

Article

Carbon Footprint of Lamb and Wool Production at Farm Gate and the Regional Scale in Southern Patagonia

Pablo L. Peri ^{1,2,*}, Yamina M. Rosas ³, Brenton Ladd ⁴, Ricardo Díaz-Delgado ⁵ and Guillermo Martínez Pastur ³

¹ Instituto Nacional de Tecnología Agropecuaria (INTA), 9400 Río Gallegos, Santa Cruz, Argentina

² Natural Resources Department, Universidad Nacional de la Patagonia Austral (UNPA)—CONICET, 9400 Río Gallegos, Santa Cruz, Argentina

³ Laboratorio de Recursos Agroforestales, Centro Austral de Investigaciones Científicas (CADIC CONICET), 9410 Ushuaia, Tierra del Fuego, Argentina; micala.rosas@cadic-conicet.gob.ar (Y.M.R.); gpastur@conicet.gov.ar (G.M.P.)

⁴ Escuela de Agroforestería, Universidad Científica del Sur, Lima 15067, Peru; bladd@ucientifica.edu.pe

⁵ Laboratorio de SIG y Teledetección, Estación Biológica de Doñana (CSIC), 41092 Sevilla, Spain; rdiaz@ebd.csic.es

* Correspondence: peri.pablo@inta.gob.ar; Tel.: +54-2966-442-305

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Abstract: Natural steppe grasslands are the principal food resource for sheep in the Patagonia region, reared for meat and wool. However, there is currently a concern about the relationship between ruminant livestock and climate change due to its contribution to anthropogenic greenhouse gas (GHG) emissions. The objective of this study was to determine the carbon footprints (CF) of sheep meat (lamb) and wool on a range of farms using empirical data collected on farm and then upscaled to the regional scale using models that use topographic, climatic, and vegetation indices as independent variables. At the regional level, the total CF of lamb and wool (the combination of emissions produced on farm, via transport, and via industrial processing) varied from 10.64 to 41.32 kg CO₂-eq/kg for lamb meat (carcass) and from 7.83 to 18.70 kg CO₂-eq/kg for fine-grade wool. For both, the predominant contribution was from primary production on-farm (75–90%), followed by industrial processing (2–15%), and transportation. We used multiple regression models to produce maps of lamb and wool CF at farm gate across Santa Cruz province. The model for variation of lamb CF explained 95% of the variance on the data and the most significant predictor variables were temperature seasonality and normalized difference vegetation index (NDVI, dimensionless). The most important variables for the model of CF of greasy wool production at farm gate were isothermality, temperature seasonality, and NVDI explained 98%. The lowest CF values of both products (lamb and wool) were located in more productive grasslands. The successful management of livestock GHG emissions becomes an important challenge to the scientific, commercial, and policy communities. The results of CF for lamb and wool production found in the present work assist in characterizing the greenhouse gas emissions profile of livestock products in Southern Patagonia by providing a baseline against which mitigation actions can be planned and progress monitored.

Keywords: anthropogenic greenhouse gas (GHG) emissions; rangeland; livestock; climate; lamb production; wool production

1. Introduction

Natural grasslands occupy most of Santa Cruz Province (Southern Patagonia region), and are the principal food resource for sheep, reared for meat and wool. The steppe ecosystem, mainly characterized by the presence of tussock (*Festuca*, *Stipa*), short grasses (*Poa*, *Carex*), and shrubs, covers 85% of the total area in Santa Cruz province [1]. Extensive livestock production systems in Southern Patagonia, based on low input level and natural areas, are dominant, with a marked seasonal grass production that is restricted to a 5–7-month growth period due to water stress and low winter temperatures. Main environmental factors that affect net primary production at regional level derive from the importance of mean annual precipitation, radiation, and temperature [2]. Continuous grazing with fixed stocking rates in large paddocks (1000 to 5000 ha) prevails over grazing systems subjected to regular grassland condition evaluations and rotational rests [3].

The importance of livestock in providing societies with food, income, employment, and nutrients is widely recognized. However, there is currently a concern about the relationship between livestock and climate change, highlighted in the Food and Agriculture Organization of the United Nations (FAO) report “Livestock’s long Shadow”, that claims that domestic animal production contributes 18% of anthropogenic greenhouse gas (GHG) emissions [4]. It has been reported that grazing intensely on extensively managed grasslands affects ecosystem C levels. Grassland management can determine whether extensive livestock systems could be a net sink or a source of GHGs, where steppe degradation through inappropriately implemented livestock grazing (overgrazing) systems can lead to a net release of GHGs, predominantly in the form of CO₂ from depleting soil organic carbon stocks [5,6]. About 50 Mg C/ha has been observed at sites with heavy stocking rate compared to 130 Mg C/ha under low grazing intensity [7].

To fully evaluate the positive and negative effects of mitigation strategies on greenhouse gas emissions in production chains, consequential life cycle assessments (LCA) or scenario models have been used to account for all the GHGs emitted from all stages of sheep production [8,9]). From this, the final summary of the GHGs (expressed as carbon dioxide equivalents, CO₂-eq) emitted during the production of a given product is termed its carbon footprint (CF), and there is an increasing interest in attributing global warming potential to various products via carbon footprints to give producers and consumers insight into their contribution to global warming. Advancement of the livestock production policies will require improvement in the production stream and marketing of wool and mutton as “specialty”. In this regard, the carbon footprint promises to become a determining factor for transactions of sheep products between countries. CFs can also provide an emissions benchmark against which mitigation targets can be set and progress measured, and enable carbon labeling of food products to inform sustainable consumer purchasing decisions [10,11]. Available evidence indicates that CF labeling in agriculture is an emerging reality, and many consumers evaluated through surveys in the United States and the European Union (approximately 65%) were willing to consider a product’s CF when making their purchasing decisions [12]. Given these trends, the need for assessment of the CF within the main export-oriented meat and wool industry in the province of Santa Cruz is clear. Such efforts will help the region maintain open access to environmental-minded markets and shift marketing of the region’s wool and mutton as a specialty product. There are no antecedents in the scientific literature on the CF of sheep production in Patagonia.

The main objective of the present work is to answer the question: What are the CFs of sheep meat and wool on a range of farms using empirical data collected from sheep farms across Santa Cruz province? Also, here we upscale data of CF for lamb and wool production at farm gate and also include transport and further processing at the regional scale using multiple regression that uses topographic, climatic, and vegetation indices as independent variables. We hypothesize that at farm level CF is more sensitive to the effects of grasslands condition due to grazing (stocking rates) than the other potential explanatory variables, such as transportation distances and emissions resulting from industrial processing. At regional level, CF would be lowest where the physical environmental conditions (moisture, temperature, topography) promote grasslands production.

2. Material and Methods

2.1. Definition of Sheep Farming Systems

For this study, 63 sheep farms across Santa Cruz province (Figure 1) were selected and integrated into a geographical information system (GIS) using ArcMap 10.0 software [13]. Sheep farms were randomly sampled within the categories of grassland in good ecological condition and overgrazed (determined from grasslands evaluation in each farm) in five ecosystem categories (Mata Negra Shrubland, Dry Magellanic Steppe, Humid Magellanic Steppe, Central Plateau Grasslands, and Andean Grasslands). In these ecosystems, the annual net primary production (ANPP) varied from 4.9 g/m²/yr for overgrazed grassland in the Mata Negra thicket to 59.1 g/m²/yr under moderate grazing in Andean grasslands. Overgrazing reduced ANPP by two-thirds in most ecosystems.

In the region, a significant climate gradient exists, since the Andes Mountains act as an orographic barrier; annual rainfall ranges from 800 to 1000 mm/year in the Andes Mountains and decreases to 200 mm/year in the eastern part of Santa Cruz Province. The ratio of mean annual precipitation to potential evapotranspiration ratio of the steppes fluctuates between 0.45 and 0.11, with marked deficits in spring and summer. The variations in local topographic and edaphic characteristics combined with a significant precipitation gradient substantially influence the distribution patterns of vegetation throughout the region. Santa Cruz province, a cold temperate region, possesses mean annual temperatures between 5.5 and 8.0 °C. Temperatures are highest during the short Patagonian summers between the months of December and February. The summer days are long due to the region's southern latitude. The windiest season within the region occurs between November and March, producing frequent and severe south-southwesterly wind storms reaching over 100 km/h. In Table 1 the mean values of climate and ecosystem variables for each ecosystem category are summarized.

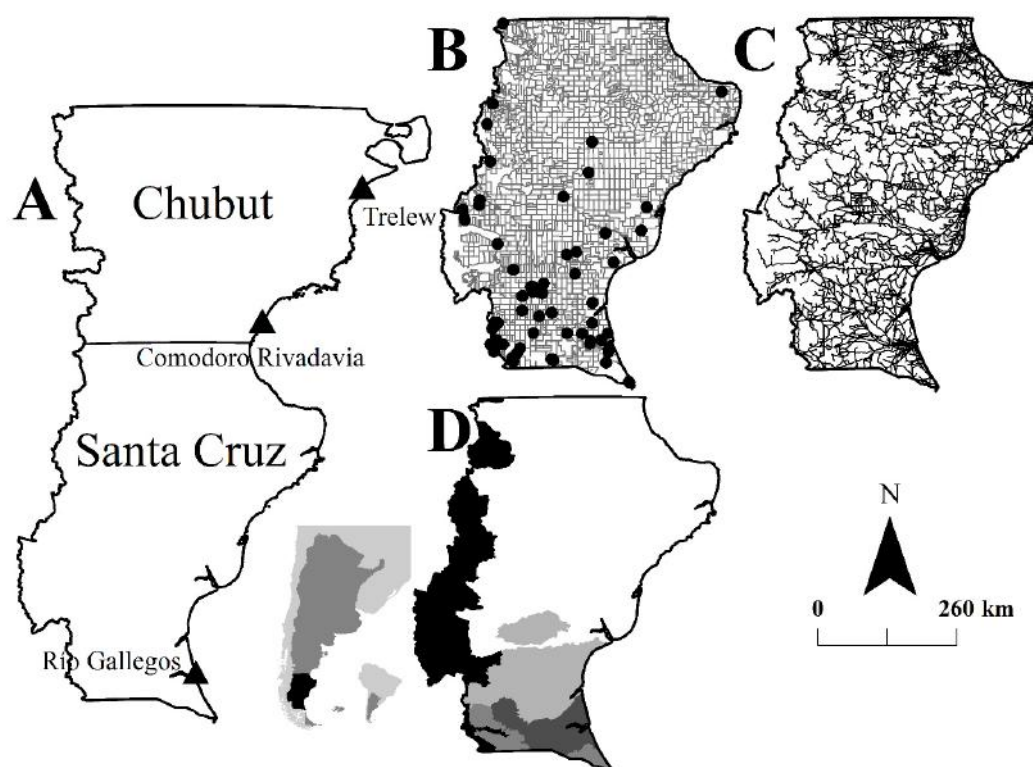


Figure 1. Study area. (A) Location and provinces (light grey = South America, dark grey = Argentina, black = Santa Cruz, black triangles = meat and wool industries); (B) provincial farms cadastre (680 productive sheep farms) and sample sites (black dots); (C) primary and secondary transport routes; (D) ecosystems (light grey = central plateau grasslands, middle grey = mata negra shrubland, grey = humid Magellanic steppe, dark grey = dry Magellanic steppe, black = Andean grasslands).

