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Are impact assessment approaches effective for addressing researches on GHG emissions from pastoral systems?

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The environmental impacts of livestock systems have been often under discussion in relation to their negative impacts to climate change. For several years, conventional assessments of such impacts have been preferably adapted and implemented on industrialized livestock systems. On the contrary, when applied to extensive systems such as pastoral ones, they have created distortions in the attribution of the related climate impacts. In the context of the in-depth studies on the topic conducted by the ERC research project PASTRES, several case studies of contextualized research on GHG emissions of three different pastoral systems in Africa, Asia and Europe were analyzed. Different assessment methodologies were compared, without or with the use of the Life Cycle Assessment (LCA) approach. Some limitations emerged from the analysis that concerned: 1) the analysis of emissions in a broader context/ecosystem-based approach 2) the definition of Functional Units 3) the provision of ecosystem services, with particular attention to biodiversity and the inclusion of C sequestration within the LCA calculation. These limitations penalize a complete and adequate estimate of environmental impacts and, consequently, a correct evaluation of implementation scenarios that aim to create conditions of greater sustainability of pastoral systems. The analysis suggests that the assessment of the impacts of pastoral systems, strongly characterized by land occupation, use of environmental resources, seasonal climate and social relations, requires a systemic approach that adapts and extends the

LCA methodology, through the harmonization of alternative metrics based on both conventional LCA and the assessment of the social and nutritional implications of pastoral farming.

KEYWORDS

pastoral systems, GHG emissions, life cycle assessment, ecosystem services, environmental impacts

Introduction

Extensive livestock systems, including pastoralism, involve many millions of people across rangelands covering over half the world's land surface. These systems play numerous roles, shaping marginalized areas with their multifunctionality, ensuring livelihoods for local communities and contributing to economic development through employment opportunities and value creation (Ragkos and Nori, 2016). The multifunctionality of pastoral systems is revealed in the form of a whole range of environmental, social and economic functions of the primary sector, since, in addition to marketable goods (food and fibre), agriculture produces a range of non-market products (OECD, 2001).

The environmental impacts of extensive livestock systems are currently under discussion among media campaigns, researches and variegate narratives in relation to their presumed cause-effect relationship with regard to climate change. A report edited by Houzer and Scoones (2021) in the framework of the ERC funded project PASTRES (pastres.org), highlighted how a better understanding of extensive livestock impacts on greenhouse gas emissions (GHG) is essential. Environmental assessment approaches such as Life Cycle Assessment (LCA) are widely used to estimate the GHG emission intensity of livestock systems (Goglio et al., 2023). LCAs allow the identification of environmental hotspots and effective mitigation solutions and are considered essential tools to guide environmental strategies within the ecological transition of production systems (Hellweg et al., 2023). The vast majority of LCA analyses on livestock systems examine standardized industrial systems, mostly from Europe and North America, in which a limited set of inputs and outputs are analyzed (Houzer and Scoones, 2021). On the other hand, data from important pastoral regions are insufficiently represented in numerous global studies, leading to potentially misleading estimates (Scoones, 2023). Clark and Tilman (2017) showed that only about 13% of assessments of GHG emissions from livestock systems comes from Asia, Latin America and Africa, where extensive livestock systems and pastoralism are widely diffused (Figure 1).

Using such simplistic and uniform criteria to evaluate the environmental impacts of such multifunctional, complex, dynamic and diversified systems, such as pastoral ones, would seem reductive (Houzer and Scoones, 2021). The consequence is that conventional assessments may cause potential flaws in the examination of such multifunctional extensive pastoral systems and rarely reflect pastoral contexts, creating distortions and misunderstandings in debates about the climate impacts (Scoones, 2023). Only a few studies performed comprehensive assessment of the pastoral production process, adequately reflecting its multifunctionality, including other relevant impact categories rather than global warming, such as land use, water consumption, biodiversity, carbon sequestration (Aguilera et al., 2021; Atzori et al., 2017a) and other related ecosystem services

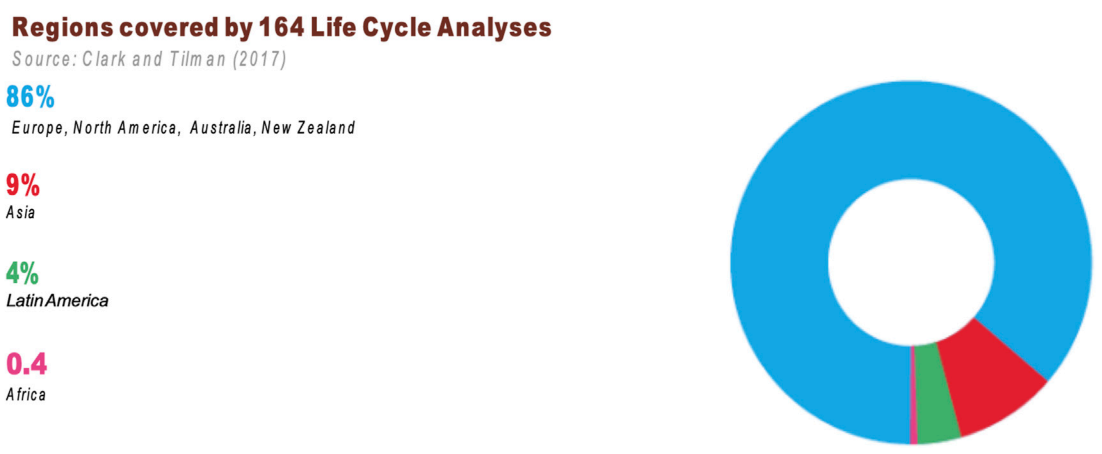

FIGURE 1
Regions covered by 164 Life Cycle Analyses (From Houzer and Scoones, 2021, source: Clark and Tilman, 2017).

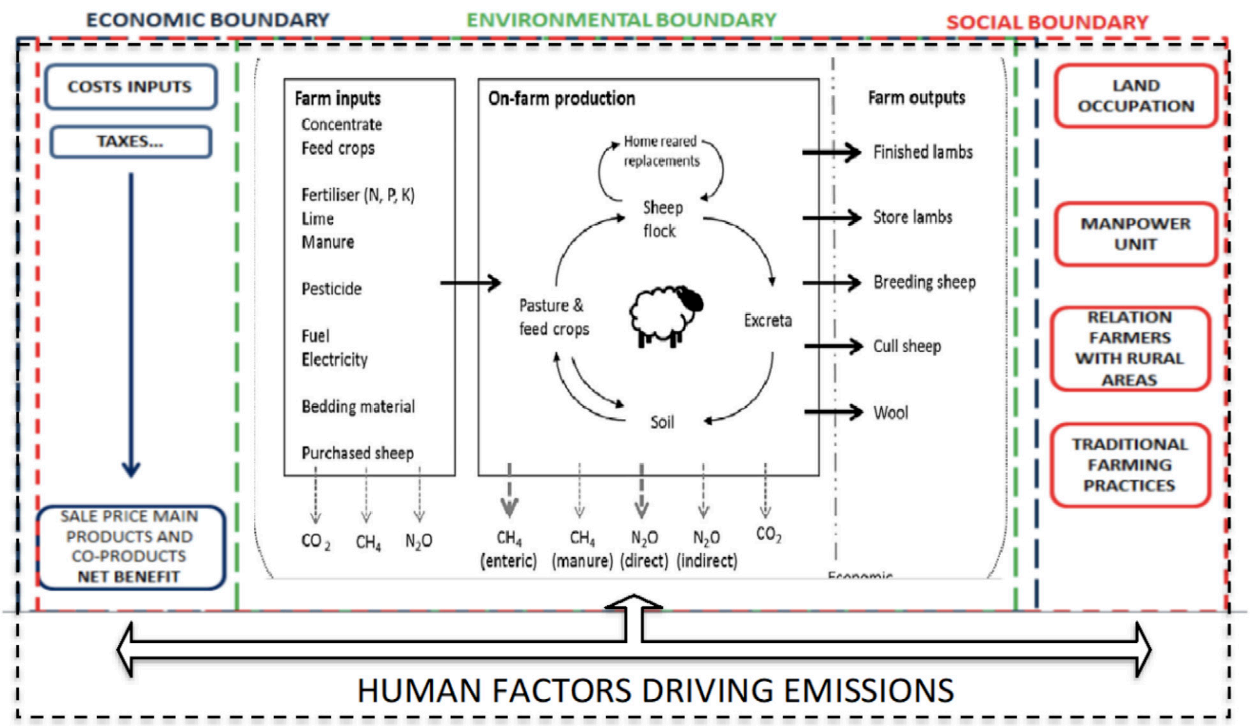

FIGURE 2
Environmental system boundaries inclusive of economic and social aspects for sheep farming systems (Adapted from Jones et al., 2014 and Batalla et al., 2014). Elaborated by LIFE SheeptoShip, deliverable A.2.1 Scientific and technical state of the art (Atzori, 2017b).

