Carbon footprint of transhumant sheep farms: accounting for natural baseline emissions in Mediterranean systems

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Abstract

Purpose Transhumance has rarely been analyzed through LCA approaches, and there is little evidence about its emissions level when conducted under different practices (by truck or on hoof), or compared to static/sedentary livestock systems. Moreover, mobile pastoralism is strongly linked to natural resources by its seasonal grazing patterns, thereby occupying the niche of wild herbivores. Considering natural emission baselines in these ecosystems could have relevant effects when estimating their carbon footprint.

Materials and methods Inventory data of 21 sheep farms was collected in order to estimate the carbon footprint (CF) of lamb meat produced. Farms were divided in 3 sub-groups representing typical management practices in the region: i) static (STAT), ii) transhumance by truck (THT) and iii) transhumance on hoof (THH). Livestock GHG emissions were modelled according to herd structure and IPCC guidelines. Off-farm emissions from external feeds and fuels were accounted based on existent LCA databases. A natural baseline of wild herbivores was established from the population of red deer reported in a hunting preserve, previously considered to be a reference for the natural carrying capacity in Mediterranean ecosystems. GHG emissions of wild herbivores were estimated through two methods based on: i) IPCC guidelines, and ii) allometric regression equations.

Results and discussion Carbon footprint ranged from 16.4 up to 30.6 kgCO2eq per kg of lamb liveweight (LW). Significant differences were identified among static and transhumant farms, which consistently showed lower CF values (STAT: 26.3 kgCO2eq/kg LW, THT: 18.1 kg CO_2eq/kg LW, THH: 18.1 kg CO_2eq/kg LW). Static farms resulted in higher GHG emissions (+31%) and higher CO_2 and N_2O, contributions derived from the consumption of additional feeds. Both methods applied to compute emissions for wild herbivores led to similar results (25.3-26.8 Mg CO_2eq/km^2), comparatively lower than estimation for transhumant sheep (47.7 Mg CO_2eq/km^2). When considering natural baseline emissions, the CF of transhumant lamb meat is reduced by almost 30%, reaching values quite below those reported for intensive lamb production systems in Spain.

Conclusions From our results, mobility of grazing livestock can be considered as a strategy promoting climate change mitigation. This is achieved mainly by reducing the need of external feeds, while maximizing the use of local forage resources that otherwise would be difficult to valorize. Further reductions in the CF result when considering natural baseline emissions. The application of this new GHG accounting perspective could have relevant implications when aiming at climate neutrality of grazing-based ruminant systems.

1 Introduction

Greenhouse gas (GHG) emissions from the livestock sector are considered a large causative agent of climate change associated to anthropogenic activity, with estimations around 7.1 Gt CO_2eq emitted yearly, representing 14.5% of total human-derived GHG emissions (Gerber et al. 2013). Feed production and processing, and enteric fermentation from ruminants, are the two main GHG sources, together accounting for more than 80% of sector emissions. Hence, a large part of them are attributed to ruminant animals (5.7 Gt CO_2eq/yr), mainly beef and dairy cattle, although small ruminants also involve a significant share (0.5Gt CO_2eq/yr) that can be of particular relevance in certain contexts and regions.

This is the case of the Mediterranean areas, where they play a crucial role for both socio-economic, and ecological aspects. They provide a source of high-value protein, contribute to food and financial security of less favored areas, and maintain valuable habitat and cultural landscapes (Manzano-Baena and Salguero-Herrera 2018). Small ruminants' husbandry in Mediterranean areas has been traditionally characterized as extensive or low-input systems, strongly linked with natural and semi-natural areas by grazing on different resources, such as mountain grasslands, shrubs, forest pastures and understorey (Bernués et al. 2005).

In Spain, transhumance, a form of mobile pastoralism in which shepherds move herds regularly between fixed summer and winter pastures (Manzano et al. 2020), has been a well-established practice in order to adapt to seasonal variability of pasture areas. Its practice probably stems from the use of migratory corridors used by wild herbivores, which got displaced by herders that used the same logic for maximizing efficiency in pasture use (Manzano Baena and Casas 2010). The "long" Spanish transhumance, characterized for using very productive pastures both in summer (northern Iberian ranges) and in winter (southwestern Iberian lowlands), was historically reserved for the most profitable livestock business, i.e. production of merino wool. It suffered a first decline at the time Spain lost its monopoly on Merino wool, at the beginning of the 19th century, and shrunk dramatically during the 20th century due to intensification, landscape fragmentation, and collapse of textiles following the introduction of artificial fibers.

In the last decades, there has been a gradual regression of traditional pastured-based systems in Spain (Manzano Baena and Casas 2010), accompanied by an intensification of livestock production towards systems with a high dependence on external feeds (Pardos et al. 2008; Castel et al. 2011; Ríos-Núñez et al. 2013; Lassaletta et al. 2014). This process has contributed to important ecological and socio-economic changes, such as woody encroachment of unfavorable marginal lands, or the abandonment of rural areas (Bernués et al. 2005), and with negative consequences on biodiversity (Plieninger et al. 2014). At the same time, livestock intensification is often indicated as a climate mitigation measure, due to a reduction in the emission intensity of animal products. However, transhumant systems have rarely been analyzed through LCA approaches, especially in developed countries, and there is no clear evidence about their emission intensity (kg CO_2eq/kg product) being greater than equivalent ruminant production systems under intensive management (Vigan et al. 2017).

Moreover, such low-input mobile pastoral systems are strongly linked to natural and semi-natural areas providing seasonal pasture resources. In these open landscapes, grazing livestock occupy similar ecological niches of wild herbivores, reproducing similar seasonal use patterns and therefore carry out similar ecosystem functions – the reason behind their high ecological value (Manzano-Baena and

Salguero-Herrera 2018, García-Fernández et al. 2019). An abandonment scenario will drive to either an increase in wild herbivore populations, more frequent wildfires, or both, constituting a scenario that in no case consists of zero GHG emissions (Manzano and White 2019). Some authors have considered such "baseline" emissions as natural GHG fluxes (Fiala et al. 2020) and they certainly have a high degree of inevitability. Given that transhumant livestock is occupying that niche and displacing wild herbivore populations, and that it is fulfilling similar ecosystem functions, it is therefore reasonable to only consider anthropogenic those transhumance-triggered emissions that depart from the natural baseline level.

For these reasons, the objectives of this study were 1) to estimate through LCA the carbon footprint associated to lamb meat production in transhumance systems, in order to contextualize the results with regards to sedentary production systems; 2) to analyze the influence on the GHG emissions of using trucks for transporting their herds in comparison with the traditional transhumance on hoof, and 3) to explore if the utilization of a baseline accounting for natural wildlife emissions could involve a relevant effect in the carbon footprint of transhumant systems linked with the use of natural grassland ecosystems.

2 Material And Methods

2.1 Definition of sheep farming systems in the study area

The study takes place in the Community of Albarracín (Teruel, Spain), located in the Iberian Range (altitude up to 2000 m a.s.l.), a mountainous area in central-eastern Spain with a historical activity dedicated to sheep husbandry (Fig. 1). We chose this area because of its current variety of sheep systems, as it comprises the three types of management practices that we wanted to analyze: i) static farms, ii) transhumance by truck, and iii) transhumance on hoof.

Historically, transhumance was the common practice in the Community of Albarracín, as its average altitude, above 1400meters, made livestock production unfeasible during harsh winter periods. However, in the last decades, transhumant activity has drastically dwindled, as many farms converted into a semi-extensive, static management model, where sheep graze communal mountain pastures in the summer and spend the winter enclosed in barns, fed with external forages and concentrates.

Transhumant pastoralism, both by truck and on hoof, still persists in the area. In this case, herders move their animals from Community of Albarracín (Teruel) to savanna-like areas ("dehesas") in the southern regions of Jaén and Ciudad Real. The southbound travel usually takes place in November, and herds spend six months in this location (December to May). After that period, they travel northwards in June, back to the mountains of Community of Albarracín (i.e. Montes Universales).