Table 1. Mean values of main climate and ecosystem variables for each ecosystem category in Santa Cruz province, Patagonia, Argentina.

Ecological Area	AMT (°C)	AP (mm/yr)	NDVI (dimensionless)	ANPP (g C/m ² /yr ¹)	ELE (m.a.s.l.)
Andean region	5.9	442	0.64	286	454
Humid Magellanic steppe	5.4	354	0.54	271	337
Dry Magellanic steppe	6.4	227	0.34	196	166
Mata Negra thicket	6.6	162	0.22	120	299
Central Plateau	8.4	192	0.17	111	315

ATM = mean annual temperature, AP = mean annual precipitation, NDVI = normalized difference vegetation index, ANPP = annual net primary production, ELE = elevation (meters above sea level).

The sheep farms evaluated in the present work are devoted to extensive sheep production, mostly the Corriedale breed. Throughout the year, the animals use different paddocks from May to September (mating and gestation), September to January (lambing and lactation), and January to May (from weaning to mating). Paddock changes are associated with specific activities, such as eye-shearing (May), pre-lambing shearing (September), and marking (January). Paddocks situated above 700 m above sea level are mostly used in summer, because they are covered with snow during the winter season. Lamb production implies a particular nutritional requirement curve, with higher demand before the start of winter to ensure both pregnancy (mating in May) and resistance to winter conditions until spring regrowth. The months before regrowth are critical because they coincide with the last two-month period of sheep gestation, when nutritional requirements increase considerably. The estimation of carrying capacity is based on the biomass production of short grasses and forbs that grow in the space among tussocks of each ecosystem and the requirements of 530 kg DM/yr for one Corriedale ewe of 49 kg of live weight, which represents a Patagonian sheep unit equivalent (PSUE) [14]. The farm and flock structure, the inputs and outputs of the productive system, and the productivity indicators are presented in Table 2.

Table 2. Farm and flock structure, inputs and outputs of the productive system evaluated in Southern Patagonia for carbon footprint calculations.

Farm and Flock Structure	Mean	Range
Farm area (ha)	24,760	20,000–30,000
Breeding ewe flock size (head/farm)	8500	5000–22,500
Stocking rate (PSUE/ha/yr)	0.35	0.20–0.75
Inputs		
Fuel diesel for electricity, tractor, and transportation (l/yr)	15,000	5800–16,000
Gas in tubes (kg/yr)	2700	1600–4900
Firewood and coal for heating (t/yr)	37	21–64
Outputs		
Average live weight of lambs sold (kg)	22.5	20–25
Greasy wool (kg/animal)	4.7	4.2–5.0
Productivity indicators		
Lambing (%)	78	70–90
Lamb growth rate from birth to finishing after 100 days (g/day)	185	170–200
Breeding ewe replacement rate (%)	27	25–30

2.2. Footprint Calculation at Farm Level

Empirical farm data were used to estimate the GHG emissions associated with sheep production on farms in Southern Patagonia. Farmers and rural extensionists provided information on important aspects of the production system, including inputs, animal stock movements, outputs (including number and weight of sheep sold), and farm characteristics.

In the present work, the CF included emissions of the three most important GHGs emitted from agricultural activities: carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄), encompassing both direct and indirect emissions. Direct emissions are those that occur on-farm, directly from mobile combustion and stationary combustion, and directly from fugitive emissions. Indirect emissions are comprised of emissions that occur elsewhere, but are attributable to ranch and industrial phase activities (e.g., those emissions arising from electricity used on-farm and in processing facilities). Although other GHGs such as halocarbons, ozone, and carbon monoxide also contribute to climate change, they are not typically included in analyses of agricultural activities [15].

The carbon footprints were calculated using an updated version of the livestock model used by Edwards-Jones et al. [10] and Taylor et al. [16]. The global warming potentials of emissions were reported relative to CO₂ over a 100-year time horizon, where 1 kg CH₄ = 25 kg CO₂-eq and 1 kg N₂O = 298 kg CO₂-eq [17]. Sheep farms typically produce multiple saleable outputs, necessitating allocation of whole farm emissions amongst products. In this study, the biophysical allocation of emissions (protein requirement ratio) between fiber and meat was assumed to be 67% for live lambs (meat) and 33% for wool production (following Livestock Environmental Assessment and Performance, LEAP [18]). The functional unit used for reporting emissions was 1 kg of live weight (LW) finished lamb and 1 kg of wool.

At farm gate we considered emissions related to the use of fuel (diesel) for internal transport (lightweight trucks on-road and trucks/tractors/all-terrain vehicle off-road) and electric generators, piped gas for cooking, coal and firewood for heating, fugitive emissions from household refrigerators and vehicle air conditioners, and the flows of GHGs into and out of animals, plants, and soils that occur on farms (Figure 2). For direct and indirect emissions associated with mobile combustion, stationary combustion, electricity consumption, and fugitive emissions, standard Intergovernmental Panel on Climate Change, IPCC [17] default emissions factors and equations were utilized when country-specific data were not available.

The measured effect of long-term livestock grazing on C content of the plant-soil grassland system (above-ground biomass, below-ground biomass, litter, and soil organic matter to 30 cm) and soil respiration (autotrophic, Ra and heterotrophic, Rh) of the studied ecosystems was based on previous studies [6,7,19–22]. The net carbon storage at the farm level ranged from 20 to 350 kg C/ha/yr depending on grassland condition and ecological area. The emission and consumption of methane by soils was estimated following Le Mer and Roger's [23] calculations. Animals' GHG emission was estimated in the form of CH₄ from enteric fermentation, and CH₄ and N₂O from manure deposition by animals on grassland (Figure 2). The emission factor used for lambs was 0.13 kg CH₄ per lamb per year from enteric fermentation. Neither nitrogenous fertilizer use nor manure management are practiced in Patagonia sheep farms. The volatile organic carbon (VOC) estimation was based on Kesselmeier and Staudt [24]. Mean direct N₂O emissions from soils over a range of grazed grassland evaluated were estimated to be 2.45–7.62 kg N₂O/ha/yr. This estimation was based on forage quality of grassland that determined a mean N intake of 26 kg N/animal/yr and an annual N excretion rate of 9.5 kg N/animal/yr. The C loss by leaching (range: 1–12 kg C/ha/yr) and soil erosion (range: 1–40 kg C/ha/yr) were calculated based in the methodological approach presented by Chartier et al. [25] (Figure 2). Animal respiration, which ranged in our study from 25.5 to 95.6 kg C/ha/yr, was estimated from previous studies [26–28]. Emissions factors for fossil fuel consumption were based on IPCC [17].

To evaluate the effect of condition of grasslands on C footprint, the long-term intensity of grazing on each farm was estimated by assuming the mean sheep stocking rates for the main five ecosystem types in Santa Cruz [1,29]: (1) Central Plateau Grasslands 0.12 ± 0.02 (moderate grazing) and 0.24 ± 0.10 (overgrazed) ewe/ha/yr, (2) Andean Grasslands 0.40 ± 0.07 (moderate grazing) and 0.75 ± 0.12 (overgrazed) ewe/ha/yr, (3) Humid Magellanic Steppe 0.35 ± 0.08 (moderate grazing) and 0.65 ± 0.11 (overgrazed) ewe/ha/yr, (4) Mata Negra Shrubland 0.17 ± 0.03 (moderate grazing) and 0.52 ± 0.22 (overgrazed) ewe/ha/yr, and (5) Dry Magellanic Steppe 0.26 ± 0.05 (moderate grazing) and 0.22 ± 0.12 (overgrazed) ewe/ha/yr.

