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LCA FOR AGRICULTURE

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 foot) or compared to 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 20 sheep farms was collected to estimate the carbon footprint (CF) of lamb meat produced. Farms were divided into three sub-groups representing typical management practices in the region: (1) sedentary (SED), (2) transhumance by truck (THT), and (3) transhumance on foot (THF). Livestock GHG emissions were modeled 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 (1) IPCC guidelines and (2) allometric regression equations.

Results and discussion Carbon footprint ranged from 16.5 up to 26.9 kgCO_2-eq/kg of lamb liveweight (LW). Significant differences were identified among sedentary and transhumant farms, the latter consistently showing lower CF values (SED: 25.1 kg CO_2-eq/kg LW, THT: 18.3 kg CO_2-eq/kg LW, THF: 18.2 kg CO_2-eq/kg LW). Sedentary farms resulted in higher GHG emissions (+27%) 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_2-eq/km^2), comparatively lower than estimation for transhumant sheep (47.7 Mg CO_2-eq/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.

Keywords LCA · GHG emissions · Transhumance · Wildlife emissions · Pastoralism · Lamb meat · Livestock mobility

1 Introduction

Greenhouse gas (GHG) emissions from the livestock sector are considered a large causative agent of climate change associated with anthropogenic activity, with estimations ranging from 7.1 (Gerber et al. 2013) to 9.9 (Xu et al. 2021) Gt CO_2-eq emitted yearly, representing 14.5 and 19% of total human-derived GHG emissions, respectively. Feed production and

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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_2-eq/yr), mainly beef and dairy cattle, although small ruminants also involve a significant share (0.5Gt CO_2-eq/yr) that can be of particular relevance in certain contexts and regions.

This is the case of the Mediterranean areas, where grazing ruminants 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 is a form of mobile pastoralism in which shepherds move herds regularly between summer and winter pastures whose location does not vary from year to year (Manzano et al. 2020). It is 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 could have gotten 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 nineteenth century, and shrunk dramatically during the twentieth century due to intensification, landscape fragmentation, and collapse of textiles following the introduction of artificial fibers (Ruiz and Ruiz 1986).

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 toward 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 (e.g., Herrero et al. 2016), due to a reduction in the emission intensity of animal products. However, transhumant systems have rarely been analyzed through LCA approaches, and most have studied systems in low- and middle-income countries (Ibidhi et al. 2017; Zhuang et al. 2017; Berhe et al. 2020; Yetişgin et al. 2022). Moreover, there is no clear evidence about their emission intensity (kg CO_2-eq/kg product) being greater than equivalent ruminant production systems under intensive management (Vigan et al. 2017; Yetişgin et al. 2022).

Such low-input mobile pastoral systems are strongly linked to natural and semi-natural areas providing seasonal pasture resources. In these open ecosystems, grazing livestock occupy similar ecological niches of wild herbivores, namely, the use of mostly fibrous resources in landscapes dominated by grassy vegetation. Both herbivore types reproduce similar seasonal patterns when using the landscape and carry out analogous ecosystem functions—the reason behind the high ecological value of mobile pastoralism (Manzano-Baena and Salguero-Herrera 2018, García-Fernández et al. 2019). Wild herbivores were abundant before human action displaced or eliminated them, both in Spain (Rodríguez et al. 2014) and globally (Manzano et al. 2023). Such abundance would imply a significant delivery of ecosystem services (Enquist et al. 2020; Schweiger and Svenning 2020) but also significant quantities of GHG emissions (Smith et al. 2016), constituting a natural baseline that is inherent to grazing ecosystems. After them being displaced, their function in ecosystems was substituted by grazing livestock, including not only the delivery of ecosystem services, but also GHG emissions they are coupled with.

When dealing with provisioning services from the natural environment, common approaches in LCA limit their system boundaries to the frontier between ecosphere and technosphere (Fig. 1). Within this methodological framework, wild herbivores are characterized as natural biotic resources that enter the system as elementary flows from the ecosphere (Crenna et al. 2018). As a result, associated emissions (e.g., enteric CH_4) are considered natural GHG fluxes occurring in the ecosphere and therefore not included in the impact assessment of the derived products, such as meat from wild animals (Fiala et al. 2020).

However, in agricultural systems, the boundary between ecosphere and technosphere can be often difficult to define, especially in those cases with a strong link to natural systems, like pastoralism (Crenna et al. 2018). While livestock husbandry is undoubtedly a "man-made" activity, grass consumed in extensive pasture lands has been pointed out as an example of resources extracted by humans from natural systems, at the same level of wood harvested from primary forests, or seafood from ocean waters (Alvarenga et al. 2013). Under this perspective, given that transhumant livestock is occupying the ecological niche of wild herbivore populations, it is therefore reasonable to consider within the ecosphere those emissions related to the consumption of natural grassland resources (i.e., natural biotic resources) and only include within the technosphere those transhumance-triggered emissions that depart from the natural baseline level associated to wild herbivore activity.

