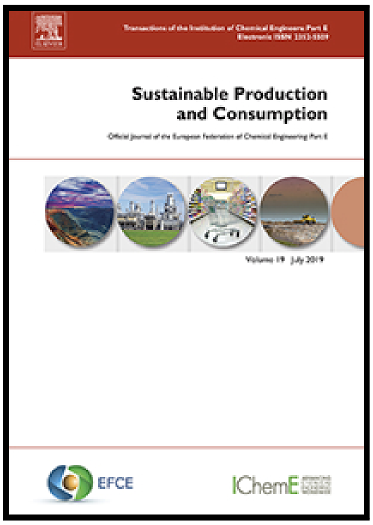

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Environmental impact assessment of beef cattle production in semi-intensive systems in Paraguay

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Acronyms and abbreviations

AAP – Average annual population
AR4 – 4th Assessment report, IPCC
AR5 – 5th Assessment report, IPCC
AU – Animal unit
CC – Climate change
CM – Characterization model
DM – Dry matter
EU – the European Union
FU – Functional unit
GHG – Greenhouse gases
LCA – Life cycle assessment
LUC – Land use change
LW – Live weight
NMVOC – Non-methane volatile organic compounds
SOC – Soil organic carbon
UNFCCC – United Nations Framework Convention on Climate Change
US – the United States of America

Abstract

Beef production has notable environmental implications on a global scale. Paraguayan beef cattle farming is characterized by being developed mostly in pastures or grasslands, but recently the practice of finishing confined to feedlots has thrived. In this context, the aim of this study was to understand the environmental performance of a semi-intensive beef farm which involved in its production system both a pasture and a feedlot stage. A Life Cycle Assessment was carried out with a "cradle-to-farm gate" perspective and 1 kg of Live Weight as the functional unit. Primary data referring to cropping and livestock systems' inputs and outputs were collected on site and a wide range of impact categories were evaluated.

Beef cattle farming proved to be responsible for intensive greenhouse gas emissions (22.0 ± 3.9 kg CO_2 eq $\cdot$ kg LW^{-1}), especially when it occurs predominantly on pasture. The breeding phase is the one that weighs most on global warming potential within the rearing cycle. Since most animals are present in the pasture stage, this contributed highly to the impact categories influenced by animal-related emissions. The feedlot stage, despite its limited duration with respect to the overall rearing cycle, weighs significantly in the categories related to non-methane volatile organic compounds emissions, toxicity, land occupation and fuel consumption, especially because of feed production (both on- and off-farm). Moreover, this stage takes on a greater environmental load when considering the impacts of land use changes related to the consumption of purchased feed, even though its short duration reduces the relative variation given by land use changes inclusion. Some possible mitigation solutions were identified in the discussion, but further studiy is required into the implications of this topic and the exploration of different scenarios.

Keywords

Life cycle assessment, livestock systems,, pasture, feedlot

1. Introduction

At a time when the demand for animal-based products is growing (FAO, 2017; Martinelli et al., 2020), concerns about the environmental sustainability of livestock production chains are emerging (Roma et al., 2015). The whole sector, and in particular beef production, is now under particular focus (Gerber et al., 2013). As regards cattle farming, a brighter side of the problem is the great variability found among different producers, within and across production systems, which reflects the heterogeneity of agro-ecological conditions, agricultural practices and supply chain management choices. In order to feed the future population in a sustainable way, it is essential to look for mitigation options within this same variability, increasingly taking inspiration from producers that apply practices with lower impacts (Gerber et al., 2013; De Vries et al., 2015).

South America plays a fundamental role in this challenge. Today, it contributes significantly to the global supply of beef, with some of its countries acting as important players in the international market. Brazil is the world's second largest producer after the United States and the world's leading beef exporter (USDA, 2020a), while Argentina, Colombia, Uruguay and Paraguay are also established producers at an international scale (FAO, 2019). These countries have immense grassland and pasture areas for livestock production, mostly cattle. At the same time, their large total area and relatively small population, a great share of which lives in urban areas, have historically permitted the diffusion of low efficiency agricultural land-use systems (Braun et al., 2016). A low stocking rate, together with traditional management techniques, is likely to cause poor productivity levels of cattle rearing, which in turn involves a heavy environmental footprint of the finished product (Gerber et al., 2015). Therefore, this is an ideal area in which to investigate, promote and apply improved farming practices in order to lower the environmental burden of beef production on a global scale.

In the specific context of Paraguay, cattle farming plays an important economic role. In 2018, the bovine population was estimated to be 13.6 million heads (SENACSA, 2020) and beef production around 560 thousand metric tons of carcass weight equivalent, of which ca. 365 thousand metric tons were exported (USDA, 2019). Cattle farming in Paraguay has historically been oriented to beef production and developed by exploiting vast natural grasslands and wetlands, where animal housing has rarely been considered. However, in recent decades, more intensive production practices have also developed, which use cultivated and rationally managed pastures and modern production techniques (WWF, 2016). Pastures and grasslands are the major agricultural land use in the country, with an estimated area of about 17 million hectares in 2017 (FAOSTAT, 2020). As is increasingly happening in other South American countries (Gerber et al., 2015), the rearing system may also include a finishing phase with animals confined to feedlots. No detailed data were found on the spread of this practice, but according to USDA estimates it concerned 10-15% of the total cattle slaughtered in Paraguay in 2018 (USDA, 2019). This rearing system has here been called *semi-intensive* to distinguish it from intensive mixed crop-livestock systems, where animals are housed permanently or through most of the year and feed supply from arable crops is predominant (LEAP, 2016).

This study aims to evaluate the environmental impact of beef cattle farming in a semi-intensive system, which involves both a grazing phase and one confined in feedlots. The life cycle assessment (LCA) method has been adopted for this purpose. LCA is a method, regulated by ISO standards 14040 (ISO, 2006) and 14044 (ISO, 2018), that aims to analyze products, processes, or services from an environmental perspective throughout their entire life cycle, or even part of it. LCA has become increasingly employed in recent years in the agricultural sector since it provides a useful and valuable tool for agricultural systems environmental evaluations and comparisons (Notarnicola et al., 2017; Bernardi et al., 2018; Anestis et al., 2020). To the authors' knowledge, this is the first LCA study applied to Paraguayan cattle systems, despite the important role they play in the country's economy and in terms of reporting national GHG emissions. Results may be improved and integrated in the future with a view to developing national inventories regarding the environmental performance of the country's agricultural sector and, consequently, integrated policy frameworks.

2. Materials and methods

2.1. System description

This study focuses on a farm in Southeastern Paraguay, in the Department of *Alto Paraná*, located in a macrozone classified by the Köppen-Geiger climate classification (Beck et al., 2018) as ‘humid subtropical’ (Cfa). According to data from the closest governmental meteorological station

(DMH, 2020), in Salto del Guairá, from 2007 to 2016 the average annual temperature was 22.4 °C, with an average annual precipitation of 1670 mm.

The farm has a total agricultural area of more than 3,000 hectares, divided between arable land and pastures (946 ha of pastures). For arable crops, production is always organized in a double-cropping system per year and, for grazing animals, forage is available all year round. Since part of crop production is intended for internal cattle consumption, to perform the LCA analysis two distinct subsystems were assessed: crop production and cattle rearing.

Crops for internal livestock consumption are oat, to produce hay, and maize, to produce silage. These are grown in winter rotation, while soybean is the main summer crop and, unlike the other mentioned crops, is sold in its entirety . Crops are normally sown without preliminary soil tillage. In the case of maize, sod seeding is practiced. This practice is known to be widely adopted in the country (WWF, 2016). Soil tillage interventions on arable land are carried out only sporadically, on average once every five years. In conjunction with this, agricultural limestone is applied to improve soil fertility, given that the soil's natural pH is acidic (between 4.5 and 5.5). The cultivation system includes neither organic fertilization nor irrigation. Therefore, all fertilizers used are of synthetic origin and crops are totally rain-fed.

