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Advancing Life Cycle Assessment of Pasture-Based Beef Systems: A High-Resolution Cradle-to-Grave Framework for Global Benchmarking

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Abstract

Beef production is widely recognized as a significant contributor to global greenhouse gas emissions, making robust and transparent environmental assessments essential for advancing sustainability within supply chains. This study applies a comprehensive cradle-to-grave Life Cycle Assessment (LCA) to evaluate the environmental performance of beef destined for export, following ISO 14040, ISO 14044 and ISO 14067 standards and the Product Category Rules for meat of mammals. Sixteen impact categories were quantified for 1 kg of vacuum-packed beef using detailed primary data from a pasture-based production system and a representative processing facility. The total climate change impact was 3.27×10^{1} kg CO_2eq, with enteric methane and feed production jointly responsible for over 70% of overall impacts. Slaughtering and distribution were associated mainly with fossil energy use and ozone depletion, while soil carbon sequestration partially compensated biogenic emissions. The results were consistent with international benchmarks, highlighting the environmental advantages of pasture-based systems, low fertilizer use, and stable land management. Key hotspots were identified in animal growth, feed efficiency, and manure management, with logistics also contributing notably. Overall, the study provides a high-resolution environmental baseline that can support Environmental Product Declarations and guide targeted mitigation strategies across beef supply chains.

Keywords: greenhouse gas emissions; environmental product declaration; enteric methane; carbon sequestration; resource use efficiency

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1. Introduction

Global warming and climate change remain among the most pressing environmental challenges for humanity and the global economy. Consequently, ensuring the sustainability of production chains, particularly agro-industrial systems, has become essential. In Argentina, the agricultural sector contributes approximately 38% of the national greenhouse gas (GHG) emissions, highlighting the need for rigorous environmental assessments to identify improvement opportunities [1]. Life Cycle Assessment (LCA) offers a robust framework for this purpose, since it allows us to estimate environmental impacts across a product's entire life cycle, from raw material extraction to end-of-life disposal [2]. This approach promotes transparency, facilitates hotspot identification, and supports circular economy strategies, as demonstrated in previous studies on the carbon footprint of Argentine beef [3–5]. Accordingly, this study aimed to evaluate the environmental impacts of beef production for export in Argentina, following Environmental Product Declaration (EPD) principles and ISO

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14025, 14040, 14044, and 14067 standards, as well as Product Category Rules (PCR) for Meat of Mammals. The analysis focuses on a complete cycle, pasture-based beef production system managed by the Catholic University of Córdoba (UCC) and beef processing in a representative slaughterhouse. This case is part of a broader initiative on Argentina's export beef chain, conducted under an agreement between the National Institute of Industrial Technology (INTI), the National Agricultural Technology Institute (INTA), and the Argentine Beef Promotion Institute (IPCVA). The initiative encompasses 17 slaughterhouses and 51 livestock producers. Previous research in Argentina has consistently identified enteric fermentation and manure management as major contributors to environmental impacts during the on-farm stage. However, variability in production systems, feeding strategies, and transport logistics underscores the need for detailed case studies to generate representative and reliable data. This report addresses that gap through a comprehensive assessment and provides relevant information for conducting analysis at the global level. For instance, a widely cited meta-analysis published in Science reviewed over 570 studies covering 38,700 livestock farms in 119 countries, estimating an average global carbon footprint of 100 kg CO_2 eq per kg of beef—substantially higher than other food products [6]. Comparative analyses, such as the Environmental Product Declaration by Coop Italia -with a carbon footprint of 25 kg CO_2 eq per kg of beef- and data from the Ecoinvent database -9.65 kg CO_2 eq per kg live weight (LW)-, further illustrate the variability of emissions across production systems and regions [7,8]. Studies conducted in the USA report feedlot footprints ranging from 14.8 to 20 kg CO_2 eq per kg LW [9–12], while Brazilian systems range from 18.3 to 42.6 kg CO_2 eq, depending on pasture type [13]. These findings emphasize the importance of context-specific assessments to inform strategies for reducing environmental impacts throughout beef supply chains. Finally, calculating environmental impacts across the value chain provides multiple benefits: it offers an integrated view of environmental performance, identifies stages with the greatest impacts, enables transparent communication of objective and comparable information, reveals opportunities for cost reduction through resource efficiency, supports the valorisation of by-products and waste via recycling or reuse, and facilitates comparisons of raw materials, packaging options, technologies, distribution methods, and alternative products or services.

2. Materials and Methods

Declared Unit and Study Scope

The declared unit (DU) for this analysis is one kilogram of chilled and vacuum-packed boneless beef. The weight of the packaging is not included in the kilogram. The scope of the study for this product is from cradle to grave, comprising animal breeding in the field and slaughtering, processing and logistics up to final consumer, as defined in the PCR for Meat of mammals. Data on production was obtained from the UCC and data on slaughter and processing, from a representative slaughterhouse.

System Boundaries

The system boundary includes the production of all the raw materials, inputs and energy used for beef production and processing, transportation up to the wholesale distributor, consumption and final waste disposal. Regarding the temporal scope of inventories, the information about the cattle breeding system corresponds to the 2021/22 season and the slaughterhouse information, to 2022.

In the upstream process, all the inputs used to produce cattle feed –forage, concentrates, maize grain, maize silage– were included. Emissions from the application of nitrogen and phosphate fertilizers applied to produce feed, and from above- and belowground residue decomposition were considered. Drinking water consumed was also taken into account. Land use and the possible soil carbon sequestration were also incorporated; they were independently reported, following the IPCC guidelines.

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Emissions derived from enteric fermentation and management of manure at all the stages of the life cycle of cattle up to their transport to the slaughterhouse were also included. Equations to calculate these emissions were taken from the IPCC guidelines (2019), volume 4, chapter 10 [14].