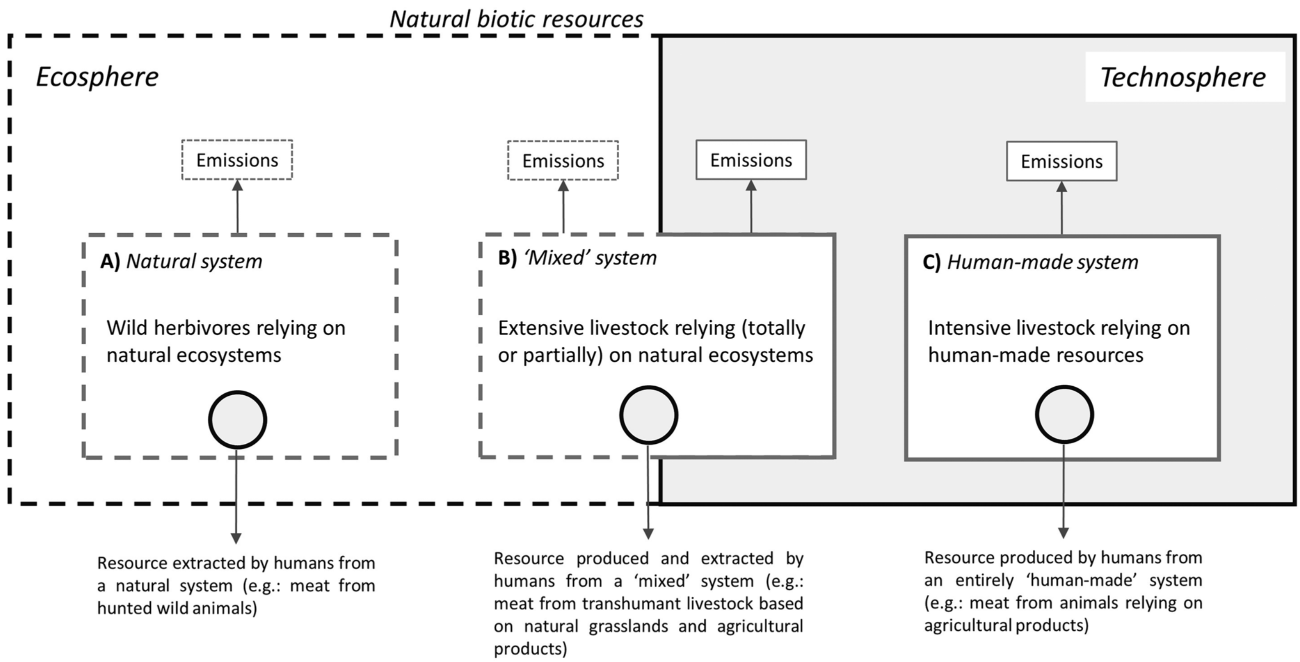

Fig. 1 System boundaries between ecosphere and technosphere for different systems producing biotic resources. In natural systems (**A**), resources are produced in natural environment, and emissions are considered within the ecosphere. Mixed systems (**B**) involve human intervention but resource production relies totally or partially on natural environment. Entirely human-made systems (**C**) are based only on resources produced through human intervention (i.e., within technosphere). Adapted from the approach developed by Alvarenga et al. (2013) and Crenna et al. (2018)

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 foot; (3) to propose a methodological framework for pastoral livestock systems that allows the separation of emissions between ecosphere and technosphere, through the utilization of a baseline accounting for natural wildlife emissions; and (4) to explore if this framework could involve a relevant effect in the carbon footprint of transhumant systems linked to natural grassland ecosystems.

2 Materials 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. 2). 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: (1) sedentary farms (SED), (2) transhumance by truck (THT), and (3) transhumance on foot (THF).

Historically, transhumance was the common practice in the Community of Albarracín, as its average altitude, above 1400 m, 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, sedentary management model, where sheep graze communal mountain pastures in the summer and spend the winter enclosed in barns, fed with external forage (straw) and concentrates.

Transhumant pastoralism, both by truck and on foot, 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, with an approximate distance of 400–450 km by road and 375–420 km on foot using the Conquense Drove Road, depending on the wintering areas chosen. Transhumance by truck and on foot used all wintering areas indistinctly. The southbound travel usually takes place in November, and herds spend 6 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). Truck transport typically uses a Scania R520 truck type, accommodating 300 sheep in three levels.