provided by livestock systems (Tsonkova et al., 2014). Ecosystem services (ES) are defined by the Millennium Ecosystem Assessment (2005) as "benefits people obtain from ecosystems". They are divided into provisioning ES (i.e. production of food and other materials) and non-provisioning ES (regulating, cultural, and supporting). Multifunctionality and ecosystem services have often been considered as two very different approaches, the first one being farm-centered versus the second one more service-oriented, with limited interactions between scientific communities using those approaches (Huang et al., 2015).

Some recent studies have highlighted how the study of GHG emissions related to extensive livestock farming systems cannot avoid developing analysis methodologies that take into account the variables that characterize these multifunctional systems. Vayssières et al. (2024) have pointed out that when studying pastoral systems, in which transhumance and mobility are the main traits and inputs are very low, C balance assessment at ecosystem scale seems more appropriate to investigate GHG balance, applying a systemic view and making strong efforts in the system boundary definition, to better consider all important sources of GHG emissions and C storage. Very recently, Vagnoni et al. (2024) revealed that the environmental performances of extensive sheep farming systems varied significantly depending on the Functional Unit (FU) used. FU is a standardized reference measure representing the function or service provided by a product, process, or system. It quantifies and normalizes all input (resources, energy) and output (emissions, waste) flows of the study, making the results comparable across different alternative systems. For instance, the Carbon Footprint (CF) calculated per kg of milk (fat and protein corrected milk) highlighted the dominant role of enteric methane emissions, while the area-based FU offered insights into the resource use per hectare, revealing how land management practices influence overall sustainability (Aguilera et al., 2021; Batalla et al., 2015). Therefore, there is still considerable uncertainty today about how to implement an analysis of GHG emissions from pastoral systems and how to correctly interpret the multifunctionality of these systems. The above mentioned PASTRES Report moved also in such context and indicated that a refined analytical approach, starting from a context-based data campaign, is needed to focus on the challenges and potentials of extensive livestock systems in a climate change mitigation scenario. The PASTRES Report took as reference of a more holistic, integrated systems level analysis, three contextualized research on GHG emissions of pastoral systems, coming from West Africa (Senegal), Asia (Qinghai-Tibetan, China) and Europe (Sardinia, Italy).

Following an inductive approach and aiming to contribute to the heated debate on the actual environmental role of extensive livestock systems, this article goes to the heart of the matter, starting from an in-depth comparison of the methodologies utilized for GHG emission estimation in the three PASTRES case-studies (Section *Description of case studies*) and referring to the analysis of the results obtained with the application of these three different methodological approaches (Section *Estimation of GHG emissions in the three case studies: methodologies used and main results obtained*). Then, the article critically analyses the limitations that emerged in the three case studies (Section *Issues emerged from the three case studies*) and, finally, provides insights (Section *Insights and suggestions for an adequate study of GHG emissions from extensive livestock farming systems*), aimed at proposing a critical perspective on the methodological challenges to make the assessment of GHG emissions from pastoral farms more reliable and appropriate. Finally, a specific focus on LCA approach is presented (Section *Further remarks from LCA research for extensive livestock farming*), aimed at proposing a reference LCA model. The paper aims to contribute to a deeper understanding of the positioning and role of these systems in the broader context of the ecological transition of agri-food systems.

Description of case studies

The PASTRES Report by Houzer and Scoones (2021) focuses on three cases – from West Africa (Senegal), Asia (Qinghai-Tibetan, China) and Europe (Sardinia, Italy) – that have adopted different and differently sophisticated approaches, adapting them to each local pastoral setting. In Table 1 the main characteristics and some methodologically relevant elements of the three case studies are reported.

In the Chinese and Italian case studies, two different methodological approaches were followed for estimating GHG emissions.

West Africa (Senegal)

A study by Assouma et al. (2019a), Assouma et al. (2019b) was set in the pastoral area of Ferlo, Senegal, with a “landscape” ecosystem approach measuring the overall carbon balance of the Widou Thiengoly service area borehole, a 706 km^2 circular area that hosts 354 pastoral camps with a population of 4,800 inhabitants. The total livestock population of the area is about 25,000 free grazing animals, including cattle (54% of total livestock units), sheep (27%), goats (8%), donkeys (8%) and horses (3%). The area under study was subdivided into different units based on land use, the type of vegetation and soils (Assouma et al., 2017), with grazing lands occupying the greater area (90% of the total area) with sparsely wooded savannas, and the remaining area shared between settlements, forest plantations, natural ponds, boreholes and enclosures, set up for experimental plots. In this area, a formal research project was set up to assess all main sources of GHG emissions and C sinks of the whole pastoral ecosystem, taking into account not only anthropogenic sources.

Asia (China, Qinghai-Tibetan Plateau)

Two territorial-scale LCA-based studies were carried out in Qinghai Province of China on GHG emission of pastoral systems in transition. In the first study (Zhuang and Li, 2017), Chanaihai village and Guinan Grassland Development Limited Company offered the opportunity to compare a traditional pastoral system with a livestock husbandry system, combining extensive and semi-intensive management systems, respectively. The Chanaihai pastoral system is characterized by 431 households practicing transhumant seasonal pastoralism on 18,779 ha of rangelands, where 63,701 sheep and 4,000 yaks are reared. The different seasonal pastures provide for the needs of livestock production throughout the year. The Grassland Development Limited Company operates an intensive livestock husbandry system, with a combination of rangelands, feedlots, artificial grasslands and stations for forage and fertilizer processing. This demonstration area is characterized by 15,800 ha of rangelands and 2000 ha of artificial grassland supporting 80,000 sheep. The rangeland is utilized for grazing, similarly to the extensive system. Feedlots are only used for rams feeding, while the rest sheep are still grazing on the rangeland. The study assessed and compared the GHG emissions under these two production management systems, and explored the major causes for the differences, comparing GHG emissions from a pastoral system with a more industrialized intensive system, involving feedlots, seeded pastures and imported feed (Zhuang and Li, 2017).

On the other side, in Sichuan Province of China, GHG emissions under two rangeland management systems were estimated in the two villages Axi and Xiareer (Zhuang et al., 2019). The two villages have similar socio-economic and ecological environments but different forms of rangeland management systems. Axi village allocated its rangelands to individual households, with all-year continuous grazing under the individual use of rangeland with fences demarcating boundaries. In the Axi territory, 20,000 ha of grassland provide pastures to 16,000 sheep and 15,000 yaks, reared by 203 households with around 1,000 herders. Xiareer village has a community-based system for the common use of the whole rangeland. Xiareer village has 12,000 ha of grassland grazed by 20,180 sheep and 6,000 yaks, reared by 140 households with 802 herders. This study compared the Axi household-based system under continuous grazing in fenced, individualised plots with the Xiareer more traditional community-based system, involving movement across four seasonal pastures.

Europe (Sardinia, Italy)

The Sardinian case study is based on the analysis of a transition from a semi-intensive to a semi – extensive dairy sheep farming system (Vagnoni and Franca, 2018; Arca et al., 2021). A farm located in North Sardinia, Italy (Osilo municipality), shifted from an intensive feeding system based on grain-cereal crops, annual forage crops and irrigated crops, with cheese industry-oriented production (milk sold to the cheese

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TABLE 1 Main characteristics and some methodologically relevant elements of the three case studies.