Emissions were calculated following IPCC Tier 2 methodology, which uses the IPCC default equations, for each feed and animal category in their different growth phases, with emission factors specific for Argentina taken from the Biennial Update Records of Argentina [1]. Tier 2 uses disaggregated activity data.

Slaughterhouse activities, corresponding to the core process, considered the consumption of energy, fuels to generate heat, use of water, generation of effluents and derived emissions, following the IPCC Guidelines, Volume 5. Waste: Chapter 6 [14].

Regarding the logistics, distribution and consumption –the downstream process– primary, secondary and tertiary packaging levels for all the products were included, and the scenario of transport by truck, ship and airplane, depending on the destination, up to the wholesale distributor was modelled.

Product Description

The studied product is chilled vacuum-packed beef of 350-kg LW heifers and steers. After slaughter and deboning, beef is packed in vacuum bags and stored in boxes of about 20 kg that are then put in pallets for distribution and commercialization.

Regarding storage and consumption at the final consumer's home, a consumption scenario was modelled, which included the calculation of energy consumption and type of cooking of the studied product based on the different sales destinations and product weight with respect to the total commercialized in the country. For this purpose, we used the database of exports of 350-kg LW heifers and steers. The model assumes a storage time of 5 days at the distributor, a storage of 15 days at the consumer's home and one hour of cooking in oven.

Analysis of Life-Cycle Phases

Field Production (Upstream Phase)

This phase included livestock management during breeding, rearing and fattening in Santa Julia (Montecristo), La Toma (Pedro Vivas) and Las Cañitas (La Para), Córdoba province [15]. Production data of the surveyed field, such as initial and final weight of animals, daily weight gain and length of each stage, are detailed in Tables 1–3. Animal feeding consisted of a diet that included natural pastures, maize silage, maize grain, alfalfa hay, mixed grass pastures, protein concentrate and soybean expeller. GHG emissions from enteric fermentation and manure management were considered; they were calculated following the guidelines of the Intergovernmental Panel on Climate Change [14]. Emissions derived from food production and use of agricultural inputs were modelled using profiles of international databases.

The UCC has an important productive structure, with five fields covering a total area of 7500 ha. Using state-of-the-art technology, students and graduates perform internships working in the production of beef, bulls, and grain and oilseed crops. Santa Julia ranch, located in Monte Cristo, 20 km away from Córdoba city, covers 600 ha that were purchased in 1987. There, cattle production activity is very intense, with an Animal Breeding Centre, where embryos and semen are frozen. La Toma ranch, located in Pedro Vivas, 80 km away from Córdoba, covers 1700 ha of productive lands, acquired in 1989. It has a breed stock of Aberdeen Angus, Hereford, Simmental, Tuli and Braford. Las Cañitas Ranch is near La Para, 150 km from Córdoba city, and has 2400 ha acquired in 1997 [15].

Table 1. Characteristics of the herd.

	Females	Males	Unit
Birth weight	29.5	29.5	kg

Weight at slaughter – parents (sire and dam)	560	780	kg
Age at slaughter - parents	108	108	months
Age at first pregnancy and first service	24	24	months
Calving interval	12	-	months
Number of cows per bull	25	-	cows
Serviced cows per year	-	25	cows
Number of calves per cow over her lifetime	7	-	calves
Percentage kept for replacement	25%	1%	%
Weaning percentage	78%	-	%
Percentage of pregnancy	87%	-	%

Table 2. Categories considered, weight gain and length of each cycle.

	Weaned calf: early weaning	**Young bull** (from weaning to 1st service)	**Bull** (from 1st service to slaughter)	**Heifer** (from weaning to 1st pregnancy)	**Pregnant cow**	**Cow with calf**	**Steer / heifer at rearing** (up to 320 kg)	**Steer / heifer at fattening** (up to 420-480 kg)
Initial weight at stage (kg)	**60**	**180**	**600**	**180**	**380**	**425**	**180**	**250**
Final weight at stage (kg)	**180**	**600**	**780**	**380**	**425**	**425**	**250**	**350**
Cycle (days)	**120**	**540**	**2700**	**540**	**270**	**180**	**180**	**100**

Table 3. Feeding of the categories considered.

Kg DM per animal per day	**Weaned calf: early weaning**	**Young bull** (weaning to 1st service)	**Bull** (from 1st service to slaughter)	**Heifer** (from weaning to 1st pregnancy)	**Pregnant cow**	**Cow with calf**	**Steer / heifer at rearing** (up to 320 kg)	**Steer / heifer at fattening** (up to 420-480 kg)
Maize silage	-	**13**	**5**	**4.5**	**1.7**	-	**4.2**	**2.7**
Maize grain	-	**1.08**	-	-	-	-	**2.1**	**4.05**
Alfalfa hay	-	**1**	-	-	-	-	-	-
Mixed grasses pasture 1 (Gatton Panic)	-	-	**8.75**	**2**	**5**	**6**	-	-

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Mixed grasses pasture 2 (Gramma Rhodes)	-	-	8.75	2	5	6	-	-
Mixed grasses pasture 3 (Panicum coloratum)	-	-	-	2	-	-	-	-
Protein concentrate	0.1	-	-	-	-	-	-	-
Soybean expeller	-	1.43	-	0.6	-	-	1.2	1.31
Control: total daily consumption (kg DM/day)	0.1	16.51	22.5	11.1	11.7	12	7.5	8.06

Allocation of Environmental Burdens in Primary Production (Upstream)

Allocation of environmental burdens is a necessary step in the calculation of a product's environmental impacts following the LCA method, also including the byproducts. It consists of "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" [16]. In primary production (Upstream), mass or biophysical allocation criterion was used to allocate the corresponding impact of emissions from breeding cows and bulls to calves at the breeding stage.