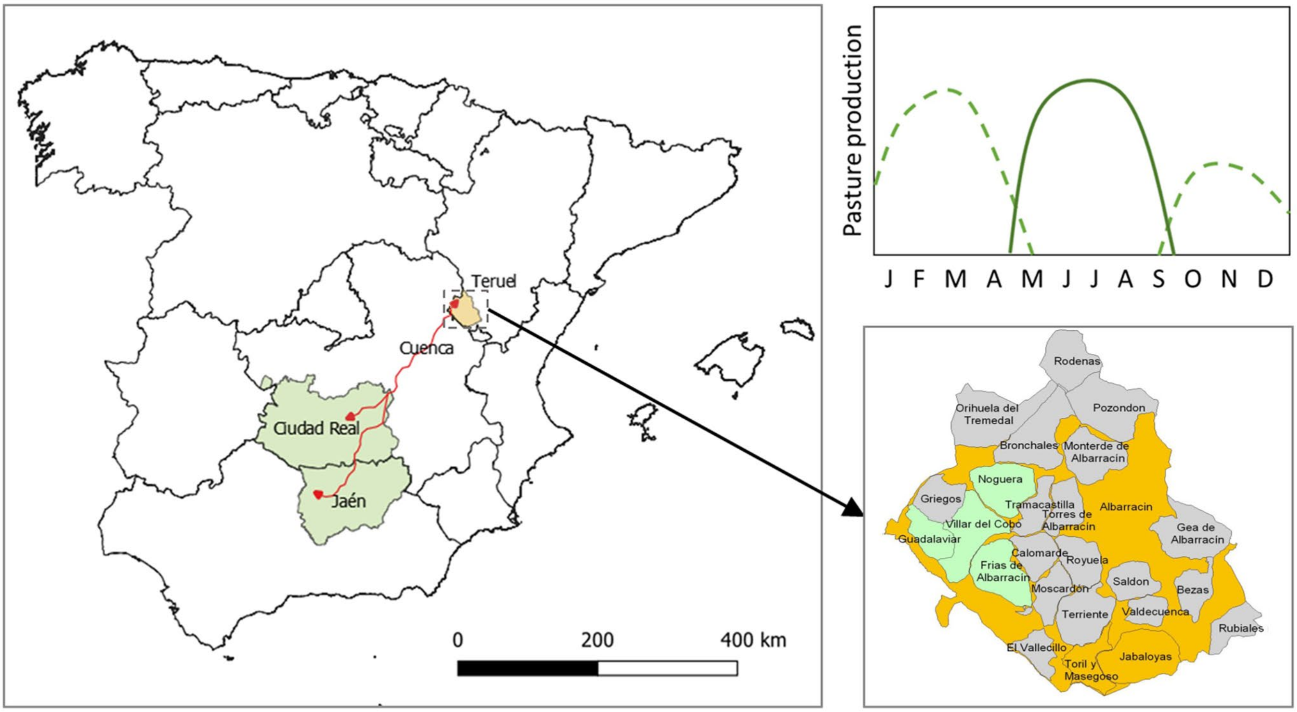

Fig. 2 Location of the study area in Spain (left): red line shows the route of sheep pastoralism between mountain pastures in Community of Albarracín (Teruel) and Mediterranean pastures (Jaén, Ciudad Real). Detail of municipalities in Community of Albarracín (bottom right): in green, areas with transhumance towards Ciudad Real and Jaén; in gray, areas with no transhumance. Pasture production distribution along the year (top right): continuous line describes mountain pastures, and dotted line describes Mediterranean pastures

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" (de los Ángeles Ramo et al. 2018), although other local ovine breeds are also found among the sheep farms in the area, such as Rasa Aragonesa. In 2009, there was a total of 34 transhumant farms in the Community of Albarracín, representing 19% of farms and 32% of total sheep in the area. Among them, 8 farms practiced transhumance on foot, representing 25% of transhumant sheep (Casas Nogales and Manzano Baena 2011).

2.2 Carbon footprint assessment

2.2.1 Data collection and sample description

A total of 20 sheep farms were analyzed through the study in order to estimate their carbon footprint. Seven farms from each of the three sub-groups, (1) sedentary (SED), (2) transhumance by truck (THT), and (3) transhumance on foot (THF), 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). Lambs are sold at the same live weight (26 kg). Key characteristics of the farms involved in the study are provided in Tables 1 and S1.

2.2.2 System boundaries and functional unit

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. 3). 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 from the analysis as they imply few additional GHG emissions for this case study. The functional unit (FU) considered was 1 kg of lamb live weight (LW) leaving the farm gate.