Country	Region	Reference	Approach	Case study scale	Extension (ha)	Farming system	Livestock	Functional unit	LCI	Output
Senegal	Widou Thiengoly	Assouma et al. (2019a)	Ecosystem C balance	Landscape scale	63,542 (Widou Thiengoly Service Area)	Extensive on common rangelands	33,095 LU: Cattle (54%), Sheep (27%), Goat (8%), Donkey (3%), Horses (8%)	not considered	no	Measurement and estimation of all GHG fluxes
China 1	Guinan county	Zhuang and Li (2017)	LCA from cradle to gate*	Territorial scale	18,779 (Chanaihai Village)	Extensive on common rangelands	63,701 Sheep, 4,000 Yaks	1 ha of total area 1 kg carcass weight	no	GHG emission inventory
					17,800 (Guinan GDLC)	Semi-intensive animal husbandry			no	
China 2	Ruoergai county	Zhuang et al. (2019)	LCA from cradle to gate	Territorial scale	20,000 (Axi Village)	Extensive on household rangelands	16,000 Sheep 15,000 Yaks	1 kg carcass weight	no	GHG emissions inventory
					12,000 (Xiareer Village)	Extensive on common rangelands	20,180 Sheep 6,000 Yaks			
Italy 1	Sardinia	Vagnoni and Franca (2018)	LCA from cradle to gate	Farm scale	85 (Pulinas farm, Osilo)	Semi-extensive on sedentary farms	340 dairy sheep	1 kg of FPCM	yes	Carbon footprint (IPCC) + other 17 impact categories (ReCiPe endpoint)
Italy 2	Sardinia	Arca et al. (2021)	LCA from cradle to gate	Farm scale	85 (Pulinas farm, Osilo)	Semi-extensive on sedentary farms	340 dairy sheep	1 kg of FPCM 1 ha of UAA	yes	Carbon footprint (IPCC) + other 17 impact categories (ReCiPe endpoint)

industry), towards a semi-extensive system switched to valorisation of natural feed resources. Extensification of the production system was part of a wider new farm management strategy oriented to a direct on-farm cheese manufacturing, and to reducing production costs. Extensification slightly reduced flock size (from 340 to 320 sheep) and animal diet switched from hay/silage consumption from temporary grasslands to the grazing of legume-rich permanent grasslands that increased from 10% to 90% of 70 ha farm agricultural area, with a strong reduction of concentrates, fertilizers and irrigation use. This diversification process has certainly increased the complexity of the work on the farm, requiring know-how on cheese making and marketing, but valorising the role of young family members employed into the renewed farming system (Dumont et al., 2022).

Estimation of GHG emissions in the three case studies: methodologies used and main results obtained

The three different methodological approaches utilized for estimating the GHG emissions are described. Here we report exclusively the main methodological options proposed by the three studies. For details and further information, we refer the reader to the individual papers indicated in the text and in Table 2.

West Africa (Senegal)

The conceptual model based on an ecosystem approach was aimed at estimating the main C and N stocks and flows at Sahelian pastoral ecosystem level. In detail, GHG emissions to the atmosphere (CO_2, CH_4, N_2O), were analysed accounting for enteric fermentation (CH_4) emitted by both livestock and termites, anaerobic degradation (CH_4) in standing water of ponds closed to the boreholes, organic matter decomposition (N_2O and CH_4), combustion (CO_2) and bush fires from grasses and trees (N_2O and CH_4). On the other hand, C sinks are represented by woody plants, deposited excreta and bodies of the animals. In the study, Assouma et al. (2019a) have found that the emission estimated by IPCC Tier I protocol for Africa (25 g dry matter/kg live weight) is probably too high for the pastoral landscape they observed. The authors proposed a new standard of either 18 g dry matter/kg live weight for cattle and 34 g/kg live weight for small ruminants, or 73 g/kg metabolic weight for all ruminants, as a result of this ecosystem approach, revealing a level of dry matter intake/kg live weight for cattle and for small ruminants lower than that estimated by the current standard of IPCC used in emissions calculations. This approach application permitted finding a negative C balance, which clashes with the negative image of African livestock consolidated by previous sectorial and LCA studies (Gerber et al., 2013), based only on anthropogenic sources of GHG.

Asia (China, Qinghai-Tibetan Plateau)

Two studies were carried out, both applying an LCA approach. In the first one (China 1), the study was based on the GHG emission inventory and a calculation method applied to two different livestock production systems (traditional pastoral vs. combined extensive/intensive). The GHG emission inventory included enteric CH_4 emission, direct and indirect N_2O emission from manure, CH_4 soil emission, N_2O and carbon emission/uptake, and emission from manure combustion. In addition, carbon emission/uptake from artificial grassland, and feedlot, and other external inputs (seed, diesel, electricity, organic fertilizer, etc.) were accounted for in the estimation of GHG emission in the combined extensive/intensive system. GHG emissions were higher in the intensive system, both per ha of area and per kg of carcass weight. The intensive system had a slightly lower production of methane, but with a reduction of methane emissions significantly lower than is suggested by the literature. The reduction of methane emissions in combined extensive/intensive system was significantly lower than often suggested by the literature, at 6.95% rather than between 22% and 62%. Moreover, the higher emissions in the traditional pastoral system were offset by lower emissions from external inputs and higher levels of C sequestration. Overall, the intensive system had 40% higher emissions per carcass weight.

In the second study (China 2) two livestock production systems (household-based under continuous grazing vs. traditional community-based system) were compared. LCA was used to evaluate the GHG emissions intensity of both systems. Enteric emissions and manure CH_4, and N_2O emissions were calculated using the S-GAF model (Zhuang and Li, 2017). The soil CH_4 and N_2O emission data were measured on-site by using the static chamber method. On the other hand, soil organic carbon was measured by sampling the topsoil (0–30 cm) in 2011 and 2014 on-site. As a result, on-farm emission patterns of the two systems were broadly similar (around 9 kg CO_2-eq per kg of meat), but when the C sequestration levels were added, the contrasts were striking. The traditional community-based system showed a positive C balance (0.62 kg CO_2-eq per kg meat), while the household-based system had a relatively high net emission level (10.51 kg CO_2-eq per kg meat). This huge difference is explained by the authors through differences in soil C sequestration, due to the predominance of perennials, incorporation of litter and the spreading and trampling of manure in the traditional system (Chen et al., 2015). Overall, the study reported that light grazing contributes to soil C and N sequestration, while enclosed areas have compacted soil, less mineralization, lower root biomass and reduced quality of forage biomass from artificial grassland.

Europe (Sardinia, Italy)

The LCA was conducted using two different impact assessment methods: Carbon Footprint-IPCC (2013) and ReCiPe endpoint (H) V1.12. From an environmental point of view, extensification of this dairy sheep system increased

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TABLE 2 GHG estimations and related references for the analysed case studies.

Country	Approach	GHG emissions estimates	Reference for formulae	Direct measurements
Senegal	Ecosystem C balance	Enteric fermentation	Archimède et al. (2011)	
		GHG fluxes from soil and water	Assouma et al. (2017)	
		Other GHG emissions (termites, fuel consumption)	Traoré et al. (2008), Jamali et al. (2011)	
		Livestock C accumulation		Estimates measuring changes in the livestock population
		Plant C accumulation (trees and shrubs)		Direct measurements and estimates
		Soil C accumulation (stocks)		Variations in C monthly stored in the soil (C inputs – C output)
		Soil C accumulation (C inputs)		Organic matter deposited as livestock excreta, litter from trees, shrubs and herbaceous plants (root turnover) and rhizodeposition
		Soil C accumulation (C outputs)		Static chamber
China 1	LCA from cradle to gate	CH_4 from enteric emissions	Zhuang and Li (2017)	
		CH_4 from manure	Zhu (2014)	
		Manure direct N_2O emission	Zhu (2014)	
		Manure indirect N_2O emission	Zhu (2014)	
		Rangeland soil C change	Yang et al. (2010)	
		Rangeland soil CH_4 change	Zhang et al. (2010), Hu (2010), Jin et al. (2015), Yu et al. (2013), Zhang et al. (2014)	
		Rangeland soil N_2O emission	Zhang et al. (2010), Hu (2010), Zhang et al. (2014)	
		Artificial grassland soil C change	Animal husbandry bureau in Guinan (2007), experiment (2014)	
		Artificial grassland soil CH_4 change	Jin et al. (2015)	
		Artificial grassland soil N_2O direct emission	Jin et al. (2015)	
		Artificial grassland soil N_2O indirect emission	Jin et al. (2015)	
		Feedlot manure CH_4 emission	Xu et al. (2014)	
		Feedlot manure N_2O emission	Xu et al. (2014)	
		Manure combustion (CO_2 + NO_2)	Tian et al. (2011)	
		Diesel	Ma (2002)	
		Electricity	Hou et al. (2012)	

(Continued on following page)

TABLE 2 (*Continued*) GHG estimations and related references for the analysed case studies.

