9.0
Total, animals, #	56	54	97	96	96	79	37	56
Milking cows, #	17	14	18	22	22	32	13	15
Dry cows, #	11	11	15	20	20	14	11	4
Replacements, #	17	23	50	30	30	19	9	26
Bulls (reproductive male), #	2	1	2	1	0	2	1	1
Beef, #	9	5	12	24	24	12	3	10
Cull cows, #	3	3	3	4	4	5	2	2

[a]Farm 1, [b]farm 2, [c]farm 3, [d]farm 4, [e]farm 5, [f]farm 6, [g]farm 7, [h]farm 8

19 ± 6.2 were in the lactating stage. An average number of replacements and remnant animals (calves and bulls) were 30 and 13, respectively. Each farm owned one male breeder since natural breeding predominates (Table 2).

The average milk production was 9.7 ± 0.82 L of milk/cow/day (Table 2). Gyr x Holstein crosses were the predominant breed on farms evaluated. In regard to the grazing area, the main cultivated pasture was *Brachiaria brizantha* and living fences with *Guazuma ulmifolia* Lam leading was the main silvopastoral system arrangement. In addition, external inputs such as feed additives or cereals were used in negligible quantity. Finally, it should be highlighted that none of the farms used synthetic fertilizers into the pasture.

Greenhouse gas emissions

The major source of emissions was enteric CH_4 (80%), followed by N_2O from manure handling (10%). CH_4 emissions from milking cows were 312 ± 32 g CH_4/cow/day. Meanwhile, CO_2 emissions from fuel only represented 2% of total emissions. Only farms 2, 4, and 5 showed CO_2 emissions from the use of electrical energy because the remaining used solar panels (Table 3).

Greenhouse gas allocation

When a mass assignment was used, the average GHG emissions were 2.26 kg CO_2e/kg FPCM in a range of 1.76 to 3.09 kg CO_2e/kg FPCM (Table 3).

Regarding economic allocation, the allocation factor (AF) for milk was higher than the AF for meat (0.75 vs 0.25). The results showed an average value of 1.68 ± 0.41 kg CO_2e kg/FPCM; enteric fermentation was the most important source with 1.34 ± 0.34 kg CO_2e/kg FPCM, followed by manure management (0.19 ± 0.04 kg CO_2e/kg FPCM), land use (0.11 ± 0.03 kg CO_2e kg/FPCM), and energy/transport (0.04 ± 0.03 kg CO_2e/kg FPCM) (Table 4). Numerical differences were found between farmers, obtaining lower CF values (1.12 vs 2.38 kg CO_2e/kg FPCM) on farms with improved food quality (high digestibility and protein in the diet), larger production levels, and a higher percentage of lactating animals compared to dry cows.

Discussion

Greenhouse gas emissions

The proportion of enteric CH_4 emissions was similar to Rivera et al. (2016), who reported that CH_4 represented up to 84% of the GHG for an intensive SPS (SPSi) of milk production in Colombia. However, it is greater than reported by Morais et al. (2018) in pastoral dairy farms in Portugal, with an emission range of 33 to 52%. Similarly, it is larger than emitted by pastoral dairy systems in New Zealand (62%) (Flysjö et al. 2011). In the same way, comparing with non-pastoral systems, the results of this study were higher to that reported by Flysjö et al. (2011) in Sweden for semi-stable systems, where the enteric CH_4 emission represented 46%.

Regarding N_2O emissions, this study estimated higher emissions (16%) than reported by Rivera et al. (2016) in Colombia, who estimated that 12% of total emissions inside farms with SPSi were for N_2O (related to chemical and organic fertilizers, N excretions via manure and urine). Nonetheless, they are lower than those found in a Brazil study, where manure emissions and excrement deposited into the field represented between 20 and 33% (including the use of fertilizers, lime, and pesticides) (Cerri et al. 2015).

Finally, regarding CO_2 emissions from energy use and transportation, this study obtained lower values (2%) than Rivera et al. (2016), who found an emission of 4% for CO_2 in farms with SPSi, although the results observed on this study are inside the range observed by Cerri et al. (2015), who calculated those emissions from agricultural inputs, fossil fuels, and electricity that ranged from 1 to 11%.