Most of the animal husbandry in the study area is represented by ruminant livestock systems (mainly sheep and cattle) dedicated to meat production under semi-extensive conditions. In the case of sheep systems, the most common breed is Merino, specifically a local variety denominated "Merino de los

Montes Universales" (Ramo et al. 2018), although other local ovine breeds are also found among the sheep farms in the area, such as Ojinegra de Teruel, or Rasa Aragonesa.

2.2 Carbon footprint assessment

2.2.1 Data collection and sample description

A total of 21 sheep farms were analyzed through the study in order to estimate their carbon footprint. Seven farms from each of the 3 sub-groups i) static (STAT), ii) transhumance by truck (THT) and iii) transhumance on hoof (THH) were randomly selected in the area, representing the typical sheep management systems that are present in the region.

Average size farm is 612 ewes, ranging from 110 up to 1300 ewes. Most of the farms had a similar reproductive management, based on 1.5 lambings per ewe per year (3 lambings every 2 years). Key characteristics of the farms involved in the study are provided in Table S1.

2.2.2 System boundaries and functional unit (FU)

We followed a "cradle to farm-gate" perspective for defining the boundaries of the sheep production system, involving all processes until the lamb meat leaves the farm, and excluding its transport and processing afterwards (see Fig. 2). This implies the aspects related to on-farm activity, such as energy consumption, animal housing, ruminant digestion, grazing pastures and manure management, but also off-farm activities like crop and forage production, feed processing and transport to the farm. Post-farm gate processes were excluded of the study, as they were assumed equal for all the farms. Capital goods (e.g. equipment, machinery, buildings) and inputs for ancillary activities (e.g. medicines) were also excluded of the analysis. as they were considered not relevant for this case study. The functional unit (FU) considered was 1 kg of lamb live weight (LW) leaving the farm-gate.

2.2.3 Allocation of co-products

Sheep farms are multifunctional systems which produce more than one product. The main purpose is lamb meat production, although wool and meat from culled sheep are also obtained as co-products. In order to estimate the environmental impacts of the single product analyzed in the study (i.e. lamb meat), the overall impacts have to be partitioned among the various outputs of the system. In this study, we distributed the GHGs emissions associated to the sheep system following an economic allocation approach, based on the relative economic value of the different co-products from the farm.

To do so, the economic value of wool and meat outputs (lamb meat, sheep meat) was calculated by multiplying the production sold annually with the average price obtained of the different items at farm gate along the year, which was collected at every farm.

2.3 Life cycle inventory (LCI)

2.3.1 Farm inputs and outputs

In order to acquire the inventory data, a survey was designed, systematically collecting details about farm structure, management applied, and main input and output flows. To do so, the selected farms were analyzed by field investigation, through several visits and personal interviews with farmers, involving an accompanying walk during their journey in the case of herds that practiced transhumance on hoof. Building on such opportunities, structured farmer surveys were conducted that allowed the quantification of main farm inputs, such as feeds and forages used, or fuel consumption, as well as the obtention of a precise description of the herd structure (animal classes), productivity parameters (e.g. replacement rate, lamb mortality rate) and main management practices (e.g. grazing practices, manure management, transhumance type and period).

Farm outputs such as lambs sold, culled sheep or wool produced, were registered from the information gathered in the survey, together with average price received by farmers from the different co-products. An overview of the collected data by farm typology is shown in Table 1, with details for every specific farm in Table S1.

Table 1
Average results of collected parameters by farm typology: static (STAT), transhumance by truck (THT) and transhumance on hoof (THH). (SD: Standard Deviation)

	STAT		**THT**		**THH**	
	Mean	SD	Mean	SD	Mean	SD
No of adult ewes	586 [a]	385	661 [a]	358	590 [a]	228
Replacement rate (%)	17%[a]	2%	14% [b]	2%	14% [b]	2%
Mortality rate (%)	23%[a]	5%	11% [b]	2%	10% [b]	0%
Outputs						
Lambs sold (lambs/ewe)	0.90[a]	0.08	1.11 [b]	0.03	1.12 [b]	0.08
Sheep culled (ewes culled/ewe)	0.14 [a]	0.02	0.11 [b]	0.02	0.11 [b]	0.02
Wool sold (kg/ewe)	2.04 [a]	0.02	2.14 [a]	0.16	2.07 [a]	0.02
Inputs						
Mountain pastures (ha/ewe)	0.35 [a]	0.01	0.35 [a]	0.01	0.35 [a]	0.01
Dehesa pastures (ha/ewe)	0.00	0.00	0.60 [a]	0.01	0.60 [a]	0.01
Sheep concentrate (kg/ewe)	159.5 [a]	23.5	102.6 [b]	18.4	97.4 [b]	4.7
Lamb concentrate (kg/ewe)	41.8 [a]	6.4	10.1 [b]	4.5	8.4 [b]	0.7
Forage (kg/ewe)	170.6 [a]	31.8	11.1 [b]	3.5	13.8 [b]	5.7
Diesel (kg/ewe)	5.02 [a]	2.42	1.49 [b]	0.45	1.16 [b]	0.42

[a,b] Different letters indicate differences between averages on the same column ($P < 0.05$)

Additionally, feed suppliers were consulted to collect sheep and lamb concentrates composition. Specific feed ingredients used, and countries of origin are shown in Table 2.

Table 2
Concentrate composition (%) used for feeding sheep and lambs

Ingredients	Inclusion (%)	Origin
Concentrate for sheep		
Lucerne	26%	Spain
Barley grain	24%	Spain
Oat grain	20%	Spain
Maize	12%	Spain
Wheat bran	6%	Spain
Rapeseed meal	3%	Spain
Maize DDGS	3%	Spain
Sunflower meal	3%	Spain
Mineral additives	2%	Spain
Concentrate for lambs		
Maize	30%	Spain
Barley grain	28%	Spain
Soybean meal	25%	Brazil, Argentina, USA
Wheat grain	8%	Spain
Wheat bran	5%	Spain
Mineral additives	3%	Spain
Palm oil	2%	Indonesia, Malaysia

2.3.2 Estimation of emissions

Based on the collected data, a model was built aiming to capture the farm and flock structure as well as the main interactions among its components, according to technical parameters and animal management practices reported. The different animal classes comprising the herd along the year (adult sheep, males, replacement sheep and lambs) were considered in the analysis, involving their respective requirements and excreta when estimating the GHG emissions at farm-level.

Methane (CH_4) emissions from enteric fermentation were estimated following the Tier 2 approach of IPCC 2019 guidelines (Gavrilova et al. 2019), based on the energy requirements of the animals, diet composition and feed characteristics. Annual diet of the different animal classes (i.e. adult animals, lambs) was defined considering the different proportions of the feeds consumed along the year, from the data gathered in the farm surveys. The share of grazing in the diet was computed by subtracting the energy consumed from supplied feed sources (i.e. concentrates, forages) from the total energy requirements of the herd, following the procedure indicated by FAO (2016) guidelines for small ruminants. Main feed nutritional characteristics (e.g. dry matter, digestibility, protein content) were collected from the Spanish Foundation for Animal Nutrition Development database (FEDNA, 2019), while additional herbage quality data for mountain and Mediterranean pastures was complemented using specific scientific literature (Riedel et al. 2013; Fernández et al. 2014).

Gross energy (GE) was calculated applying the equations described in the IPCC 2019 guidelines (Gavrilova et al. 2019), for estimating the energy requirements for the different metabolic functions of the animals, and considering diet digestibility. CH_4 emissions from enteric fermentation were then calculated by applying the default CH_4 conversion factor (Y_m) of 6.7% for sheep.

