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Looking for the ecological transition of Mediterranean small ruminant sector. Characterization and main drivers of environmental performance of the Sardinian sheep farming systems

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ABSTRACT

A Life Cycle Assessment (LCA) study was carried out to assess the environmental profile of the main Sardinian dairy sheep farming systems, with the scope to provide a detailed and robust baseline for the identification of effective mitigation solutions at farm level and to develop environmental strategies at regional scale. Both product- and area-based functional units (FUs) were adopted, considering sixteen impact categories and soil carbon sequestration estimates as well. Water Use, Climate Change, Land Use, Ecotoxicity Freshwater, Marine Eutrophication and Fossils Resource Use resulted the main impact categories, cumulatively contributing over 80% of the total environmental impact (single score). Environmental performances significantly varied according to the geo-pedological traits of the different sheep milk production areas and were driven by the farming systems' structure and production level. The group of farms located in less fertile areas showed significantly worse environmental performance per kg of normalized milk for the impact categories Climate Change and Land Use, whereas no significant differences were observed for the remaining main impact categories. Considering the area-based FU, this farm group resulted less impacting for all main categories compared to the group of farms located in more plain and productive soils, with a significantly lower impact observed for Marine Eutrophication and Fossils Resource Use. Regardless of the FU used, feed supply management represented a key area of improvement, and soil carbon sequestration impact compensated the high GHG emission intensity of grassland-based farms despite the limited nutritional value of natural pasture. Regional strategies should be based on ecosystem services optimization and eco-innovative solutions tailored according to both the specific geo-pedological conditions and the production level of each farming system.

1. Introduction

Worldwide, the most innovative agricultural policies (European Commission 2020; Interim Climate Change Committee, 2019; U.S. Department of Agriculture, 2020) emphasize the concept of sustainability. The transition of agricultural systems toward sustainability requires a thorough examination of the trade-offs between productivity and the environment (Hayashi, 2023). Multiple indicators (footprints) are needed to (i) properly compare the performance of novel agricultural practices with traditional or conventional ones, and (ii) summarize available information along the whole food supply chain (from cradle to grave) (Notarnicola et al., 2017). The issue of sustainability in agriculture is particularly relevant in the case of livestock farming, which constitutes a substantial contributor to agricultural GHG emissions accounting for about 11.2% of global anthropogenic emissions (FAO, 2022). In addition, combining pastures used for grazing with land used to grow crops for animal feed, livestock accounts for 77% of global farming land (Poore and Nemecek, 2018). Sheep and goats

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account for nearly 30% of the added value of livestock globally (FAO, 2018) and, like all livestock systems, have non-negligible environmental impacts (emissions of GHG, nutrient losses, land use, etc.) (Pardo et al., 2023). Although their contribution to global milk and meat production is relatively small, sheep farming systems play a significant socio-economic role both in developing countries (subsistence economies) and in Europe (definitely trade-oriented) (Atzori et al., 2022; FAOSTAT, 2023; Vargas-Bello-Pérez et al., 2022), as recognized by the UN Sustainable Development Goals and the EU Farm to Fork Strategy (European Commission, 2020). According to FAOSTAT (2023), sheep meat, milk, and cheese production trends in the Mediterranean area have steadily increased over the past 30 years. In particular, sheep milk and cheese production increased significantly from 2010 to 2020, while meat production (with the exception of Turkey) grew more linearly. These explain both the high consumption of dairy products from small ruminants in the Mediterranean region and the global leadership of Mediterranean countries in the export of dairy sheep products (FAOSTAT, 2023). Due to the dimension and heterogeneity of the environment and sheep systems, Sardinia (Italy) provides an interesting case study to investigate the relationship between land use potential and the environmental performance of dairy sheep farms. In fact, Sardinia plays a well-known productive and social role in the national and European dairy sheep industry, producing more than 13% of total European sheep milk production (EUROSTAT, 2022). Dairy sheep farming in Sardinia is widespread throughout the region and is characterized by semi-extensive pasture-based herds that primarily rely on natural and semi-natural grasslands as feed sources (Pulina et al., 2018). A distinctive feature of the sheep milk production system in Sardinia is also the great variability of farm characteristics determined by geographical conditions and the resulting management practices: the proportion of permanent pasture varies from a minimum of 5% to a maximum of 97% of the Utilized Agricultural Area (UAA). Life Cycle Assessment (LCA), an internationally recognized and standardized methodology that reports the impact of all inputs and outputs of a production system, is commonly used to calculate the environmental footprints of livestock (Goglio et al., 2023). However, few studies performed comprehensive assessment of the sheep production process including other relevant impact categories rather than global warming, such as eutrophication, water consumption and land use (Atzori et al., 2017). Moreover, the majority of comparative LCA livestock studies do not consider carbon sequestration (Cseq), assuming soil carbon equilibrium (Aguilera et al., 2021; Stanley et al., 2018). In this study, the LCA approach was applied to the Sardinian sheep sector considering different sheep farming systems, in order to assess the environmental profile and the main drivers of the environmental performances of the sheep milk production, as well as to identify the environmental critical points. The ultimate aim of this study was to provide a robust knowledge framework for the identification of effective mitigation solutions and environmental strategies at both farm and territorial levels. The LCA was carried out on 18 farms under two macro soil conditions and different farming features, in Central Sardinia (granitic-effusive soils) and in Northern and Southern Sardinia (alluvial soils); the study was conducted considering 16 impact categories referred to both product- and area-based functional units (FUs). In addition, soil Cseq was included in the GHG net emissions calculation as an appropriate indicator of the ecosystem services provided by dairy sheep farming systems.