Table 3 Emission sources in kg of CO_2e for each farm evaluated in the San Martín region

Emission sources	kg of CO_2e/farm/year								Average	Standard error
	F1[a]	F2[b]	F3[c]	F4[d]	F5[e]	F6[f]	F7[g]	F8[h]		
Enteric methane	100,672	87,416	163,043	172,160	196,465	70,215	77,998	110,906	122,359	48.5
Manure methane	2,965	2,309	4,234	5,419	5,607	1,851	2,048	2,038	3,309	9.6
Nitrous oxide from manure handling	12,196	9,189	17,943	21,127	20,141	9,177	12,934	10,965	14,209	14.3
Nitrous oxide from soil management	7,108	5,653	11,353	12,448	13,119	5,349	8,184	10,648	9,233	11.3
Carbon dioxide from fuel	1,742	3,408	5,117	210	6,518	547	1,371	4,201	2,889	15.0
Carbon dioxide from energy	0	1,208	0	1,733	2,114	0	0	0	632	12.7
Total CO_2e emissions	124,683	109,182	201,689	213,096	243,964	87,139	102,535	138,759		
kg CO_2e/kg [i]FPCM	1.9	2.2	3.09	2.59	1.77	1.76	2.08	2.71		

[a]Farm 1, [b]farm 2, [c]farm 3, [d]farm 4, [e]farm 5, [f]farm 6, [g]farm 7, [h]farm 8, [i]kg of milk corrected to 4% fat and 3.5% protein

Table 4 Greenhouse gas emissions per unit of product (FPCM and meat) according to emission sources for each farm evaluated in the San Martín region

FINCAS	Enteric CH_4/kg FPCM[i]	Manure CH_4/kg FPCM	N_2O from manure handling/kg FPCM	N_2O from soil management/kg FPCM	CO_2 from fuel/kg FPCM	CO_2 from energy/kg FPCM	kg CO_2e/kg FPCM
F1[a]	1.24	0.04	0.15	0.09	0.02	0	1.54
F2[b]	1.08	0.03	0.11	0.07	0.04	0.01	1.35
F3[c]	1.93	0.05	0.21	0.13	0.06	0	2.38
F4[d]	1.56	0.05	0.19	0.11	0	0.02	1.93
F5[e]	1.29	0.04	0.13	0.09	0.04	0.01	1.6
F6[f]	1.2	0.03	0.16	0.09	0.01	0	1.49
F7[g]	0.85	0.02	0.14	0.09	0.01	0	1.12
F8[h]	1.6	0.03	0.16	0.17	0.06	0	2.02
Average	1.34	0.04	0.16	0.11	0.03	0.01	1.68
Standard error	0.10	0.02	0.03	0.03	0.05	0.04	
FINCAS	Enteric CH_4/kg beef	Manure CH_4/kg beef	N_2O from manure handling/kg beef	N_2O from soil management/kg beef	CO_2 from fuel/kg beef	CO_2 from energy/kg beef	kg CO_2e/kg beef
F1[a]	13.17	0.39	1.6	0.93	0.23	0	16.31
F2[b]	20.12	0.53	2.11	1.3	0.78	0.28	25.12
F3[c]	33	0.86	3.63	2.3	1.04	0	40.82
F4[d]	20.44	0.64	2.51	1.49	0.02	0.21	25.31
F5[e]	15.01	0.43	1.54	1	0.5	0.16	18.64
F6[f]	15.66	0.41	2.05	1.19	0.12	0	19.43
F7[g]	21.99	0.58	3.65	2.31	0.39	0	28.9
F8[h]	21.88	0.4	2.16	2.32	0.83	0	27.6
Average	20.16	0.53	2.41	1.61	0.49	0.08	25.27
Standard error	0.49	0.08	0.19	0.17	0.19	0.14	

[a]Farm 1, [b]farm 2, [c]farm 3, [d]farm 4, [e]farm 5, [f]farm 6, [g]farm 7, [h]farm 8, [i]kg of milk corrected to 4% fat and 3.5% protein

There are many factors to determine these differences in the proportion of emissions. Firstly, "off-farm" emissions; therefore, when a study considers these emissions, N_2O and CO_2 quantity increases due to external inputs use; consequently, enteric methane emissions decrease.