Emissions from manure management were estimated based on IPCC 2019 guidelines too. The proportion of manure managed on-farm or directly deposited on pastures was defined by the grazing time spent according to the farm practices (i.e. 100% for transhumant systems, 75% for static systems). Methane conversion factors (MCFs) of 4% and 0.47% were considered for manure managed by solid storage and pasture grazing, respectively, both under warm temperate dry climate. Maximum methane producing capacity (Bo) of manure was set $0.18 m^3$ CH_4/kgVS, which is the default value assumed for sheep in Western Europe.

Nitrous oxide (N_2O) emissions were estimated following IPCC (Gavrilova et al. 2019) based on excretion rate of nitrogen (N) and applying emission factors for direct N_2O of 1% for manure managed through solid storage and 0.3% for manure deposited on pastures. Indirect N_2O emissions from ammonia (NH_3) and nitrate (NO_3^-) losses, were accounted through the Tier1 from IPCC, considering dry climate conditions. Off-farm emissions from external feeds (i.e. concentrates and forages) were accounted based on Agri-footprint v4.1 database (Blonk Agri-footprint BV, 2019) including the different phases of feed production: agricultural production, processing and transport to the farm. Emissions related to fuels (i.e. diesel) consumed on-farm, were estimated from Ecoinvent 3.3 database (Ecoinvent, 2016).

2.3.3 Definition of natural baseline emissions in Mediterranean rangeland ecosystems

Considering a natural baseline of emissions from natural grassland ecosystems could involve a relevant effect in the carbon footprint of transhumant systems linked to them through direct grazing. In the Iberian Peninsula context, this kind of habitat is characterized by savanna-like open rangeland landscapes called 'dehesas' in Spain and 'montados' in Portugal, dominated by evergreen oak (*Quercus ilex)* woodlands and scrublands, combined with scattered areas of pastures.

In order to account for emissions of wild herbivores in the Mediterranean context, we used the red deer population density reported from a public hunting preserve located in Ciudad Real, South Central Spain

(Carpio Camargo et al. 2021). The selected site has a surface of 6862 km^2, an altitude ranging between 600-1100m a.s.l.), and is representative of the typology of big-game hunting estates in Mediterranean Spain where animals do not receive supplementary forage, being sustained just through grazing and browsing of natural resources. The population density observed in this site is thus considered a reference for the natural carrying capacity in our study area (Carpio Camargo et al. 2021).

The selected value (32.9 deer/km^2) is an average population, considering the fluctuations observed in livestock numbers in the area along 25 years (1989–2015). Herbivore biomass density was obtained considering the specific sex (female/male) and age (adults > 2years) structure of the deer population, by computing the proportion of adults (72.8%), and the nº female/nº male ratio (1.35). Hence, three animal classes were computed: adult male, adult female and young (< 2 year), with correspondent average body weights.

Estimating GHGs from animals in free range conditions is still subject to important limitations, especially with regards to their enteric methane output (Pérez-Barbería 2017). In an attempt to capture the variability associated to the calculation method, we applied two different approaches to estimate GHG emissions from herbivore animals.

In the first approach (IPCC Tier 1) GHG emissions from enteric fermentation and excreta deposited in pastures were calculated according to most updated version of IPCC guidelines (Gavrilova et al. 2019). Default emission factors (EFs) for deer were applied. In the case of enteric fermentation, default EFs for the different deer classes were developed, by scaling them based on the ratio of the body mass raised to the 0.75 power. That is,

$$EF_w = EF_d \cdot \left(\frac{M_w}{M_d}\right)^{0.75}$$

where EF_w is the adjusted methane emission factor of the wild herbivore (kg CH_4 $head^{-1}$ yr^{-1}); EF_d is the default emission factor for deer (kg CH_4 $head^{-1}$ yr^{-1}); M_w is the body mass of the wild herbivore (kg); and M_d is the default body mass considered for deer.

In the second approach, an allometric method was applied to estimate enteric CH_4 emissions, based on the analysis conducted by Smith et al (2015), which found a highly significant relationship between methane output and body mass. They developed specific regression equations for mammals according to digestive system. In this case, the function developed for ruminants was applied:

$$\log\left(CH_4\ output\right) = -4.564 + 3.278 \log BW^{0.592}$$

where CH_4 output is the enteric methane emissions by animal (kg CH_4 yr^{-1}), and BW is the body mass of the corresponding herbivore species (kg). Hence, total enteric CH_4 emissions in this approach were computed by multiplying the CH_4 output per animal and year estimated through allometric relationship and population of the corresponding deer classes in the studied area.

In both approaches, emissions from manure deposited in pasture were estimated based on IPCC 2019 guidelines (Tier 1). For CH_4 emissions, calculations were based on the amount of volatile solids (VS) excreted, while for direct and indirect nitrous oxide (N_2O) emissions, estimations were based on excretion rate of nitrogen (N). Indicated default factors of VS and N excretion rates for deer were applied.

2.4 Impact assessment and characterisation

The IPCC 2021 method (Masson-Delmotte et al. in press) was selected to assess the impact on climate change, considering the global warming potential factors of IPCC with a timeframe of 100 years (GWP_{100}). Emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were transformed to CO_2 equivalents (CO_2-eq) based on the following factors of conversion: 1 for 1 kg of CO_2, 27.2 for 1 kg of CH_4 (biogenic) and 273 for 1 kg of N_2O. SimaPro 9.1 LCA software (PRé Sustainability, 2020) was used to conduct the calculations.

2.5 Statistical analysis

The statistical analysis was performed using the R software (version 3.6.2 R Core Team 2020). Data were subjected to one-way analysis of variance (ANOVA) to test for possible significant differences between the three farm typologies considered in the study (STAT, THT and THH). When a general significant effect of group was found with the ANOVA Model, Tukey contrast was used to detect significant difference among groups identified by different letters. A p-value of 0.05 ($p < 0.05$) was established as threshold for statistical significance.

3 Results

3.1 Farm characteristics

The average characteristics of the three groups of farms analyzed in this study are reported in Table 1. Details for every specific farm are shown in Table S1. The selected farms presented similar characteristics in terms of size, with and average number of adult sheep ranging between 586 and 661. Some differences were observed for certain productivity parameters though. Replacement rate and lamb mortality of static farms (STAT) were found significantly higher than the values reported by farms practicing transhumance, either by truck (THT) or on hoof (THH). Static farms showed significant differences with the rest in terms of outputs too, presenting lower production of lambs per ewe (STAT = 0.90; THT = 1.11; THH = 1.12) and a higher ratio of sheep culled. Static farms also presented significantly higher consumption of inputs per ewe, such as concentrates, forage and fuel.

When comparing farms applying transhumance by truck or on hoof, no significant differences were observed between the two groups for any of the parameters studied. Average management and productivity ratios (e.g. replacement rate, lamb mortality) were particularly similar between them. However, some dissimilarities were adverted when analyzing the average results of input consumption. Farms doing traditional transhumance on hoof (THH) showed slightly lower ratios of diesel and concentrates utilization, while those farms conducting transhumance by truck (THT) presented slightly lower usage of external forages.

3.2 Carbon footprint

The carbon footprints (CF) of 1 kg of lamb live weight (LW) for the 21 sheep farms analyzed in the study are shown in Fig. 3, together with the contribution from different GHG sources. Carbon footprint results ranged from 16.4 up to 30.6 kgCO_2eq/kg lamb LW. Significant differences were identified among static and transhumant farms, which consistently showed lower CF values (STAT: 26.3 kgCO_2eq/kg LW, THT: 18.1 kgCO_2eq/kg LW, THH: 18.1 kgCO_2eq/kg LW). Static farms presented significantly higher GHG emissions from the production of external feed resources (concentrates and forages), manure management and fuel consumption, while the contribution from grazing was significantly lower (Table 3).