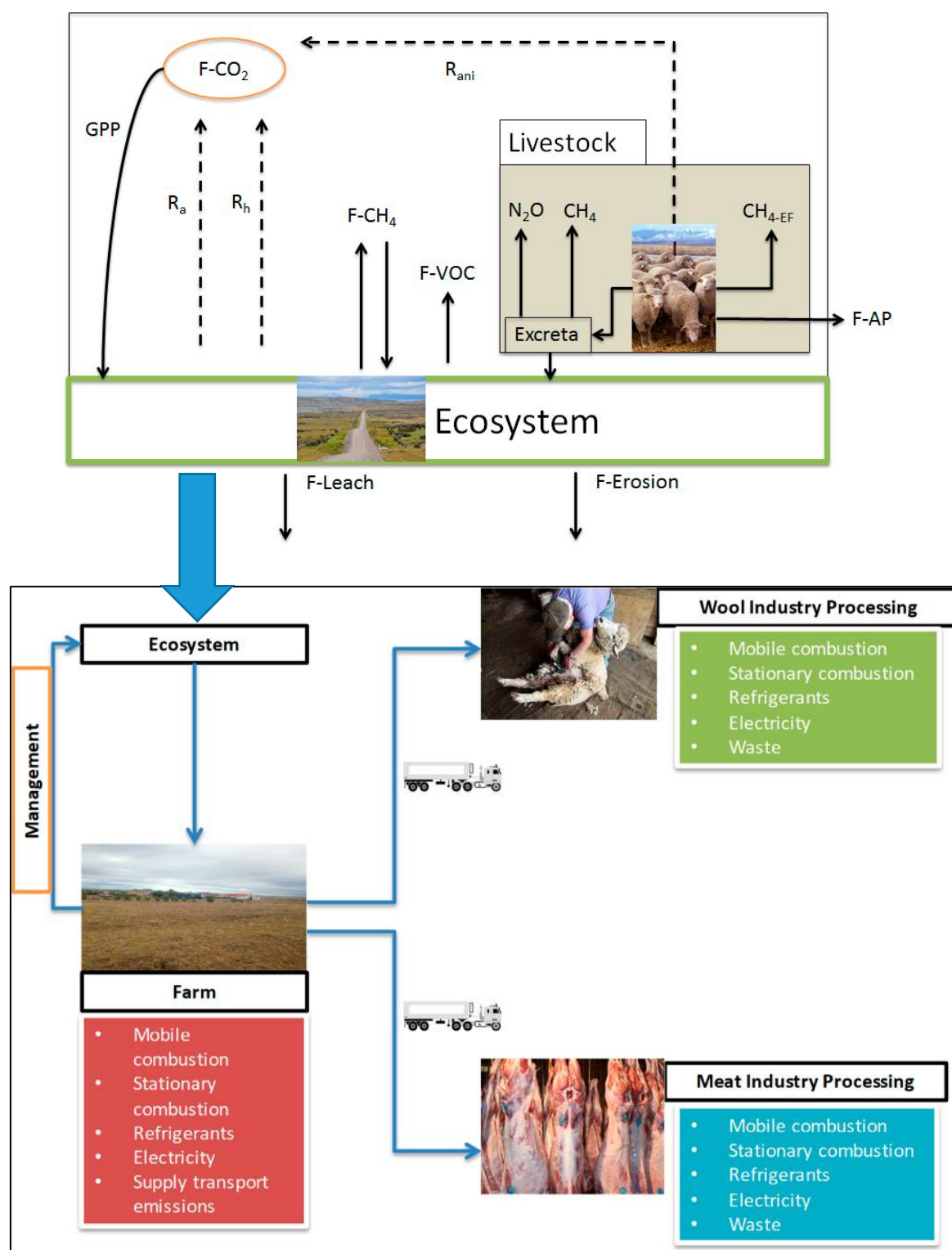


Figure 2. Diagram for the calculation of lamb and wool carbon footprint estimations at farm gate, with transport and processing in Southern Patagonia. $F\text{-CH}_4$ = emission and consumption of methane by soils (kg $\text{CH}_4/\text{ha}/\text{yr}$), $F\text{-VOC}$ = volatile organic carbon from soil (kg C/ha/yr), $F\text{-leach}$ = C leached from top soil to deeper layers (kg C/ha/yr), $F\text{-erosion}$ = C loss for soil erosion (kg C/ha/yr), $F\text{-AP}$ = carbon (kg C/yr) leaving the farm as products (wool + lamb), GPP = gross primary production (kg C/ha/yr), Autotrophic (R_a) and heterotrophic (R_h) respiration in the soil surface CO_2 flux (kg $\text{CO}_2/\text{ha}/\text{yr}$), R_{ani} = sheep respiration (kg C/animal/yr), $\text{NO}_2 + \text{CH}_4$ = C content of manure left in the ecosystem (kg C/ha/yr), $\text{CH}_4\text{-EF}$ = methane emission from enteric fermentation (kg $\text{CH}_4/\text{ha}/\text{yr}$).

2.3. Transport

Transport from farms to meat and wool industry processing plants were selected by choosing the most usual transportation in the region. In one trip, 500 lambs (cargo: 9600–12,500 kg) are transported using a semi-trailer diesel truck with three axles (fuel economy of 2.34 km/liter). To the wool industry, a semi-trailer diesel truck with three axles (flat truck) generally transports 125 greasy wool bales (cargo: 25,000 kg).

2.4. Industry

Inputs and impacts associated with lamb and wool processing (Table 3) were collected from an industry survey. Primary data on energy use, consumables, refrigerant leakage, wastes, and effluent processing were collected from lamb processing plants in Río Gallegos (three factories) and Comodoro Rivadavia (one factory in the neighboring province of Chubut) cities, covering all lambs processed in Santa Cruz province. Total factory production ranged from 600 to 1600 tons of carcasses per year, representing a processing of 60,000–120,000 lambs/yr (Table 3). This corresponds to a meat plant of 2500–11,000 m² with a labor force of 40–160 people. The industry export mainly frozen carcasses as well as in-retail. Key parameters included dressing percentages (i.e., from live animal to hot carcass) of 55%, cutting and chilling losses of 3%, and retail yield (from cold carcass to retail meat) of 76% for bone-in lamb. Allocation of co products at the point of meat processing was: hide 6.1%, blood 4.9%, wool 4.3%, inedible offal 1.8%, and tallow 6.9%.

The wool processing industry, located in Trelew city (Chubut province), processes 7000–8000 t wool annually, but demands more water than the lamb industry (Table 3) mainly to obtain scoured wool (greasy wool that has been washed to remove contaminants, such as dirt, dust, sweat residue, some vegetable matter, and wool grease). The process includes the highest grade wool defined as a continuous, untwisted, ribbon of wool (sliver) produced from the combing machine after the fleece has been scoured and carded. The combing process removes short and weak fibers (noils), leaving long fibers that are aligned parallel to one another. In the present work we estimated the carbon footprint of the finest grade wool, which represents 64% of exports according to the Argentine Wool Federation.

Table 3. Range values of major inputs and structure associated with meat and wool processing used in this study for carbon footprint calculations in Southern Patagonia.

Lamb Industry	Range
Total factory production (t carcass meat/yr)	600–1600
Working capacity (kg meat carcass/day)	10,000–30,000
Fresh water consumption (100% consumptive) (l/t carcass)	6000–8000
Electricity (MWh/yr)	2100–14,500
Natural Gas (m ³ /yr)	70,000–120,000
Diesel (l/yr)	1700–2500
Wool industry	
Total factory output (t wool/yr)	7000–8000
Fresh water consumption (100% consumptive) (l/t wool)	65,000–71,000
Electricity (MWh/yr)	6000–7000
Natural Gas (m ³ /yr)	2,500,000–280,000
Diesel (l/yr)	11,350–14,200

2.5. Footprint Calculation at Regional Level

To determine carbon footprint at the regional scale we developed four maps (kg CO₂-eq/kg): live weight lamb and wool production at farm gate, transport, and industry. To build the live weight lamb and wool production carbon footprint maps on-farm, first we used values from 63 sheep farms, and then we explored 32 potential explanatory variables (Table 4), which were rasterized at 90 × 90 m resolution using the nearest resampling technique on ArcMap 10.0 software [13]. Climatic variables

($n = 21$) [30] included temperature, precipitation, and indexes of annual, monthly, or seasonal variations, global potential evapo-transpiration and global aridity index [31]. Topography variables ($n = 8$) included elevation, slope [32], and aspect [33]. Also, Euclidean distances to population center, lakes, rivers, and roads were calculated using shape files obtained from Sistema de Información Territorial (SIT) Santa Cruz (<http://spm.sitsantacruz.gob.ar>). Finally, landscape metrics ($n = 3$), including the normalized difference vegetation index (NDVI) [34], net primary productivity (NPP) of year 2015 [35] and desertification [36] were tested as explanatory variables.

Table 4. Explanatory variables used in the carbon footprint analysis of live weight lambs and wool.

Category	Description	Code	Unit	Data Source
Climate	mean annual temperature	AMT	°C	WorldClim(1)
	mean diurnal range	MDR	°C	WorldClim(1)
	isothermality	ISO	%	WorldClim(1)
	temperature seasonality	TS	°C	WorldClim(1)
	max temperature of warmest month	MAXWM	°C	WorldClim(1)
	min temperature of coldest month	MINCM	°C	WorldClim(1)
	temperature annual range	TAR	°C	WorldClim(1)
	mean temperature of wettest quarter	MTWEQ	°C	WorldClim(1)
	mean temperature of driest quarter	MTDQ	°C	WorldClim(1)
	mean temperature of warmest quarter	MTWAQ	°C	WorldClim(1)
	mean temperature of coldest quarter	MTCQ	°C	WorldClim(1)
	mean annual precipitation	AP	mm.years-1	WorldClim(1)
	precipitation of wettest month	PWEM	mm.years-1	WorldClim(1)
	precipitation of driest month	PDM	mm.years-1	WorldClim(1)
	precipitation seasonality	PS	%	WorldClim(1)
	precipitation of wettest quarter	PWEQ	mm.years-1	WorldClim(1)
	precipitation of driest quarter	PDQ	mm.years-1	WorldClim(1)
	precipitation of warmest quarter	PWAQ	mm.years-1	WorldClim(1)
	precipitation of coldest quarter	PCQ	mm.years-1	WorldClim(1)
	global potential evapo-transpiration	EVTP	mm.years-1	CSI (2)
	global aridity index	GAI		CSI (2)
Topography	Elevation (meters above sea level)	ELE	m.a.s.l.	DEM(3)
	slope	SLO	°	DEM(3)
	aspect cosine	ASPC	cosine	DEM(3)
	aspect sine	ASPS	sine	DEM(3)
	distance to population centers	DL	km	SIT Santa Cruz(4)
	distance to lakes	DLK	km	SIT Santa Cruz(4)
	distance to rivers	DR	km	SIT Santa Cruz(4)
	distance to roads	DW	km	SIT Santa Cruz(4)
Landscape and land use	normalized difference vegetation index	NDVI		MODIS(5)
	annual net primary productivity	ANPP	g C.m ² .year ⁻¹	MODIS(6)
	desertification	DES	degree	CENPAT(7)

(1) Hijmans et al. [30], (2) Consortium for Spatial Information (CSI) [31], (3) Digital Elevation Model (DEM), Farr et al. [32], (4) SIT Santa Cruz (<http://www.sitsantacruz.gob.ar>), (5) Moderate Resolution Imaging Spectroradiometer (MODIS), ORNL DAAC [34], (6) Zhao et al. [35], (7) Centro Nacional Patagónico (CENPAT), Del Valle et al. [36].

We used stepwise multiple regressions to identify which variables helped to explain the carbon footprint of live weight lamb and wool animal production (kg CO₂-eq/kg) at landscape level. We employed $p < 0.05$ for the significance probability for each regression statistic to be included into the model, and used 500 steps for the final model selection. The model was evaluated through the standard error (SE) of estimation (the r^2 -adj), defined as the average of the difference between

predicted versus observed values, and the mean absolute error (AE), defined as the average of the difference between predicted versus the observed absolute values (Statgraphics Centurion software, Statpoint Technologies, The Plains, VA, USA).

To test the model, we performed a calibration procedure by analyzing the mean and absolute errors (differences between observed and modeled values of the carbon footprints of live weight lamb and wool animal, expressed as kg CO₂-eq/kg) (Appendix A). Also, we performed simple and two-way ANOVAs (Analysis of Variance) and Tukey tests post-hoc, considering ecosystem classification and land use intensity.