Table 1 Collected parameters, presented according to average results by farm typology: sedentary (SED), transhumance by truck (THT), and transhumance on foot (THF)

	SED Mean	SEM	THT Mean	SEM	THF Mean	SEM
Number of adult ewes	467[a]	99	661[a]	135	590[a]	86
Replacement rate (%)	17%[a]	0.2%	14%[b]	0.8%	14%[b]	0.8%
Mortality rate (%)	24%[a]	3.7%	11%[b]	0.7%	10%[b]	0.0%
Outputs						
Lambs sold (lambs/ewe)	0.93[a]	0.02	1.11[b]	0.01	1.12[b]	0.03
Sheep culled (ewes culled/ewe)	0.15[a]	0.002	0.11[b]	0.008	0.11[b]	0.007
Wool sold (kg/ewe)	2.05[a]	0.004	2.14[a]	0.060	2.07[a]	0.006
Inputs						
Mountain pastures (ha/ewe)	0.35[a]	0.001	0.35[a]	0.002	0.35[a]	0.003
Dehesa pastures (ha/ewe)	–	–	0.60[a]	0.005	0.60[a]	0.004
Sheep concentrate (kg/ewe)	163.5[a]	9.3	102.6[b]	7.0	97.4[b]	1.8
Lamb concentrate (kg/ewe)	43.0[a]	2.5	10.1[b]	1.7	8.4[b]	0.3
Straw (kg/ewe)	164.3[a]	12.1	11.1[b]	1.3	13.8[b]	2.1
Diesel (kg/ewe)	1.61[a]	0.45	1.99[a]	0.21	1.53[a]	0.21

Different letters indicate differences between averages on the same column ($p < 0.05$)

SEM standard error of the mean

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 GHG 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.

Moreover, in order to show the potential effect of allocation choice in the results, an additional procedure of allocation based on mass content was explored. Details are provided in the Supplementary material.

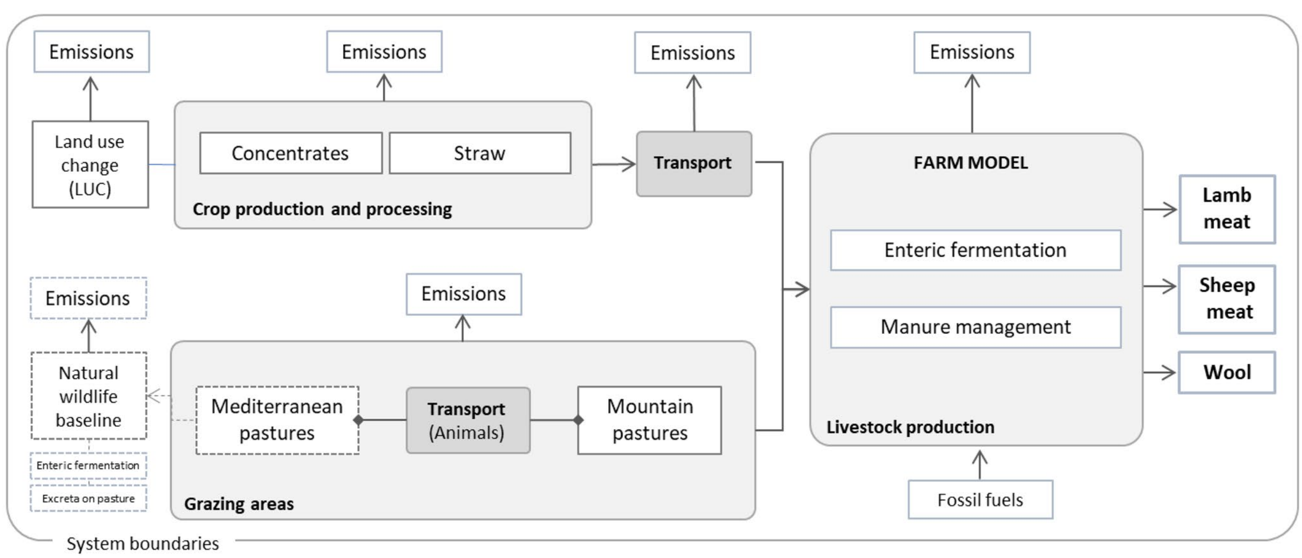

Fig. 3 Schematic representation of the system boundaries for the sheep farming systems analyzed in this study. A cradle to farm gate perspective is applied. Dotted lines indicate aspects included when considering natural baseline emissions from wildlife in the assessment

2.3 Life cycle inventory

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 during a single transhumance event in spring 2009, involving an accompanying walk during their journey in the case of herds that practiced transhumance on foot. The latter was done to make sure selected herds were actually migrating on foot. 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.

Communal pastures assigned at every farm were estimated based on herd size and grazing density according to regional statistics (INE 2010; Díaz Gaona et al. 2014). In addition, feed suppliers were consulted to collect sheep and lamb concentrates composition. Specific feed ingredients used and countries of origin are shown in Tables 2 and S2.