Processing at Slaughterhouse (Core)

Data from a representative slaughtering plant were analysed. The animals processed, beef and byproduct production, and electricity and natural gas consumption were quantified.

Transport of live animals from the ranches to the slaughterhouse was considered. Distance covered was 300 km, round trip, in 24-t trucks.

Table 4. Economic allocation of environmental burdens in the slaughtering and deboning process.

Breakdown of a steer weighing 450 to 500 kg	Mean weight per animal	2018	2019	2020	2021	2022	Average	Average price USD/kg	Economic allocation
Boneless beef	261.67	3.79	3.64	3.77	4.64	5.08	USD 4.18	USD 4.18	93.98%
Fat produced from deboning	16.17	0.20	0.19	0.21	0.38	0.54	USD 0.30374	USD 0.30	0.42%
Loss from deboning	5.77								0.00%
Bones and deboning leftovers x kg	2.54	0.03	0.04	0.11	0.05	0.17	USD 0.08	USD 0.08	0.02%
Blood per kg	17.10	0.04	0.15	0.12	0.12	0.03	USD 0.09	USD 0.09	0.13%
Hide x kg	36.65	0.31	0.13	0.10	0.49	0.36	USD 0.28	USD 0.28	0.88%
Fat and deboning sweep x kg	42.85	0.20	0.19	0.21	0.38	0.54	USD 0.30	USD 0.30	1.12%
Leg and head bones x kg	17.35	0.02	0.02	0.02	0.05	0.07	USD 0.03	USD 0.03	0.05%

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Ears x unit		0.01	0.01	0.01	0.01	0.01	USD 0.01	USD 0.01	0.00%
Tail tip x kg	0.18	0.03	0.02	0.04	0.04	0.03	USD 0.03	USD 0.03	0.00%
Red and white offals x kg/hook	27.25	1.01	1.02	1.15	1.59	1.64	USD 1.28	USD 1.28	3.00%
Tripe x kg	5.75	0.49	0.83	0.68	1.07	0.59	USD 0.73	USD 0.73	0.36%
Tripe remnants x kg	1.95	0.17	0.13	0.11	0.13	0.10	USD 0.13	USD 0.13	0.02%
Bile x kg	0.45	0.97	0.66	0.35	0.34	0.34	USD 0.53	USD 0.53	0.02%
Ruminal content	46.78	0.00	0.00	0.00	0.00	0.00	USD 0.00	USD 0.00	0.00%
Slaughter loss	17.55								0.00%
	500.00								**100.00%**

Distribution Logistics (Downstream)

The distribution of the final product (chilled boneless beef) to the wholesale distributors was evaluated. Different international means of transport were considered (aerial, terrestrial and maritime), and their respective distances. Beef is exported to the US by plane, to Germany by ship and to Chile by truck (Table 5).

Table 5. Distances and means of transport.

	Distance (km)		**Vehicle loading capacity**
	Forward	**Return**	**(t)**
Slaughterhouse – airport	58.1	58.1	16-32
Airport – Miami	6577	0	airplane
Miami Airport – Distributor	50	0	5
Slaughterhouse –Buenos Aires port	657	657	16-32
Buenos Aires port – Rotterdam port	11.375	0	Ship with refrigerated containers
Rotterdam port – Distributor in EU	245	0	30
Distributor – Retailer	96.4	0	7.5
Slaughterhouse – Distributor in Santiago de Chile	1.060	1.060	23

Environmental burdens were allocated to beef and byproducts using the economic allocation method, following the EPD protocol. Allocation of environmental burdens at the slaughtering and processing stages (Core) used the economic criterion, according to the PCR used, in order to partition the environmental burden among the products under study and the byproducts with economic value obtained from the slaughter of a cow at the slaughtering stage. The prices of each beef product and byproduct were averaged to define the allocation of environmental burdens. The allocation to the product results from the integration of the weighted steer and the survey of prices in US dollars of product and byproduct obtained by slaughterhouses over a 5-year period.

Boneless beef destined for the international market was packed in polyethylene vacuum bags (about 1.8 kg per bag). Then the cuts were placed in a bigger bag and in a box (about 20 kg capacity). Each box required 40 g of plastic (including the polyethylene of each cut and the big bag of the box) and 500 g of corrugated card box and Kraft paper. The environmental profiles of packaging production were taken from international databases. Between 30 and 35 boxes were placed in a pallet, with a total weight of about 1000 kg. The pallet that was sent to the USA by plane also included a thermal cover and dry ice to keep the product cool, whereas the pallet shipped to the European Union was placed in refrigerated containers.

Assessment of Environmental Impacts

The environmental categories recommended by the PCR of the EPD system (https://www.environdec.com/pcr/env-perf-indic/gpi5) related to 1 kg of the DU under study are presented in Table 6.

Table 6. Environmental impact categories, parameters evaluated and models applied.