Additionally, other factors are the annual milk yield and the number of cows (Knapp et al. 2014). This study found that on average 23.7% of total animals were cows in production, a nether percentage than reported by Morais et al. (2018) for pastoral dairy farms in Portugal, which had a greater average (49.2%). Hence, if the total environmental burden from CF is divided exclusively on milking cow's category instead of total animals, CF will be lower.

Furthermore, both animal genetics and feed digestibility are crucial factors in CH_4 emission (NRC 2001; Lassen and Løvendahl 2016). Other factors such as region (6.38 kg/animal/day; FAO 2018), heat stress (Polsky and von Keyserlingk 2017), the type of tropical pasture, and management practices (Pezo 2017), feed consumption rate, type of carbohydrate, quality and forage species, physical processing, forage conservation, and feeding frequency (Knapp et al. 2014) are important.

Concerning CO_2 emissions, Cool Effect (2021) indicates that the carbon footprint of the solar panel is about 20 times less than the carbon output of coal-fired electricity sources. Thereby, the use of renewable energy, as well as reduced use of fuel compared to intensive systems, supports the small emissions in the Peruvian tropical zone.

Greenhouse gas allocation

The CF found in this study (1.68 kg CO_2e/kg FPCM) is lower than reported by Rivera et al. (2016) for intensive silvopastoral systems (SSPi) and conventional systems (2.05 and 2.35 kg CO_2e kg/FPCM, respectively) on dairy farms in Colombia. Therefore, it is worth highlighting the viability of SPS to avoid importing balanced feed in large quantities, favoring self-sufficiency with protein banks (e.g., *Leucaena leucocephala*) (Pezo et al. 2019), helping to reduce CF. Likewise, the results of this work were within the range reported by Rivera et al. (2014) in Colombia to pastoral and intensive systems (1.61 and 1.76 kg CO_2e/kg FPCM, respectively).

Compared to pastoral farms, the average emission estimated in this study is greater than those reported by Del Prado et al. (2013) in the UK on farms with 195 days of grazing and with extended grazing (1.07 and 1.77 kg CO_2e/kg FPCM, respectively). In the same way, the results of this study were greater to those reported by Flysjö et al. (2011) for pastoral systems in New Zealand (0.6–1.52 kg CO_2e/kg FPCM), and by Laca et al. (2019) for Spain in pasture-based systems (0.69 kg CO_2e/kg FPCM).

However, dairy production systems in Eastern and Western European countries (19.6 kg/cow/day) or New Zealand (15.23 L/cow/day) have milk production levels higher than this study. Thereby, CF decreases while productivity per animal increase, and other factors (Salas 2020; FAO and GDP 2018).

Compared to other Latin American studies, the average CF in this study was higher to reported by Wattiaux et al. (2016) in Costa Rica on pastoral dairy farms, where a range of partial CF (methane and nitrous oxide) from 0.38 to 1.02 kg CO_2e/kg FPCM were found. Besides, the results of this work were larger than those reported by Lizarralde et al. (2014) in Uruguay on grazing dairy farms (0.99 ± 0.10 kg CO_2e/kg FPCM).

Although, it should be emphasized that both milking cows' numbers as average milk production were higher in these studies (Costa Rica and Uruguay) compared to this work. It highlights the importance of intensification of these systems.

Nevertheless, the CF calculated in this work (1.68 ± 0.41 kg CO_2e kg/FPCM) is lower than that reported by Gaitán et al. (2016) in Nicaragua on small and medium pastoral farms (3.1 and 2.4 kg CO_2e kg/FPCM, respectively). Since Nicaragua study evaluated emissions "on" and "off-farm"; while this research only carried out emissions "on-farm." Moreover, it is minor then the CF on dairy farms in South Asia, Sub-Saharan Africa, West Asia, and North Africa, where emission intensities were larger (between 4.1 and 6.7 kg of CO_2e kg/FPCM) (FAO and GDP 2018).