With the carbon footprint of live weight lamb and wool (kg CO₂-eq/kg) models, we obtained two final maps for the entire Santa Cruz province (Argentina), where the variables derived from the multiple linear regression models were integrated into a geographical information system (GIS) using ArcMap 10.0 software. Then we applied a screening criteria to remove areas with: (i) NDVI < 0.05, which included glaciers, water bodies, rocks, and areas without vegetation cover [37], (ii) elevation > 1200 m.a.s.l., where livestock activities are not practiced due to extreme climate, and (iii) natural protected areas.

To build maps of the carbon footprints (kg CO₂-eq/kg) of live weight lamb and wool animal transport, first we calculated the accumulated distances (km) from each pixel in the map to the industrial processing facilities (origin of the production to the final destination in the local industry). For this, we defined Río Gallegos and Comodoro Rivadavia as the final destinations for live lambs, and Trelew as the final destination for greasy wool. The modeling was performed considering for each pixel the Euclidean distance to the closest road and the accumulated minimum distance to the final destination of the existing road network. Each map was the combination of the accumulated minimum distance and the Euclidian distance. When two possible destinations existed, the modeling selected the minimum distance (e.g., Río Gallegos or Comodoro Rivadavia). Finally, we applied the same mask to remove areas without analysis, as was applied in the carbon footprint production analyses. The accumulative distances (km) to Río Gallegos ranged from 0 to 973 km, for Comodoro Rivadavia they ranged from 24 to 978 km, and for Trelew from 412 to 1366 km. The final two maps of carbon footprints were the combination of production, transport, and processing of live lamb and wool.

For the map of CF of live lambs resulting values were assigned to three categories: (i) low (10.64–32.47 kg CO₂-eq/kg), (ii) middle (32.48–3.05 kg CO₂-eq/kg), and (iii) high (36.06–41.32 kg CO₂-eq/kg). For the carbon footprint of greasy wool resulting values were allocated to the following: (i) low (7.83–16.42), (ii) middle (16.43–17.02), and (iii) high (17.03–18. kg CO₂-eq/kg). The limits of each CF class were defined so that each category contained an equal quantity of pixels for the whole province. We analyzed the two maps of CF, considering climatic, topographic, and vegetation variables (Table 4) to determine differences among categories using a hexagonal binning processes (each hexagon = 250,000 ha) and also one-way ANOVAs and Tukey post-hoc test.

3. Results

3.1. Carbon Footprint (CF) at Farm Level

The CF of lamb at the farm gate varied between 12.15 and 38.45 kg CO₂-eq/kg live weight lamb produced (Table 5). The CF of wool on-farm ranged from 7.83 to 16.92 kg CO₂-eq/kg greasy wool (Table 5).

Table 5. Carbon footprint of live weight lamb and greasy wool at farm gate in different ecological areas of Santa Cruz province (Southern Patagonia, Argentina) under two contrasting grassland conditions.

Ecological Area	Grassland Condition	kg CO ₂ -eq/kg Live Weight Lamb	kg CO ₂ -eq/kg Greasy Wool
Andean region	Overgrazed	13.92	8.82
	Good	12.15	7.83

	Mean	12.85	8.15
Humid Magellanic Steppe	Overgrazed	23.55	12.37
	Good	15.42	11.46
	Mean	20.64	12.15
Dry Magellanic Steppe	Overgrazed	26.05	13.74
	Good	16.02	12.43
	Mean	22.74	13.28
Mata Negra Thicket	Overgrazed	33.31	14.66
	Good	22.71	13.29
	Mean	30.11	14.15
Central Plateau	Overgrazed	38.45	16.92
	Good	25.87	15.13
	Mean	35.16	16.33

On-farm emissions, the largest contributors to the CF (75–90% of total carbon footprint) were determined by natural processes associated with sheep utilizing grasslands as a feed source. These processes included methane production from rumen digestion of grass and herbs via enteric fermentation, which account for 60–65% of the carbon footprint. The direct and indirect N₂O emissions represented 27–30% of the total on-farm carbon footprint. Emissions from external inputs, such as fuel and electricity, only accounted for a small percentage of the carbon footprint (7–8%) of sheep farming in Patagonia.

3.2. Transport, Meat, and Wool Processing

Transport emissions ranged from 0.30 to 0.95 kg CO₂-eq/kg product/km. Depending on distances to industrial processing facilities, they represented from 3% to 15% of the total carbon footprint.

The mean CF of lamb after processing was 3.31 kg CO₂-eq/kg of product (carcass), and ranged from 1.52 to 4.40 kg CO₂-eq/kg of product depending on the size and efficiency of the industrial processing facility. Meat processing made up 6–10 percent of the total lamb carbon footprint. This was mainly from energy use (electricity: 76–91% of total carbon footprint of the processing plant and fuel: 4–14%) and wastewater processing (5–10%). A range of fossil fuels are used across different processing facilities, largely for hot water and steam. The main use of electricity is for chilling and freezing meat. Electricity is also used to operate machinery, for lighting, and wastewater treatment. Methane and nitrous oxide are emitted during some wastewater processes.

The mean CF of fine-grade wool after processing was 1.20 kg CO₂-eq/kg of product. Wool processing made up only 2–5 percent of the total lamb carbon footprint. This was mainly from fuel (55% of total carbon footprint in the wool processing factories), purchased electricity (28%), and wastewater processing (17%).

3.3. Carbon Footprints (CF) at Regional Level

Modeling of CF (kg CO₂-eq/kg live weight) for lambs at the farm gate that used a stepwise multiple regression procedure identified a regression model with two important independent variables: temperature seasonality (TS) and normalized difference vegetation index (NDVI, dimensionless). The fitted model (r^2 -adj = 0.955; F = 660.8; SE = 5.06; AE = 4.32) explained 95.5% of variation in CF of lamb and had the following form:

$$\text{Carbon footprint lamb (kg CO}_2 \text{ eq/kg live weight lamb)} = 7.55791 \cdot \text{TS} - 21.6853 \cdot \text{NDVI} \quad (1)$$

The most important variables for the model of CF of greasy wool production were isothermality (ratio of average day variation in temperature divided by annual variability in temperature) (ISO, %), temperature seasonality (TS), and normalized difference vegetation index (NDVI, dimensionless).

The fitted model ($r^2\text{-adj} = 0.987$; $F = 1607.5$; $SE = 1.41$; $AE = 1.05$) explained 98.7% of variation in CF of greasy wool and had the following form:

$$\text{Carbon footprint Wool (kg CO}_2\text{ eq/kg greasy wool)} = 0.23941 \cdot \text{ISO} + 1.21981 \cdot \text{TS} - 10.5486 \cdot \text{NDVI} \quad (2)$$

When univariate correlations were performed these variables correlated strongly with the CFs of lamb and wool and there was no evidence of collinearity between them ($p < 0.001$).

The map of the adjusted CF of live weight lamb production at farm gate model showed a continuous increase from west-southwest to the northeast and central areas of Santa Cruz province (variation from 7.17 to 37.95 kg CO₂-eq/kg live weight lamb) (Figure 3). The map of the CF of wool production on-farm across Santa Cruz exhibited similar spatial trend to the pattern for lamb and ranged from 5.40 to 16.42 kg CO₂-eq/kg greasy wool (Figure 4). The lowest CF values of both products (lamb and wool) were located in more productive grasslands.

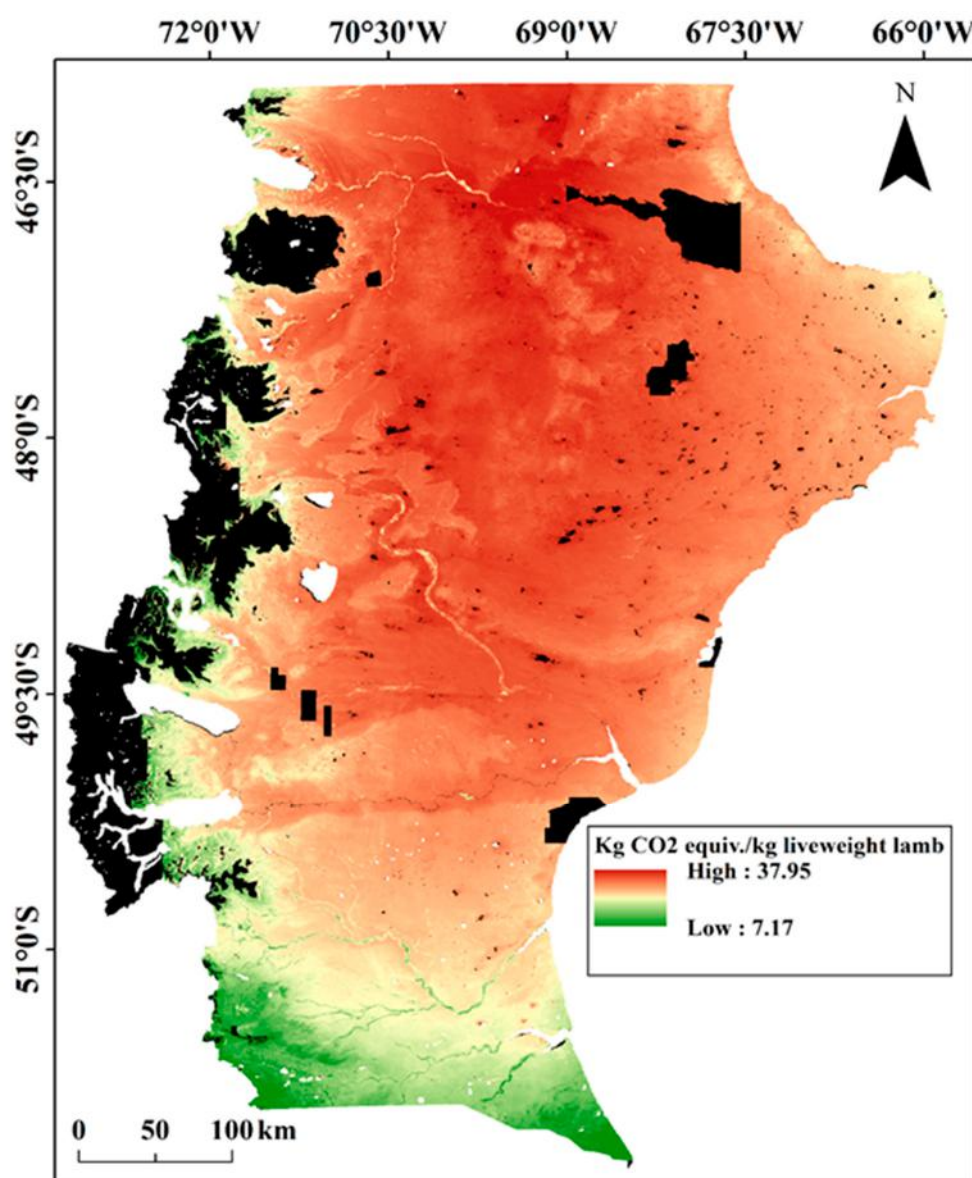


Figure 3. Carbon footprint of lamb production (kg CO₂-eq/kg live weight lamb) at farm gate in Santa Cruz province, South Patagonia, Argentina. Black areas represent NDVI < 0.05, elevation > 1200 m.a.s.l., and natural protected networking areas where there are no livestock.