Environmental impact category	Parameter	Model
1. Climate change– total	kg CO_2 eq	IPCC's baseline model of GHG emissions for a 100-year timescale [17]
2. Depletion of abiotic resources – fossil fuels	MJ. net calorific value	kg Sb eq/kg of extracted resource. CML [18,19].
3. Depletion of abiotic resources – minerals and metals	kg Sb eq.	kg Sb eq/MJ. CML [18,19].
4. Acidification	mol H+ eq	Proton release or acid rain [20] y [21].
5. Eutrophication – freshwater	kg P eq	Excessive nutrients in freshwater. ReCiPe [22,23] EUTREND [24].
6. Eutrophication - marine	kg N eq	Excessive nutrients in marine environment. ReCiPe [22,23] EUTREND [24].
7. Eutrophication – terrestrial	mol N eq	Excessive nutrients in soils [20,21]
8. Ozone depletion	kg CFC-11 eq	Ozone destruction exceeds ozone creation [25,26]
9. Photochemical ozone creation	kg NMVOC eq	Degradation (NOx. VOCs) in the presence of sunlight (ReCiPe [22,27].
10. Water deprivation	m^3 world eq of deprived water	AWARE (Available Water Remaining) method + ISO 14046 2014 [28].
11. Ecotoxicity – freshwater	CTUe	Cause-effect: fate. exposure and toxicity [29,30].
12. Human toxicity. cancer effects	CTUh	Comparative toxic units for humans (CTUh) per mass unit emitted, cancer effects
13. Human toxicity. non-cancer effects	CTUh	Comparative toxic units for humans (CTUh) per mass unit emitted. non-cancer effects
14. Particulate matter emissions	Disease incidence	Emissions of particulate matter < 2.5 µm [31]

15. Ionizing radiation. human health	kBq U235 eq	Exposure to U235 (ICRP) [32]
16. Land use related impacts/ soil quality	Dimensionless	Soil quality potential (SQP) index. LANCA method [33]

Land Use and GHG Removals

Land use and GHG removals in the fields were estimated following ISO 14067:2018. 3.1.1, which indicates that "the quantification of the carbon footprint of a product (CFP) consists of the sum of GHG emissions and removals in a product system, expressed as CO_2 equivalents and based on an LCA, using the single impact category of climate change". This ISO 14067, in section 6.4.9.5 "Land use change", indicates that "The GHG emissions and removals occurring as a result of direct land use change ... shall be assessed in accordance with internationally recognized methods, such as IPCC guidelines for National Inventories ... and included in the CFP". For this purpose, "a period of 20 years is frequently used".

In this sense, equation 2.25 was used to estimate land-use related emissions or removals, based on changes in soil organic carbon (SOC) stock, as described in IPCC's Chapter 2 (Volume 4) (IPCC Ch.2. 2019).

Equation 2.25 of IPCC

$$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$

$$SOC_{Mineral} = \sum_{c,s,i} \left(SOC_{REF_{c,s,i}} \bullet F_{LU_{c,s,i}} \bullet F_{MG_{c,s,i}} \bullet F_{I_{c,s,i}} \bullet A_{c,s,i} \right)$$

The initial SOC stock is a crucial variable for this calculation. The initial carbon value corresponded to the department or district where the ranch under study is located. Such information was in the same format as that available from GIS http://54.229.242.119/GSOCmap/ (GSOCmap) [34], or in the maps of carbon storage in soils from INTA [35].

The second variable considered was whether the same land management type has been applied in the ranch for the last 20 years. Thus, a coefficient for the Factor of Land Use (FLU) of 1 was used for the fields where there was no change in land use or land clearing or grassland burning (IPCC Ch.5. 2019). However, if agricultural activities have been performed in the last 20 years, the coefficient of 0.86 should be used, as suggested in local studies [36].

The third factor in the IPCC method is the type of grassland management (FMG), which followed the Table 6.2 of IPCC.

The fourth factor refers to the carbon inputs to the system or organic matter input to the soil through residues; FI of Table 6.2 of IPCC was used.

For the UCC's ranches under study, a standard condition was assumed for land use for crops, pastures, native grasslands and /or permanent grasslands. A low to moderate grazing pressure was considered, with important management enhancements. We distinguished between improved pastures and improved grasslands, using additional management inputs, besides a low to moderate grazing pressure. The change in SOC stocks estimated for the three ranches under study was a weighted average of 160.70 kg CO_2 eq/ha.

Table 7. Changes in SOC stocks estimated for the three ranches under study.

Crop/pasture	**Maize silage**	**Maize grain**	**Alfalfa hay**	**Mixed grasses pasture 1**	**Mixed grasses pasture 2**	**Mixed grasses pasture 3**
Production (kg/ha)	12000	7500	7520	4000	3500	2500

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Pasture/Crop	Crop	Crop	Pasture	Pasture	Pasture	Crop
Type of seeding	No-tillage	No-tillage	N/A	N/A	N/A	No tillage
Grazing	N/A	N/A	Low or intermediate grazing intensity	Low or intermediate grazing intensity	Low or intermediate grazing intensity	N/A
Climate	Temperate dry	Temperate dry	Temperate dry	Temperate dry	Temperate dry	Temperate dry
Inputs (fertilizer, weeding, etc.)	N/A	N/A	One or more inputs	No inputs	No inputs	N/A
Residues	Annual crops with high residue, rotations, cover crops or irrigation	Annual crops with high residue, rotations, cover crops or irrigation	N/A	N/A	N/A	Annual crops with high residue, rotations, cover crops or irrigation
Area (ha)	160.00	70.00	23.00	197.00	453.00	57.00
Calculations						
Initial stock (t C/ha)	52.87	52.87	52.87	52.87	52.87	52.87
Land Use factor (FLU)	0.86	0.86	1.00	1.00	1.00	0.86
Fmg (Crop)	1.04	1.04	N/A	N/A	N/A	1.04
Fmg (Pasture grassland)	N/A	N/A	1.00	1.00	1.00	N/A
Fi (crop)	1.04	1.04	N/A	N/A	N/A	1.04
Fi (Pasture grassland)			1.11	1.00	1.00	
Results						
Final stock of SOC (t C/ha)	52.69	52.69	53.16	52.87	52.87	52.69
Change in SOC (t C/ha)	-0.18	-0.18	0.29	0.00	0.00	-0.18
Change in emissions (t CO_2 eq/ha)	**0.68**	**0.68**	**-1.07**	**0.00**	**0.00**	**0.68**
Removal from the system						

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Total annual Emissions / Removal (t CO_2 eq)	**108.29**	**47.38**	**-24.52**	**0.00**	**0.00**	**38.58**
	676.81	676.81	-1066.24	0	0	676.81

3. Results

3.1. General Results

The results of the different impact categories for the product "1 kilogram of chilled vacuum-packed boneless beef, excluding the packaging weight" for the 2021/22 period, are presented in Table 8.