Compared to intensive dairy farms, the results of this study were larger than those reported by Del Prado et al. (2013) in the UK on farms in confinement (1.14 kg CO_2e kg/FPCM) and by Vergé et al. (2013) in Canada on intensive dairy production systems (0.93–1.12 kg CO_2e kg/FPCM). This study agrees with Wattiaux et al. (2016), who indicate that methane emissions were mainly reduced with the high up consumption of feed with respect to the amount of pasture provided to the animal. Although the GHG emissions found in this research were smaller than those estimated by Mazzetto et al. (2020), in Costa Rica on intensive specialized dairy farms in the highlands (3.86 kg CO_2e kg/FPCM).

In Latin American (LA) and subtropical regions, the results of this study were higher to those reported by Ribeiro-Filho et al. (2020), who calculated emission of 0.88 to 1.04 kg CO_2e/kg ECM on pastoral dairy systems in subtropical regions. Similarly, Zhu et al. (2016) reported lower values for LA (1.45 kg CO_2e/kg FPCM). Differences between studies can be partly explained by various assumptions (e.g., emission factors, allocation of co-products, estimation of methane emissions, and CO_2-C sequestered), in addition, by the herd productivity and manure management (Ribeiro-Filho et al. 2020).

Nationally, there are few studies carried out on GHG emissions. For example, Bartl et al. (2011) estimated a CF of 1.74 and 5.42 kg CO_2e/kg ECM on farms in the coast and highlands of Peru, respectively. In the same way, Alvarado-Bolovich et al. (2021) estimated enteric methane production by cows, during dry and rainy seasons using IPCC Tier 3 in the highlands.

In conclusion, farms with improved livestock management (higher percentage of cows in production, and higher production levels) and better feed quality had a lower CF. Moreover, it was found that the principal source of emission was enteric fermentation. Consequently, dairy farms in the Peruvian Amazon region could reduce their emissions by improving their current management and feeding practices. Additionally, the CF can be decreased if sustainable management practices are incorporated such as solar panels use, and small use of chemical fertilizers. However, more studies are also needed that consider estimating carbon sequestration from trees, soil, and crops, and CF from off-farm feed to determine the true carbon balance of these systems.

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Data availability The datasets generated during the current study are available on reasonable request.

Ethics approval: The animals were cared in accordance with Peru's Law on Animal Protection and Welfare, No. 30407.

Declarations

Consent for publication All authors agree to the publication of this paper.

Competing interests The authors declare no competing interests.

References

Alegre, J., Vega, R. and La Torre, B., 2012. Manual de manejo de suelos con sistemas silvopastoriles. https://doi.org/10.13140/RG.2.2.20163.30245. Accessed 04 January 2022.

Alonso, J., 2011. Los sistemas silvopastoriles y su contribución al medio ambiente, Revista Cubana de Ciencia Agrícola, 45, 107--115. http://www.redalyc.org/service/redalyc/downloadPdf/1930/193022245001/1+&cd=1&hl=es-419&ct=clnk&gl=pe. Accessed 04 January 2022.

Alvarado-Bolovich, V., Medrano, J., Haro, J., Castro-Montoya, J., Dickhoefer, U. and Gómez, C., 2021. Enteric methane emissions from lactating dairy cows grazing cultivated and native pastures in the high Andes of Peru, Livestock Science, 243. https://doi.org/10.1016/j.livsci.2020.104385

Austin, D., Urnes, P. and Fierro, L., 1983. Spring Livestock grazing affect crested wheatgrass Regrowth and Winter use by Mule deer, Journal of Range Management, 36, 589--593p.

Bartl, K., Gómez, C. and Nemecek, T., 2011. Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru, Journal of Cleaner Production, 19, 1494--1505. https://doi.org/10.1016/j.jclepro.2011.04.010

Cerri, C.C., Moreira, C.S., Alves, P.A., Silva, G., de Almeida, C.B., Mello, F.F.C., Cerri, D.G.P., Cerri, C.E.P., 2015. Assessing the carbon footprint of beef cattle in Brazil: a case study with 22 farms in the State of Mato Grosso, Journal of Cleaner Production, 112, 2593--2600. https://doi.org/10.1016/j.jclepro.2015.10.072

Cool Effect. Carbon footprint of solar panel manufacturing. In: Cool Effect Blog. 2021 https://www.cooleffect.org/solar-carbon-footprint. Accessed 03 Jan 2022.