In terms of livestock, the rearing system, schematically reported in **Figure 1**, is organized in a cow-calf closed cycle. Therefore, the herd can be divided into two distinct components:

- the mother herd, composed of cows deputed to reproduction and nursing new calves, heifers deputed to replace yearly culled cows and breeding bulls;
- fattening cattle, composed of almost all weaned males and the remaining heifers which does not undergo cow replacement.

The mother herd graze all year round. The breeding cycle is managed so that all cows are inseminated in 3-month seasons. The cows first undergo a fixed-time artificial insemination and are then moved into pasture plots together with breeding bulls for a period of up to two months in order to raise the conception rate. Cattle are not pure-bred because the cross-breeding is not controlled, which produces randomly-mixed hybrids of the Angus, Red Angus, Hereford, Brahman, Braford, Brangus and Nellore breeds. After birth, calves spend the first months of life at pasture with their mothers, suckling. Starting from the second month, their diet is implemented with specific mineral supplements. They are later weaned at seven months of age at a LW of about 170 kg and start grazing. Almost all steers are for fattening, apart from a minimum number intended to replace breeding bulls. Heifers may replace the annually culled suckler cows for failure to rebreed or illnesses, or be sent for fattening. At the end of their breeding career, cows can either be sold directly to the slaughterhouse or added to the finishing phase in feedlots together with young animals if they have low live weight.

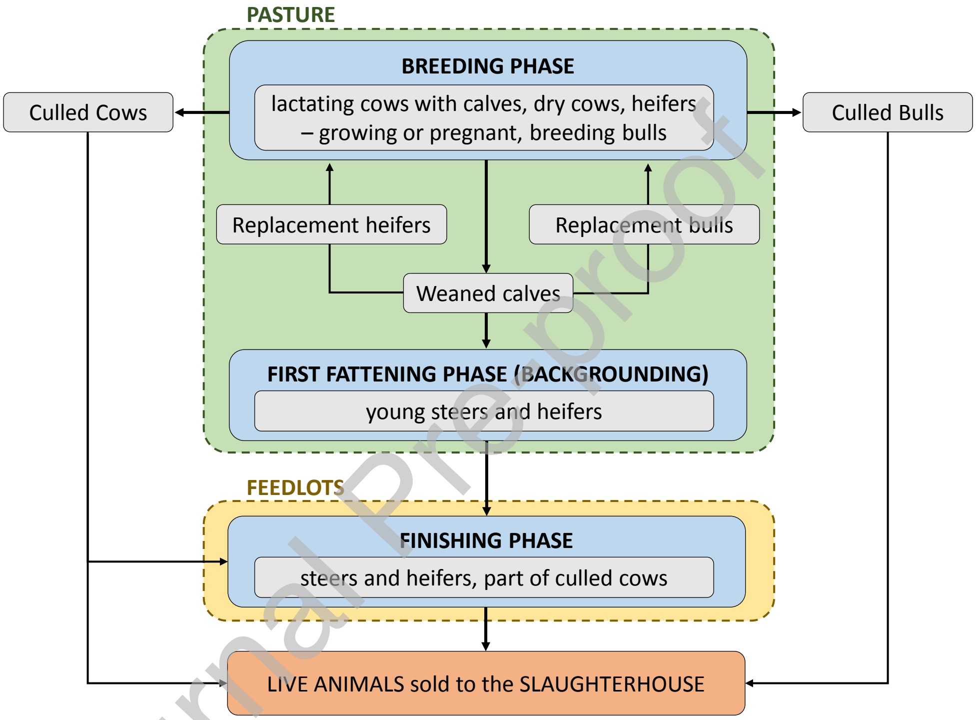

Figure 1 – Schematic framework of the rearing system. The stages, which refer to where the animals are physically hosted, are represented by dotted boxes, namely pasture (green) and feedlots (yellow); the three rearing phases by blue boxes; cattle categories by gray boxes; arrows symbolize animal flows between the different rearing phases and/or stages up to the system endpoint, represented by the red box.

The fattening cycle is divided into two phases:

- a first phase of rotational grazing (hereinafter, backgrounding), which begins after weaning and takes up most of the overall duration of the fattening cycle, or about 15 months;

- a short finishing phase of about 3 months in feedlots, which ends with the animals sale to the slaughterhouse. Animals are moved to feedlots at a live weight of at least 350 kg and sold after having exceeded 450 kg.

Pastures are sown entirely in *Brachiaria spp.* and divided into plots, divided by fences, to allow rotational grazing. Soil tillage (i.e., a chiseling and a harrowing intervention) and sowing renewal are carried out on a ten-year rotation period for each plot. The forage production is commonly affected by climatic variations. Therefore, the cycle is organized and managed so that the finishing phase takes place between winter and early spring, during which the grazing areas are poorly productive due to the relatively cold season. The mother herd and the other animals which do not enter the finishing phase remain grazing even during this period, but their feeding is supported by oat hay distribution.

The entire production of animal excreta deposited either on pastures or in feedlots returns to the soil as it is, without undergoing any handling. In fact, the farm has neither manure storage structures nor machinery for its distribution on fields.

2.2. Goal and scope definition

This LCA study aims to quantify the environmental impact related to a semi-intensive cattle rearing system for beef production in Paraguay and identify the processes responsible for this impact in order to discuss potential mitigation strategies. Finally, results are compared with those of previous studies both in South America, in order to contextualize the present study, and in other areas where more intensive rearing systems are normally adopted (e.g. US, Europe) with the aim to check for analogies and differences.

Although large cattle farms (> 500 heads) are only about 3% of the total in Paraguay, these are home to 65% of the total cattle population (SENACSA, 2020). The farm analyzed belongs to this small quota, that is the one with the greatest productive importance and where to seek the most significant mitigation. Therefore, the outcomes of this study can be useful for stakeholders involved in the beef industry to identify the best environmental management, as well as for policymakers to identify the less impacting rearing systems.

2.3. Functional unit and system boundaries

The choice of an appropriate functional unit (FU) is an important step since it provides the mathematical relation in which the environmental results are reported. This study is focused on the agricultural phase of beef production in a cradle-to-farm gate perspective (see **Figure 2**). This phase deserves particular attention as it has been proven to be the main cause of the whole life cycle impact of beef (Wiedemann et al., 2015; Asem-Hiablie et al., 2019). Considering that the function of the system is to deliver a certain amount of live beef cattle for slaughter, 1 kg of live weight (LW) of animals leaving the farm was chosen as the FU, as suggested by LEAP guidelines (2016). Impacts resulting from post-production transport, processing, distribution, consumption and all related waste disposal have been excluded from the assessment.