Table 8. Environmental impacts of chilled vacuumed-packed beef throughout its life cycle.

IMPACT CATEGORY INDICATORS			
Parameter		Unit	**TOTAL**
Global warming potential (GWP)	Fossil	kg CO_2 eq	7.65E+00
	Land use and land transformation	kg CO_2 eq	1.48E+00
	Biogenic	kg CO_2 eq	2.35E+01
	Global warming potential Total (GWP)	kg CO_2 eq	3.27E+01
Ozone layer depletion (ODP)		kg CFC11 eq	6.41E-07
Acidification potential (AP)		mol H+ eq	2.35E-01
Eutrophication potential (EP)	Eutrophication aquatic freshwater	kg P eq	1.47E-03
	Eutrophication aquatic marine	kg N eq	3.51E-02
	Eutrophication aquatic terrestrial	mol N eq	6.68E-01
Photochemical oxidant creation potential (POCP)	Photochemical oxidant creation potential	kg NMVOC eq	5.24E-02
Abiotic depletion potential (ADP)	Abiotic depletion potential metals and minerals	kg Sb eq	2.26E-05
	Abiotic depletion potential fossil resources	MJ. net calorific value	6.15E+01
Water deprivation potential (WDP)	Water deprivation potential	m^3 world eq deprived	9.29E-01

RESOURCE USE INDICATORS			
Primary energy resources – Renewable	Use as energy carrier	MJ. net calorific value	1.58E+02

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	Used as raw materials	MJ. net calorific value	5.68E+01
	Total	MJ. net calorific value	2.15E+02
Primary energy resources – Non-renewable	Use as energy carrier	MJ. net calorific value	3.59E+01
	Used as raw materials	MJ. net calorific value	3.72E+01
	Total	MJ. net calorific value	7.31E+01

Additional environmental impact indicators		
Particulate matter emissions (PM)	Disease incidence	1.50E-06
Ionizing radiation. human health (IRP)	kBq U235 eq	3.61E-01
Eco-toxicity - freshwater (ETP-fw)	CTUe	8.98E+02
Human toxicity. cancer effect (HTP-c)	CTUh	3.44E-09
Human toxicity. non-cancer effects (HTP-nc)	CTUh	2.32E-07
Land use related impacts/Soil quality (SQP)	dimensionless	5.33E+03

Table 9. Hotspots of the environmental impacts throughout the life cycle of chilled vacuum-packed beef.

	Feed production	**Animal growth**	**Packaging production**	**Slaughterhouse**	**Product distribution**	**Storage**	**Cooking**	**Packaging End-of-life**
GWP fossil	55.16%	0.69%	3.73%	13.98%	16.84%	4.66%	4.34%	0.59%
GWP LULUC	99.66%	0.00%	0.06%	0.22%	0.02%	0.02%	0.02%	0.00%
GWP Biogenic	0.11%	97.80%	0.53%	1.02%	0.02%	0.12%	0.11%	0.28%
Global warming potential	**17.5%**	**70.6%**	**1.3%**	**4.0%**	**4.0%**	**1.2%**	**1.1%**	**0.3%**
Ozone layer depletion	17.0%	1.8%	3.8%	29.8%	44.3%	1.7%	1.6%	0.0%
Acidification potential	2.4%	87.9%	0.7%	3.5%	4.3%	0.6%	0.6%	0.0%
Eutrophication freshwater	21.8%	3.8%	5.4%	9.7%	3.6%	28.7%	26.8%	0.2%
Eutrophication - Aquatic marine	77.6%	0.4%	1.4%	8.6%	9.9%	1.1%	1.0%	0.0%

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Eutrophication terrestrial	48.6%	39.1%	0.7%	4.9%	5.7%	0.5%	0.5%	0.0%
Photochemical oxidant creation potential	10.8%	46.2%	3.1%	17.5%	19.3%	1.6%	1.5%	0.1%
Abiotic resources depletion - Metals and minerals	33.3%	0.8%	8.1%	38.6%	13.6%	2.9%	2.7%	0.0%
Abiotic resources depletion - Fossil resources	20.7%	1.3%	9.0%	23.8%	29.6%	8.0%	7.5%	0.0%
Water deprivation potential	27.0%	29.7%	18.9%	15.5%	3.7%	2.5%	2.3%	0.4%