Del Prado, A., Crosson, P., Olesen, J.E. and Rotz, C.A., 2013. Whole-farm models to quantify greenhouse gas emissions and their potential use for linking climate change mitigation and adaptation in temperate grassland ruminant-based farming systems, Animal, 7, 373--3857. https://doi.org/10.1017/S1751731113000748

Ecoinvent (2010). Ecoinvent database v 2.2. Swiss Centre for Life Cycle Inventories, Dübendorf. https://ecoinvent.org/the-ecoinvent-database/. Accessed 04 January 2022

Food and Agriculture Organization (FAO) and Global Warming Platform (GDP). 2018. Climate Change and the Global Dairy Cattle Sector - The role of the dairy sector in a low carbon future. In FAO. 2018. https://www.fao.org/publications/card/es/c/CA2929EN/. Accessed 04 January 2022.

Fernández, N.E., 2008. Sistemas Silvopastoriles establecidos con *Pinus radiata*-productividad, biodiversidad y sumidero de carbono, (unpublished PhD Thesis, Universidad de Santiago de Compostela).

Flores, E., 1983. Applying the Concept of Feeding Stations to the Behavior of Cattle Grazing Variable Amounts of Available Forage. A thesis submitted in partial fulfullment of the requirements for the degree of Master of Science in Range Science. EEUU: Utah State University. 67 p. https://digitalcommons.usu.edu/etd/3516. Accessed 02 Jan 2022.

Flysjö, A., Henriksson. M., Cederberg. C., Ledgard. S. and Englund, J.E., 2011. The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden, Agricultural Systems 104, 459--469. https://doi.org/10.1016/j.agsy.2011.03.003

Fluker, R.S., Sánchez, V. and Pérez, R.J., 2016. Captura de carbono en un sistema silvopastoril con aliso (*Alnus acuminata*): pasto, suelo y hojarasca en el distrito de Molinopampa, Amazonas, (unpublished Bachelor's thesis, Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas).

Gaitán, L., Läderach, P., Graefe, S., Rao, I. and van der Hoek, R., 2016. Climate-Smart Livestock Systems: An Assessment of Carbon Stocks and GHG Emissions in Nicaragua, PLOS ONE, 11, e0167949. https://doi.org/10.1371/journal.pone.0167949

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. and Tempio, G., 2013. Enfrentando el cambio climático a través de la ganadería – Una evaluación global de las emisiones y oportunidades de mitigación. Organización de las Naciones Unidas para la alimentación y la agricultura (FAO). In FAO. https://www.fao.org/publications/card/es/c/9add29f2-bd94-57f4-8ca8-a63c863ce1f5/. Accessed 04 January 2022.

Infraestructura de Datos Espaciales del Gobierno Regional de San Martin (IDERSAM). 2016. Mapa de Ecosistemas del Departamento de San Martín. In IDERSAM. http://siar.regionsanmartin.gob.pe/mapas/mapa-ecosistemas-departamento-san-martin-minam. Accessed 03 Jan 2022.

International Dairy Federation (IDF). 2015. A common carbon footprint approach for the dairy sector: The IDF guide to standard life cycle assessment methodology. Brussels, Belgium. 70 p.

Intergovernmental Panel on Climate Change (IPCC). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm

Intergovernmental Panel on Climate Change (IPCC). 2014. Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC). 2019a. Glossary. In Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/0_Overview/19R_V0_02_Glossary.pdf. Accessed 04 January 2022.

Intergovernmental Panel on Climate Change (IPCC). 2019b. Agriculture, Forestry and Other Land Use. In Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/. Accessed 04 January 2022.

Intergovernmental Panel on Climate Change (IPCC). 2019c. N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application. In Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/. Accessed 04 January 2022.