Table 3
Average results of carbon footprint of 1 kg of lamb meat (liveweight) by farm typology: static (STAT), transhumance by truck (THT) and transhumance on hoof (THH). (SD: Standard Deviation)

	STAT		**THT**		**THH**	
	Mean	SD	Mean	SD	Mean	SD
Enteric fermentation CH_4	16.1 [a]	1.6	13.5 [b]	0.3	13.7 [b]	0.8
Manure management CH_4	0.4 [a]	0.0	0.2 [b]	0.0	0.2 [b]	0.0
Manure management N_2O	0.2 [a]	0.0	0.0 [b]	0.0	0.0 [b]	0.0
Grazing	0.9 [a]	0.1	1.3 [b]	0.0	1.3 [b]	0.1
External forages	1.9 [a]	0.5	0.1 [b]	0.0	0.1 [b]	0.0
Concentrates	4.8 [a]	0.5	2.4 [b]	0.3	2.2 [b]	0.1
Concentrates (Land use change)	1.5 [a]	0.2	0.5 [b]	0.1	0.4 [b]	0.0
Energy	0.7 [a]	0.3	0.2 [b]	0.0	0.1 [b]	0.0
Carbon footprint (TOTAL)	*26.3 [a]*	*2.4*	*18.1 [b]*	*0.6*	*18.1 [b]*	*1.0*

[a,b] Different letters indicate differences between averages on the same column ($P < 0.05$)

In all the groups, the larger proportion of total GHG emissions was associated with enteric fermentation, with significant differences between static farms (61%) and transhumant farms, where the contribution of enteric CH_4 was higher (75–76%). Slight differences were detected between the CF profiles of the two transhumant groups analyzed, although not statistically significant. The farms conducting transhumance by truck showed higher share of GHG emissions from diesel and concentrate consumption. In contrast, in the group of farms carrying on transhumance on hoof, higher contributions from forage consumption as well as from enteric fermentation were identified.

3.3 Natural baseline emissions from Mediterranean ecosystem

Results of estimated natural GHG emissions of wild herbivores in a Mediterranean grassland ecosystem are shown in Table 4, on a surface basis (kg CO_2eq/km^2). Enteric fermentation was identified as the main source contributing to these natural GHG emissions, accounting for ca. 80% of the total, followed by N_2O emissions from manure directly deposited in the pastures (16–17%).

Table 4
Estimated natural emissions from wild herbivores in Mediterranean grasslands ecosystem and comparison with transhumant grazing-based sheep.

Animal class	Density	Biomass	Enteric CH_4	Manure CH_4	Manure N_2O	TOTAL
	No/km^2	kg/km^2	(Mg CO_2eq/km^2)			
Wild herbivores						
Red deer[1]	32.9	4814	20.5	0.3	4.4	25.3
Red deer[2]	32.9	4814	22.0	0.3	4.4	26.8
Domestic herbivores						
Transhumant sheep	105.0	5775	42.6	0.5	4.6	47.7

[1]Enteric CH_4 emissions applying IPCC Tier 1 method, [2]Enteric CH_4 emissions applying allometric method

Both methods applied to compute enteric CH_4 from wild herbivores led to similar results, although IPCC Tier 1 resulted in a slightly lower estimation (20.5 Mg CO_2eq/km^2) in comparison with the allometric method (22.0 Mg CO_2eq/km^2).

Estimated biomass density of wild herbivores (4814 kg/km^2) was lower, but in the same magnitude order than computed for transhumant sheep grazing natural grassland areas (5775 kg/km^2). When compared with direct GHG emissions from transhumant sheep (excluding emissions from external inputs accounted in a LCA perspective), natural baseline emissions where 43–46% lower per km^2.

4 Discussion

4.1 Effect of livestock mobility

Under the conditions analyzed in this study, mobility of livestock is a strategy that promotes climate change mitigation in semi-extensive farms (Fig. 3), reducing the carbon footprint of lamb meat by about one third (Table 3). This is achieved mainly as a result of a substantial improvement of lamb productivity, and an optimal utilization of available forages through grazing of natural and semi-natural grasslands, which minimizes the needs of external feed resources.

Significantly lower consumption of forage and concentrates for sheep and lambs was observed in transhumant farms (Table 1), involving important GHG savings related to the embodied emissions in bought feedstuffs. These emissions are mostly linked to N_2O from fertilization, CO_2 emissions from agricultural activities requiring fossil fuel consumption, like crop cultivation, processing, and transport, and also GHG emissions associated to direct land use change (LUC) processes, mainly due to CO_2 released through deforestation for soybean cultivation in South America.

Conducting seasonal transhumance allows to reduce these feed inputs, and its embodied GHG emissions, by adapting ruminant husbandry to the natural productive cycles of upland and lowland grassland ecosystems, which in the Mediterranean context complement each other throughout the year. In the Iberian Peninsula, natural upland grasslands mostly grow on mountainous areas with high slopes, making cultivation unfeasible. Cold conditions limit plant growth during most of the year, so forage can only be grazed around summer months. In contrast, lowland Mediterranean rangelands go through a summer dry period and maximize plant growth in spring and autumn, with some plant growth also in winter (Manzano Baena and Casas 2010). Still, unbalanced distribution of herbage production along the year implies a management problem for grazing-based livestock systems. Savanah-like landscapes (i.e. dehesa), where grasslands are combined with scattered trees, help to mitigate this issue by: i) extending the grass growing season under the canopy and ii) providing a source of food for harsh periods (e.g. acorns, browsed leaves) that ruminants can utilize as a supplementary resource (García de Jalón et al. 2018).

Livestock mobility also provided positive effects with regards to herd/animal productivity (Table 1), ultimately leading to a higher ratio of lambs sold per ewe (STAT:0.90, THT, THH:1.11–1.12). Transhumant farms showed a significantly lower lamb mortality rate (Table 1), together with an extended longevity of the adult ewes, reflected on lower requirement of annual replacement rates (STAT:17%, THT, THH:14%). A similar pattern was observed by previous studies analyzing static and mobile flocks in the area (Ramo et al. 2018). These differences are attributed to the animal handling provided by transhumant management, which allows animals to graze outdoors continuously along the year, while protecting them from extreme temperatures through seasonal mobility. The negative effect of low ambient temperature on sheep farms is well-known. Cold weather environment is a crucial factor increasing perinatal lamb deaths (Horton et al. 2018), and it also affects lambs rearing process by reducing average daily gain while increasing feed consumption, ultimately leading to a reduction in protein and feed efficiency ratio (Ames et al. 1977).

Differences in animal management among systems also impact direct consumption of fossil fuels (STAT:5.0 kg/ewe, THT: 1.5 kg/ewe, THH:1.2 kg/ewe). Increased diesel use in static farms was attributed to energy demand linked to machinery for cleaning operations and preparation of feed (forage/concentrate) rations.

Farms applying transhumance by truck or on hoof showed very similar results in their CFs, and in most of the parameters studied, although some differences were identified. Transhumance by truck showed a higher diesel consumption than on hoof, which is associated to the road transport of the animals requiring an extra input of fuel. A higher need of concentrates for adult ewes and lambs was observed too (THT: 103 kg/ewe, THH: 98 kg/ewe). Transhumance by truck reduces the time animals are on the move but it involves extending the stay in the upland area during several weeks, so to limit damage to vegetation in the southern rangelands happening through extended grazing pressure (Carmona et al. 2013). This implies an additional consumption of external concentrates. In contrast, farms conducting transhumance on hoof start their journey earlier, taking advantage of the available grazing areas they find along the traditional paths or “cañadas”. The width of these paths, of up to 75m, and the daily displacement of about 24km, provides to the animals the necessary food and time for intake and rest, thus maintaining an adequate body condition (Ramo et al. 2018).

Still, during the journey, ewes expend a significant amount of energy by walking. In our model, this was captured by applying a higher coefficient for computing energy requirements during the travelling periods. This aspect, together with differences in feed quality, are the main factors leading to slightly higher CH_4 emissions from enteric fermentation in the farms conducting transhumance on hoof compared to by truck (THT:13.5 kgCO_2/kg LW, THH: 13.7 kgCO_2/kg LW), which in the end resulted in a very similar overall value of the CF from the two transhumant managements.