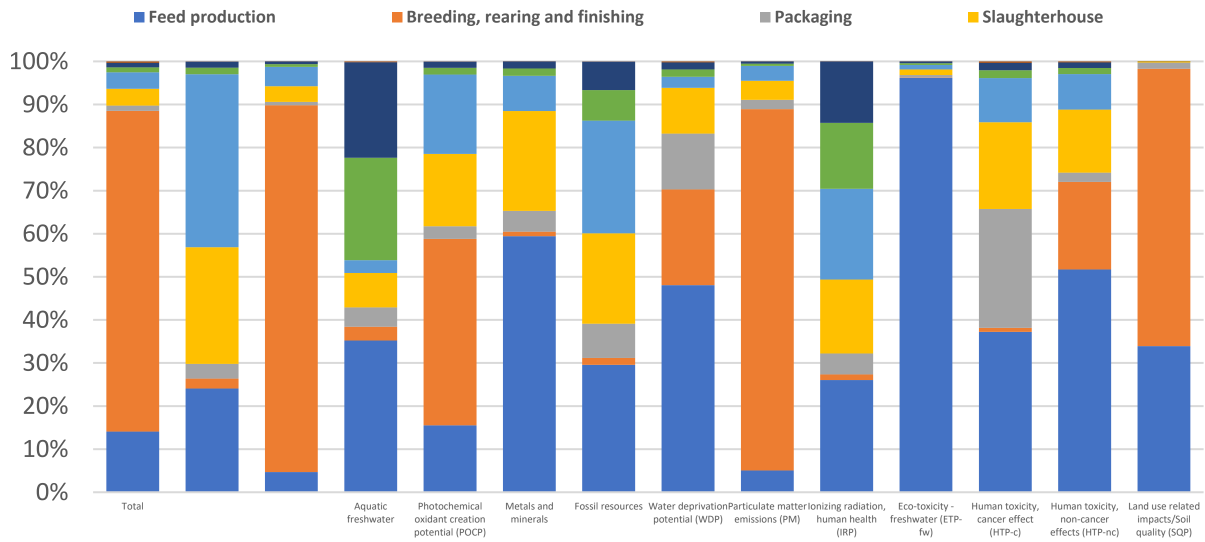

Figure 1. Relative components of the environmental impacts throughout the life cycle of chilled vacuum-packed beef.

3.2. Intermediate results for a live weight of 1 kg

Table 10 shows the environmental impacts of the upstream process for 1 kg of live weight of the finished animal, at the ranch gate, as an intermediate beef product. Emissions from enteric fermentation and manure management, feed production, and the field management system are detailed.

Table 10. Environmental impacts of 1 kg of live weight in the upstream process.

	Upstream

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		Enteric fermentation and manure management	Feed	Field management	Total
Climate Change- Fossil	kg CO_2 eq	0.00	1.84	0.02	1.86
Climate Change - LULUC	kg CO_2 eq	0.00	0.64	0.00	0.64
Climate Change - Biogenic	kg CO_2 eq	10.04	0.01	0.00	10.05
Climate Change – total	kg CO_2 eq	10.04	2.50	0.02	12.56
2. Depletion of abiotic resources – fossil fuels	MJ	0.00	5.54	0.35	5.89
3. Depletion of abiotic resources – minerals and metals	kg Sb eq	0.00	0.00	0.00	0.00
4. Acidification	mol H+ eq	0.09	0.00	0.00	0.09
5. Eutrophication – freshwater	kg P eq	0.00	0.00	0.00	0.00
6. Eutrophication – aquatic marine	kg N eq	0.00	0.01	0.00	0.01
7. Eutrophication - terrestrial	mol N eq	0.11	0.14	0.00	0.26
8. Ozone depletion potential	kg CFC11 eq	0.00	0.00	0.00	0.00
9. Photochemical ozone creation	kg NMVOC eq	0.01	0.00	0.00	0.01
10. Water deprivation	m^3 depriv.	0.00	0.11	0.12	0.23
11. Ecotoxicity – freshwater	CTUe	0.00	371.20	0.30	371.49
12. Human toxicity. cancer effects	CTUh	0.00	0.00	0.00	0.00
13. Human toxicity. no cancer effects	CTUh	0.00	0.00	0.00	0.00
14. Particulate matter emissions	disease incidence	0.00	0.00	0.00	0.00
15. Ionizing radiation. human health	kBq U-235 eq	0.00	0.03	0.00	0.03
16. Land use related impacts/ soil quality	Pt	1831.21	446.16	0.23	2277.61

Renewable energy	Total	MJ	0.00	90.28	0.98	91.26
	Used as energy carriers	MJ	0.00	65.56	0.98	66.54
	Used as raw material	MJ	0.00	24.72	0.00	24.72
Non-renewable energy	Total	MJ	0.00	31.68	0.01	31.69
	Used as energy carriers	MJ	0.00	15.52	0.01	15.52
	Used as raw material	MJ	0.00	16.16	0.01	16.17

The performance of 1 kg LW produced by the UCC was compared with an international average value. That average was obtained from global databases, including information from Brazil, South

Africa and other regions in the world. It is a robust international reference that allows us to put the performance under study in context and assess its environmental competitiveness at the global scale.

To facilitate the interpretation of complex environmental data for executive decision making, a traffic light (also known as RAG -red, green, amber) classification system was implemented. This system uses three visual categories, represented by the colors of a traffic light, to assign a code to project performance. This classification enables a fast identification of the strong points, and those below the average performance.

Green: Indicates a significantly higher performance (30% or above) than the international average

Amber: Performance is within a range of ±30% of the international average. suggesting there is no significant positive or negative difference

Red: Indicates a significantly lower performance (30% or below) than the international average.

Table 11. Comparison of the environmental impacts of 1 kg live weight in the upstream processes.

Environmental Impact Categories	Parameter	Average of cases (metadata)	UCC – Live weight (at ranch gate)	Traffic Light
1. Climate Change – total	kg CO_2 eq	20.00	12.56	
2. Depletion of abiotic resources – fossil fuels	MJ. net calorific value	11.80	5.89	
3. Depletion of abiotic resources – minerals and metals	kg Sb eq.	195,000.00	0.00	
4. Acidification	mol H+ eq	17.70	0.09	
5. Eutrophication – freshwater	kg P eq	0.01	0.00	
6. Eutrophication – aquatic marine	kg N eq	0.11	0.01	
7. Eutrophication - terrestrial	mol N eq	0.10	0.26	
8. Ozone depletion potential	kg CFC-11 eq	9.23E-08	5.26E-08	
9. Photochemical ozone creation	kg NMVOC eq	0.02	0.01	
10. Water deprivation	m^3 world eq of deprived water	1.94	0.23	
11. Ecotoxicity – freshwater	CTUe	861.00	371.49	
12. Human toxicity. cancer effects	CTUh	0.00	0.00	
13. Human toxicity. no cancer effects	CTUh	0.00	0.00	
14. Particulate matter emissions	Disease incidence	0.05	0.00	

15. Ionizing radiation. human health	kBq U235 eq	0.00	0.03	
16. Land use related impacts/ soil quality	Dimensionless	5,230.00	2,277.61	

4. Discussion

The comprehensive LCA of chilled vacuum-packed boneless beef produced by the UCC system provides crucial data for benchmarking the environmental competitiveness of Argentine export beef. The seven core environmental impact categories assessed via the EPD protocol were generally found to be within a medium range when compared to established international values derived from other EPDs (Coop Italia, Logros S.A.) and global databases (Ecoinvent, metadata averages). The methodological rigor of this study, including adherence to ISO 14040, 14044, and 14067, ensures comparability of results with other international analyses.