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 (Fig. S1). 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 in Chapter 10 of the latest 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 (Tables 3 and S3). 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) and feed intake were 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 sedentary 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 (B_o) of manure was set 0.18 m^3 CH_4/kg VS, 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

Table 3 Feed intake in kg of dry matter (DM) for the different animal categories and feed sources, presented according to average results by farm typology: sedentary (SED), transhumance by truck (THT), and transhumance on foot (THF)

Animal	Feed type	SED		THT		THF	
		Mean	SEM	Mean	SEM	Mean	SEM
Sheep	Concentrate	69.0	15.1	58.5	9.2	52.0	7.0
	Straw	71.3	18.6	5.9	0.9	7.5	1.5
	Pastures	117.1	21.4	273.5	56.0	243.1	33.1
	TOTAL	*257.4*	*53.5*	*338.0*	*64.5*	*302.6*	*41.0*
Lamb	Milk	8.7	1.7	12.3	2.3	10.9	1.5
	Concentrate	17.4	4.0	7.6	2.9	5.2	0.8
	Straw	3.2	0.6	0.0	0.0	0.0	0.0
	Pastures	11.7	2.3	52.2	8.5	51.1	6.8
	TOTAL	*41.0*	*8.2*	*72.1*	*13.1*	*67.2*	*9.1*

SEM standard error of the mean

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 (Hergoualc'h et al. 2019). Indirect N_2O emissions from ammonia (NH_3) and nitrate (NO_3^-) losses were accounted through the Tier 1 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. GHG emissions from direct land use change (LUC) were accounted through Agri-footprint datasets for the different crops and feedstuffs involved in the system. A specific tool is applied (PAS 2050–1: Land Use Change Assessment Tool) that uses data of land use under different periods from official statistics derived from FAOSTAT. Emissions related to fuels (i.e., diesel) consumed on-farm were estimated from Ecoinvent 3.3 database (Ecoinvent 2016). Truck fuel usage was calculated considering a Scania R520 truck type, with a consumption of 32 l/100 km of diesel and a capacity of 300 sheep (SoloCamión.es 2022).

2.3.3 Definition of natural baseline emissions in Mediterranean rangeland ecosystems

In this work, we propose a methodological framework for setting the boundaries between ecosphere and technosphere for livestock systems dealing with biotic resources extracted from natural systems ("mixed systems" in Fig. 1). To do so, we followed the approach proposed by Alvarenga et al. (2013) and Crenna et al. (2018). According to this, a system is categorized as natural if the production of its biomass can be maintained with no or negligible human intervention (e.g., ploughing and fertilization), and this is the case of natural grassland ecosystems. In this framework, wild herbivores are considered resources from natural systems, whose emissions occur in the ecosphere. Similarly, intensive livestock based only on agricultural products is considered a human-made system, with its emissions occurring entirely in the technosphere. However, there are livestock systems with a strong link to natural ecosystems, where the boundary between ecosphere and technosphere can be difficult to define. We consider this is the case of transhumant pastoralism that exploits the grass seasonally from different extensive pastures in an analogous way that wild herbivores would do through migratory behavior. Under this perspective, given that transhumant livestock is occupying the ecological niche of wild herbivore populations, we propose to consider within the ecosphere those emissions related to the consumption of natural grassland resources (i.e., no, or negligible, human intervention) and only include within the technosphere those transhumance-triggered emissions that depart from the natural baseline level associated to wild herbivore activity. We introduce here the concept of natural "baseline" emissions, which is the reference amount of GHG fluxes intrinsically associated to the activity of wild herbivores in a natural ecosystem. Following the proposed framework, we argue that when pastoral livestock systems are based on the use of natural grassland landscapes, thus occupying the ecological niche of wild herbivores, a proportional fraction of their emissions could be considered to be produced in the ecosphere. As a proxy to establish that amount we propose to use the so-called natural "baseline" GHGs emitted from wild herbivores in an equivalent natural grassland ecosystem.

According to this framework, the procedure for calculating emissions in the technosphere from "mixed systems" would be as follows (Eqs. 1–3):

$$Emissions('Mixed\ system')_{TOTAL} = Emissions_{Ecosphere} + Emissions_{Technosphere} \quad (1)$$

$$Emissions_{Ecosphere} = Emissions('Natural\ system')_{Baseline} \quad (2)$$

$$Emissions_{Technosphere} = Emissions('Mixed\ system')_{TOTAL} - Emissions('Natural\ system')_{Baseline} \quad (3)$$

where $Emissions_{TOTAL}$ are the total emissions from a "mixed" livestock system; $Emissions_{Ecosphere}$ and $Emissions_{Technosphere}$ are the emissions from a "mixed" livestock system considered within the ecosphere and technosphere, respectively; and $Emissions_{Baseline}$ are the emissions from a natural system (i.e., wild herbivores) in an equivalent ecosystem.

Depending on many climatic and ecological factors, natural rangeland ecosystems can lead to different herbage productivities, wild herbivore carrying capacities, and, ultimately, associated natural GHG emissions, which must be carefully considered in every case. In the context of the Iberian Peninsula, natural grassland ecosystems are 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. This kind of habitat is intrinsically related to the presence of herbivores consuming the available feed resources (grass and forbs, leaves and branches, acorns), who are shaping the landscape while inevitably releasing some amounts of GHGs into the atmosphere through enteric fermentation and excreta deposition.