The production system determines the profile of GHG emissions obtained in CF, with transhumant herds showing a higher contribution of CH_4 in comparison to static herds. Increased use of concentrates in intensive/static systems reduces enteric CH_4 emissions due to improved feed digestibility, but it involves increasing CO_2 and N_2O contribution linked to fossil fuel consumption and crop cultivation. A similar trend has been reported in previous studies (Vigan et al. 2017; Ripoll-Bosch et al. 2015). Climatic implications of these GHG profiles must be carefully analyzed, especially when analyzing dynamic scenarios, due to the different behavior of long-lived pollutants (i.e. CO_2, N_2O) versus short-lived (i.e. CH_4) (del Prado et al. 2021).

Establishing comparisons among LCA studies of livestock systems is difficult, as methodological choices and modelling approaches have a strong influence on the results. Overall, the CFs estimated for all farms in our study are within the ranges reported for sheep systems in Spain (Ripoll-Bosch et al. 2013), but also for sheep systems in other Mediterranean (Ibidhi et al. 2017) and Northern European (Morgan-Davies et al. 2021) contexts. For the same region as our analysis, Ripoll-Bosch et al. (2013) reported a CF value from a grazing-based system of 25.9 kgCO_2eq/kg lamb LW (compared to 26.3 kgCO_2eq/kg lamb LW for static extensive farms in this study) and of 19.5 kgCO_2eq/kg lamb LW from a zero-grazing system. Hence, according to our results, the CF estimated for transhumance systems (18.1 kgCO_2eq/kg lamb LW) is in a similar range (or lower) to the equivalent intensive systems. This is in accordance with the conclusions of Vigan et al. (2017), which calculated similar CF values for intensive and transhumant systems in a French Mediterranean context.

In addition to this, transhumance can further promote climate mitigation linked to carbon sinks, by practicing extensive grazing throughout the year, and allowing system extensification. When accounting for C sequestration, low stocking rates have been associated to decreased carbon footprint of livestock products from extensive systems, even lower than equivalent intensive systems (Batalla et al. 2015). This is of particular importance in Mediterranean savanna-like agroforestry landscapes ('dehesas'), where in some cases, carbon sequestration has been estimated to compensate all GHG emissions from ruminant farms, leading to negative CF values (Reyes-Palomo et al. 2022).

Mobile pastoralism and transhumance – particularly on hoof – is known to provide additional benefits to the environment. These range from the promotion of plant, insect or scavenger diversity to wildfire and erosion prevention (Manzano-Baena and Salguero-Herrera 2018). Mobile livestock is also key for climate change adaptation by acting as an effective dispersal vector of seeds, and it also preserves pollinators by grazing times adapted to plant phenology, with tangible effects on the genetic pool of plants (García Fernández et al. 2019).

Although not considered in the present paper, previous studies have pointed out the importance of considering these other functions in LCA approaches. When including valuation of ecosystem services in the economic allocation of sheep farms, Ripoll-Bosch et al. (2013) showed that the most extensive grazing-based system resulted in the lowest values of CF. Accordingly, we prospect that, if multifunctionality could be properly accounted and captured, transhumance on hoof should result in lower environmental impacts than calculated by current methodologies.

4.2 Effect of considering natural baseline emissions

Current GHG accounting methods, as reflected in the IPCC guidelines, exclude wild ruminants from GHG estimates, as these are considered a natural source of emissions, and therefore, not anthropogenic. Similarly, from an LCA perspective, wild herbivores can be categorized as "naturally occurring biotic resources" (Crenna et al. 2017), and therefore, computed as elementary flows entering the system from the ecosphere, which implies, for example, excluding direct emissions (e.g. enteric CH_4) of wild ruminants when assessing the environmental impact of deer meat (Fiala et al. 2020).

In the present study we attempt to adapt a similar approach for the case of domestic animals that are managed mimicking the ecosystem functions and production patterns of wild herbivores in nature. Taking into account that transhumant livestock is occupying their ecological niche and displacing wild herbivore populations, and that it is fulfilling similar ecosystem functions, it is therefore reasonable to only consider as anthropogenic the transhumance-triggered emissions that depart from the natural baseline level. In order to account for this baseline effect, we subtracted the corresponding natural emissions from the displaced wild ruminants grazing in the equivalent area from the total farm GHG emissions.

As a proxy estimation of the biomass of wild herbivores in Mediterranean grasslands, we used the reported population density of red deer in a public hunting preserve, with similar characteristics of the savanna-like ecosystems grazed seasonally by transhumant sheep flocks. Average population density in this site was 32.9 deer/km2, within the range found in other studies in the Iberian Peninsula that reporting > 30 deer/km2 in Spain (Perea et al. 2014) and up to 40 deer/km2 in Portugal (Silva et al. 2014). We estimated a biomass density of wild herbivores of 4814 kg/km^2. This was slightly lower but close to the natural baseline of herbivore biomass (5173 kg/km^2) calculated by Fløjgaard et al. (2022) for Faia Brava (Portugal), a natural reserve representative of Mediterranean ecosystems.

In comparison, our estimations indicate higher biomass densities (5775 kg/km^2) for transhumant sheep grazing Mediterranean grasslands. Supplementation with forages and concentrates allows to keep biomass densities above the natural carrying capacity of the ecosystem, which has been observed not only for livestock but for red deer populations in the same study area (Carpio Camargo et al. 2021). In addition to this, mobility may also affect significantly the biomass density of herbivores. Seasonal movements in pastoralism mimic the typical patterns previously used by wild ruminant during migrations, as a strategy to take advantage of different natural pasture resources along the year (Manzano and Casas, 2010). Currently, landscape fragmentation, and confinement, either in protected reserves or hunting preserves, drastically restrict these movements for wild herbivores, thus limiting their population density.

Considering herbivores grazing in nature as an elementary flow entering the system, and therefore, not an anthropogenic source of emissions, has a crucial effect on the impact assessment of products derived from them. As a result, the meat from hunted ungulates has been pointed out as a sustainable alternative to conventional meat from livestock ruminants due to its low environmental footprint (Fiala et al. 2020). In our study, when subtracting the estimated natural baseline emissions to the GHGs accounted for transhumant sheep, the CF of lamb meat is reduced by almost 30% (Table 5), reaching absolute values that are quite below those reported for intensive lamb production systems in Spain. Furthermore, in other contexts, applying a similar approach to extensive ruminant systems could have even more relevant effect. For example, in Africa, where higher biomass densities of wildlife are estimated (Flojgaard et al. 2022), traditional low-input pastoral systems relying only on natural grasslands, could be close to climate neutrality if considering baseline emissions, especially when implementing complementary mitigation options for improving herd and grazing management (Gerber et al. 2013).

Table 5
Profile of GHGs for the average carbon footprint of 1 kg of lamb meat (LW:liveweight) by farm typology: static (STAT), transhumance by truck (THT) and transhumance on hoof (THH). Results with and without considering natural baseline emissions from wild herbivores in Mediterranean grasslands ecosystem.

	Without baseline			**With baseline**	
GHG contribution	STAT	THT	THH	THT	THH
CH_4 (%)	62%	76%	77%	73%	74%
CO_2 (%)	25%	13%	12%	18%	17%
N_2O (%)	13%	11%	11%	9%	9%
Carbon footprint (kg CO_2eq/kg LW)	*26.3*	*18.1*	*18.1*	*12.9*	*12.9*

5 Conclusions

In light of our results, transhumance is shown to have a low carbon footprint when put in context for the whole Spanish livestock production system, thanks to its efficient use of natural resources. Impact is being reduced by an efficient use of local rangeland resources, which reduces need for imported fodder and maximizes productivity by avoiding harsh climatic conditions. Moreover and in the Spanish case analyzed here, a significant portion of its GHG emissions can be attributed to natural, non-anthropogenic GHG flows, which persist under the current abandonment scenario of grazing livestock in the country. Such natural GHG flows build up a natural baseline emission level and can have important implications on how grazing-based ruminant systems can be considered in the future. At the global scale, a large portion of such systems implies traditional animal husbandry with negligible external inputs and varying degrees of livestock mobility as coping mechanisms for managing seasonal variations in vegetation growth – with obvious parallelisms to the Spanish transhumance system. The efficiency of mobile pastoralist systems and the baseline nature of some of its GHG emissions call for a reconsideration of their role as climate-smart production systems.