The environmental impact categories analyzed in this study were found to fall within a medium value range compared to international values published for South Africa, Brazil, and Italy. The international literature is more abundant in studies on the Global Warming Potential (GWP) or Carbon Footprint impact, which increases the possibility of making comparisons. Our study results for carbon footprint fall within a low range, despite the wide variability in published data. A detailed review of the literature allows for a deeper insight into possible causes of these differences in impact. Key features of the production system analyzed include lower relative emissions during the feedlot finishing stage, with grain- and corn-silage-based diets that have lower methane emission factors than pasture-fed animals.

Within primary production of grains and pastures, the limited use of nitrogen fertilizers represented an advantage, reducing emissions of nitrous oxide, ammonia, and nitrogen oxides—gases contributing to global warming, eutrophication, acidification, and photochemical ozone formation. All economic activities consume energy and generate emissions, causing environmental impacts. Agriculture and livestock production are no exceptions; both activities entail the use of diverse energy sources and emit significant methane through enteric fermentation, which is unavoidable but can be reduced with sustainable diet management. For instance, dietary additives can reduce enteric methane emissions by up to 30%.

Another hotspot identified was manure management during breeding, rearing, and finishing. In the finishing stage, manure piles generate high emissions of methane, nitrous oxide, ammonia, and nitrogen oxides, contributing to global warming, acidification, eutrophication, and photochemical ozone formation. Improvements could include integrating feedlots with biodigesters to convert effluents into heat and energy on-site, creating a circular economy system with benefits across the chain. Alternatively, manure could be used as fertilizer for crop fields.

Regarding slaughterhouse processes, actions promoting efficient use of energy and water, and reducing effluent generation, would lower environmental impacts. Adding value to byproducts would also influence the beef footprint, since burden allocation was based on economic criteria.

Finally, in transportation, air freight generated the highest impacts, exceeding those of maritime transport. Road transport within Argentina also significantly influenced the calculated impacts.

Upstream performance (1 kg live weight at the ranch gate)

The total carbon footprint of the UCC system at the ranch gate was calculated as 12.56 kg CO_2 eq per kg of LW. This result confirms a competitive position within the global context. The UCC value is slightly higher than the 11.91 kg CO_2 eq/kg LW reported for a similar Argentine export beef case (Logros S.A.); on the other hand, the UCC result is significantly better than the average GWP for heavy animals in US feedlot systems, often reported at about 15.23 kg CO_2 eq/kg LW (Environmental Working Group, 2011) or the value of 20.0 kg CO_2 eq/kg LW reported by Phetteplace et al. (2001). A previous review from Argentina showed a wide range for complete cycles, between 15.9 and 36.4 kg

CO_2 eq/kg LW (Faverín et al, 2014). In comparison with the Ecoinvent database profiles, the UCC value is higher than the reported for feedlot production in South Africa (9.7 kg CO_2 eq/kg LW) (Russo et al, 2018). However, the UCC performance is substantially better than the GWP reported for Brazilian pasture-based systems (18.3 kg CO_2 eq/kg LW). The relatively moderate GWP in the UCC system is attributed to the pasture-based feeding system and the low relative emissions during the feedlot finishing stage, where grain- and corn-silage-based diets have lower methane emission factors than pasture-based diets.

Cradle-to-grave performance (1 kg packaged boneless beef)

For the final DU (1 kg chilled vacuum-packed boneless beef. including consumption), the UCC total GWP was 32.7 kg CO_2 eq. This result is 8% higher than the cradle-to-grave GWP reported for the Logros S.A. case (30.16 kg CO_2 eq/kg beef) and 12% higher than the maximum value reported by Coop Italia (29.1 kg CO_2 eq/kg meat), which included two hours of pot cooking. The UCC footprint is significantly lower –approximately one third– than the widely reported global average GWP for beef (Poore and Nemecek, 2018) and it is also 21% higher than the value reported for meat consumed in the USA (27.0 kg CO_2 eq/kg beef).

Comparison of other environmental impact categories.

The UCC system demonstrated greater performance than international metadata averages across several key impact categories, particularly those related to resource consumption and ecotoxicity, reflecting a higher resource use efficiency.

The UCC result for Abiotic Depletion (Fossil Fuels, 61.5 MJ) is slightly lower than the Logros result (62 MJ) and remarkably lower than the Coop Italia EPD (95 MJ). This reduced fossil fuel depletion is likely linked to the low reliance on nitrogen fertilizers in the production of grains and pastures within the UCC system.

Similarly, the Water Deprivation Potential (0.929 m^3/kg beef) is substantially below international values (1.94 m^3/kg beef), including Ecoinvent South Africa (Russo et al, 2018).

For the Acidification Potential and Terrestrial Eutrophication Potential categories, the upstream impacts in UCC production confirm that emissions are dominated by manure and effluent management. The low use of nitrogen fertilizers partially mitigates these impacts compared to other global systems.