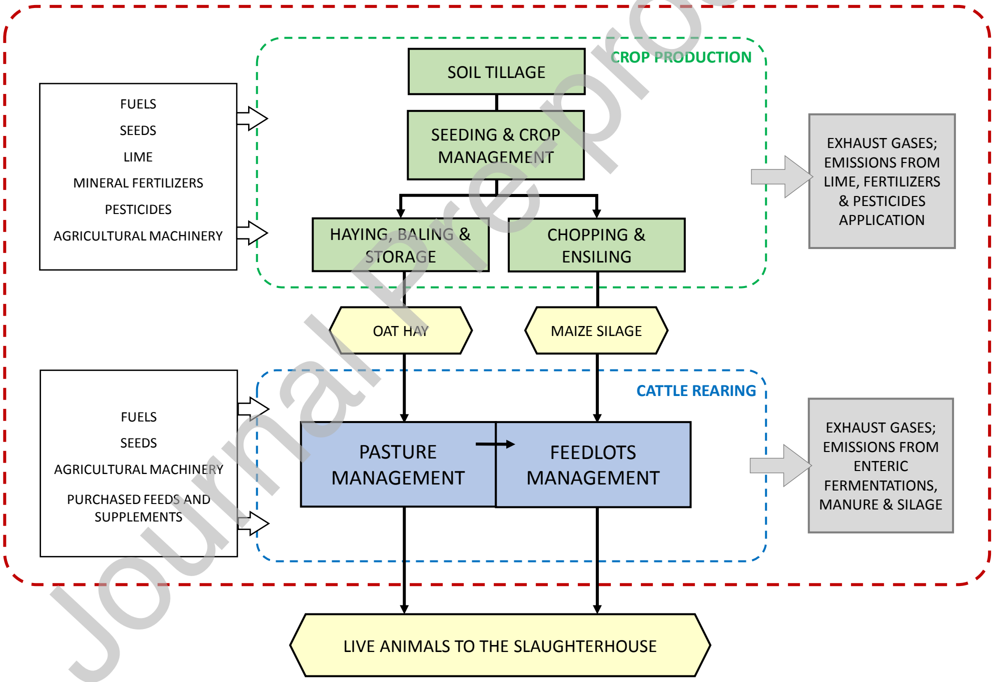

Figure 2 - System boundaries, marked by the red dotted line. Two subsystems can be distinguished: crop production (green) and cattle rearing (blue), each containing different processes, in boxes. Each subsystem consumes inputs from background processes (white boxes) and generates outputs, in particular emissions to the environment (gray boxes) and products (yellow boxes). The products from the crop production subsystem are entirely intended for consumption within processes of the cattle rearing subsystem, while products from the latter correspond to the final product of the whole system (i.e. live animals for slaughter).

Regarding crop production, the boundaries cover manufacture (including the extraction of raw materials), supply and use of inputs necessary for the production cycle (fuels, fertilizers, pesticides, seeds, lime, etc.). Due to the high level of agricultural mechanization, the indirect environmental burdens of tractors and other machinery, including maintenance and final disposal, were considered. In contrast, the indirect impact of the farm's capital goods (buildings, warehouses, fences, etc.) was not taken into account.

For the cattle rearing subsystem, the boundaries include the whole rearing cycle, thus considering the consumption of inputs (e.g., self produced maize silage and oat hay, purchased mineral supplements and feeds), mechanized operations (e.g., pasture renewal, ration distribution by means of feed wagon during finishing phase) and animal-related emissions (i.e., enteric fermentations and manure-related emissions). Impacts associated with production and usage of veterinary medicines and semen for artificial insemination were not included in the study due to lack of information.

Farm land use has remained constant for over 20 years. Hence, soil organic carbon (SOC) was assumed to be in a steady-state, thus not involving CO_2 emission to the atmosphere or carbon sequestration (IPCC, 2006; IPCC, 2019). Therefore, no direct land use changes (LUCs) were considered on-farm, neither for the land devoted to pastures nor for that of arable crops. In contrast, direct LUCs related to off-farm feed production for the finishing phase were considered.

2.4. Inventory analysis

Primary data refer to the four-year period from 2016 to 2019 and were collected in the analyzed farm by means of interviews with farmers and technicians. Furthermore, corporate databases on productive factors purchase and sales of agricultural products, made available by the farm's owners, were analyzed in order to fill in some data limitations from the interviews.

For the crop production subsystem, primary data were collected for each crop: rotations and yields, quantities and types of productive factors used, the sequences of field mechanized operations, agricultural machinery used and their characteristics, including mass, working speed, working width and fuel consumption. The area devoted to maize to produce silage was equal to

21.3 ± 10.3 ha per year and yielded 34.8 ± 8.9 t · ha^{-1} with a dry matter (DM) content of 34.3 ± 5.7 %. Inventory data regarding field operations for both crops are reported in **Tables 1-2**.

For the cattle rearing subsystem, primary data collected included the subdivision of the rearing cycle in phases and their duration, entry and exit body weights for the different phases, consumption of feeds and supplements, as well as animal flows (i.e., sales, births, deaths, etc.) and herd productive parameters. The most relevant inventory data flows are presented in **Table 3**.

Feeding in the finishing phase involved the distribution twice per day by means of a forage wagon of a total mixed ration consisting of a large base of silage maize, entirely self-produced on-farm, and dried distiller grains with solubles (only for 2019), integrated by a concentrate feed, a non-protein nitrogen additive and a mineral supplement, all purchased. The main ingredients of the concentrate feed were maize grain, soybean meal, wheat grain, barley grain, oats, wheat bran, whole rice and cane-vinasse. For the forage wagon, a fuel consumption of 7 kg · hr^{-1} was considered and a working time for each feeding session of half an hour.

Table 1 - Field operations for the cultivation of 1 ha of maize for silage production (yield: 34.8 t · ha^{-1}; with a DM content of 34.3 %)

Field operation	**N.**	**Tractor[a]**		**Operative machine[a]**		**Fuel cons.[c]**	**Working time**	**Notes on productive factors**
		Power (kW)	**Mass (t)**	**Type[b]**	**Mass (t)**	**kg · ha^{-1}**	**h · ha^{-1}**	
Soil tillage	1 every 5 years	65	3.8	Chisel (ww: 2 m)	0.8	15.50	1.43	-
		55	3.0	Lime spreader	1.0	5.29	n/a	Lime fertilizer - 2000 kg
		65	3.8	Disc harrow (ww: 4 m)	0.8	4.90	0.45	-
Sod seeding	1	105	5.4	Precision seed drill (ww: 4.5 m; 11 lines)	4.0	9.60	0.57	Seeds - 30 kg $N-P_2O_5-K_2O$ (10-15-15) fertilizer - 220 kg
Chemical weeding	4	-	-	Self-propelled sprayer (ww: 24 m; 94 kW)	6.6	1.25	0.043	1.9 kg atrazine, 0.102 kg luferunon (pre-seeding); 0.065 kg thiametoxam, 0.1135 kg luferunon, 0.013 kg emamectin benzoate, 0.742 kg azoxystrobin, 0.742 kg tebuconazole (post-emergence).

Chopping	1	-	-	Forage harvester + tractor and trailer	5.0 + 4.5	52.49	n/a	-
Internal transport to ensiling point	-	55	3.0	Trailer	1.5	0.043 $(kg \cdot t^{-1} \cdot km^{-1})$ [d]	-	1.5 km [e]

[a] The following parameters were considered: theoretical lifespan of 12 years for tractors, chisel and disc harrow, 8 years for seeder and self-propelled sprayer (Lovarelli & Bacenetti, 2017); annual working time of 1060 h for the 105 kW tractor, 815 h for the 65 kW tractor, 672 h for seeder, 255 h for self-propelled sprayer, 326 h for chisel, 102 h for disc harrow (effective data collected from the interviews on the studied farm, considering the overall use of machineries, also for other crops throughout year). [b] ww: working width (primary data collected from the interviews on the studied farm). [c] Fuel consumption refers to one intervention. Data are primary for sowing and chemical weeding, while for other operations were retrieved from the Ecoinvent® database. [d] Considering that ensiling operation has a marginal impact with respect to the entire maize production cycle (Bacenetti and Fusi, 2015) and that the ensilage takes place on the ground and not in the bunker silos the fuel consumption for pressing was not accounted separately respect to that recorded for the chopped maize transport. [e] Average distance from fields to the ensiling place.