Knapp, J.R., Laur, G.L., Vadas, P.A., Weiss, W.P. and Tricarico, J.M., 2014. Invited review: Enteric methane in dairy cattle production:

Quantifying the opportunities and impact of reducing emissions, Journal of Dairy Science, 97, 3231--3261. https://doi.org/10.3168/jds.2013-7234
Laca, A., Gómez, N., Laca, A. and Díaz, M., 2019. Overview on GHG emissions of raw milk production and a comparison of milk and cheese carbon footprints of two different systems from northern Spain, Environmental Science and Pollution Research, 27, 1650--1666. https://doi.org/10.1007/s11356-019-06857-6
Lassen, J. and Løvendahl, P., 2016. Heritability estimates for enteric methane emissions from Holstein cattle measured using noninvasive methods, Journal of Dairy Science, 99, 1959--1967. https://doi.org/10.3168/jds.2015-10012
Lizarralde, C., Picasso, V., Rotz, C.A., Cadenazzi, M. and Astigarraga, L., 2014. Practices to reduce milk carbon footprint on grazing dairy farms in southern Uruguay: Case studies, Sustainable Agriculture Research, 3, 2. https://doi.org/10.5539/sar.v3n2p1
Mainar, F., 2019. La huella de carbono de la producción de leche de vaca. Grupo NySA. Programa Producción de Leche Área de Nutrición, Pastos y Forrajes del SERIDA. In SERIDA. http://www.serida.org/clipping/articulo2036.pdf. Accessed 04 January 2022.
Mazzetto, A.M., Bishop, G., Styles, D., Arndt, C., Brook, R. and Chadwick, D., 2020. Comparing the environmental efficiency of milk and beef production through life cycle assessment of interconnected cattle systems, Journal of Cleaner Production, 277, 124108. https://doi.org/10.1016/j.jclepro.2020.124108
MIDAGRI (Ministerio de Desarrollo Agrario y Riego)., 2020. Boletín estadístico mensual "El Agro en cifras" mes diciembre 2020. In MIDAGRI. https://cdn.www.gob.pe/uploads/document/file/1692287/Bolet%C3%ADn%20Mensual%20%22El%20Agro%20en%20Cifras%22%20-%20Diciembre%202020.pdf. Accessed 03 Jan 2022.
MINAGRI (Ministerio de Agricultura y Riego)., 2017. Estudio de la ganadería lechera en el Perú. Análisis de su estructura dinámica y propuestas de desarrollo. In MINAGRI. https://www.midagri.gob.pe/portal/analisis-economico/analisis-2018?download=13414:ganaderia-lechera-en-el-peru-2017. Accessed 03 Jan 2022.
Murgueitio, R.E., Chará, O.J., Barahona, R.R., Cuartas, C.C. and Naranjo, R.J., 2012. Los sistemas silvopastoriles intensivos, herramienta de mitigación y adaptación del cambio climático. In ResearchGate. https://www.researchgate.net/publication/263848440_Los_sistemas_silvopastoriles_intensivos_herramienta_de_mitigacion_y_adaptacion_del_cambio_climatico. Accessed 04 January 2022.
National Research Council (NRC). 2001. Nutrient Requirements of Dairy Cattle. Seventh Revised Edition. Washington, D.C.
Montagnini, F., Ibrahim, M. and Murgueitio, E., 2013. Silvopastoral systems and climate change mitigation in Latin America, Bois et Forêts des Tropiques. 316, 3--16.
Morais, T., Teixeira, R., Rodrigues, N. and Domingos, T., 2018. Carbon Footprint of Milk from Pasture-Based Dairy Farms in Azores, Portugal, Sustainability, 10, 3658. https://doi.org/10.3390/su10103658
Pérez, A., Sotelo, M., Ramírez, F., Ramírez, I., López, A. and Siria, I., 2005. Conservación de la biodiversidad en sistemas silvopastoriles de Matiguás y Río Blanco (Matagalpa, Nicaragua), Ecosistemas, 15, 3. https://www.revistaecosistemas.net/index.php/ecosistemas/article/view/497. Accesed 04 January 2022