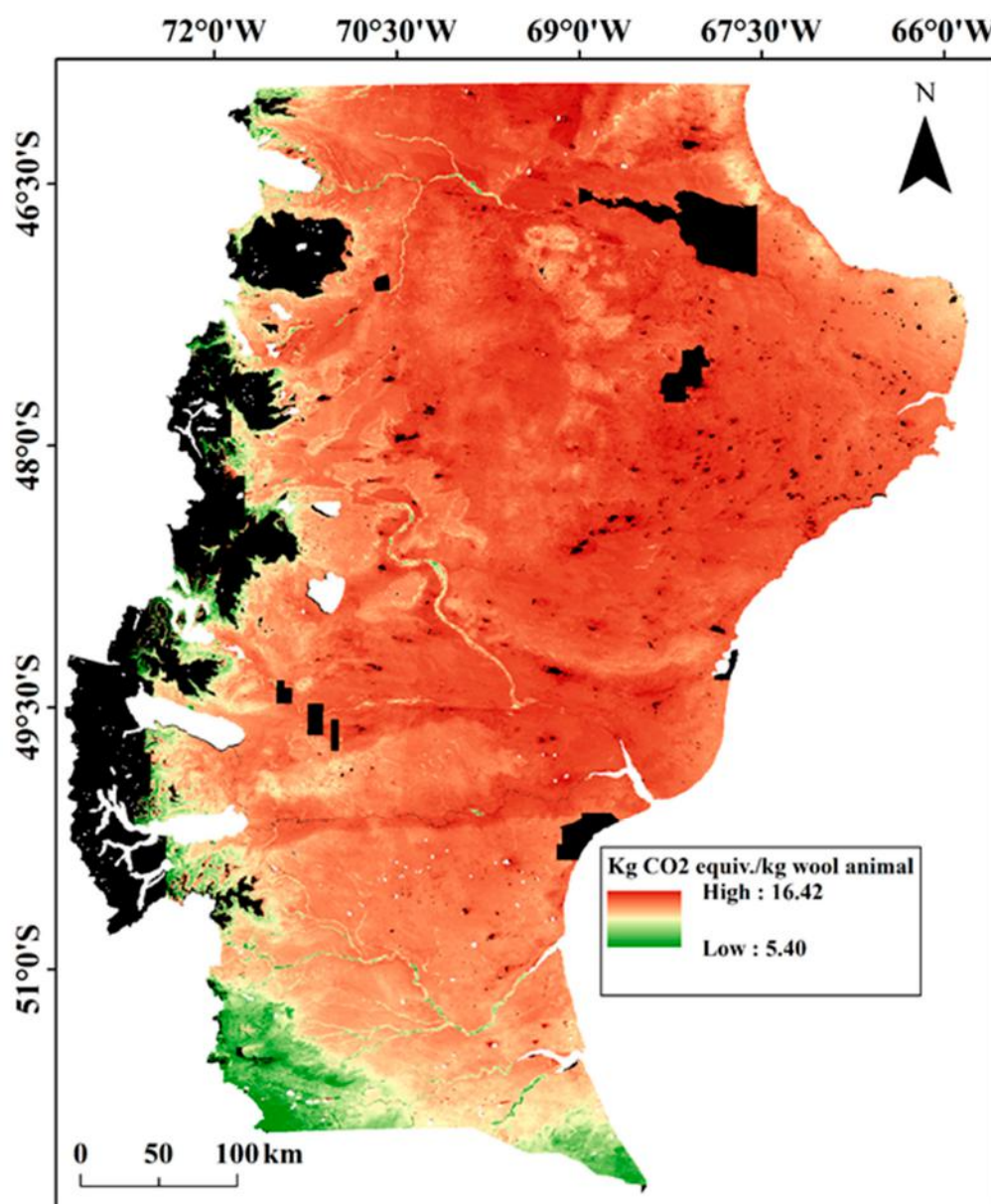


Figure 4. Carbon footprint map of greasy wool production (kg CO₂-eq/kg wool) at farm gate in Santa Cruz province, South Patagonia, Argentina. Black areas represent NDVI < 0.05, elevation > 1200 m.a.s.l., and natural protected networking areas where there are no livestock.

When assessed on a univariate basis the majority of the independent variables considered in this analysis presented significant correlations with the CF of lamb and greasy wool production (Figures 5 and 6). At low Mean Annual Temperature (MAT), for example, the CF at farm gate of meat and wool production was also low (Figure 5). Other related temperature variables showed similar correlations with the CFs (TS, MAXWM, MINCM, MTDQ, MTWAQ, MTCQ, TAR, MDR). MTWEQ did not present a clear pattern of variation, and the CF was high at low values of isothermality (ISO). Rainfall (MAP) also influenced the CF of lamb and greasy wool at farm gate. A low CF occurred at higher precipitation (Figure 6). The correlation between CF and other rainfall variables (PWEM, PDM, PWEQ, PDQ, PWAQ, PCQ) followed a similar pattern. CF values decreased with evapotranspiration (EVTP). CF values were generally low where slope values were high, and there was no correlation, either positive or negative, of elevation with the CFs. As normalized difference vegetation index (NDVI) and net primary productivity (NPP) increased, values of lamb and wool CF at farm gate decreased (Figure 6).

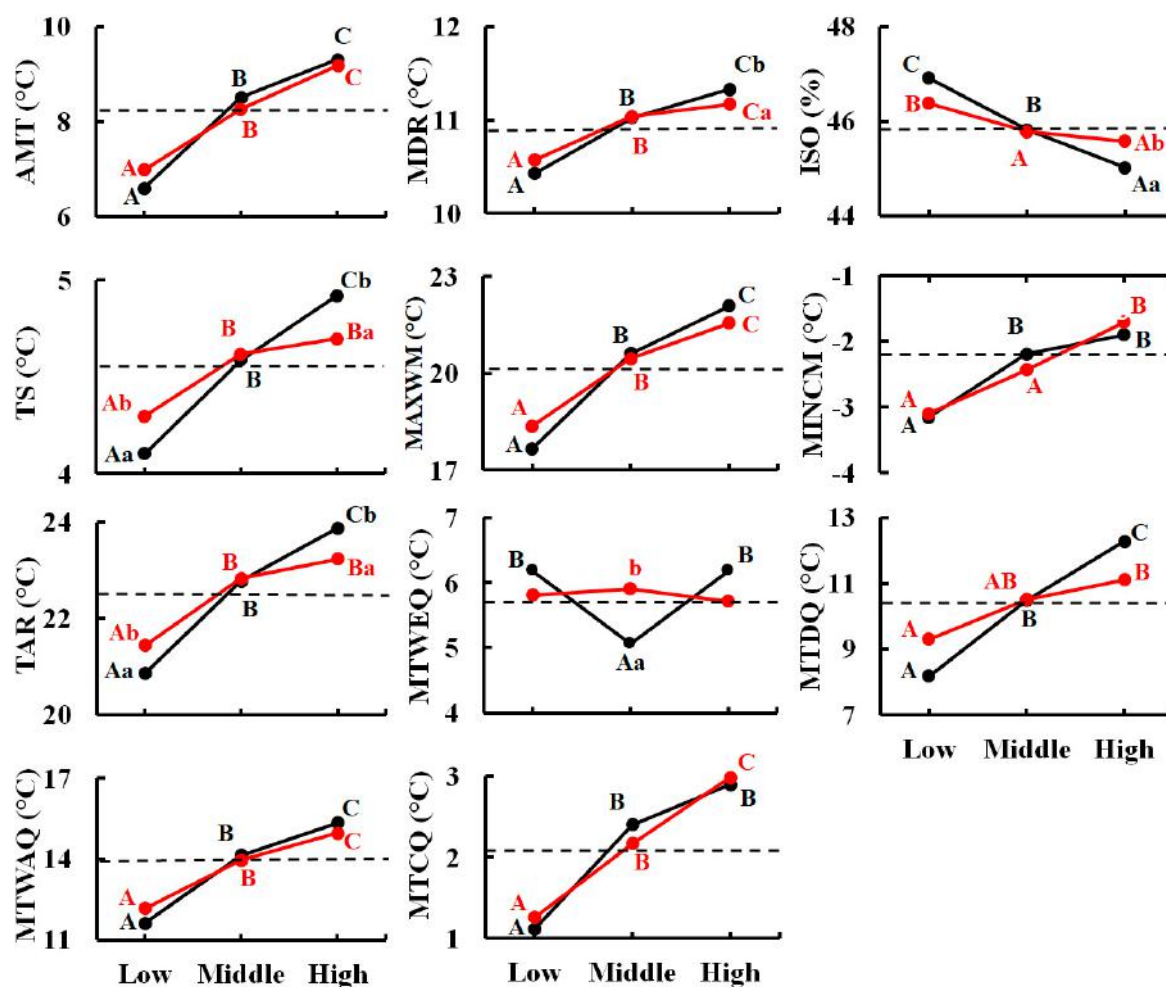


Figure 5. Mean values of carbon footprint at farm gate (kg CO₂-eq/kg product) for the Santa Cruz province (dotted line) and ANOVAs for temperature (°C) variables classified according to the carbon footprint map for live weight lamb (black) and wool (red). Capital letters show differences among carbon footprint map classes (low, middle, and high) and lowercase letters show differences between products (lamb and wool) using Tukey test at $p < 0.05$.