Table 2 – Field operations for the cultivation of 1 ha of oat for hay bales production (yield 2.56 t [DM, at mowing] $\cdot ha^{-1}$; resulting in 12.5 bales of 225 kg (82% DM) $\cdot ha^{-1}$

Field operation	**N.**	**Tractor[a]**		**Operative machine[a]**		**Fuel cons.[c]**	**Working time**	**Notes on productive factors**
		Power (kW)	**Mass (t)**	**Type[b]**	**Mass (t)**	**$kg \cdot ha^{-1}$**	**$h \cdot ha^{-1}$**	
Soil tillage	1 every 5 years	65	3.8	Chisel (ww: 2 m)	0.8	15.50	1.43	-
		55	3.0	Lime spreader (ww: 10 m)	1.0	5.29	n/a	Limestone - 2000 kg
		65	3.8	Disc harrow (ww: 4 m)	0.8	4.90	0.45	-
Sowing	1	65	3.8	Broadcasting seeder (ww: 1.6 m)	1.6	3.82	0.18	Seeds - 85 kg
Rolling	1	65	3.8	Roller (ww: 4 m)	0.5	3.18	0.4	-
Mowing	1	65	3.8	Rotary mower (ww: 2.4 m)	0.5	4.31	0.74	-
Windrowing	1	65	3.8	Hay rake (ww: 4)	0.5	2.94	0.6	-
Baling	12.5	65	3.8	Round baler (ww: 8 m)	0.5	9.29	0.6	-
Bale loading	12.5	55	3.0	Front loader	0.5	1.01	0.6	-
Internal transport	-	-	-	Lorry	10	0.16 $(kg \cdot km^{-1})$	-	3 km [d]

[a] The following parameters were considered: theoretical lifespan of 12 years for tractors, chisel, disc harrow and roller,10 years for lime spreader and broadcasting seeder, 8 years for rotary mower, hay rake and round baler (Lovarelli & Bacenetti, 2017); annual working time of 815 h for the 65 kW tractor, 326 h for chisel,102 h for disc harrow, 27 h for broadcasting seeder, 60 h for roller, 114 h for rotary mower, 90 h for hay rake and 76 h for round baler (effective data collected from the interviews on the studied farm, considering the overall use of machineries, also for other crops throughout the year).

[b] ww: working width. Where expressed is a primary datum collected on farm.

[c] Fuel consumption refers to one intervention. Data were retrieved from the Ecoinvent® database.

[d] Average distance from fields to the storing place.

Primary data were supplemented with secondary data in order to account for data gaps or background information of the production systems involved in the foreground system. For both subsystems, pollutant emissions were estimated using different models available in the literature. In the first place, on-field nitrogen compound emissions due to fertilizer application were computed based on the model proposed by Brentrup et al. (2000), considering climatic data and soil conditions.

Table 3 – Main inventory data relating to the cattle rearing subsystem: herd characteristics and parameters, inputs and outputs.

		Unit	2016	2017	2018	2019
Herd composition[a] and productive parameters	Calves	heads *(AAP)*	215	207	225	239
	Fattening steers and heifers, at pasture stage (backgrounding)	heads *(AAP)*	330	333	306	342
	Heifers, growing or pregnant, of the mother herd	heads *(AAP)*	91	95	98	102
	Cows of the mother herd – lactating	heads *(AAP)*	213	223	229	238
	Cows of the mother herd	heads *(AAP)*	265	278	286	296
	Bulls	heads *(AAP)*	18	18	18	20
	Fattening steers and heifers, feedlot stage	heads *(AAP)*	27	30	41	72
	Fattening culled cows, feedlot stage	heads *(AAP)*	8	12	24	9
	Share of total AU (considering the AAP) at pasture stage[b]	%	95.9	95	93	91
	Share of total AU (considering the AAP) at feedlot stage[b]	%	4.1	5	7	9
	Pasture stocking rate[b]	AU · ha^{-1}	0.8	0.82	0.83	0.87
	Feedlot stage duration - steers and heifers	days	73	95	107	98
	Feedlot stage duration - culled cows	days	69	96	109	81
	Daily weight gain at feedlot stage - steers and heifers	kg · head^{-1} · day^{-1}	0.965	0.968	0.963	1.482
	Daily weight gain at feedlot stage - culled cows	kg · head^{-1} · day^{-1}	0.993	0.859	0.762	1.530
supplements consumpti	Maize silage (fresh mass), feedlot stage	t · year^{-1}	374.4	464.9	687.1	640.9
	Oat hay (fresh mass), pasture stage	t · year^{-1}	112.5	112.5	112.5	112.5
	Dried distiller grain with solubles (fresh mass), feedlot stage	t · year^{-1}	-	-	-	77.0

	Concentrate feed (fresh mass), feedlot stage	t · year^{-1}	13.9	17.2	25.4	46.9
	Non-protein nitrogen additive, feedlot stage	t · year^{-1}	1.9	2.3	3.4	-
	Mineral supplement, pasture stage	t · year^{-1}	39.9	40.6	41.0	43.7
	Mineral supplement, feedlot stage	t · year^{-1}	1.2	1.5	2.3	3
Live animals sold for slaughter	Steers and heifers, after feedlot stage	heads	133	117	141	260
		kg LW · head^{-1}	468	479.1	449	526.3
	Culled cows, after feedlot stage	heads	40	45	82	40
		kg LW · head^{-1}	437.8	489	460.5	541.7
	Culled cows, directly from the pasture stage	heads	59	55	43	54
		kg LW · head^{-1}	434.5	478.2	471.5	465.2
	Steers and heifers, after weaning[c]	heads	120	-	-	-
		kg LW · head^{-1}	170.0	-	-	-
	Culled bulls, directly from the pasture stage	heads	2	0	13	2
		kg LW · head^{-1}	700.0	0	700.0	700.0
	Total	kg LW	127191.5	104360.7	130444.5	185026.8

[a] Herd subcategories composition is expressed as annual average population (AAP), according to IPCC (2006, 2019). [b] AU: Animal Unit, equal to 450 kg of LW. Method commonly adopted in Brazil (Cardoso et al., 2016; Silva et al., 2017). [c] normally the farm sells the animals only as adults, but due to a frost in 2016 it was forced to sell also young animals due to the scarce availability of pastures that were severely compromised.

Secondly, phosphate (PO_4^{3-}) emissions were calculated following Prahsun (2006) and Nemecek & Kägi (2007) considering two different emission sources: leaching to ground water and, due to the semi-hilly landscape in the area assessed, run-off to surface water. Phosphorus losses caused by soil erosion, on the other hand, were not taken into account due to lack of information. For maize silage production, the active ingredients of pesticides (see **Table 1**) have been considered as having been released totally into the soil.

As for the emissions of the cattle rearing subsystem (**Table 4**), CH_4 and N_2O from enteric fermentations and manure management were estimated following the IPCC guidelines (2006; 2019).

Table 4 – Inventory of estimated emissions from enteric fermentations, manure management and silage for the cattle rearing subsystem.

	Unit	**2016**	**2017**	**2018**	**2019**
Emissions to air					
CH_4, enteric, pasture stage	kg	64792.0	66925.4	66629.6	70587.7
CH_4, enteric, feedlot stage	kg	2335.9	2916.8	4221.6	7342.5
CH_4, manure management, pasture stage	kg	868.6	893	893.7	947.1

CH_4, manure management, feedlot stage	kg	60.9	76.1	110.1	191.6
Direct N_2O, pasture stage	kg	620.8	636.3	634.9	675.2
Direct N_2O, feedlot stage	kg	66.2	85.8	127.2	155.5
Indirect N_2O, pasture stage	kg	372.8	382.1	381.3	405.5
Indirect N_2O, feedlot stage	kg	15.2	19.7	29.2	35.7
NH_3, pasture stage	kg	7003.8	7179.1	7163.1	7617.2
NH_3, feedlot stage	kg	767.1	994.1	1474.1	1802.9
NMVOC, pasture stage	kg	424.7	436.3	437.1	463.3
NMVOC, feedlot stage	kg	589.2	735.7	1064.8	1852.1
Emissions to water					
NO_3^-, pasture stage	kg	62692.2	64260.7	64118	68182.1
NO_3^-, feedlot stage	kg	326.4	423	627.2	767.1
PO_4^{3-}, pasture stage	kg	1004.8	1002.4	990.7	997.9
PO_4^{3-}, feedlot stage	kg	21.55	27.8	41.3	42.7

The Tier 2 approach was used for CH_4, whereas Tier 1 was applied for N_2O, which was based on nitrogen excretion, estimated considering the balance between intake and retention. As no country-specific parameters and emission factors were found, the default ones proposed by the IPCC were used, considering references for low productivity grazing systems in wet climates. Nitrogen excretion was also used for computing ammonia (NH_3) volatilization and nitrate (NO_3^-) leaching from dung and urine through emission factors from IPCC (2006; 2019) and Cai & Akiyama (2016). Similarly, the annual excretion of phosphorous was estimated in order to compute PO_4^{3-} emissions from manure deposited, using the emission factors proposed by Prahsun (2006) and Nemecek & Kägi (2007). Non-methane volatile organic compounds (NMVOC) emission from manure and silage (both from storage and from the feeding table) was calculated using the method proposed by the EEA (EEA, 2019).