Declarations

6. Data availability statement

All data generated or analysed during this study are included in this published article and its supplementary information files.

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Competing interests

Financial interests: The authors declare they have no financial interests.

Non-financial interests: Pablo Manzano has served on advisory boards for the International Year of Rangelands and Pastoralists, as well as for the Spanish Plataforma por la Ganadería Extensiva y el Pastoralismo.

References

1. Ames DR, Brink DR (1977) Effect of temperature on lamb performance and protein efficiency ratio. J Anim Sci 44:136–144
2. Batalla I, Knudsen MT, Mogensen L, del Hierro Ó, Pinto M, Hermansen JE (2015) Carbon footprint of milk from sheep farming systems in Northern Spain including soil carbon sequestration in grasslands. J Clean Prod 104:121–129. https://doi.org/10.1016/j.jclepro.2015.05.043
3. Bernués A, Riedel JL, Asensio MA, Blanco M, Sanz A, Revilla R, Casasús I (2005) An integrated approach to studying the role of grazing livestock systems in the conservation of rangelands in a protected natural park (Sierra de Guara, Spain). Livest Prod Sci 96:75–85. https://doi.org/10.1016/j.livprodsci.2005.05.023
4. Camargo AJC, Barasona J, Acevedo P, Fierro Y, Gortazar C, Vigal C, Moreno A, Vicente J (2021) Assessing red deer hunting management in the Iberian Peninsula: The importance of longitudinal studies. PeerJ 9:1–22. https://doi.org/10.7717/peerj.10872
5. Carmona CP, Azcárate FM, Oteros-Rozas E, González JA, Peco B (2013) Assessing the effects of seasonal grazing on holm oak regeneration: Implications for the conservation of Mediterranean dehesas. Biol Cons 159:240–247. https://doi.org/10.1016/j.biocon.2012.11.015
6. Castel JM, Mena Y, Ruiz FA, Camúñez-Ruiz J, Sánchez-Rodríguez M (2011) Changes occurring in dairy goat production systems in less favoured areas of Spain. Small Rumin Res 96:83–92. https://doi.org/10.1016/j.smallrumres.2011.01.002
7. Crenna E, Sozzo S, Sala S (2018) Natural biotic resources in LCA: Towards an impact assessment model for sustainable supply chain management. J Clean Prod 172:3669–3684.

https://doi.org/10.1016/j.jclepro.2017.07.208

8. del Prado A, Manzano P, Pardo G (2021) The role of the European small ruminant dairy sector on stabilizing global temperatures: lessons from GWP* warming-equivalent emission metrics. J Dairy Res 8:8–15. https://doi.org/10.1017/S0022029921000157
9. FAO (2016) Greenhouse gas emissions and fossil energy use from small ruminant supply chains. Guidelines for assessment
10. FEDNA (2019) Tablas FEDNA de composición y valor nutritivo de alimentos para la fabricación de piensos compuestos (4.ª edición). Fundación Española para el Desarrollo de la Nutrición Animal, Madrid
11. Fernández P, Carbonero MD, García A, Leal JR, Hidalgo MT, Vicario V, Arrebola F, González MP (2014) Variación de la proteína bruta y de la digestibilidad de los pastos de dehesa debida a una supresión temporal del pastoreo. 53ª Reunón Científica de la SEEP, pp 413–420
12. Fernández-Giménez ME, Ritten J (2020) An economic analysis of transhumance in the Central Spanish Pyrenees. Pastoralism 10:10. https://doi.org/10.1186/s13570-020-00163-4
13. Fiala M, Marveggio D, Viganò R, Demartini E, Nonini L, Gaviglio A (2020) LCA and wild animals: Results from wild deer culled in a northern Italy hunting district. J Clean Prod 244. https://doi.org/10.1016/j.jclepro.2019.118667
14. Fløjgaard C, Pedersen PBM, Sandom CJ, Svenning J-C, Ejrnæs R (2022) Exploring a natural baseline for large-herbivore biomass in ecological restoration. J Appl Ecol 59:18–24. https://doi.org/10.1111/1365-2664.14047
15. García de Jalón S, Graves A, Moreno G, Palma JH, Crous-Durán J, Kay S, Burgess PJ (2018) Forage-SAFE: a model for assessing the impact of tree cover on wood pasture profitability. Ecol Modell 372:24–32. https://doi.org/10.1016/j.ecolmodel.2018.01.017
16. García-Fernández A, Manzano P, Seoane J, Azcárate FM, Iriondo JM, Peco B (2019) Herbivore corridors sustain genetic footprint in plant populations: a case for Spanish drove roads. PeerJ 7:e7311. https://doi.org/10.7717/peerj.7311
17. Gavrilova O, Leip A, Dong H, MacDonald DJ, Gomez-Bravo CA, Amon B, Barahona-Rosales R, del Prado A, de Lima MA, Oyhantcabal W, van der Werden T, Widiawati Y (2019) Emissions from livestock and manure management. In: Calvo Buendia E, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P, Federici S (eds) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse gas Inventories, vol 4. Intergovernmental Panel on Climate Change, Geneva. 10.1–10.225
18. Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A, Tempio G (2013) Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome
19. Horton BJ, Corkrey R, Doughty AK, Hinch GN (2018) Estimation of lamb deaths within 5 days of birth associated with cold weather. Anim Prod Sci 59:1720–1726

20. Ibidhi R, Hoekstra AY, Gerbens-Leenes PW, Chouchane H (2017) Water, land and carbon footprints of sheep and chicken meat produced in Tunisia under different farming systems. Ecol Indic 77:304–313. https://doi.org/10.1016/j.ecolind.2017.02.022
21. Jones AK, Jones DL, Cross P (2014) The carbon footprint of lamb: Sources of variation and opportunities for mitigation. Agric Syst 123:97–107. https://doi.org/10.1016/j.agsy.2013.09.006
22. Lassaletta L, Billen G, Romero E, Garnier J, Aguilera E (2014) How changes in diet and trade patterns have shaped the N cycle at the national scale: Spain (1961–2009). Reg Environ Change 14:785–797. https://doi.org/10.1007/s10113-013-0536-1
23. Mansard L, Vigan A, Meuret M, Lasseur J, Benoit M, Lecomte P, Eugène M (2018) An enteric methane emission calculator (DREEM) built to consider feed diversity: Case study of pastoral and sedentary farming systems. Small Rumin Res 167:6–15. https://doi.org/10.1016/j.smallrumres.2018.07.024
24. Manzano Baena P, Casas R (2010) Past, present and future of trashumancia in Spain: nomadism in a developed country. Pastoralism: Res Policy Pract (Practical Action) 1(1):72–90
25. Manzano-Baena P, Salguero-Herrera C (2018) Mobile Pastoralism in the Mediterranean: Arguments and evidence for policy reform and to combat climate change. Liza Zogib. ed. Mediterranean Consortium for Nature and Culture, Geneva
26. Manzano P, White SR (2019) Intensifying pastoralism may not reduce greenhouse gas emissions: wildlife-dominated landscape scenarios as a baseline in life cycle analysis. Clim Res 77:91–97. https://doi.org/10.3354/cr01555
27. Manzano P, Galvin KA, Cabeza M (2020) A global characterization of pastoral mobility types. Open Anthropol Res Repository 120. https://doi.org/10.1002/oarr.10000335.1
28. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (in press) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.Cambridge University Press, Cambridge. https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/
29. Morgan-Davies C, Kyle J, Boman IA, Wishart H, McLaren A, Fair S, Creighton P (2021) A comparison of farm labour, profitability, and carbon footprint of different management strategies in Northern European grassland sheep systems. Agric Syst 191:103155. https://doi.org/10.1016/j.agsy.2021.103155
30. Odintsov Vaintrub M, Levit H, Chincarini M, Fusaro I, Giammarco M, Vignola G (2021) Review: Precision livestock farming, automats and new technologies: possible applications in extensive dairy sheep farming. Animal 15:100143. https://doi.org/10.1016/j.animal.2020.100143
31. Olea L, Verdasco M, Paredes J (1990) Características y producción de los pastos de las dehesas del SO de la Península Ibérica. Pastos 21:131–156
32. Pardo G, del Prado A (2020) Guidelines for small ruminant production systems under climate emergency in Europe. Small Rumin Res 193. https://doi.org/10.1016/j.smallrumres.2020.106261