Country	Approach	GHG emissions estimates	Reference for formulae	Direct measurements
China 2	LCA from cradle to gate	CH_4 from enteric emissions	Zhuang and Li (2017)	
		CH_4 from manure	Zhuang and Li (2017)	
		Manure direct N_2O emission	Zhuang and Li (2017)	
		Manure indirect N_2O emission	Zhuang and Li (2017)	
		Rangeland soil C change	Li (2013)	
		Rangeland soil CH_4 change	X. Zheng, pers. comm, direct data by static chamber	
		Rangeland soil N_2O emission	X. Zheng, pers. comm, direct data by static chamber	
		Manure Combustion CO_2	Zhuang and Li (2017)	
Italy 1	LCA from cradle to gate	CH_4 from enteric emissions	Vermorel et al. (2008)	
		GHG from pesticides and fertilizers	IPCC (2006)	
		NO_2 emitted through animal excreta	IPCC (2006)	
Italy 2	LCA from cradle to gate	CH_4 from enteric emissions	Vermorel et al. (2008)	
		C Seq from crops and natural grassland	Petersen et al. (2013)	
		GHG from pesticides and fertilizers	Nemecek and Kaği (2007)	
		N_2O direct and indirect and CO_2 emissions to air	Tier 1 - IPCC method (IPCC, 2019)	
		NH_3 emissions to air	Tier 2 IPCC method (IPCC, 2019), ISPRA (2011)	
		N_2O emitted through animal excreta	IPCC (2019)	
		Daily N excretion of animal categories	Decandia et al. (2011)	

grassland biodiversity (+53% of surface covered by natural grasslands), provided a reduction of environmental impact assessed through a land use-based FU, with −43% kg CO_2-eq per ha of utilized agricultural area-UAA (Vagnoni and Franca, 2018) and a further environmental benefit in terms of soil C sequestration (+63% of sequestered C in the soil) (Arca et al., 2021). On the other hand, carbon footprint assessed using a mass-based FU was similar in both systems at farm level, being respectively 2.99 CO_2-eq and 3.25 CO_2-eq per kg of normalized milk. In both systems, enteric methane resulted in around half of all GHG emissions. Similar results have been found in other Mediterranean systems, including in northern Spain (Batalla et al., 2015), as well as elsewhere in Sardinia (Atzori et al., 2017b). Two methodological issues arise from this study:

1) When emission intensity was expressed per ha of UAA, semi-extensive dairy sheep farming led to better environmental performance even without C sequestration accounting. On the other hand, semi-intensive systems resulted in lower impacts when GHG emission intensity was referred to 1 kg of normalized milk.
2) The semi-extensive system had a strong potential for offsetting GHG emissions through sequestration in permanent grasslands. When soil C sequestration was included, the study showed slightly lower GHG emissions per kg of milk in the semi-intensive production system (from 3.37 CO_2-eq to 3.12 CO_2-eq per kg), but the reduction was higher in the semi-extensive system (from 3.54 kg to 2.90 kg CO_2-eq per kg).

Issues emerged from the three case studies

From the three case studies analysed, some limitations emerge that penalize a complete and adequate estimate of GHG emissions and, consequently, a correct assessment of implementation scenarios that aim to create conditions of greater sustainability for pastoral systems.

West Africa (Senegal)

This case study estimated the main C and N stocks and flows and GHG fluxes between the pastoral system and the atmosphere, measuring the overall emissions balance at landscape scale. For doing this, Assouma et al. (2019b) suggested an *ecosystem approach*, considering all the ecosystem components (livestock, soil and plants) and the interactions between themselves and with the atmosphere. Indeed, this ecosystem angle revealed some key points that should be taken into account when allocating impacts between livestock and natural processes: firstly, seasonal patterns of rainfall may drive the entire variability of gas flows, which should be taken into consideration when approaching studies on the environmental performance of systems with a strong territorial and ecosystemic vocation such as extensive pastoral ones. Thus, wet and dry seasons can completely change the outcomes of the environmental assessment of these systems. Focusing on specific emissions for each season could enable addressing seasonally hotspots in emission and designing more relevant mitigation options. Another source of variation was referred by the authors to emissions from manure in pastoral systems with such a wide territorial basis. In fact, in such conditions manure cannot be assumed to be distributed uniformly, as pointed out in most environmental assessments (Houzer and Scoones, 2021). Thus, direct field-level data and not constant livestock excretion rates should be established and used in the emission analysis. Moreover, further uncertainties arise in relation to the proportion of the manure that is managed and the emission factors for nitrogen used may not reflect the context of most extensive livestock production systems (Rufino et al., 2014). In general terms, when only anthropogenic sources of GHG are taken into account, instead of considering the whole ecosystem angle, studies about the environmental impact of pastoral products might be a source of uncorrected interpretation of GHG flows. Starting from this assumption, Assouma et al. (2019a) suggested that, in the case of transhumant livestock that grazes seasonally in different ecosystems during a year, estimating C balances for diverse ecosystems along agro-climatic gradients might better integrate mobile livestock impacts in studies on the environmental impacts of pastoral products, with a focus on the dynamic relationship between pastoral practices and land use. By recognizing the importance of landscape variability and seasonal pasture availability, pastoralists can develop land use strategies that support sustainable pastoral systems, enhance biodiversity, and improve the resilience of both pastoralists and ecosystems in the face of climate change.

Asia (China, Qinghai-Tibetan Plateau)

Both Chinese case studies investigated GHG emissions of pastoral systems at territorial scale, by using an LCA “from cradle to gate” approach. The two studies underlined some recommendations for better address the studies on GHG emissions from pastoral systems, albeit with different nuances. The Case Study China 1 Zhuang and Li (2017), revealed that enteric CH_4 emissions calculations based on a model rather than field observations could affect the accuracy of results to some extent. Indeed, direct measurements and estimations of emissions allow a context-based analysis, bounding the system not just by focusing on animals and feed, but using a wider system approach. More precisely, the *context-based approach* should include observations on the vegetation (e.g., plant biodiversity) and grazing managements, in order to have direct and more detailed data regarding, for example, the effect of vegetation and grazing patterns on C sequestration. It means that the approach to be used for estimating GHG emission should not exclude a complex framework of data collection, with direct measurements on plant biodiversity at territorial scale.

In the China 2 case study, recommendations by authors Zhuang et al. (2019) mainly concerned issues relating to the accounting for soil C sequestration, in the case in which different grazing techniques and regimes are taken into consideration, frequent when pastoral systems are linked to the grazing of large portions of territories with mobile and transhumant animals. Land use practices directly influence soil carbon sequestration potential. As highlighted in this case study, understanding the dynamics of soil C sequestration requires accurate assessments of land use changes and grazing management. Zhuang et al. (2019) suggested how an accurate study on soil C sequestration dynamics should be included in the LCA analysis, when it is addressed to define the environmental impact of a changing scenario in terms of a transition from mobile seasonal to sedentarized continuous grazing. Also, more direct field data is needed to better describe this transition. For example, exactly as in the China 2 case study, they suggested that enteric CH_4 emissions should be based on field observations for having more accurate results to some extent. Finally, when grazing management affects vegetation, Zhuang et al. (2019) suggested the collecting of more detailed vegetation measurements, which might help in making observation on the indirect effect of changing vegetation on, for instance, soil C sequestration potential of the changed plant environment.