Background data for the production of crop seeds, lime, fertilizers, agrochemicals, diesel fuel, agricultural machinery, purchased feed for the finishing phase and supplements were taken from the Ecoinvent® database v. 3.6 (Weidema et al., 2013; Moreno-Ruiz et al., 2019). For mechanized operations, the agricultural processes reported in the database have been modified considering the machinery (tractors and implements) and site-specific parameters (mass, power, specific fuel consumptions, etc.) described above.

Considering that the origin of the purchased feed ingredients was unknown, crop production processes were retrieved from references related to Brazil and Argentina for soybean and maize.

These were considered representative of the South American agricultural basin, as they together represent more than 90% of continental production of these commodities (USDA, 2020b; Zortea et al., 2018). Soybean and maize were considered to be 68% and 66%, respectively from Brazil, and from Argentina for the remaining share (USDA, 2020b). As regards LUCs accounting, these crop production processes retrieved from the database include both impacts from land transformation (in this case, clear-cutting of primary forest and shrubland) and subsequent land occupation (i.e., SOC changes during crop cultivation). Detailed information on how LUCs are modeled in the database can be found in Nemecek et al. (2014) and Donke et al. (2020). Wheat, barley, oats and rice, lacking detailed regionalized references, were retrieved from the global market. More details on secondary and background data regarding emission estimates and processes retrieved from Ecoinvent® database can be found in the supplementary material.

2.5. Impact assessment

In the Life Cycle Impact Assessment phase, inventory data are translated into indicators that reflect environmental pressures as well as resource scarcity. The dataset was characterized by means of the ReCiPe 2016 Midpoint (H) method, version 1.04 / World (Huijbregts et al., 2017). In total, 16 midpoint impact categories have been evaluated. Water use was excluded due to the lack of details relating to water consumption of the livestock cycle, while ionizing radiation was excluded on account of the low prevalence of nuclear power in the region. The analysis was performed using SimaPro® LCA software v 9.1 (Pré-Sustainability, 2018).

2.6. Sensitivity analysis

A sensitivity analysis was carried out to investigate the effect of assumptions, methodological choices and key parameters of the study.

First, the modeling of the dispersion in the environment of active ingredients from pesticides during maize silage production was modified following Margni et al. (2002), considering 76.5% release into the soil, 8.5% into groundwater, 10% emitted into the air while 5% absorbed by plants.

Secondly, the variation resulting from the exclusion of LUC-related impacts for South American soybean and maize was explored. This was performed considering that there is still no shared consensus on how to consider them and the choice of the calculation method, the allocation and the time-frame to refer the emissions to (e.g., CO_2 emissions from LUC may have occurred in the past and/or may occur in the future) can drastically affect the results (LEAP, 2016). For these reasons, the LEAP guidelines (LEAP, 2016) suggest reporting LUC-related impacts separately. Therefore, the processes related to LUCs in the background data of the database related to soybeans and maize production in Brazil and Argentina have been modified by setting them to zero to carry out this analysis.

Finally, to test to what extent an improvement in internal crop production yields could affect the environmental performance of the system, the analysis was run with the yields of maize silage and oat hay increased by 25%.

3. Results

Table 5 reports the potential environmental impacts for the selected FU while **Figure 3** shows the contribution analysis.

Table 5 – Environmental impact for the selected FU, i.e. 1 kg of LW at the farm gate. The observed variability refers to environmental performance over the four different years considered.

Impact category	Unit of measure	Mean	SD	Min	Max
Climate change (GWP)	kg CO_2 eq	22.02	3.90	17.57	27.06
Ozone depletion (ODP)	g CFC-11 eq	0.102	0.017	0.084	0.124
Fine particulate matter formation (PMFP)	kg PM2.5 eq	0.017	0.003	0.014	0.020
Photochemical oxidant formation: terrestrial ecosystems (EOFP)	g NO_x eq	6.49	1.00	5.05	7.34
Photochemical oxidant formation: human health (HOFP)	g NO_x eq	5.20	0.76	4.10	5.84
Terrestrial acidification (TAP)	kg SO_2 eq	0.131	0.022	0.107	0.158
Freshwater eutrophication (FEP)	g P eq	2.94	0.56	2.25	3.62
Marine eutrophication (MEP)	g N eq	34.4	6.3	27.0	42.5
Terrestrial ecotoxicity (TETP)	kg 1,4 DCB eq	10.9	1.3	9.9	12.7
Freshwater ecotoxicity (FETP)	kg 1,4 DCB eq	0.083	0.008	0.072	0.093
Marine ecotoxicity (METP)	kg 1,4 DCB eq	0.106	0.011	0.094	0.120
Human toxicity: cancer (HTPc)	kg 1,4 DCB eq	0.020	0.003	0.016	0.023
Human toxicity: non-cancer (HTPnc)	kg 1,4 DCB eq	1.79	0.20	1.55	1.98
Land use (LOP)	m^2 × yr annual cropland eq	84.8	10.5	69.3	91.8
Mineral resource scarcity (SOP)	kg Cu-eq	0.020	0.002	0.018	0.023
Fossil resource scarcity (FFP)	kg oil-eq	0.153	0.026	0.121	0.185

Enteric CH_4 is the leading contributor to GWP (83%), followed by GHG emissions from manure (13%). The latter are mostly (91%) represented by N_2O (direct and indirect). Therefore, GWP is dominated by animal-related emissions while all productive inputs show a limited influence, as the sum of the different contributions given by consumption of on- and off-farm feeds and pasture management is 4%. N_2O is a major contributor also for ODP (94%).

Apart from N_2O, nitrogen- and phosphorus-based emissions from manure are the main carriers for PMFP, TAP, FEP and MEP, with their impact ranging from 88% to 96%. In particular, NH_3 is the substance which most contributes to TAP and PMFP. For MEP, the limiting substance is nitrogen, while for FEP it is phosphorus. In fact, the substances that contributed to the impacts were NO_3^- for MEP and PO_4^{3-} for FEP. NMVOC emissions, instead, were found to be hotspots for HOFP (37%) and EOFP (48%).