33. Pardos L, Maza MT, Fantova E, Sepúlveda W (2008) The diversity of sheep production systems in Aragón (Spain): characterisation and typification of meat sheep farms. Span J Agric Res 6:497–507. https://doi.org/10.5424/sjar/2008064-344
34. Perea R, Girardello M, San Miguel A (2014) Big game or big loss? High deer densities are threatening woody plant diversity and vegetation dynamics. Biodivers Conserv 23:1303–1318. https://doi.org/10.1007/s10531-014-0666-x
35. Pérez-Barbería FJ (2017) Scaling methane emissions in ruminants and global estimates in wild populations. Sci Total Environ 579:1572–1580. https://doi.org/10.1016/j.scitotenv.2016.11.175
36. Plieninger T, Hui C, Gaertner M, Huntsinger L (2014) The impact of land abandonment on species richness and abundance in the mediterranean basin: a meta-analysis. PLoS ONE 9:e98355. https://doi.org/10.1371/journal.pone.0098355
37. PRé S (2020) Software LCA SimaPro 9.1 http://www.pre.nl
38. Ramo MdlÁ, Monteagudo LV, Tejedor MT, Sierra I (2018) The ovine variety “Merino de los Montes Universales” and its good adaptation to traditional transhumant breeding system. Small Rumin Res 166:35–40. https://doi.org/10.1016/j.smallrumres.2018.07.011
39. Reyes-Palomo C, Aguilera E, Llorente M, Díaz-Gaona C, Moreno G, Rodríguez-Estévez V (2022) Carbon sequestration offsets a large share of GHG emissions in dehesa cattle production. J Clean Prod 358:131918. https://doi.org/10.1016/j.jclepro.2022.131918
40. Riedel JL, Bernués A, Casasús I (2013) Livestock grazing impacts on herbage and shrub dynamics in a Mediterranean Natural Park. Rangel Ecol Manag 66:224–233. https://doi.org/10.2111/REM-D-11-00196.1
41. Ríos-Núñez SM, Coq-Huelva D, García-Trujillo R (2013) The Spanish livestock model: A coevolutionary analysis. Ecol Econ 93:342–350. https://doi.org/10.1016/j.ecolecon.2013.06.019
42. Ripoll-Bosch R, de Boer IJM, Bernués A, Vellinga TV (2013) Accounting for multi-functionality of sheep farming in the carbon footprint of lamb: A comparison of three contrasting Mediterranean systems. Agric Syst 116:60–68. https://doi.org/10.1016/j.agsy.2012.11.002
43. Silva JS, Catry FX, Moreira F, Lopes T, Forte T, Bugalho MN (2014) Effects of deer on the post-fire recovery of a Mediterranean plant community in Central Portugal. J For Res 19:276–284. https://doi.org/10.1007/s10310-013-0415-0
44. Toro-Mujica P, Aguilar C, Vera RR, Bas F (2017) Carbon footprint of sheep production systems in semi-arid zone of Chile: A simulation-based approach of productive scenarios and precipitation patterns. Agric Syst 157:22–38. https://doi.org/10.1016/j.agsy.2017.06.012
45. Vigan A, Lasseur J, Benoit M, Mouillot F, Eugène M, Mansard L, Vigne M, Lecomte P, Dutilly C (2017) Evaluating livestock mobility as a strategy for climate change mitigation: Combining models to address the specificities of pastoral systems. Agric Ecosyst Environ 242:89–101. https://doi.org/10.1016/j.agee.2017.03.020

Figures

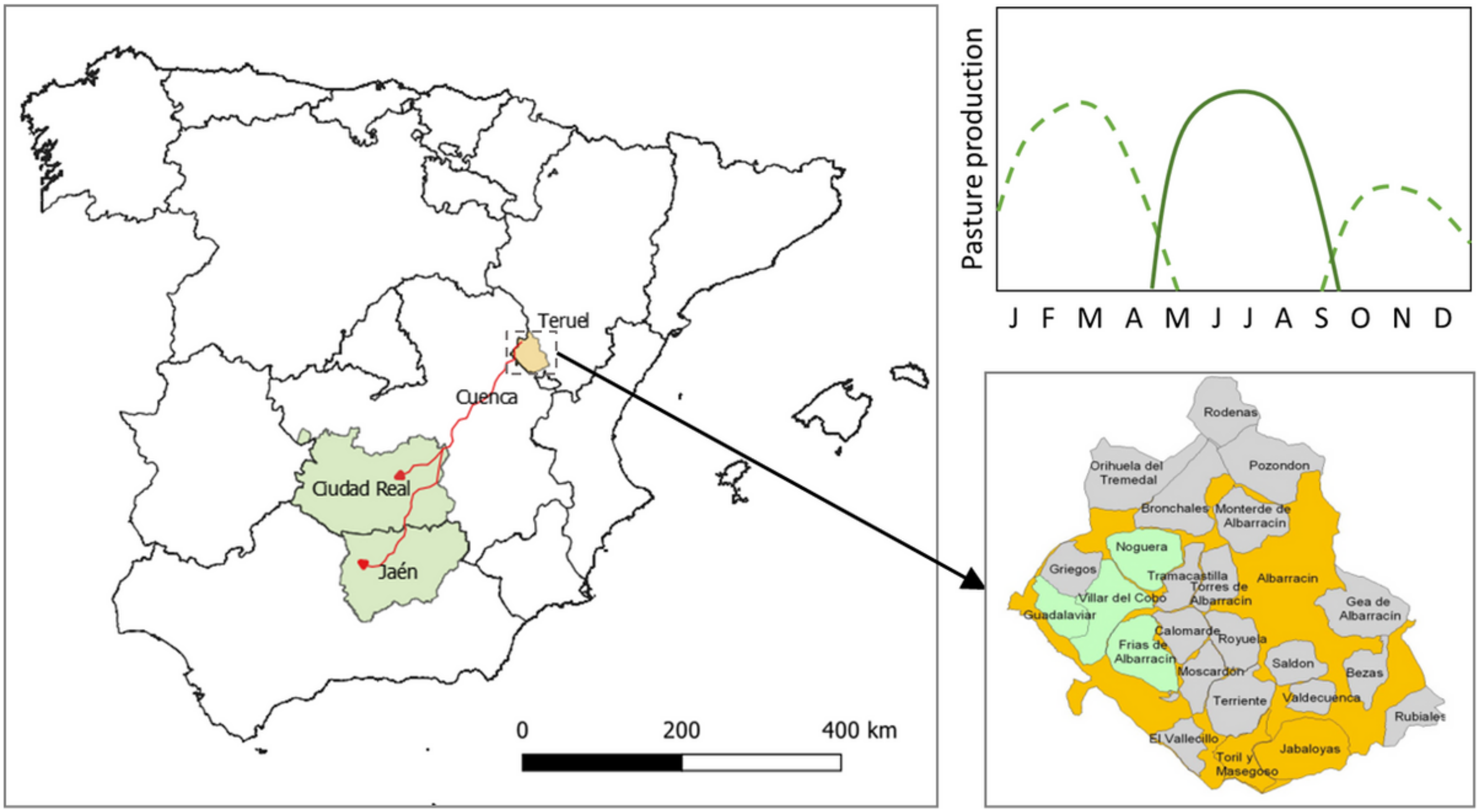

Figure 1

Location of the study area in Spain (left): red line shows the route of sheep pastoralism between mountain pastures in Community of Albarracín (Teruel) and Mediterranean pastures (Jaén, Ciudad Real). Detail of municipalities in Community of Albarracín (bottom right): in green, areas with transhumance towards Ciudad Real and Jaén, in grey, areas with no transhumance. Pasture production distribution along the year (top right): continuous line describes mountain pastures, and dotted line describes Mediterranean pastures.