In both Chinese case studies, the interplay between land use and pastoral sustainability is clear. By adopting practices that enhance soil health, biodiversity and resource management, pastoralists can create systems that are not only productive but also resilient to environmental changes (Teague and Wright, 2018; Díaz et al., 2018). Understanding and integrating land use considerations into GHG emissions assessments and lifecycle analyses will be essential for developing sustainable pastoral systems in the Qinghai-Tibetan Plateau and beyond.

Europe (Sardinia, Italy)

When estimating GHG emissions from a Sardinian dairy sheep farm, after a land use change due to a transition scenario of extensification, a clear environmental benefit was revealed, accounting for soil C sequestration in emission intensity estimation, whatever the FU considered, product-based or area-based. It suggests that LCA of pastoral products, systems and scenarios should be based on a more complete and wider estimation of the environmental performances, reclaiming the use of different FUs in order to allow a more comprehensible and suitable assessment of the environmental impacts. Moreover, in a land use change scenario towards pasture-based systems, soil C sequestration is favoured by the presence of large grazing areas covered by permanent grasslands, whether natural (natural pastures) or semi-natural (artificial pastures). The improvement of soil organic C stock associated with permanent grasslands would contribute effectively to mitigating GHG emissions in Mediterranean dairy sheep farms, highlighting the positive role of ecosystem services provided by extensive farming systems.

Insights and suggestions for an adequate study of GHG emissions from extensive livestock farming systems

From the analysis of the methodological issues that emerged from the analyzed case studies, useful indications arise for redefining the assessment approaches for GHG emissions from pastoral systems, with the aim of trying to understand if a reference LCA model is possible to better address the environmental impacts and carbon footprint of extensive animal farming systems. More precisely, the needs that emerged were to consider: 1) analysis of emissions with a broader context/ecosystem-based approach; 2) definition of the FUs; 3) the provision of ecosystem services, with special focus on biodiversity and the inclusion of C sequestration within the LCA calculation.

Context/ecosystem based approach

Considering the data scarcity on pastoral systems, and high time, energy and economic costs to complete them, the majority of LCA studies in literature make use of data from high-income countries and industrial systems. These global and standardized assessments do not permit catching the complexity and variability of pastoral systems and therefore risk being highly partial and poorly adequate (Houzer and Scoones, 2021). Some authors (Glatzle, 2014; Manzano et al., 2023a; Vagnoni et al., 2024), highlighted that it a new front of investigation and research is urgent, aimed at deepening the assessments relating to the environmental impacts of extensive livestock systems, particularly in relation to the emissions of climate-altering gases, in such a way as to establish, more and more accurately, the effective impact of pastoral farming on climate change. This would allow studies of extensive systems to be freed from standard parameters relating to industrial, intensive and product-oriented farming systems. Direct data and surveys at territorial and ecosystem level are necessary for better describing the complexity of emissions from pastoral systems, and it is even more necessary as these systems are characterized by mobility, nomadism and the use of large portions of grazing lands. The use of default emissions factors (Tier 1), can induce the risk of not reflecting the variability inherent in the extensive production conditions, which is the very basis of production in a non-equilibrium system, especially in pastoral settings (Krätli, 2015). Also in semi-extensive systems, with flock partial sedentarization and where pasture utilization is the principal feed resource, direct data collection is needed to better express the variability of quali-quantitative pasture traits. Models that continue to assume stability and uniformity in livestock systems, ignoring the pivotal importance of this variability, cannot be applied in region-specific contexts where ecosystem and livestock differences emerge. New models, and LCA approaches, should be able to capture this contextual variability which translates into a range of operational options, in particular mobility, as a crucial tool for the adaptive capacity and resilience of pastoralists (Krätli et al., 2023).

The mobility of livestock on large portions of grazing territories and their use characterizes pastoral systems in all their forms (Rugani et al., 2019; Gac et al., 2020). Considering impacts from pastoral systems simply as an aggregate assessment of impacts could miss important patterns of spatial heterogeneity and temporal variability (Houzer and Scoones, 2021). Particularly, GHG emissions are highly variable over space and time in extensive systems, being potentially positive and negative in the same area at different times, requiring much more focused mitigation measures compatible with livestock-keepers' practices (Charteris et al., 2021). This spatial and temporal heterogeneity should be reflected when analysing GHG emissions from pastoral systems. As an example, permanent grasslands in extensive systems are the most important, and in many pastoral settings the unique, source of feed for livestock. Numerous studies have established that in permanent grasslands the relationship between soil organic carbon, nitrogen, and site factors varies according to the land use types, vegetation types, environment, and soil types (Busman et al., 2023). But, on the contrary, when LCA analysis is performed on productive basis, pasture-based diets, that valorise the availability of permanent grasslands, are often associated with higher GHG emissions due to higher methane emissions from low-quality diets and to the low production efficiency of extensive livestock (Steinfeld et al., 2006; Gerber et al., 2013). Efficiency is often measured in terms of emissions per unit of output (milk or meat), but this does not take account of the multi-functional use of livestock and land into pastoral systems. This standardised measure of efficiency reveals an anthropogenic perspective, for which this mass-based FU results in an indicator aimed at minimizing the input use and the impacts per unit of marketable product (Molle et al., 2017). The utilization of these units derives from the challenge of increasing productivity and production efficiency, typical of industrialised sectors. Extensive systems are considered the least efficient, although they actually make productive use of areas that have limited alternative uses and allow the production of valuable proteins for food use starting from herbaceous biomasses of low nutritional value (Houzer and Scoones, 2021).

Land use is defined as "total arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions)" and it refers to the social and economic purposes for which land is managed (Verones et al., 2017). Variability of land use and land use changes may affect not only productivity and resilience of land and rural territories and related communities, but also the wider ecosystem benefits provided by their pastoral use (Davies et al., 2012). In many marginal areas of the world, where livestock have long played an important role in maintaining silvopastoral ecosystems, land abandonment and intensification of agricultural production systems via land use intensification is affecting farmland biodiversity (Houzer and Scoones, 2021). The positive impacts of extensively grazing livestock for reducing GHG emissions in open forest-mosaic and savanna landscapes is clear, when compared with land abandonment scenarios, moreover when practices of sustainable grazing are applied (Manzano and White, 2019). Land abandonment leads to woody vegetation encroachment, and related increased fire risk. Pastoral land use can greatly reduce the potential fuel load for forest fires and vegetation structure can be maintained in a way that promotes greater species diversity (Franca et al., 2016; Bernués et al., 2011). On the other hand, environmental benefits of grazing activity may be hindered by inadequate grazing management, and can be obtained only if the pastures are managed in a rational and sustainable way. In practice, avoiding phenomena of overgrazing and undergrazing, which *vice versa* can create environmental damage, such as soil compaction and loss of biodiversity (Schrama et al., 2023). For these reasons, the proper characterization of Land Use and Land Use Changes (LULUC) within extensive small ruminant systems is of special concern and it's a matter of yet greater complexity, as no consistent methodology exists for calculating and characterizing the impacts of LULUC over time. Regarding the inclusion of LULUC impacts within LCA of livestock systems, several organizations have given guidelines for their incorporation. In case of an attributional LCA of a small ruminant supply chain, for instance, different standards may be helpful for considering the inclusion of LULUC, including recommendations from the International Life Cycle Data System (ILCD) Handbook (ILCD, 2010; ILCD, 2011) and Product Environmental Footprint (PEF) guidelines (PEF, 2013), the International Dairy Federation (IDF) (IDF, 2010), and FAO-LEAP guidelines (FAO, 2016a; FAO, 2016b). In the framework of SheepToShip LIFE project (www.sheeptoship.eu), recommendations of the EU-PEF, IDF, and LEAP guidelines were followed, utilizing the Ecoinvent database as a source of secondary data, as the LULUC modelling tool utilized by this database considers the PAS 2050 calculation scenarios, and is therefore already compliant with both PEF and FAO LEAP guidelines (Reinhard et al., 2017).