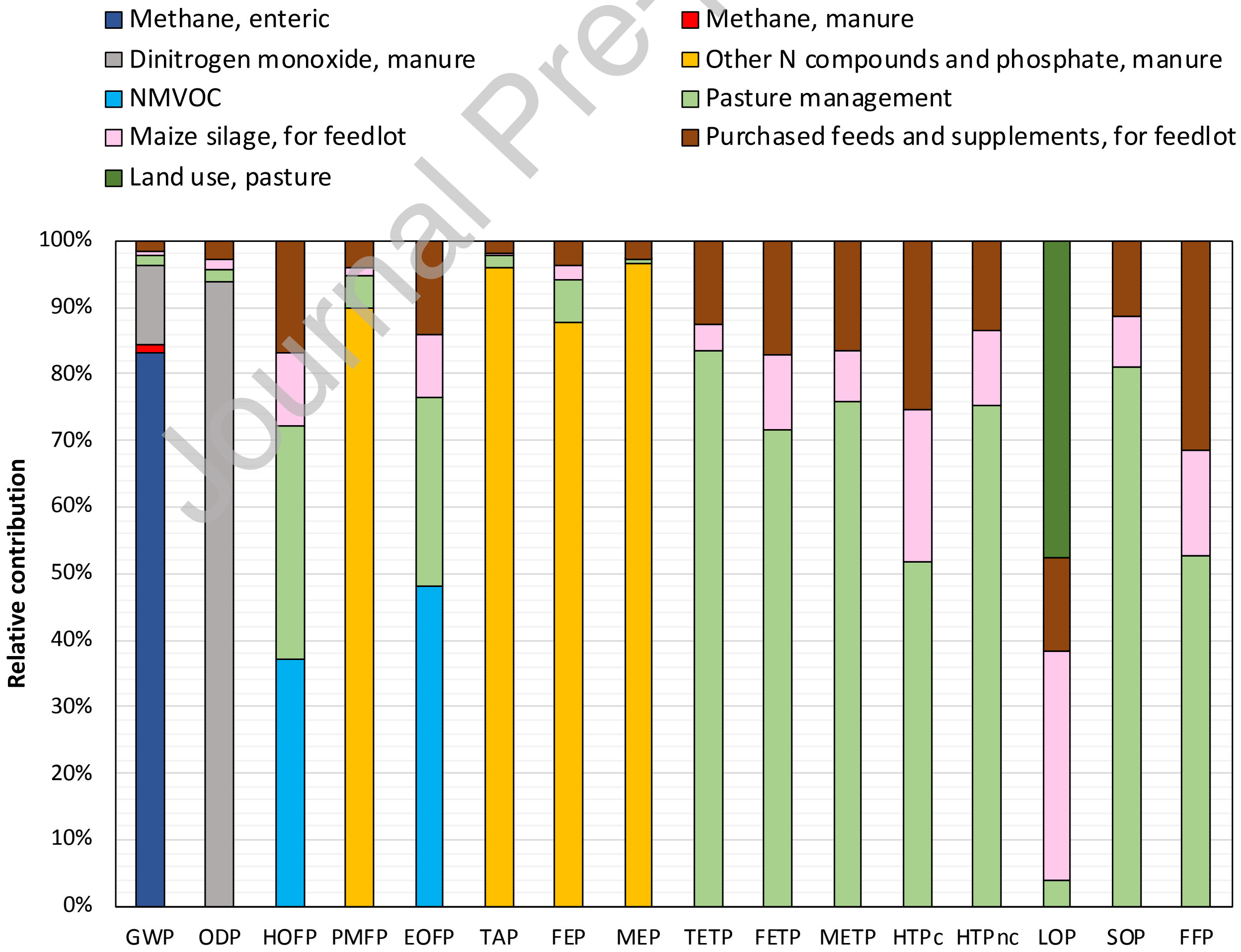

Figure 3 – Relative contribution, related to the FU, of the different inputs (resource consumption) and outputs (emissions) of the system. The percentages represent the average contribution for the four years considered. *Pasture management* refers to the ten-year renewal of pastures (tillage and sowing), as well as to production and supply of oat hay and mineral supplement for grazing animal.

Unlike the impact categories mentioned so far, the categories related to toxicity (i.e., TETP, FETP, METP, HTPc, HTPnc) and resource scarcity (i.e., LOP, SOP, FFP) are not affected by animal related emissions. For LOP, the land devoted to pasture represents the main contributor (47%), followed by land occupation for maize silage production (34%). Agricultural land occupation due to the feedlots themselves (2.1 ha per year overall) presented a minor role (about 0.2%) and is not shown in the graph. On the other hand, for the remaining categories, the impact is mainly due to the production and combustion of fuels and the production of machinery and energy and related consumption. For SOP, the impact is also linked to the extraction of metals, as well as to machinery manufacturing, maintenance, use and disposal. Finally, categories related to human and ecosystem toxicities are also influenced by upstream processes (pollutants produced during mining operations) and by the application of on-field pesticides during crop production (for maize silage and purchased feeds). Pasture management operations have emerged as an environmental hotspot for these categories, ranging from 52% for HTPc to 83% for TETP.

Table 6 shows the relative contribution of the pasture stage to each impact indicator, considering all inputs and outputs.

Table 6 – Average contribution (%) of pasture stage (considering all related inputs and emissions) on the impact for each category in the four years considered.

Impact category	Mean (± SD)
GWP	91.5 ± 4.0
ODP	85.3 ± 5.7
PMFP	81.7 ± 6.4
EOFP	43.8 ± 12.3
HOFP	46.7 ± 12.8
TAP	83.7 ± 5.4

FEP	91.5 ± 4.5
MEP	96.4 ± 2.8
TETP	83.4 ± 9.8
FETP	71.5 ± 13.1
METP	75.8 ± 12.4
HTPc	51.6 ± 14.7
HTPnc	75.4 ± 16.2
LOP	51.4 ± 13.3
SOP	80.9 ± 9.1
FFP	52.8 ± 15.7

This appears on average greater than the impact of the feedlot stage (i.e., the remaining share) for all impact categories except for HOFP and EOFP. It can be noted that the pasture stage is more influential on the categories highly affected by animal-related emissions. This is related to the fact that the vast majority of the farm AAP, or 93.7 ± 2.2 % of the total AU, is present in the pasture stage. Comparing the share of the AU present in the two stages with the relative contribution to the impacts of the stages themselves, the impact intensity per stage can be better appreciated: the feedlots stage involves a greater impact per AU for all categories except MEP. This emphasizes the environmental burden given by resources demand and pollutants emission for feed production (both on- and off-farm) for the finishing phase, despite its limited inclusion in the overall rearing cycle.

Focusing on climate change, given that the impact depends almost entirely on animal-related emissions, this source has been better explored, dividing it in terms of rearing phases. **Figure 4** shows the contribution of the three rearing phases (namely breeding, backgrounding and finishing, see **Figure 1**) to total CO_2 eq emissions. The breeding phase is clearly the most relevant, mainly due to emissions related to suckler cows.

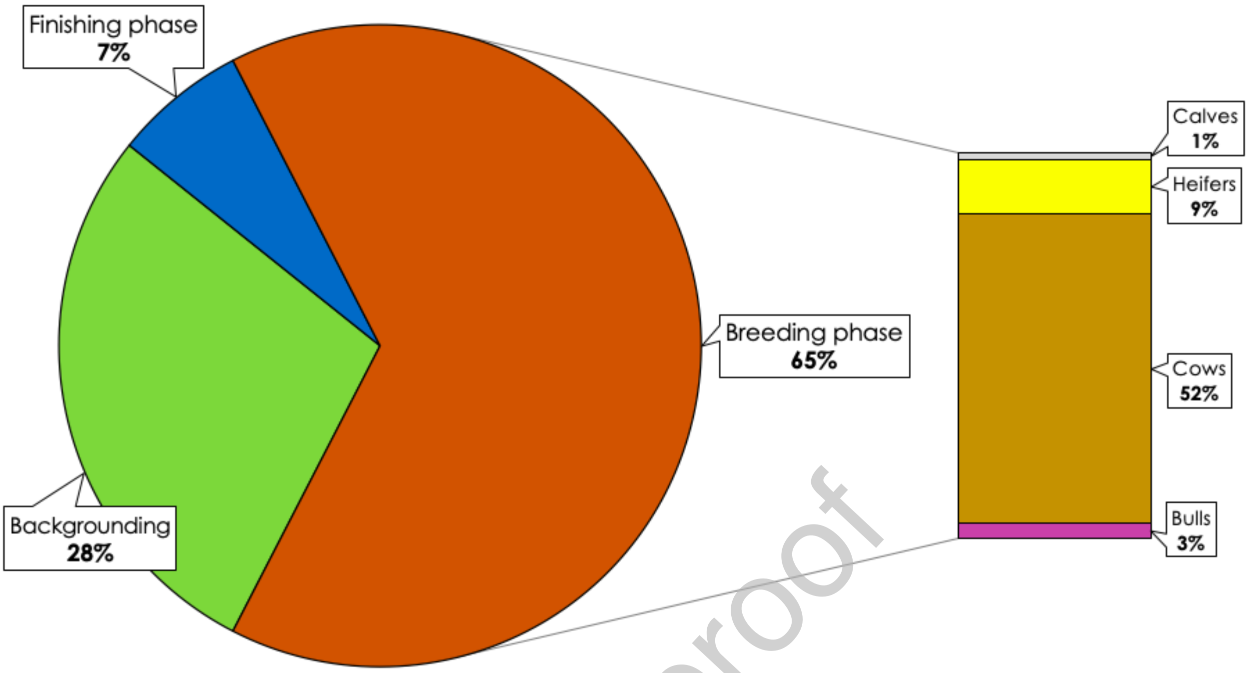

Figure 4 – Contribution of different rearing phases and herd categories to CO_2 eq emissions from enteric fermentation and manure. The percentages represent the average contribution for the four years considered. The characterization model used is that proposed by AR5 (IPCC, 2013).