In order to account for the natural "baseline" emissions of wild herbivores in the Mediterranean context, we used the red deer population density reported from Quintos de Mora public hunting preserve located in Ciudad Real, South Central Spain (Carpio Camargo et al. 2021). Here, no supplements are provided to the resident population of wild herbivores and the hunting use is of an extremely low intensity, making it ideal to study natural ungulate abundances. The local ecosystem is similar to the Mediterranean open landscapes that constitute the range of the transhumant herds studied. The selected site has a surface of 6862 km^2, an altitude ranging between 600 and 1100 m a.s.l., and is representative of the kind of big-game hunting estates in Mediterranean Spain where animals do not receive supplementary feeds, 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 > 2 years) structure of the deer population, by computing the proportion of adults (72.8%), and the number of female/male ratio (1.35). Hence, three animal classes were computed: adult male, adult female, and young (< 2 years), 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,

$$EF_w = EF_d \cdot \left(\frac{M_w}{M_d}\right)^{0.75} \tag{4}$$

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:

$$\log\left(CH_4\ output\right) = -4.564 + 3.278 \log\ BW^{0.592} \tag{5}$$

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 characterization

The IPCC 2021 method (Chen et al. 2021) 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 (SED, THT, and THF). 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 sedentary farms (SED) were found significantly higher than the values reported by farms practicing transhumance, either by truck (THT) or on foot (THF). Sedentary farms showed significant differences with the rest in terms of outputs too, presenting lower production of lambs per ewe (SED = 0.90; THT = 1.11; THF = 1.12) and a higher ratio of sheep culled. Sedentary farms also presented significantly higher consumption of external feed inputs per ewe, such as concentrates and forage (straw).

When comparing farms applying transhumance by truck or on foot, 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 foot showed slightly lower ratios of diesel and concentrates utilization, while those farms conducting transhumance by truck presented slightly lower usage of external forage (straw).

3.2 Carbon footprint

The carbon footprints (CF) of 1 kg of lamb live weight (LW) for the 20 sheep farms analyzed in the study are shown in Fig. 4 and Table S4, together with the contribution from different GHG sources. Carbon footprint results ranged from 16.5 up to 26.9 kgCO_2-eq/kg lamb LW. Significant differences were identified among sedentary and transhumant farms, which consistently showed lower CF values (SED:

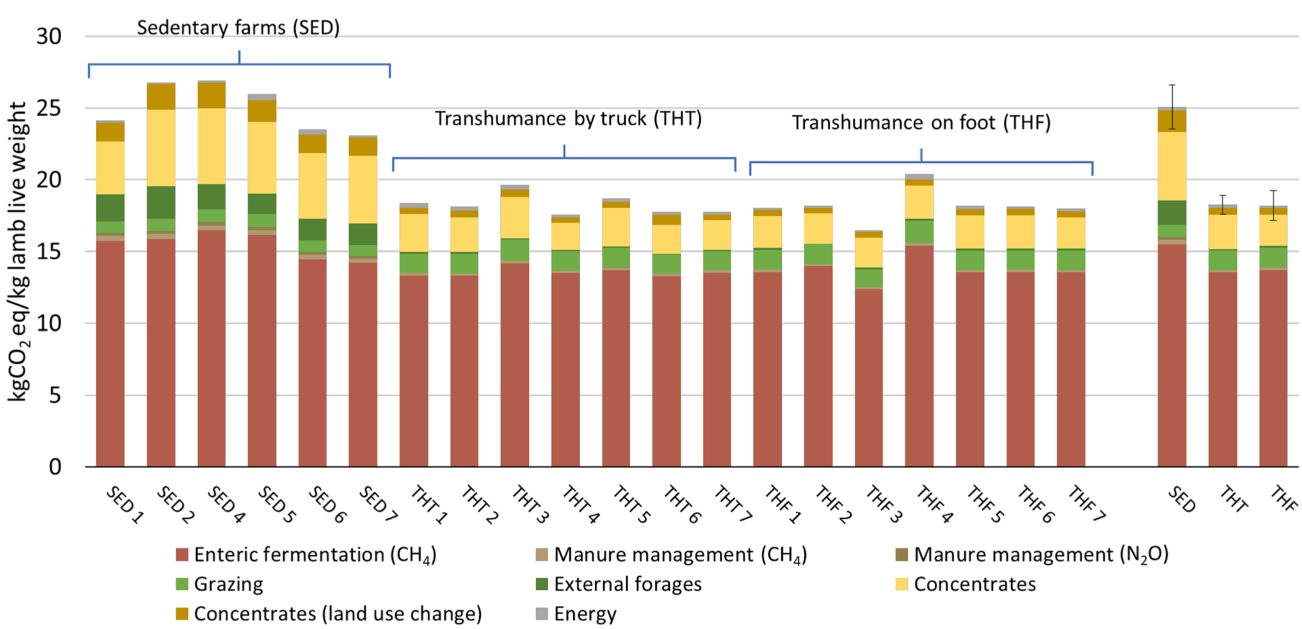

Fig. 4 Estimated carbon footprint of lamb meat from the different sheep farm analyzed, and average results for the 3 typologies considered: sedentary (SED), transhumance by truck (THT), and transhumance on foot (THF). Bars represent standard deviation of calculated average footprints analyzed