When considering LULUC, great attention needs to be taken on the baseline scenarios. Extensive livestock systems, making use of permanent grasslands (often as patches within wooded ecosystems), can be considered as replications of 'natural' or 'wild' systems. This makes assessing baselines crucial, as livestock may not add to 'natural' emissions (as assumed in standard LCA measures and climate scenarios). As a result, the complete abandonment of livestock production in certain extensive contexts could therefore have negative impacts on landscape-level emissions (Manzano and White, 2019). LCAs current practice used to derive emission estimates usually do not consider such baseline conditions, whether shifts following advocated removal of livestock resulting in a return to 'wild' ecosystems or shifts to intensified agriculture. IPCC (2010) uses managed land as a proxy for anthropogenic emissions and removals, thereby not considering such baseline emissions either. This results in large distortions in the interpretation of results, with major implications for policy (Manzano and White, 2019). A new perspective in accounting GHG emissions from extensive livestock systems requires the accounting of natural baseline emissions, the fluxes from a livestock abandoned scenario, where the increase of wild herbivores and fires certainly does not paint an "emissions-zero" scenario (Pardo et al., 2024).

Choice of the functional units

The LCA food scientific community has been wondering for some time about the criteria to be used to identify the most appropriate FU to express the environmental impacts of livestock systems. In fact, the effects of intensification on emission intensity can significantly depend on the FU adopted; some authors have observed that intensification does not produce variations in emission intensity per kg of normalized milk (mass-based FU), while higher values of emission intensity per ha (area-based FU) have been observed in more intensive systems (Salou et al., 2017). Furthermore, the choice of FU can produce controversial results in terms of environmental output, depending on whether the systems are intensive or extensive (Baldini et al., 2017). The use of the FU based on area and the inclusion of the soil Cseq in the estimation of emission intensity are considered by Escribano et al. (2020) as more appropriate for the assessment of environmental impacts of extensive agricultural systems based on permanent grasslands. This conclusion was confirmed by an LCA study on a semi-extensive Sardinian dairy sheep farm, conducted by Arca et al. (2021). In addition, FU based on area avoids large debate about mode of allocation between products (Kyttä et al., 2022). Finally, the attribution of emissions that have a fossil origin vs. a biogenic origin, and the distinction in the latter between their natural and anthropogenic character, can also be very relevant to measure impacts (Manzano et al., 2025).

Inclusion of ecosystem services

Pastoral systems can contribute to ES in a broader and more complex way and the extent of this contribution can vary widely. Indeed, they are mainly based on land use and in particular on pastures, often of low productivity, and with extensive use of grasslands, associated not only with the ES mentioned above, but also with a wider series, including, for example, biodiversity conservation (which contributes, for example, to pollination), fire prevention and many others (Vagnoni et al., 2015; Bengtsson et al., 2019; Zhao et al., 2020; Arca et al., 2021; Von Greyerz et al., 2023).

Given the complexity and multifunctionality of pastoral systems and the wide variability of climatic and economic conditions that they have to face, a large scale assessment of all ecosystem services for all general land use types would be necessary for the application in LCA. Yet, as underlined by Barnaud and Couix (2020), ecosystem services as a concept appear as a legitimate analytical tool to investigate multifunctionality. In this perspective, in order to assess the impacts on ecosystem services, a set of indicators would be necessary (van Oudenhoven et al., 2012). Several authors include suggestions for indicators of ecosystem services for land management, both capacity indicators (representing the potential to provide services, e.g., carbon storage) and flow indicators (representing the actual provision of a service experienced by people, e.g., erosion prevention) (Tsonkova et al., 2014). Some ecosystem services can instead be measured directly, mainly provisioning services: e.g., crops, wood or fibre, number of animals and freshwater withdrawal (Kandziora et al., 2013). Cultural services depend on human values and can only be estimated indirectly, e.g., from the number of visitors or facilities, preference surveys and the number of protected species or habitats (Kandziora et al., 2013; de Groot et al., 2010). Regulatory and supporting services are the most difficult to measure, because they often arise from complex interactions of ecosystem properties or occur at spatial scales other than the observed landscape scale (e.g., climate regulation or gene pool protection) (Zhang et al., 2022).

Having pastoralists a functional role for the use and preservation of permanent grasslands, their traditional pasture practices and grazing management help in providing various ecosystem services. But, in general, the multiple functions of pastoral systems, are not considered in LCA calculations. LCAs, for example, do not weigh production against any upper limit on demand, thus distorting the results in favour of industrial systems. Failing to distinguish between different types of "proteins" and specific dietary requirements, these biases are further reinforced (García-Dory et al., 2022; Moughan, 2021). Conversely, an adequate LCA study should be able to highlight whether the negative impact of the low production efficiency of extensive grazing systems can be offset by the positive effect of the ES they provide to the territories in which they operate (Vagnoni et al., 2018; Manzano et al., 2023b). LCA for ruminant systems commonly include only beef and milk as valuable outputs, and no other ES potentially provided (Baldini et al., 2017; Clune et al., 2017). The risk is to overlook the positive contributions to ES, other than direct food provisioning, and this can be misleading when making decisions about future livestock systems, such as promoting the idea that meat produced in intensive systems generally has lower climate impacts than meat from extensive systems (Von Greyerz et al., 2023). The risk is even greater in the case of traditional, mobile pastoralism (Manzano et al., 2023b).

So, including non-provisioning ES in LCA studies might represent a new strategy for more adequately accounting for environmental impacts of multifunctional pastoral productions. However, while food products can be valued using market prices, attributing value to other ES is less straightforward. Some authors (Ripoll-Bosch et al., 2013; Kiefer et al., 2015; Bragaglio et al., 2020) have attempted to include foods and other ES into the LCA study, using economic allocation, where the environmental impact is distributed proportionally to outputs (foods and other ES) based on their economic value. In order to allocate emissions to ecosystem services, Ripoll-Bosch et al. (2013) proposed for grazing systems an approach that uses agri-environmental payments from CAP (EU Common Agricultural Policy). This method is a viable solution to consider for future LCA application to Mediterranean sheep farming system. Of course, this method might be taken into consideration only in European Union countries where these payments are applied, where they are interpreted as subsidies supporting farmers because of recognizing the environmental role of their sustainable productive activities into marginal and rural territories (Tchakerian, 2008). In these countries, agri-environmental payments are directly associated with support for both organic farms and farms in areas of "natural constraints," where agricultural production is more difficult due to unfavourable natural conditions. There are also a range of payment schemes more directly connected to livestock, including support for biodiversity conservation in semi-natural pastures or preservation of local livestock breeds. It can therefore be difficult to decide which payment scheme/s to include when using these as a base for economic allocation in LCA to account for non-provisioning ES, especially as payments are sometimes only vaguely reflecting the ES provided (Simoncini et al., 2019), which can give variable results.

More recently, von Greyerz et al. (2023) studied the environmental impacts of varying cattle production systems in Sweden, with different levels of extensification, and attributed the climate impact not only to beef and milk, but also to a set of provided ES, applying economic allocation. Results were influenced by the differences between farms in coupling the payment schemes. Particularly, when payments were directly related to livestock rearing (e.g., as mentioned before, related with biodiversity conservation or preservation of local breeds) the differences in the climate impact were still large between farm types, while the difference decreased considerably when all environmental schemes were included. Including ES in the LCA analysis, does not reduce or cancel the emissions, but gives a more realistic and adequate estimate of the environmental impact of a livestock system, moreover when it is related with a large pasture utilization and land occupation, like pastoral systems are. While emissions do not disappear, ES-corrected climate impact can potentially be useful as part of consumer communication or in decision-making, reducing the risk of overlooking ES provided by ruminant production in a simpler way than using separate indicators. Otherwise, including ecosystem services in LCA shall lead to a more complete comparison among the environmental profile of extensive livestock systems. Vagnoni et al. (2018) consider this method as a viable solution to consider for future LCA application to Mediterranean sheep farming systems, mainly if further CAP measures will more strictly recognize the environmental role of Mediterranean pastoralism. In the long term, Atzori et al. (2022) highlighted that considering the LCA method from a systemic perspective, which may enable a transition in the small ruminant sector toward a more sustainable bio-economy based society, prioritizing rural development and capacity building for sustainable production of dairy sheep sector is likely to stimulate both productivity and ecosystem services maintenance.