Fattening animals contributed to 35% of CO_2 eq emissions, mostly due to the backgrounding. It should be taken into account that the share attributed to the finishing phase also consists of the emissions from the cows from the mother herd that enter the feedlots before being sent to the slaughterhouse, other than emissions related to steers and heifers.

3.1. Sensitivity analysis results

The environmental results of the sensitivity analysis are reported in **Table 7**. In general, the base model showed low sensitivity for all tested parameters. It can be seen that the impact of the toxicity-related categories was slightly increased when the pesticide fate in the environment (for internal maize silage production) was modeled according to Margni et al. (2002).

Table 7 – Results of the sensitivity analysis, expressed as a percentage change (%, mean ± SD) with respect to the base model in the four years considered.

Impact category	Pesticides (for internal maize silage production) fate modeling	LUC linked to South American maize and soybean excluded	Increase in yields of on-farm maize and oat production
GWP	/	-0.41 ± 0.19	-0.19 ± 0.03
OD	/	-0.08 ± 0.03	-0.28 ± 0.06
PMFP	/	-0.62 ± 0.26	-0.43 ± 0.05
EOFP	/	-0.76 ± 0.15	-3.29 ± 0.67
HOFP	/	-0.75 ± 0.15	-3.93 ± 0.79
TAP	/	-0.03 ± 0.01	-0.14 ± 0.02
FEP	/	-0.00 ± 0.00	-0.98 ± 0.09
MEP	/	-0.00 ± 0.00	-0.03 ± 0.01
TETP	+2.46 ± 0.55	-0.04 ± 0.02	-1.07 ± 0.18
FETP	+3.98 ± 0.89	-0.01 ± 0.00	-2.73 ± 0.53
METP	+0.39 ± 0.09	-0.01 ± 0.00	-1.97 ± 0.36
HTPc	+0.66 ± 0.16	-0.87 ± 0.16	-6.14 ± 1.38
HTPnc	+0.03 ± 0.01	-0.01 ± 0.00	-3.16 ± 0.69
LOP	/	-0.08 ± 0.02	-7.38 ± 1.42
SOP	/	-0.00 ± 0.00	-1.97 ± 0.33
FFP	/	-0.11 ± 0.02	-5.06 ± 1.21

Regarding the exclusion of LUCs, all impact categories undergo an impact variation less than 1% for. This is explained, on the one hand, by the fact that impacts per kg of LW are already relevant in absolute terms, making the contribution of LUCs relatively low. On the other hand, purchased feed consumption is limited, being consumed only during the finishing phase and in a low share of total DM intake.

LUCs are commonly associated with CO_2 emission due to mineralization of soil carbon stocks, but for changes of land use from forests it also includes impacts related to deforestation operations. Interestingly, PMFP, EOFP and HOFP suffer a higher influence linked to the exclusion of LUCs as compared to GWP, due to substances (particulates and volatile organic compounds) emitted from forest burning, which represents a share of total deforestation, and biomass decay.

Finally, as expected, an increase in yields of on-farm crop production would lead to an improvement, albeit limited, for all evaluated categories. The categories that appear most mitigated in this way are LOP, HTPc and FFP.

4. Discussion

4.1. Comparisons with other studies

Results were compared with those of previous studies relating to South America in order to contextualize them and check their consistency (**Table 8**). In recognition of the limitations of making comparisons between different LCA studies, the most important methodological choices of the different studies are also stressed, namely the FU (Cooper, 2003), the inclusion of LUCs (Gerssen-Gondelach et al., 2017) and the characterization model (CM) adopted (Lynch, 2019).

What generally emerges in all studies is that GWP decreases as the production system intensifies in resources use and herd and pasture management. Beef production in South American pasture-based systems has a GWP at the farm gate generally higher than the ranges observed in other important players in the world market such as the US (Asem-Hiablie et al., 2019) or European countries (De Vries et al., 2015; Berton et al., 2017). This is primarily due to the shorter rearing cycles commonly observed in such production systems, which translate into lower CH_4 emissions per head per fattening cycle (Gerber et al., 2013; Rearte & Pordomingo, 2014). This fact also assumes greater weight when considering that cattle in Latin America normally have lower dressing percentages (LEAP, 2016). These considerations underline the importance of aiming at continuous sustainable intensification and improved efficiency in beef cattle farming in this region.

In all studies where it was possible to find disaggregated values, the contribution of enteric CH_4 appears highly influential. Enteric CH_4 represents a smaller share of GWP in studies related to more intensive farming systems compared to South American ones. For instance, about 50% was observed in the EU (Lesschen et al., 2011), 42% and 47% in two different studies conducted in the US (Pelletier et al., 2010; Asem-Hiablie et al., 2019). On the other hand, manure management and feed production normally have a strong influence on GWP in intensive livestock systems, while their contribution is reduced in pasture-based systems (Dick et al., 2014), as also observed in this study.

LUCs that could be potentially related to feed production were never considered in the revised literature, although in some cases feed consumption was included within the system boundaries. Instead, the inclusion of the off-farm feed-related LUCs was tested in this study, and what emerged is that its influence is reduced compared to the total absolute impact.

Table 8 – GWP values observed in recent studies relating to beef cattle production in South America. All results are expressed over a 100-years time horizon.

Reference	Country	Rearing	FU	kg CO_2 eq per FU	Contribution	LUC	CM[b]

		system[a]		***Average***	***Range***	**(%) of enteric CH_4**		
This study	PY	P+F	1 kg of LW	22.0	17.6-27.1	81-84	Included, for off-farm feeds	AR5
Becoña et al. (2014)	UY	EP	1 kg of LW	20.8	11.4-32.2	68-78	Included, but null	AR4
Picasso et al (2014).	UY	EP & P+F	1 kg of LW	n/a	9.7-20.3	n/a	Not mentioned	AR4
Dick et al. (2014)	BR	EP	1 kg of LW	n/a	9.2-22.5	78-85	Excluded	Other
Mazzetto et al. (2015)	BR	EP	1 kg of carcass [c]	41.3 [d]	21.5-48.7 (15.7-176.2 including LUC)	57-98	Included, as SOC change of pastures	AR4
Ruviaro et al. (2015)	BR	EP	1 kg of LW	n/a	18.3-42.6	n/a	Excluded	AR4
Cardoso et al. (2016)	BR	EP & P+F	1 kg of carcass [e]	n/a	29.4-58.3	61-94	Excluded	AR4
Kamali et al. (2016)	BR	EP & P+F	1 kg of LW	n/a	18.7-27.3	63-70	Excluded	AR5
Florindo et al. (2017)	BR	EP	1 kg of LW	n/a	17.1-31.2	90-92	Excluded	AR5

[a] EP: Entirely at pasture/grassland; P+F: pasture/grassland-based, with feedlots finishing

[b] AR4: 25 x CH_4 & 298 x N_2O, IPCC Fourth Assessment Report (IPCC, 2007); AR5: 28 x CH_4 & 265 x N_2O, IPCC Fifth Assessment Report (IPCC, 2013); *Dick et al.* (2014) used 22 x CH_4 & 298 x N_2O.

(c) considering a dressing percentage varying between 50% and 55% depending on different scenarios, without considering impacts related to the slaughtering phase.

(d) calculated considering the relative estimated diffusion in Brazil of the different cattle rearing scenarios assessed, LUC-excluded.

(e) considering a dressing percentage varying between 48% and 54% depending on different scenarios and animal categories, without considering impacts related to the slaughtering phase.