Table 4 Average results of carbon footprint (in kg CO_2-eq) of 1 kg of lamb meat (liveweight) by farm typology: sedentary (SED), transhumance by truck (THT), and transhumance on foot (THF)

	SED		THT		THF	
	Mean	SD	Mean	SD	Mean	SD
Enteric fermentation CH_4	15.5[a]	0.8	13.5[b]	0.3	13.7[b]	0.8
Manure management CH_4	0.3[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	0.8[a]	0.1	1.3[b]	0.0	1.3[b]	0.1
External forages	1.7[a]	0.3	0.1[b]	0.0	0.1[b]	0.0
Concentrates	4.8[a]	0.6	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	0.2[a]	0.1	0.2[a]	0.1	0.2[a]	0.1
Carbon footprint (without LUC)	23.6[a]	1.3	17.8[b]	0.7	17.8[b]	1.0
Carbon footprint (TOTAL)	25.1[a]	1.7	18.3[b]	0.7	18.2[b]	1.1

Different letters indicate differences between averages on the same column ($P < 0.05$)

SD standard deviation, *LUC* Land Use Change

25.1 kgCO_2-eq/kg LW, THT: 18.3 kgCO_2-eq/kg LW, THF: 18.2 kgCO_2-eq/kg LW). Results from the sensitivity analysis using an additional allocation method (based on mass) are shown in Table S5. Allocation based on mass content resulted on lower CF estimations for lambs' meat (14–25% lower than economic), by attributing more environmental load to the wool and meat from culled ewes.

Independently of allocation method, some differences were observed between the farms of the different groups. Sedentary farms presented significantly higher GHG emissions from the production of external feed resources (straw and concentrates) and manure management, while the contribution from grazing was significantly lower (Table 4). In all the groups, the larger proportion of total GHG emissions was associated with enteric fermentation, with significant differences between sedentary farms (62%) and transhumant farms, where the contribution of enteric CH_4 was higher (72–74%). 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 (1.25% vs. 0.97%) and concentrate consumption. In contrast, in the group of farms carrying on transhumance on foot, higher contributions from straw 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 5, on a surface basis (kg CO_2-eq/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%).

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_2-eq/km^2) in comparison with the allometric method (22.0 Mg CO_2-eq/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

Table 5 Estimated natural emissions from wild herbivores in Mediterranean grasslands ecosystem and comparison with transhumant grazing-based sheep

Animal class	Density Number/km^2	Biomass kg/km^2	Enteric CH_4 (Mg CO_2eq/km^2)	Manure CH_4	Manure N_2O	TOTAL
Wild herbivores						
Red deer[a]	32.9	4814	20.5	0.3	4.4	25.3
Red deer[b]	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

[a]Enteric CH_4 emissions applying IPCC Tier 1 method

[b]Enteric CH_4 emissions applying allometric method

a LCA perspective), natural baseline emissions were 43–46% lower per square kilometer.

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. 4), reducing the carbon footprint of lamb meat by about one third (Table 4). 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 straw 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 land use change 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 pasture 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 (1) extending the grass growing season under the canopy and (2) 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 productivity (Table 1), ultimately leading to a higher ratio of lambs sold per ewe (SED: 0.90, THT, THF: 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 (SED: 17%, THT, THF: 14%). A similar pattern was observed by previous studies analyzing sedentary and mobile flocks in the area (de los Ángeles 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 under favorable environmental conditions, protecting them from extreme temperatures through seasonal mobility. The negative effect of low air 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 and Brink 1977). Such effects would compensate for eventual improvements in productivity brought by use of concentrates or by lower predation rates for the three winter months that the sedentary herds are spending in the barn.

Differences in mobility among systems do not have a great impact on direct consumption of fossil fuels at farm (Fig. 5), mostly linked to machinery for cleaning operations and provisioning of feed (straw/concentrate) rations. However, although not accounted within the boundaries of the CF analysis, an increased fuel use was observed at farmers' households in sedentary farms (Table S6) (SED: 8.5 kg/ewe, THT: 0.7 kg/ewe, THF: 0.0 kg/ewe). This was attributed to a higher energy demand for heating due to longer periods spent under cold temperatures compared to transhumant farmers.