The majority of LCA studies prioritize the assessment of a limited number of environmental indicators, i.e. GHG emissions and land use, reflecting the limited data available for other factors such as biodiversity and ecotoxicity (Clark and Tilman, 2017; Sahlin et al., 2020). LCAs therefore often fail to integrate the diverse interactions (both positive and negative) between livestock and the ecosystems they encounter into their analyses, and they often do not account for the various ecosystem services that well-managed livestock can offer in a pastoral context (Houzer and Scoones, 2021). Besides its primary function of producing milk and meat (and wool), most extensive farming systems provide other functions to society. Some examples of ecosystem services attributed to pastoral grazing include: maintaining both the vitality and the traditions of rural communities (specially, in marginal areas), as well as preventing environmental issues (i.e., soil erosion and desertification, wildfire, biodiversity depletion, etc.); conserving cultural landscapes; maintaining rangeland (which maintains sequestration potential in soils and vegetation), nutrient and water cycle regulation and soil health (Schils et al., 2022). The actual contribution of pastoral systems to such services has rarely been quantified (Glimskär et al., 2023).

In Europe, farming systems such as pasture-based systems - evolved towards complex socio-ecological systems in situations of natural resource scarcity, where production is integrated with biodiversity conservation and the delivery of ecosystem services to society - are considered farming systems with High Nature Value (HNV) that require quantifying and paying ecosystem services as a tool for developing strategies to simultaneously meet future food security and sustainable agriculture (Pinto-Correia et al., 2018; Pinto-Correia et al., 2022). However, this approach constitutes a formidable challenge and a requires continuous renewal of policy mechanisms to compensate management models that ensure the delivery of societally desired public goods, gaining new practices and business models that allow for the preservation or even regeneration of natural resources, biodiversity and landscapes (Bouma, 2021; Schröder et al., 2020). After performing as literature review about the inclusion of ecosystem services into LCA analyses on food production systems, Vanderwilde and Newell (2021) clustered the LCA-ES literature in the main categories of "biodiversity and ES clusters," "land use cluster" and "dynamic modelling," highlighting how reconsidering LCA with an ecosystem services extension can provide a complementary evaluation both of beneficial contribution of ecosystem services to wellbeing and, also, their detrimental impacts. Nevertheless, despite the recent progress in explicit consideration of ES in LCA (Zhang et al., 2010), today there is still a general lack of a methodological consensus on how to comprehensively integrate ES accounting in LCA and the first steps are being taken to unite the theory and practice of accounting for ecosystem services in LCA, albeit with difficulties linked to a methodological and procedural consensus (McLaren et al., 2021). More recently, Damiani et al. (2023) stated that biodiversity loss can be assessed in different ways into LCA environment but will presumably include a broader set of information regarding, for example, taxonomic coverage and other ecosystem services.

Biodiversity

Currently, a relevant discussion is still ongoing on how to fit biodiversity conservation with LCA studies on products' and services' value chains. Crenna et al. (2020) reviewed approaches for the impact assessment of biodiversity in LCA, highlighting that the "*existing metrics of biodiversity impact assessment in LCA are poor at capturing the complexities of biodiversity,*" and pointing out that LCA framework was not yet sufficient to support decision-making based on available biodiversity indicators. Into this *in progress* context, FAO (2021) assessed that several crucial issues determine the impact of agriculture on biodiversity at farm level. Among them, issues related with land use (namely geographical location, intensification and fragmentation of agricultural lands), composition of the modified native vegetation and the on-farm measures for biodiversity conservation. When specifically related to livestock systems, UNEP Life Cycle Initiative (FAO, 2021) assessed that the development of sophisticated research methods for considering biodiversity in studying LCA of livestock systems and products should account for land-use intensity and habitat fragmentation, but also global extinction probabilities, and indicators of biodiversity loss, referring to research outcomes from many authors (Kuipers et al., 2021; Larrey-Lassalle et al., 2018; Chaudhary and Brooks, 2018). When using an ecosystem approach for assessing the environmental footprint of a pastoral system/product, FAO (2021) suggests that the effect of extensive grazing on landscape biodiversity might be evaluated through observing and measuring the impact on seed dissemination, species conservation, plant species control and habitat's regeneration and preservation. García-Dory et al. (2022) observed that many long-standing debates that show how such production systems, including pastoralism, may increase biodiversity and help in preserving landscapes and ecosystems, that are seriously affected when pastoral mobility is restricted, or grazing activity is forbidden (Behnke and Mortimore, 2016). In Mediterranean environment, for example, extensive grazing has a significantly positive effect on biodiversity indicators, such as Shannon and species richness indices (Landsberg et al., 2002; Brooks et al., 2006; Franca et al., 2018) and has been considered as a tool for maintaining the genetic diversity within plant populations, particularly in silvopastoral conditions, where plant diversity may ensure a higher tolerance of pastures under shading conditions (Perevolotsky, 2005). Extensive grazing may also provide human and animal food and moreover cultural services, through cultural identity, traditional knowledge, and tourism (Plieninger et al., 2006; Assouma et al., 2018a; Paul et al., 2020; Russell et al., 2018). All add up to substantial environmental and conservation benefits of particular types of livestock production that should be taken into account. As discussed further below, an ecosystems approach more effectively integrates these factors into any analysis, addressing the landscape as a whole, and is thus more suitable for assessing complex, variable, extensive systems. In general, all these functions are not considered in LCA calculations of extensive farming. Assessments that stop at the boundary of the farm can miss the wider contributions of extensive livestock production to biodiversity, and also to overall environmental and landscape improvements. Otherwise, including ecosystem services in LCA shall lead, for example, to a more complete comparison among the environmental profiles of extensive and intensive livestock farming systems.

C sequestration

Soil C has historically been excluded from LCA studies for a variety of reasons, including the lack of soil C sequestration data to provide conservative GHG estimates and an assumption that soils, without additional carbon inputs, are in long-term equilibrium (Rotz et al., 2019). Under this assumption, livestock would add additional emissions to an otherwise balanced carbon cycle. As a result, most assessments do not include C sequestration in their analyses (Rowntree et al., 2020). Moreover, many LCA assessments assume that the grazing abandonment might be beneficial for the re-wilding/re-naturalization of the land, allowing more effective soil C sequestration (Houzer and Scoones, 2021). This assumption is fed by LCA studies focused on high-income countries, in which experts prioritized GHG emissions and land use (Paul et al., 2020; McClelland et al., 2018), while other environmental indicators are comparatively neglected (Nordhagen et al., 2020; Sahlin et al., 2020), with only a patchy focus on potential environmental benefits of livestock production, including sequestration and biodiversity maintenance.

On the other hand, the exclusion of C sequestration from LCA analyses is challenged by some studies relating to permanent grasslands, attesting that pastoral practices have been tested and proven successful fitting to the aim of maintaining or improving pasture-based systems, ideally increasing the capacity of grasslands to store carbon (Blanfort et al., 2010; Calado et al., 2018; Arca et al., 2021) and then, consequently, showing how C sequestration can be significant in extensive systems. Such systems may be in balance or seasonally negative, meaning that livestock here may not be net contributors to emissions. However, support towards more research on carbon and nitrogen flows, context-specific emissions and C sequestration in extensive livestock systems, including in pastoral areas across the world, is needed. Such research should be based on analyses that must encompass differences across times and spaces, reflecting the complex dynamics of carbon and nitrogen cycles in such systems (Houzer and Scoones, 2021). Again, a systems approach would acknowledge movement across rangelands and account for the benefits to potential C sequestration and, more in general, to ecosystem services.