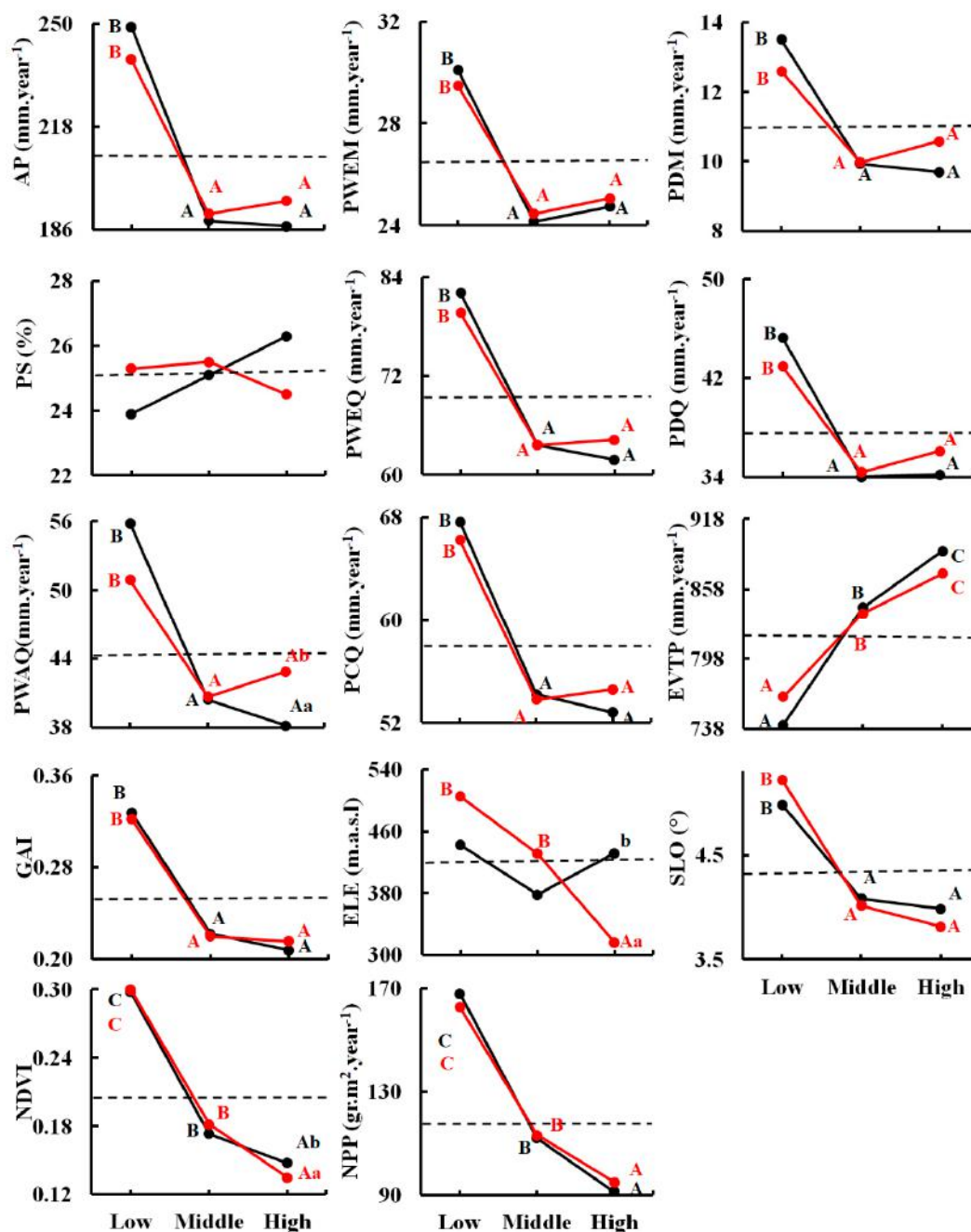


Figure 6. Mean values of carbon footprint at farm gate (kg CO₂-eq/kg product) for the Santa Cruz province (dotted line) and ANOVAs for precipitation, topographic, and vegetation variables classified according to the carbon footprint map of live weight lamb (black) and wool (red). Capital letters show differences among carbon footprint map classes (low, middle, and high) and lowercase letters show differences between products (lamb and wool) using the Tukey test at $p < 0.05$.

The final maps at regional level of total CF of lamb and wool were obtained from the combination of emissions from on farm production, transport, and industrial processing. The total CF of lamb production varied from 10.64 to 41.32 kg CO₂-eq/kg for lamb meat (carcass) (Figure 7) and for fine-grade wool from 7.83 to 18.70 of kg CO₂-eq/kg wool (Figure 8).

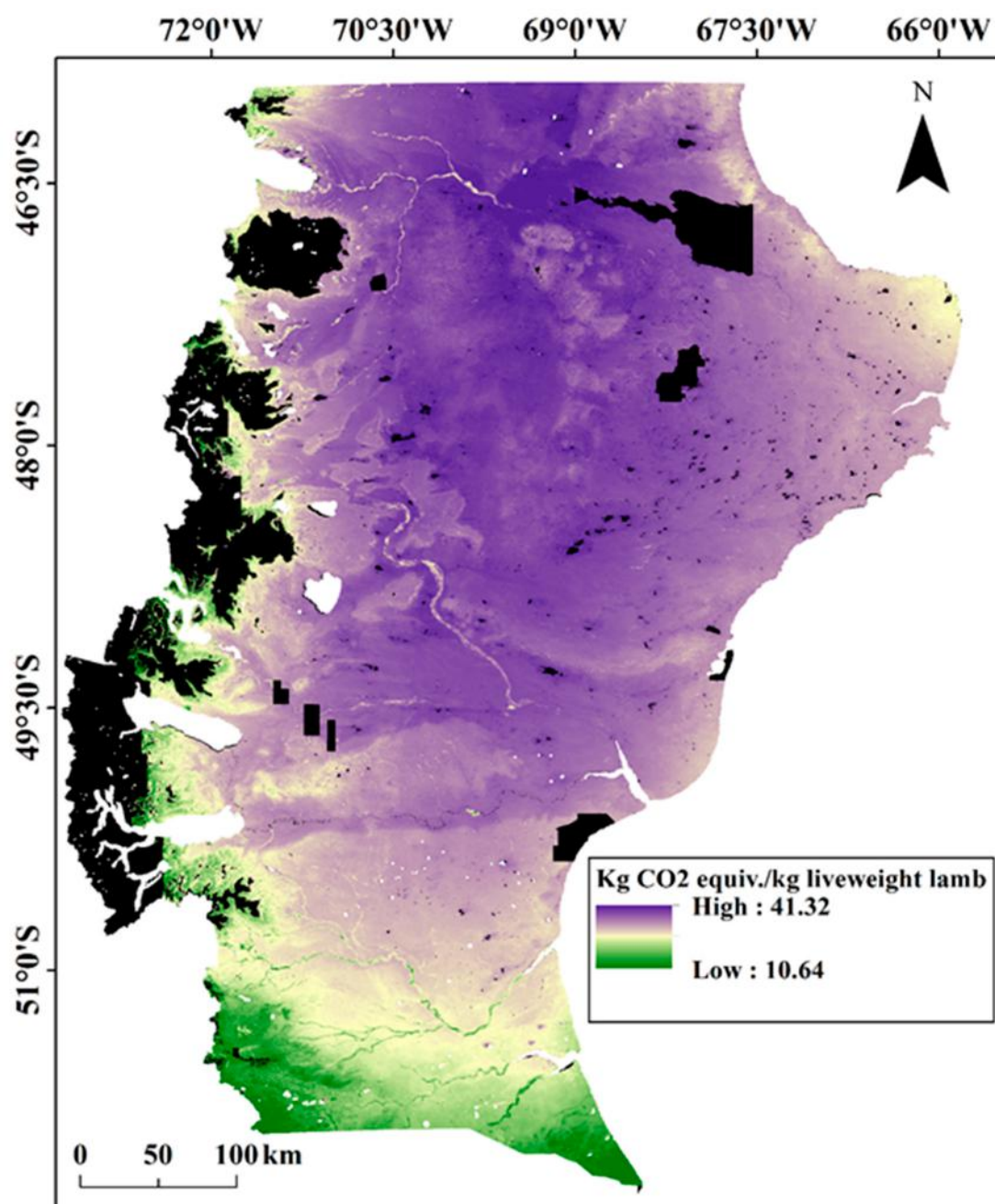


Figure 7. Total carbon footprint (the combination of emissions produced on farm, via transport and via industrial processing) of lamb production (kg CO₂-eq/kg lamb carcase) in Santa Cruz province, South Patagonia, Argentina. Black areas represent NDVI < 0.05, ELE > 1200 m.a.s.l., and natural protected areas where there are no livestock.

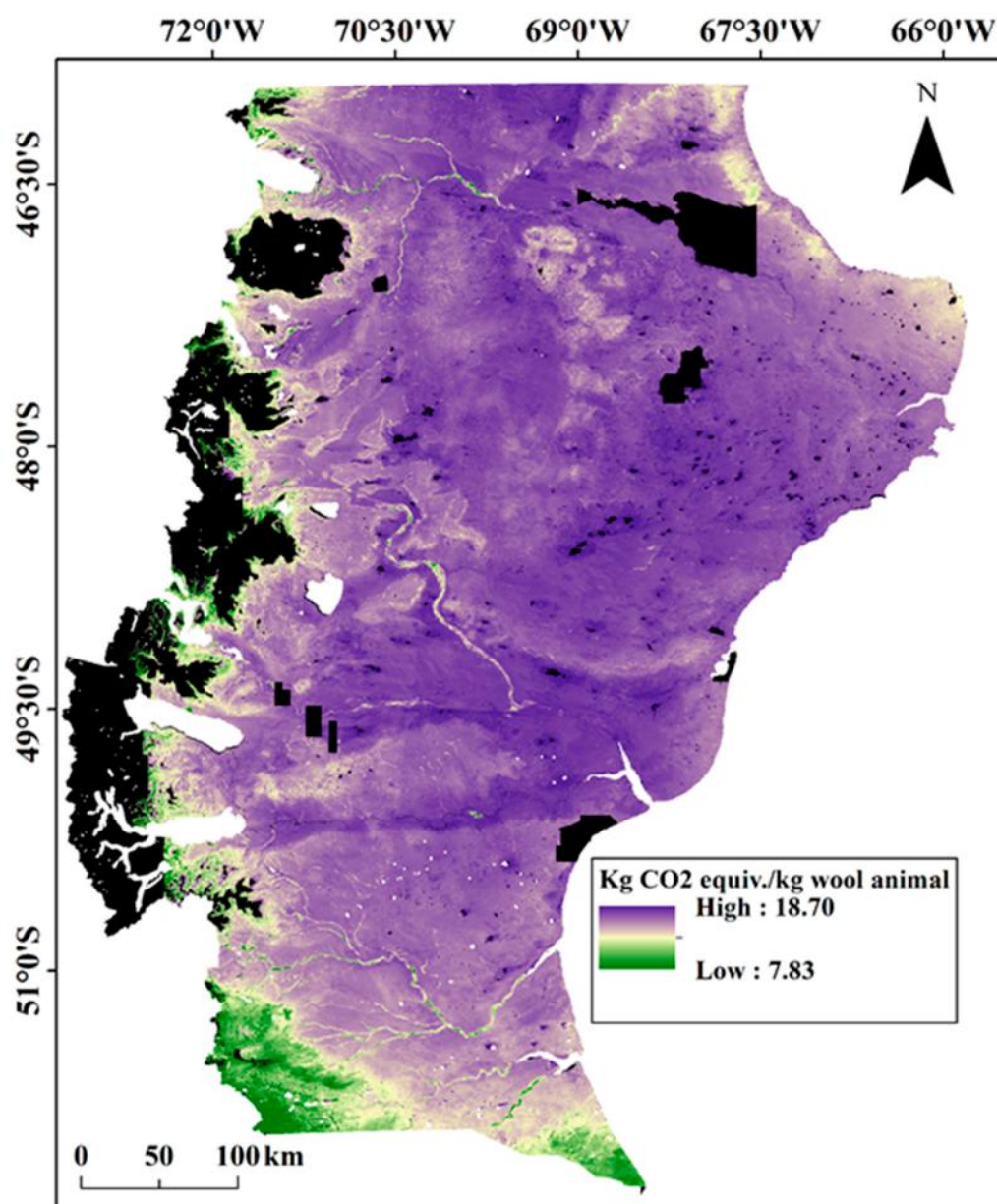


Figure 8. Total carbon footprint (the combination of emissions produced on farm, via transport and via industrial processing) of fine grade wool (kg CO₂-eq/kg wool) in Santa Cruz province, South Patagonia, Argentina. Black areas represent NDVI < 0.05, ELE > 1200 m.a.s.l., and natural protected areas where there are no livestock.