Pezo, D., 2017. Tecnologías forrajeras para la intensificación de la ganadería en el contexto del cambio climático. Universidad Técnica Nacional. N°78–2017. https://www.fontagro.org/wp-content/uploads/2018/03/REVISTA-78-ART%C3%8DCULO-DANILO-PEZO.-Tecnologi%CC%81as-forrajeras-para-la-intensificacio%CC%81n-de-la-ganaderi%CC%81a.pdf. Accessed 04 January 2022.
Pezo, D., Ríos, N., Ibrahim, M. and Gómez, M., 2019. Silvopastoral systems for intensifying cattle production and enhancing forest cover: The case of Costa Rica. https://www.profor.info/sites/profor.info/files/Silvopastoral%20systems_Case%20Study_LEAVES_2018.pdf. Accessed 04 January 2022.
Pizarro, D., Vásquez, H., Bernal, W., Fuentes, E., Alegre, J., Castillo, M. and Gómez, C., 2019. Assessment of silvopasture systems in the northern Peruvian Amazon, Agroforestry Systems. https://doi.org/10.1007/s10457-019-00381-9.
Polsky, L. and von Keyserlingk, M.A.G, 2017. Invited review: Effects of heat stress on dairy cattle welfare. Journal of Dairy Science, 100, 8645--8657. https://doi.org/10.3168/jds.2017-12651
Ribeiro-Filho, H.M., Civiero, M. and Kebreab, E., 2020. Potential to reduce greenhouse gas emissions through different dairy cattle systems in subtropical regions, PLOS ONE, 15, e0234687. https://doi.org/10.1371/journal.pone.0234687
Rivera, J.E., Arenas, F.A., Rivera, R., Benavides, L.M. and Sánchez, J., 2014. Life cycle assessment in milk production: comparison of two specialized dairy herds, Livestock Research for Rural Development, 26, 1–9. https://www.cabdirect.org/cabdirect/abstract/20143224549. Accesed 04 January 2022
Rivera, J., Chará, J. and Barahona, R., 2016. Análisis del ciclo de vida para la producción de leche bovina en un sistema silvopastoril intensivo y un sistema convencional en Colombia, Tropical and Subtropical Agroecosystems, 19, 273--251.
Salas, D., 2020. Producción de leche en Nueva Zelanda. https://proyectosperuanos.com/produccion_leche_nueva_zelanda/. Accessed 04 January 2022.
Thoma, G., Jolliet, O. and Wang, Y., 2013. A biophysical approach to allocation of the cycle environmental burdens for fluid milk supply chain analysis, International Dairy Journal, 31, S41--S49. https://doi.org/10.1016/j.idairyj.2012.08.012
Vistoso, E., Salazar, F. and Gonzáles, S., 2015. Estimación de la huella de carbono para la producción de leche en zona sur de Chile. XXXVIII Congreso Sociedad Chilena de Producción Animal (SOCHIPA). Agrovet MARKET. https://www.engormix.com/ganaderia-leche/articulos/estimacion-huella-carbono-produccion-t31102.htm. Accessed 05 January 2022.
Vergé, X.P.C., Maxime. D., Dyer. J.A., Desjardins, R.L., Arcand, Y. and Vanderzaag. A., 2013. Carbon footprint of Canadian dairy products: Calculations and issues, Journal of Dairy Science, 96, 6091--6104. https://doi.org/10.3168/jds.2013-6563
Wattiaux, M.A., Iñamagua-Uyaguari, J.P., Guerra, L., Casasola, F. and Jenet, A., 2016. Feeding and fertilization practices and greenhouse gas emissions in specialized dairy farms of Dos Pinos in Costa Rica, Tropical Grassland-Forrajes Tropicales, 4, 146e158. https://doi.org/10.17138/tgft(4)146-158
Wellenstein, A. and Hickey, V., 10 key points on climate change impacts, opportunities and priorities for Latin America and the Caribbean. In: World Bank Blogs. 2021. https://blogs.worldbank.org/latinamerica/10-key-points-climate-change-impacts-opportunities-and-priorities-latin-america-and. Accessed 03 January 2022.
Zhu, B., Kros, J., Lesschen, J.P., Staritsky, I.G. and de Vries, W., 2016. Assessment of uncertainties in greenhouse gas emission profiles of livestock sectors in Africa, Latin America and Europe, Regional Environmental Change, 16, 1571--1582.