Pastoral systems, particularly in the Mediterranean regions, are characterized by contrasting livestock systems with different extensification level (Caballero et al., 2009; Porqueddu et al., 2017). Even in the context of semi-extensive systems, where temporary grasslands (i.e., annual forage crops) are combined with permanent grasslands, correct agronomic practices of managed grasslands may affect the increase of soil C sequestration, how shown by Arca et al. (2021) in Mediterranean dairy sheep farms. In any cases, permanent grasslands improve soil C stock with respect to forage crops, partly explained by a greater supply of C from crop residues left in the soil, due to their extensive root systems, and partly by the increased residence time of C, due to the absence of soil tillage (Jones, 2010; Seid et al., 2016). In contrast, grassland degradation leads to the release of carbon into the atmosphere (Van den Pol-van Dasselaar, 2017). The management of grazing can improve soil C sequestration on grasslands, decreasing or increasing the grazing pressure on overgrazed and slightly grazed lands, respectively. The management of N fertilization can affect N_2O emission and soil C input from biomass residues.

Thus, including soil C sequestration in LCA analyses aimed at pastoral systems, in presence of large areas covered by permanent grasslands and destined to the grazing, can be suggested (Gutierrez-Pena et al., 2019; Batalla et al., 2015; Arca et al., 2021). The improvement of soil organic C stock associated to the permanent grasslands would contribute effectively to mitigate GHG emissions in pastoral territories, highlighting the positive role of ecosystem services provided by extensive farming systems. Data can sometimes be available in the literature. However, they can widely differ according to different parameters as local ecosystems, pastoral systems management including grazing pressure, climate conditions of the assessed year. In Mongolia for instance, references on C flows in the literature show large differences in annual C balance for different rangeland types, ranging from – 160–187 g C $m^{-2}yr^{-1}$ (Morton et al., 2024). In addition, the estimation of soil C sequestration is often influenced by the models used to estimate grazed biomass. In this sense, direct field measurements related to ecosystems, production systems and practices under study are advisable in order to improve estimation accuracy, data quality and results reliability.

Finally, it can be highlighted the need to improve LCA methodology to capture agricultural systems characteristics. In particular, key aspects include soil CO_2 emissions, soil C sequestration, soil N_2O emissions, circular economy solutions, biodiversity, nutrient flows (Goglio et al., 2024). A key tool in this sense may be a harmonized multiscale approach for LCA methodological developments, with special consideration to soil resources and their contribution. The systematic inclusion of soil in LCA would allow enhancement agroecosystems sustainability and give soil resources their rightful place in the quest to tackle sustainable development goals and combat climate change. Therefore, we propose to insert the soil C storage rate as CO_2 soil uptake from atmosphere lowering the environmental impacts of agroecosystem management (De Feudis et al., 2022).

Further remarks from LCA research for extensive livestock farming

Harmonizing LCA methods to improve its accuracy and robustness in addressing sustainability across livestock systems and products, Goglio et al. (2023) identified several key topics based on structured workshops and survey between LCA experts: biodiversity had the highest priority among respondents followed by social aspects, soil C sequestration and food-feed production. Social aspects therefore play a significant role in the general definition of the sustainability of a production cycle or a production system. Particularly, as in the case of extensive livestock farming, when the system under examination has strong implications for large portions of territory and for the populations that live and produce in it. But even if analysing LCA at single farm level (Figure 2), the general boundaries of a livestock farm might be extended to variables that approaches social (manpower units, relationships with rural areas, tourism and traditional cultural aspects, etc.) and economic boundaries (cost and revenues, taxes and national subventions, local economic advantages of added values, general willingness to pay for environmental goods and ecosystem services). Social impacts of a product's life cycle might be assessed trough of the practice of Social Life Cycle Assessment (S-LCA) (UNEP et al., 2020). S-LCA measures the impact of a product or process on society along the full life cycle (Dyson, 2024). S-LCA is one of three methodologies (together with Environmental LCA and Life Cycle Costs) that have been developed to assess the sustainability of organizations, products and services and considers many types of impacts directly to people, and the impacts can be positive and negative (Finkbeiner et al., 2010; UNEP, 2009).

The direct dimension of these impacts requires a major as possible collection of primary data and information at local level with a site-specific approach. Potentially, S-LCA could be helpful in completing an impact analysis of pastoral products, enlarging the system boundaries in LCA studies also to social aspects, and representing a solid and more coherent option for trying to include variability and multifunctionality into studies on environmental impacts of extensive production systems (Flysjö et al., 2012; Ripoll-Bosch et al., 2013; Batalla et al., 2014). But at present, such an approach can only be used prospectively, as there are only a few S-LCA papers based on agri-food supply chains in the scientific literature (Møller et al., 2024). This limitation is mainly due to the fact that onsite data collection is funds- and time-consuming, and that field investigation may be made difficult by the wide distribution of the locations where a pastoral value chain can occur, when mobility and land use variability remain the more characterizing factors of such extensive livestock systems (UNEP et al., 2020). In addition, impact pathways which relates primary data to social indicators are still few (Sureau et al., 2020).

Another way of facing the difficulty of defining the complexity and dynamicity of pastoral systems into CO_2eq-based simplistic quantitative criteria, is to consider the nutritional value and socio-geographic context of food provided by extensive livestock, accounting for the function of that food in providing human sustenance and supporting health (Manzano et al., 2023c; McAuliffe et al., 2020). Nutritional LCA (nLCA) has been developed in the past decade to achieve this nuance (Saarinen et al., 2017; Sonesson et al., 2017; Sonesson et al., 2019), starting from the consideration that extensive livestock generates not only food, but also nutritional coproducts, valorizing unproductive marginal land. Nutritional LCA, being useful in valorizing the interconnection between food production and the environment in which food is produced, can represent an important contribution to express how and how much the pastoral product reflects and incorporates the complexity and variability of the socio-geographical context in which it is produced.

The three case studies suggest that when assessing climate change impact of pastoral systems, strongly characterized by land occupation, use of environmental resources, seasonal climate and social relations, an approach that adapts and extends the LCA methodology is needed. Variability and uncertainty of socio-economic and environmental/climate conditions that shepherds face requires an approach capable of differentiating between contrasting contexts. Only with such a shift in approach will we get beyond the sometimes simplistic and misleading policy messages emerging from much research on the livestock–environment nexus. This paper confirms that LCA must be approached in a holistic manner, and advances the following methodological measures on how to set up and formulate an LCA method suitable for pastoral systems: first of all, accurately define the objectives, the boundaries of the context in which one operates and the quality of the inventory data. If the interest is limited to knowing the environmental impacts of a single pastoral product, LCA is confirmed as the most appropriate method. If instead the aim is to assess the entire pastoral system, considering its characteristics of variability and uncertainty, further analysis methods can integrate the conventional LCA and achieve a satisfactory evolution of the LCA methods, including the Social LCA, for the socio-economic implications, and the Nutritional LCA, for those more related to the food and subsistence function of pastoral products. Research in this field is active and it would be important to improve the knowledge regarding the choice of impact categories and FUs most suitable for estimating impacts at the territorial level, integrating information and databases deriving from other methodological approaches, such as remote sensing and precision farming techniques applied to extensive contexts. Finally, it is desirable to produce site-specific LCI databases for pastoral systems in regions of the world where pastoralism remains a fundamental food resource.

Conclusion

The multifunctionality of extensive livestock systems justifies the use of alternative metrics that assess the environmental performance of such systems in a more complete and adequate way. LCA is a scientific method and for this reason it must be approached in an objective way, without falling into the temptation of advocacy positions towards a sector, that of pastoral production, in difficulty at a global level, despite being in line with the evolutions of the Farm to fork context and the goals of sustainable development. LCA researchers should work for the harmonization of alternative metrics based on Conventional, Social and Nutritional LCA, contributing to a deeper understanding of the positioning and role of global extensive livestock systems in the broader context of the ecological transition of agri-food systems.

Author contributions

AF and IS conceptualized the study and drafted the manuscript. PA, EV, and GA handled data collection and analysis, offered insights and feedback and drafted the manuscript. HA, GZ, JV, and MV contributed to case studies' design and reviewed the manuscript, PM offered insights and feedback and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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