4.2. Mitigation solutions, trade-offs and policy implications

A greater efficiency of the entire system is needed to reduce environmental impacts for all impact categories. Several studies highlight that through improved pasture management it is possible to increase forage quality and quantity and, therefore, maximize the grazing intensity, the stocking rate and the herd productive (e.g. daily weight gain) and reproductive (e.g. conception and weaning rates) performances (Mazzetto et al., 2015; Cardoso et al., 2020). The use of grass varieties improved to resist drought and frost would make it possible to have a higher yield of pastures and enhance continuity during the year; diversified cultivated pastures would improve ecosystem resilience; incorporation of legumes would increase soil nitrogen availability, increasing both herbage mass and protein content (Latawiec et al., 2014). All these technical solutions could lead to shorter rearing cycles with the same or even greater productivity, reducing the impacts per unit of product without upsetting the traditional pasture-based system and reducing the need for feeding support during grazing.

SOC changes within the farm were not included in the current study due to the finite carbon sequestration potential of pastures. Therefore, when land use remains unchanged for long periods of time (decades), carbon stocks reach a balance (Cardoso et al., 2016). However, it should be noted that a net carbon sequestration condition could occur as a result of changes in pasture management that induce biomass gains (Dick et al., 2015; Jeswani et al., 2018). This represents a possible GWP mitigation strategy, at least in the short-medium term.

Moreover, by improving the pasture productivity and the management of rotational grazing, significant increases in the stocking rate could be obtained (Garcia & Peixoto, 2011). The pasture stocking rate of the analyzed farm was 0.83 ± 0.03 AU · ha^{-1}. This value appears to be in line with the Brazilian overall average of 0.85 AU · ha^{-1} estimated by *Strassburg et al.* (2014). According to the authors, there is the potential to at least double this value in most of Brazil's pastures. Therefore, it is assumed that similar stocking rate improvements may be attained in Paraguay. Moreover, increasing productivity per hectare also means meeting the rising beef demand without the need for further land expansion. Even improvements in the mother herd management (e.g. reducing age at the first calving and calving interval, genetic selection and improvement) are fundamental to lighten the environmental burden of the breeding phase on the production system as a whole, especially as regards its contribution to GWP, which was found to be remarkable in our study.

Another approach for mitigation could be to intensify the system by reducing the permanence of the animals at pasture, in particular the backgrounding of young steers and heifers, and increasing the duration of the finishing phase. Fattening animals have shown a daily weight gain more than double during confinement in feedlots. Therefore, this would lead to a reduced time-to-slaughter. On the other hand, a similar change in the fattening cycle organization would require a greater amount of feed, which would cause a series of burdens in all impact categories linked to its production, processing, transport and distribution. It has been shown that the production of feeds for feedlots influences photochemical oxidant formation, toxicity-related categories, and mineral and fossil resource scarcity. These impacts are likely to be amplified in this scenario. Furthermore, the excessive accumulation of manure in feedlots could become an issue for the farm, which should study and apply manure management strategies requiring economic and managerial efforts. *Picasso et al.* (2015) found it paradoxical that reducing carbon footprint in grazing systems could result in increasing resource consumption by mixed crop-livestock or feedlot systems. Similarly, *Modernel et al.* (2013) claimed that as cattle rearing systems intensify inputs use and increase productivity per unit of resource (land, animals, capital), they perform better in terms of GWP per kg of LW, but worse in fossil fuel derived energy consumption and pesticide emissions. Capper (2010; 2012), referring to the US, claimed that the feedlots system and the use of concentrate feed can improve the environmental performance of beef production because impacts deriving from the massive use of inputs are distributed over an increased production.

Agro-forestry systems constitute a possible alternative system to the traditional pasture-based ones. Some recent studies related to South America (among others, Braun et al., 2016; Rivera et al., 2016; de Figueiredo et al., 2017) have shown that this system can represent a valid solution for the reduction of GHG emissions from pasture-based systems, provided that it is implemented on land suitable for forestry plantation.

Reducing the carbon footprint of beef production should be a primary environmental objective for Paraguay: according to the latest national inventory of GHG emissions (MADES, 2019), agriculture is the main sector contributing to GHG emissions, constituting approximately 53% of the total national CO_2 eq emitted. In turn, enteric fermentations account for 63% of the agricultural share, demonstrating the heavy influence of cattle rearing. The agricultural sector has also been listed among the priorities in which to intervene within the National Adaptation Plan by 2030 under the UNFCCC (SEAM, 2017), in order to comply with Paraguay's nationally-determined contributions towards the Paris Agreement. In this framework, policymakers should consider encouraging the widespread adoption of the mitigation interventions discussed above by farmers across the country. The use of LCA to support nation-oriented GHG monitoring and reporting would allow a more holistic understanding of upstream and downstream processes (Vázquez-Rowe et al., 2019).

4.3. Limitations and possibilities for future improvements

Considering that the emission factors used to quantify animal-related emissions have a degree of uncertainty (e.g., likely in the order of ±20% for Tier 2 IPCC models; IPCC, 2006), future efforts are needed to adapt the estimation models as much as possible to the specific conditions of the country in order to improve the accuracy of the results. Likewise, for the crop production subsystem, specific emission factors for pesticides were missing. The PestLCI 2.0 model (Dijkman et al., 2012) did not work for this case study due to the lack of a suitable pedo-climatic scenario. Models based on site-specific and climate data, however, generally present lower impacts for the toxicity-related impact categories in LCA studies (Rivera et al., 2017). Therefore, it is important to highlight that such impacts may have been slightly overestimated in the current study. More detailed modeling of the fate of active ingredients in the environment would be desirable.

Based on the comparison with the available literature, it was not possible to define if the pasture-based system integrated by feedlot finishing is better performing than the one entirely developed on pasture in all the circumstances, because distinct pasture management scenarios can lead to extremely different results (Kamali et al., 2016). In this regard, a limitation of the present study is that it considers only a single type of pasture management.

Future studies could investigate the feasibility of the intensification of pasture-based Paraguayan systems towards feedlots considering environmental trade-offs and economic profitability. Factors such as pasture management systems (including agro-forestry) and the degree of farm's feed self-sufficiency for the finishing phase could also be explored.

5. Conclusions

Despite the importance of beef production in Paraguay, an environmental impact assessment of beef cattle production had not been previously conducted. The results obtained suggest that the impact on climate change is in line with other studies relating to South American beef systems, both in terms of absolute value and hotspots, suggesting similar practices in beef cattle farming across the continent, which translate into common productive and environmental issues. This confirms beef to be a high-range GWP impactful food product, especially when its production takes place mostly on pasture, with a high time-to-slaughter and low inputs.

Improved efficiency in resource use and herd management would have positive effects from an environmental (lower impact per kg of product for each impact category), economic (higher productivity) and food security (meet beef growing demand) perspective. Moreover, large room for improvement exists both from an agronomic and zootechnical point of view.

This study focused on semi-intensive cattle rearing system, based on pasture but finished in feedlots. This system is increasingly adopted in Paraguay and South America. The pasture stage has a significant weight in all impact categories, especially those affected by animal-related emissions. At the same time, feed consumption in feedlots, despite its limited inclusion in the overall rearing cycle, involves far from negligible environmental burdens, which resulted in a greater impact intensity per animal unit present in the feedlot stage. The feedlot stage also involved LUC-related impacts linked to some ingredients of the purchased feed production, while such impacts do not occur in a grazing system, provided that it happens on land that has not recently undergone use change. It is certainly difficult to find an environmental solution valid for all impact categories in view of the trade-offs highlighted. The comparison between the pasture-based semi-intensive systems characterizing mainly the South America and the European and US intensive ones highlight how, due to the shorter rearing cycles, which translate into lower CH_4 emissions per head per fattening cycle, the intensive systems achieve better environmental results with regard to climate change. Nevertheless, the semi-intensive fattening cycle, if improved in all its productive aspects, may represent a balanced middle ground between an exclusively grazing fattening cycle, given the high GHG emissions normally connected to it, and an exclusively feedlot-based one, given the high resources consumption and the various pollutant emissions connected to feed production and supply.

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