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 sedentary herds. Increased use of external feeds did not involve a reduction

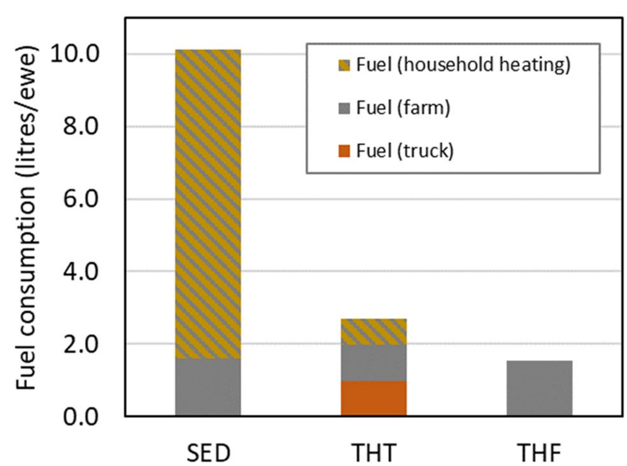

Fig. 5 Different sources of diesel consumption at every livestock system analyzed in the study. Household heating is not accounted in the carbon footprint of lamb meat as it is considered out of system boundaries, but data are shown for discussion purposes

in enteric CH_4 emissions for sedentary farms though. While they consumed more concentrates, they also use more external forage (straw) with very low digestibility. Hence, despite having different diets, feed digestibility among systems did not differ much (SED = 57.6%, THT = 58.4%, THF = 58.1%). On the other hand, increased use of concentrates in sedentary systems 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. 2013). 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 ones (i.e., CH_4) (del Prado et al. 2021).

Establishing comparisons among LCA studies of livestock systems is difficult, as methodological choices and modeling 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 contexts (Morgan-Davies et al. 2021). For the same region as our analysis, Ripoll-Bosch et al. (2013) reported a CF value from a grazing-based system of 25.9 $kgCO_2$-eq/kg lamb LW (comparable to 25.1 $kgCO_2$-eq/kg lamb LW for sedentary extensive farms in this study) and of 19.5 $kgCO_2$-eq/kg lamb LW from a zero-grazing intensive system. Hence, according to our results, the CF estimated for transhumance systems (18.2 $kgCO_2$-eq/kg lamb LW) is in a similar range 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 (Reyes-Palomo et al. 2022).

4.2 Differences between transport by truck and on foot

Farms applying transhumance by truck or on foot 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 foot (THT: 2.0 kg/ewe, THF:1.5 kg/ewe), which is associated to the road transport of the animals requiring an extra input of fuel (Fig. 5). A higher need of concentrates for adult ewes and lambs was observed too (THT: 103 kg/ewe, THF: 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 foot 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 75 m, and the daily displacement of about 24 km, provides to the animals the necessary food and time for intake and rest, thus maintaining an adequate body condition (de los Ángeles 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 traveling 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 foot compared to by truck (THT:13.5 $kgCO_2$/kg LW, THF: 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.

Mobile pastoralism and transhumance—particularly on foot—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-Baen 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 foot should result in lower environmental impacts than calculated by current methodologies. Additional considerations of higher GHG emissions linked with livelihood aspects, such as the lower household heating consumption among transhumant families, and more so when moving on foot (Fig. 5), would further highlight their lower environmental impacts.

4.3 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. 2018), 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 (Table S7).

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/km^2, within the range found in other studies in the Iberian Peninsula reporting > 30 deer/km^2 in Spain (Perea et al. 2014) and up to 40 deer/km^2 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 Baena 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.

Table 6 Profile of GHGs for the average carbon footprint of 1 kg of lamb meat (LW: live weight) by farm typology: sedentary (SED), transhumance by truck (THT), and transhumance on foot (THF)

GHG contribution	Without baseline			With baseline	
	SED	THT	THF	THT	THF
CH_4 (%)	62%	72%	74%	68%	71%
CO_2 (%)	24%	12%	11%	16%	15%
N_2O (%)	14%	16%	15%	16%	14%
Carbon footprint (kg CO_2-eq/kg lamb LW)	25.1	18.3	18.2	13.1	13.0

Results with and without considering natural baseline emissions from wild herbivores in Mediterranean grasslands ecosystem

Considering herbivores grazing in nature as an elementary flow entering the system from the ecosphere, 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 6), 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). Our study deliberately did not follow approaches that account for negative GHG emissions from soil–plant C sequestration, as applied, e.g., for Senegal (Assouma et al. 2019) or Spain (Reyes-Palomo et al. 2022). While they share with our study their territory scale, their conclusions rely on increases in carbon stocks that would not involve further GHG absorption once the ecosystem reaches a state of equilibrium (Smith 2014; Sanderson et al. 2020). Such circumstantial increases are not coherent with the baseline approach, which conceptually relies on ecological systems at equilibrium.

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. Impact is being reduced by an efficient use of local rangeland resources, which reduces the 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. A pastoralism abandonment scenario would likely 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) and that, according to estimates for global herbivore baselines, could translate into relevant emission levels (Manzano et al. 2023). 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.

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

Declarations

Conflict of interest PM 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.

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