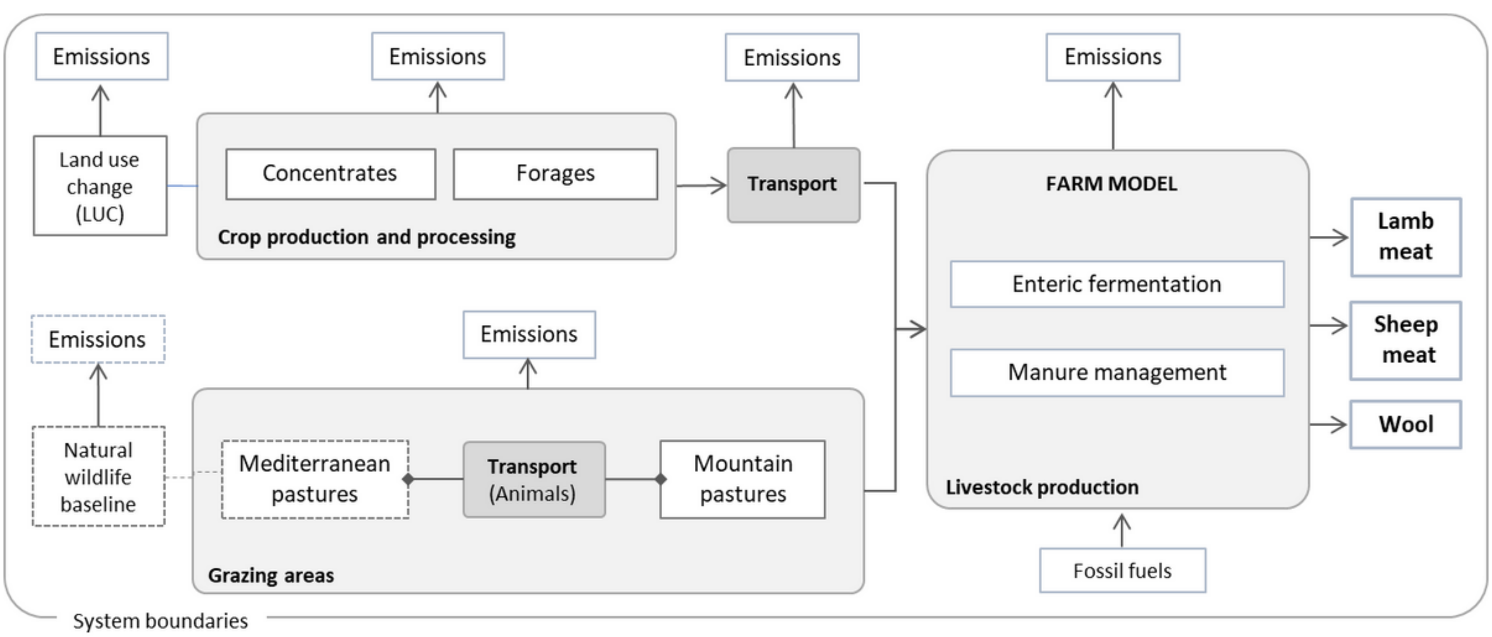

Figure 2

Schematic representation of the system boundaries for the sheep farming systems analyzed in this study. A cradle to farm gate perspective is applied. Dotted lines indicate aspects included when considering natural baseline emissions from wildlife in the assessment.

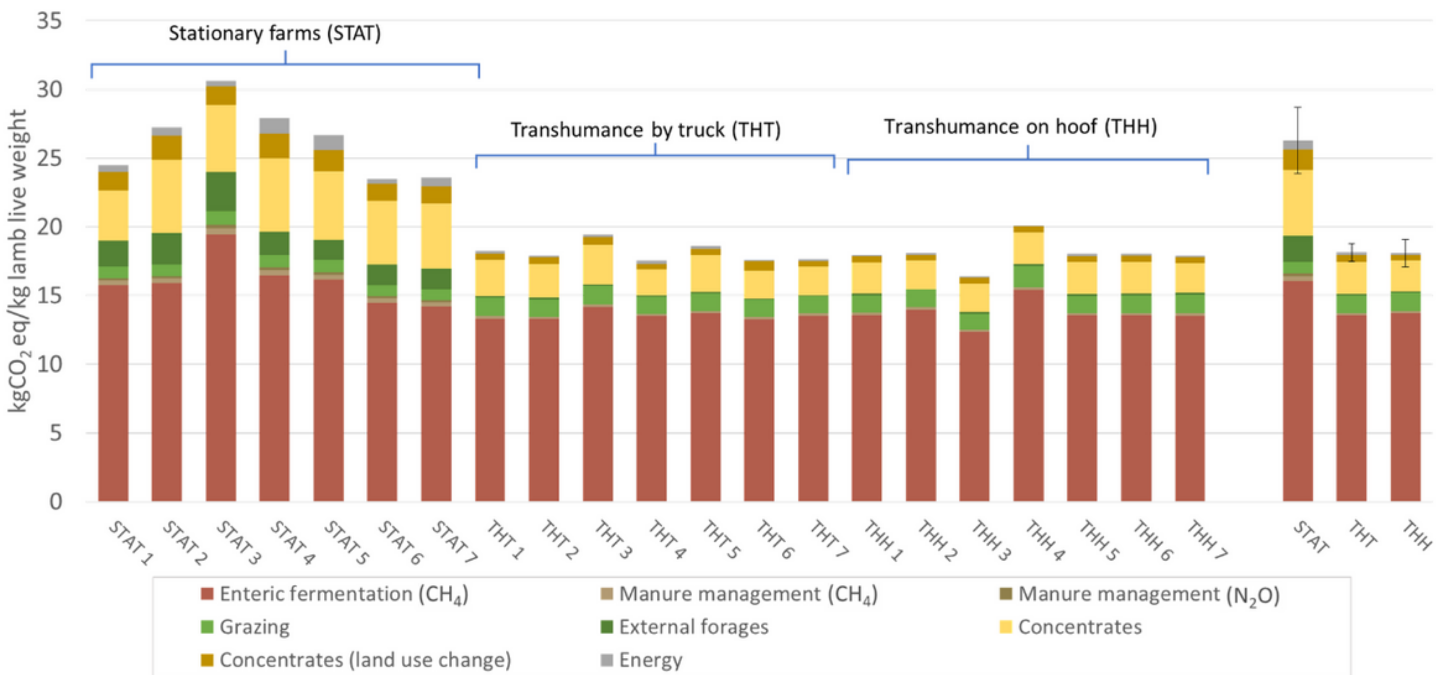

Figure 3

Estimated carbon footprint of lamb meat from the different sheep farm analyzed, and average results for the 3 typologies considered: stationary (STAT), transhumance by truck (THT) and transhumance on foot (THF). Bars represent standard deviation of calculated average footprints analyzed.

Supplementary Files

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- TableS1.docx