Identification of environmental hotspots and system benefits

Consistently with previous Argentine studies and international findings, enteric fermentation remains the dominant environmental driver, accounting for 70.6% of the total GWP for the final product. The UCC system benefits from lower relative emissions during the finishing stage due to the diet composition. The second critical hotspot identified is manure management, which contributes to Acidification Potential and Photochemical Oxidant Creation Potential. Accumulation of manure in piles, especially during the finishing stage, generates high emissions of methane, nitrous oxide, ammonia, and nitrogen oxides.

The analysis confirms that the choice of transportation means significantly influences the overall footprint. Air freight (which is used for distribution to the US) generates the highest impacts, exceeding maritime transport. Air transport is particularly dominant in categories related to resource depletion and ozone depletion, contributing of the Ozone Layer Depletion and Abiotic Depletion - Fossil Resources impact.

Soil carbon sequestration

A distinctive element of this study is the quantification of the soil's capacity to remove carbon from the atmosphere, which was 160.70 kg CO_2 eq/ha. This coexistence of significant biogenic emissions and carbon sequestration potential in grazing soils reveals the complexity of grazing production systems and highlights a fundamental characteristic and strategic opportunity for mitigating the net carbon footprint of the sector. The results of this study confirm the trends identified in previous research works on carbon footprint of beef production in Argentina (Bongiovanni & Tuninetti, 2023; Bongiovanni et al., 2023; Logros S.A., 2022).

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Enteric fermentation in ruminants is an unavoidable biogenic emission and remains the main driver of environmental impact in beef production. Grass- or pasture-based feeding used in production systems of the UCC proved to be a key factor for maintaining the carbon footprint below the average of other intensive systems. In addition, GHG removal in the surveyed ranches contributed to a relatively lower net carbon footprint, which highlights the role of soil and vegetation in carbon sequestration. The efficiency of the UCC's production system, characterized by the high productivity and low dependence on external outputs, is reflected in a competitive carbon footprint at the international level. This result is attributed to the efficient use of resources, lack of changes in land use, technological innovations and an efficient animal diet.

The slaughtering phase, though with a lower impact than field production, presents opportunities for improvement, primarily in energy efficiency and effluent management. Optimization of the distribution logistics, especially to export markets that depend on air freight, is another key aspect to reduce the environmental impact of the final product. Our findings provide a solid basis for strategic decision making, both for the UCC and the production sector, with the aim of continuously improving and promoting a sustainability image in the global market. Overall, the analysis of the integrated system shows that it is possible to produce beef with a reduced environmental footprint, taking advantage of the benefits of pasture-based production systems.

5. Conclusions

The LCA results for the UCC production system confirm that the pasture-based model, combined with efficient resource use, offers a competitive environmental footprint at the international level. The results, which align with international findings regarding the dominance of biogenic emissions, provide a robust foundation for identifying targeted improvement strategies. Future efforts should focus on maximizing load capacity and using lower-emission vehicles in logistics, promoting efficient use of energy and water in slaughterhouses, and implementing strategies for optimized manure management, such as integration with biodigesters.

Recommendations include maximizing load capacity, reducing empty trips, and using vehicles with EURO 5 fuel technologies, with lower contribution to emissions per liter consumed. Future studies could incorporate more precise soil carbon balance using FAO protocols and IPCC methods. The LCA results revealed that the animal growth stage during primary production is the main driver of the product's environmental footprint. This impact is attributed mostly to emissions of enteric methane, a biogenic GHG, as well as to the emissions of nitrogen oxide from manure management. However, a distinctive element of this study is the rigorous quantification of the system capacity to remove carbon from the atmosphere.

The coexistence of biogenic emissions and soil carbon sequestration highlights the need for net balance assessment in sustainability studies. The results of this case study confirm that the dominance of the biogenic emissions in the carbon footprint of beef is a common challenge at the global level. Regardless of the figures, the greatest value of this research lies in the methodology. The use of a disaggregated life cycle inventory analysis, which considers specific variables, like genetics, diet, and length of the growth stages, revealed notable differences, like those in environmental impact among categories. This level of detail in the activity data is crucial for decision making.

The results reveal that optimization is not achieved using generic measures, but through fine and specific adjustments. This lesson learned, which highlights the importance of data granularity, can be applied to any production sector that seeks to improve its environmental performance efficiently and accurately. High-quality and specific information is the basis for the development of truly effective improvement strategies. The methodological rigor of this work not only makes it comparable to other analyses but also contributes significantly to the current knowledge about environmental assessment in livestock production. The study used well known standards, like the Product Environmental Footprints PEF 3.1 of the European Union, for characterization factors and the Ecoinvent database for environmental profiles.

One of the limitations of this study is that the findings are based on a particular production system (that of the UCC) and cannot be considered representative of the entire Argentine livestock production system. Relying on activity data from a limited group of suppliers for breeding, rearing and fattening stages also hinders direct extrapolation of conclusions. To increase the validity and representativeness of the findings, inventory databases should be extended; thus, a greater diversity of production systems, breeds and agroecological regions would be included. A promising research line is the comparative and detailed analysis of environmental impacts between pasture-based and confinement systems.

Finally, studies on soil carbon sequestration stability should be conducted for climate change mitigation. This work goes beyond calculating indicators; it serves as a functional model for managing and improving sustainability in the export beef sector. Despite the limitations inherent to a case study, the methodological rigor and adherence to international standards of this work confers it a strategic value. The most important achievement of this research is that it offers a clear and scientifically solid pathway for the Argentine beef industry to reliably measure, manage and inform its environmental performance. This research provides a knowledge base that allows the sector to advance towards sustainability by transforming deficiencies into opportunities for innovation and continuous improvement and ensuring competitiveness in an increasingly demanding global market.

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