The mean total CF across Santa Cruz province was 33.25 kg CO₂-eq/kg for lamb meat (carcass), segmented into 90% for the on-farm stage, 1% for transportation, and 9% for meat processing (Figure 9). For wool, the mean provincial total CF was 16.45 kg CO₂-eq/kg for fine grade wool, segmented into 88% for the on-farm stage, 5% for transportation, and 7% for wool processing (Figure 9).

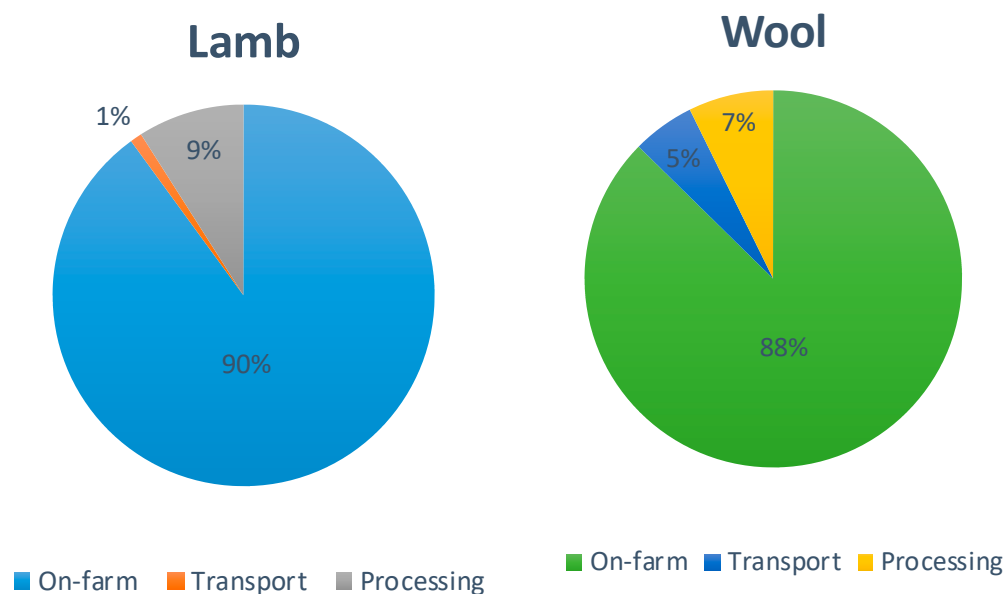


Figure 9. Relative contribution (as a proportion) to mean total carbon footprint (kg CO₂-eq/kg product) of lamb meat (carcass) and fine-grade wool in Santa Cruz province, South Patagonia, Argentina.

4. Discussion

Variability in gas emissions between farms can be attributed to differences in grassland condition, that in turn can be related to long-term grazing management and climate conditions. Our models for CF prediction of lamb and greasy wool at the farm gate were able to account for 95–98% of the variation of CFs across the entire Santa Cruz province. In the present study, CFs were mainly a function of climate (isothermality and temperature seasonality) and vegetation (normalized difference vegetation index, NDVI). Also, the prediction and mapping of CF at the macro scale is possible using freely available geospatial data. The correlation between CFs and climate variables may reflect the influence of climate variables on semi-arid ecosystem productivity, which is mainly related to water limitation. In this work, production from grassland in good ecological condition in the Andean grasslands had significantly lower CF for lamb and greasy wool than production on overgrazed and ecologically degraded sites in the less productive Central Plateau Grasslands. Thus, the climate, the topography, and the vegetation all influenced CF, and all interacted with grazing intensity in the long-term. The variation in CFs from meat and wool production across the province may reflect the impact of harsh environmental conditions (low temperature and drought). Production of meat and wool on low-productivity grasslands had relatively high CFs, whereas CFs on more productive grasslands (higher NDVI and NPP) tended to be lower. This is consistent with Jones et al. [38], who reported an increase in lamb CF from lowland intensive flocks to more extensive flocks in the uplands and hills, and this difference was attributable to the number of lambs reared per ewe mated and lamb growth rates calculated from empirical data collected from 64 sheep farms across England and Wales. Similarly, Ripoll-Bosch et al. [39] reported a lamb CF that ranged from 19.5 kg CO₂-eq/kg LW in productive high-intensity grazing areas to 25.9 kg CO₂-eq/kg LW under extensive management in less favorable areas in Spain. These results showing a lower CF from higher productivity grazing systems parallel to some degree the results on land sharing versus land sparing, which demonstrated that increasing food production could probably be achieved at the least cost to biodiversity by investing in high-yield agriculture on relatively small extensions of land and sparing completely other tracts of land [40]. The fact that CFs appear to be lower in these high-productivity grazing systems is another compelling reason to consider the land sparing strategy. However, additional criteria, such as the tendency for species at risk of extinction to be concentrated on

productive land [41], needs to be integrated in a systematic way into these types of analysis and decision-making.

In the present study the CF from lamb and greasy wool production was always greater, in all five types of ecosystem studied, when said production took place on degraded/overgrazed grassland (Table 5). This has been recognized by Schonbach et al. [42], who reported that sheep grazing on Inner Mongolian Steppe changed the net GHG balance of the grassland from a significant sink at ungrazed sites ($-1476 \text{ kg CO}_2\text{eq/ha/yr}$) to a significant source at heavily grazed areas ($3115 \text{ kg CO}_2\text{eq/ha/yr}$), predominantly determined by respiratory losses of CO_2 from topsoil organic carbon. Higher losses of carbon from topsoil on overgrazed sites is also the case in the Patagonian sites [1].

4.1. Comparison of the Patagonian Data with Data from Other Regions

The synthesis of results from previous studies of CFs in grazing systems is made difficult by the fact that significant methodological differences exist between studies. The CFs are derived from different models and/or use different system boundaries. In Table 6 we present lamb CF data at farm gate from other countries. In the present study, the CF of lamb at the farm gate varied between 12.2 and 38.4 $\text{kg CO}_2\text{-eq/kg}$ live weight lamb using empirical data collected on-farm, and from 7.2 to 37.9 $\text{kg CO}_2\text{-eq/kg}$ live weight lamb when estimates were obtained from the fitted regional model (map). When comparing with the international literature, the values in the present work overlapped with most of the other published data (Table 6). For example, our data were in the range of those reported by Edwards-Jones et al. [10] for lamb production in Wales. However, in Santa Cruz province most of the farms (75% of the total province area) showed values $> 33 \text{ kg CO}_2\text{-eq/kg}$ live weight lamb (Figure 3), which is higher than those from the literature (Table 6). This may be due to differences in on-farm management systems and the fact that Patagonian grasslands have low levels of primary productivity due to the extreme climate. The low $\text{CO}_2\text{-eq}$ values found in New Zealand [43] may reflect a higher wool production per ewe and the fact that wool is economically more important for producers in New Zealand than in other countries. Furthermore, it has been reported that emission of CH_4 increases as feed digestibility decreases [44]. The low digestibility of grasses in Patagonia ($49 \pm 5.5\%$) may have increased CH_4 emissions at farm level compared with the more intensive productive grazing systems common in New Zealand. Furthermore, in the case of New Zealand the economic focus is on wool production, instead of meat [43], and this also may have contributed to the lower carbon footprint in New Zealand.

The choice of models to calculate carbon footprints may also explain some of the discrepancy between results from Patagonia and the results reported in the wider literature. According to Wiedemann et al. [45,46], GHG emissions based on mass balance calculations resulted in 10–12 $\text{kg CO}_2\text{-e/kg}$ greasy wool across Merino farms (New Zealand, Australia, and UK), whereas this value increases to 24–38 $\text{kg CO}_2\text{-e/kg}$ greasy wool when emissions from sheep are made using physiological-based process models that include, for example, enteric methane liberation from the digestion of grass. In Western Australia, for example, Eady et al. [47] found for a mixed sheep and grain farm that mass balance calculations gave a result of 28.7 $\text{kg CO}_2\text{-eq/kg}$ greasy wool while a more sophisticated model that included sheep physiology gave a value of 36.2 $\text{kg CO}_2\text{-eq/kg}$ greasy wool. This highlights method selection when considering GHG mitigation approaches.

Table 6. Estimates of lamb ($\text{kg CO}_2\text{-eq/kg}$ live weight lamb) and greasy wool ($\text{kg CO}_2\text{-eq/kg}$ wool) at farm level carbon footprints reported in the literature.

System and Methods	Country	Carbon Footprint ($\text{kg CO}_2\text{-eq/kg}$ product)	Reference
Lamb			
Conventional extensive with real farm data	Patagonia, Argentina	12.2–38.4	This study
Modeled at the regional scale		7.2–37.9	This study

Conventional with real farm data	Wales, UK	8.1–31.7	Edwards-Jones et al. [10]
Average sheep system in Ireland	Ireland	10	Casey and Holden [48]
Conventional with real farm data (lowland—27 farms, upland—12 farms, hill—21 farms)	UK	10.8–17.9	Jones et al. [38]
Model and real farm data (three systems)	Spain	19.5–25.9	Ripoll-Bosch et al. [39]
Survey from 104 farms	France	12.9	Gac et al. [49]
Model	Australia	10.1–21.7	Bell et al. [50]
Model	Australia	14.4	Wiedemann et al. [45]
Survey from 437 farms	New Zealand	8–10	Ledgard et al. [43]
Experimental study sites with different grazing intensity levels	Northern China	10.4–92.0	Schonbach et al. [42]
Greasy wool			
Conventional extensive with real farm data	Patagonia, Argentina	7.8–16.9	This study
modeled at the regional scale		7.8–18.7	This study
Study cases	Australia, New Zealand, UK	10–12	Wiedemann et al. [46]
Farm-scale data in three contrasting regions	Australia	19.5–25.1	Wiedemann et al. [51]
Study case	Australia	36.2	Eady et al. [47]
Inventory data for two Merino farms and model	Australia	8.5–8.7	Cottle and Cowie [52]
4941 breeding ewe enterprise on 1000 ha	Australia	14.8–24.9	Brock et al. [53]

4.2. Industrial Processing

The mean CF of lamb after processing by industrial facilities (abattoirs) ranged from 1.52 to 4.40 kg CO₂-eq/kg carcass (6–10% of total carbon footprint) and for fine-grade wool it was 1.20 kg CO₂-eq/kg of product (2–5% of total carbon footprint). These values depend on the size and efficiency of the processing plant. There are opportunities for meat processors to reduce this contribution further, particularly with regard to energy used for refrigeration, water heating, and operation of machinery, and also by improving wastewater management [45]. Nevertheless, the CF improvements that can be achieved through improved industrial processes are small. In the wool industry in Australia, the most effective strategies for reducing greenhouse gas emissions have been achieved by improving grazing management and through genetic improvement programs that increase wool yield [54].

4.3. Carbon Footprints (CF) at Regional Level

Total CF of lamb and wool (the combination of emissions produced on farm, via transport, and via industrial processing) varied from 10.64 to 41.32 kg CO₂-eq/kg for lamb meat (carcass) and from 7.83 to 18.70 of kg CO₂-eq/kg for fine-grade wool. On-farm emissions represented the largest contribution to the CF (75–90% of the total), mainly attributable to methane from rumen digestion of grass (enteric fermentation), which accounted for 60–65% of the CF. Transport represented 3–15%, meat processing 6–10%, and wool processing 2–5% of the total CF. This is consistent with Wiedemann et al. [46], who reported in an analysis of Australian red meat export supply chains that lamb primary production was the main source of greenhouse gases, accounting for 90% of said emissions, from which 75% of emissions were from enteric methane production. Meat processing (6%) and transportation (4%) were only minor sources of greenhouse gases. Similarly, for New Zealand lamb production, greenhouse gas emissions are dominated by the production phase of the supply chain [43]. Cottle and Cowie [52] also reported that for Merino wool production total GHG emissions are dominated (76–79%) by livestock (enteric methane production and methane and nitrous oxide emissions from manure), with emissions from purchased inputs, transport, and services contributing 13–14%. Thus, on-farm emissions are the most significant contributor to the footprint and also the most challenging to reduce. Improvements on-farm through management interventions that increase the conversion of forage to meat (genetics/breeding) are important [52]. In New Zealand, improvement of the carbon footprint in the sheep sector is occurring through an increase in the proportion of ewe hoggets mated, resulting in more lamb production for each kilogram of feed eaten by the sheep flock [43]. Other alternatives are related to feeding management, where practices increasing feed efficiency and animal performance generally reduce CH₄ emissions [55]. For example, feed supplements in cows with unsaturated lipids usually decrease CH₄ emissions [56]. Also, a number of rumen modifiers that decrease CH₄ production have been proposed and tested in the past decade, the most promising of which appear to be biochar-based supplements [55].

Farms with higher productivity maximize their output from the resources invested and emissions linked to adult animals, and consequently reduce their CF per kilogram of lamb meat and wool produced. In this context, intensifying animal production is generally advocated to mitigate the emission of greenhouse gases associated with production of animal food or wool [57]. From the perspective of a carbon footprint, extensive livestock systems common in Patagonia result in low production efficiency, which then results in high gas emissions per unit of product produced. This highlights the potential conflict between carbon efficiencies and other environmental objectives [10]. In Patagonia, we can improve lamb output per ewe by selective breeding that improves ewe productivity, increasing lamb survival through better management at birth and by improving nutritional management.

Besides its primary function of producing lamb meat and wool, most sheep farming systems in Patagonia provide other benefits to society, such as sustainable management of renewable natural resources, conservation of some components of biodiversity, and the maintenance of socio-economic viability for many rural areas, especially in remote areas. The wide open spaces on sheep farms are also a central component of the national identity and sense of place [58]. These cultural ecosystems services are generally ignored when comparing emissions of greenhouse gases among production systems that differ in intensity, which generally favor intensive production systems. Furthermore, we believe that assessing carbon footprints of products does not give complete answers to what is the best strategy for mitigating greenhouse gas emissions. Life cycle assessments (LCA) is a widely accepted and standardized method to evaluate environmental impact during the entire life cycle of a product [59]. The carbon footprint is a single-facet of LCA that focuses on emission of greenhouse gases for a single product. The product in an LCA not only refers to material products, such as meat or wool, but may also include ecosystem services, such as landscape biodiversity conservation [60,61]. In the case of ruminants and their gas emissions, extensive systems are usually found to have a lower per-area footprint than intensive grain-fed systems but a higher footprint when expressed as per kg of product produced. Emissions per kg of product expressed per unit of land used are important once issues concerning land quality (and the impact of livestock on this quality) and the

multifunctional aspects of land use are included in the analysis. In this context, promotion of sustainability-oriented economies within the region could bring Patagonian export commodities recognition in international markets and facilitate entrance into niche, premium markets. Evidence for this is available under the Patagonia Grassland Regeneration and Sustainability Standard (GRASS) implemented by Patagonia Inc., the Nature Conservancy and Ovis XXI's in conjunction with Argentinian government agencies and conservation organizations. In addition, it is strategic for the region to study the issue as a means to define local or regional emission factors as well as disseminate and discuss among the various stakeholder cost-effective mitigation options throughout Patagonia. It is encouraging that many of the measures that could mitigate GHG emissions at the farm level could also improve productivity and profitability in the sheep business. Furthermore, should markets develop for grassland C sequestration, results of previous studies suggest that arresting overgrazing and implementing moderate grazing intensity could sequester substantial amounts of atmospheric C in grassland soils [5–7]. Thus, grassland C sequestration could offset a significant proportion of emissions associated with ruminant production systems. Analysis that includes ecosystem C stocks will favorably position the region to take advantage of these grassland carbon credits. This should gain traction in compliance and/or voluntary markets.

5. Conclusions

This study has provided the first CF of lamb and wool production in Patagonia at farm gate and at the regional scale, including the principal ecosystem types found on Patagonian rangeland. We found that CF was more sensitive to the effects of grassland condition due to grazing (stocking rates) than the other variables, such as transportation distances and emissions resulting from industrial processing. The successful management of livestock GHG emissions becomes an important challenge to the scientific, commercial, and policy communities. The results of CF for lamb and wool production found in the present work assist in characterizing the greenhouse gas emissions profile of livestock products in Southern Patagonia by providing a baseline against which mitigation actions can be planned and progress monitored.

Author Contributions: P.L.P. and G.M.P. conceived and designed the experiments, and wrote the paper; Y.M.R., R.D.-D. and B.L. mainly analyzed the data and contributed analysis tools. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Model performance analysis of carbon footprint of lamb production (kg CO₂ equiv./kg live weight) using ecosystem classification and model selected variables, where (*) indicates overgrazing.

Ecosystem Classification	N	Carbon Footprint	Modeled	Mean Error	Absolute Error
Central Plateau	5	25.87	30.48	−4.61	4.61
Central Plateau*	4	38.45	31.24	7.21	7.21
Humid Magellanic Steppe	3	15.42	12.22	3.20	3.20
Humid Magellanic Steppe*	2	23.55	18.76	4.79	4.79
Dry Magellanic Steppe	4	16.02	22.27	−6.25	6.25
Dry Magellanic Steppe*	5	26.00	22.31	3.69	3.69
Mata Negra Thicket	8	22.71	27.35	−4.64	4.84
Mata Negra Thicket*	11	33.31	28.23	5.08	5.08
Andean Region	10	12.15	15.97	−3.82	3.98
Andean Region*	11	13.92	13.64	0.28	2.13

Temperature seasonality (°C)					
<3.80	20	14.96	14.11	0.85	2.47
3.80–4.20	21	20.16	21.65	−1.48	4.84
>4.20	22	30.48	29.75	0.74	5.51
NDVI (dimensionless)					
<0.23	20	30.20	29.80	0.40	5.35
0.23–0.50	21	23.55	23.38	0.17	5.17
>0.50	22	13.40	13.83	−0.43	2.58
Total	63	22.12	22.08	0.03	4.32

Table A2. Model performance analysis of carbon footprint of greasy wool production (kg CO₂ equiv./kg wool) using ecosystem classification and model selected variables, where (*) indicate overgrazing.

Ecosystem Classification	N	Carbon footprint	Modeled	Mean Error	Absolute Error
Central Plateau	5	15.13	14.50	0.63	0.68
Central Plateau*	4	16.92	14.89	2.03	2.03
Humid Magellanic Steppe	3	11.46	9.13	2.33	2.33
Humid Magellanic Steppe*	2	12.37	11.71	0.66	0.79
Dry Magellanic Steppe	4	12.43	13.02	−0.59	0.66
Dry Magellanic Steppe*	5	13.74	12.91	0.83	0.84
Mata Negra Thicket	8	13.29	14.24	−0.95	1.32
Mata Negra Thicket*	11	14.66	14.39	0.27	0.39
Andean Region	10	7.83	9.49	−1.66	1.66
Andean Region*	11	8.82	8.83	−0.01	0.74
Isothermality (%)					
<47	16	12.08	12.08	0.00	1.53
47–48	34	12.16	12.30	−0.15	0.89
>48	13	12.09	11.70	0.39	0.91
Temperature seasonality (°C)					
<3.80	20	9.73	9.39	0.34	0.92
3.80–4.20	21	11.55	12.07	−0.52	1.34
>4.20	22	14.85	14.66	0.19	0.90
NDVI (dimensionless)					
<0.23	20	14.86	14.69	0.17	1.00
0.23–0.50	21	13.02	12.99	0.03	0.97
>0.50	22	8.78	8.96	−0.18	1.18
Total	63	12.12	12.12	0.00	1.06

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