2. Material and methods

2.1. Characterization of Sardinian dairy sheep production systems

The period under consideration was the 2016–2017 agricultural year (October 2016–September 2017). In this study, we considered the variability associated with pedoclimatic conditions by selecting the main representative Sardinian sheep farming systems located in the principal sheep milk production districts: North, South, Central-West, and Central-East (Fig. 1). Following the preliminary characterization of Sardinian sheep production systems by Molle et al. (2017), a small sample of 18 Sardinian sheep farms was selected from a large and comprehensive database of the Regional Breeder Association (ARAS) with information of approximately 4000 sheep farms (key characteristics such as farm and flock size, feed budget, and forage crop investments). An ex-post analysis of available data on farm structure and farm inputs and outputs served as the basis for sampling. First of all, the selection of the studied farms considered: (i) the flock size, expressed as the number of ewes (both primiparous and multiparous sheep), and (ii) the stocking rate, expressed as the ratio of the number of ewe heads to the farm UAA. Then, based on geo-pedological conditions and average annual rainfall, two main groups of farms were identified: (i) Central Sardinia farms (CS) - characterized by effusive and granitic rocks and average annual rainfall >800 mm - with 10 sample farms; (ii) Northern and Southern Sardinia farms (N-SS) - characterized by sedimentary soils and average annual rainfall <800 mm - with 8 sample farms, 4 each in the northern and southern zones.

2.2. Life Cycle Assessment

The LCA study was carried out according to the ISO 14040-44 (ISO, 2021) standards, and taking into account the different methodological rules of the Livestock Environmental Assessment and Performance Partnership (LEAP, 2015) and Product Category Rules (PEFCR) for Dairy Products (EDA, 2018) guidelines. A "from cradle-to-farm-gate" system boundary was adopted including, in particular: (i) the amount of hay, green forage, and concentrates consumed by flocks following animal diets; (ii) water and energy use; (iii) tractors and agricultural equipment;

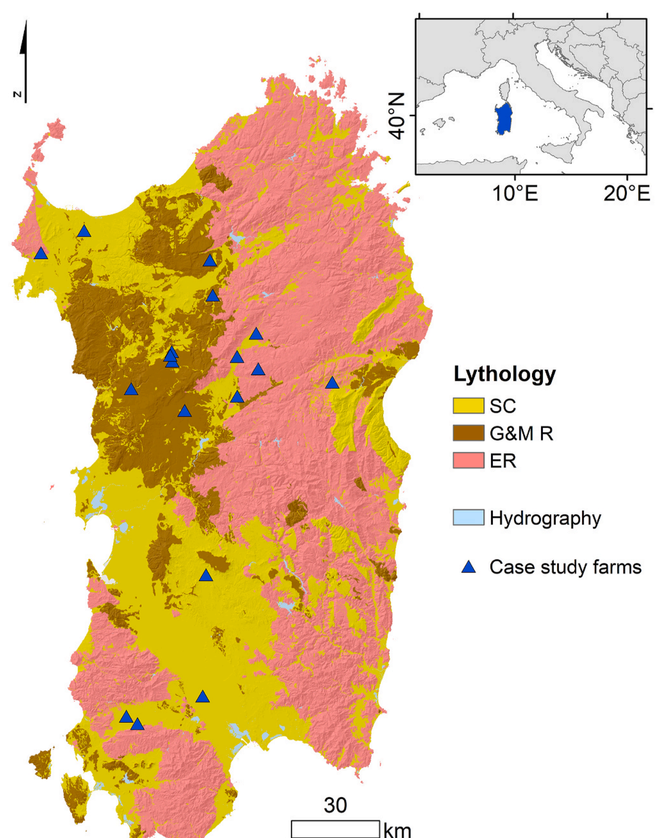

Fig. 1. Parent material of Sardinian soils and the location of the eighteen sample farms (modified from RAS, 2016; http://www.sardegnageoportale.it/). SC: sedimentary covers; G&M R: granites and metamorphic rocks; ER: effusive rocks (basaltic and trachytes).

(iv) agrochemicals and other consumables; (v) distances and modes of transportation. The primary farm data were collected through farm register examinations, several field visits, and interviews with farmers. All representative secondary data were obtained from the Ecoinvent Centre v3.8 database (Moreno Ruiz et al., 2021), with the exception of the sunflower meal and soybean feed datasets, which were obtained from the Agri-footprint 4.1 database (2017). No generic data were used. To account for the multifunctional role of small ruminant systems, including the production of market goods and the provision of ecosystem services (Arca et al., 2021; Gutiérrez-Peña et al., 2019), both 1 kg of Fat Protein Corrected Milk (FPCM - Pulina and Nudda, 2002) and 1 ha of UAA were used as FUs. The farm surface areas were delimited by comparing the cadastral data from farm registers with the information collected during the farmers' interviews and drawing boundaries on orthophotos (Google Earth, earth.google.com/web/). Subsequently, non-productive unused areas were identified, measured, and excluded from the calculation of UAA. The monthly diet of each animal category was represented in the LCA model based on the type and amount of feed derived from primary data collected on-farm. Biomass intake from pastures was calculated by subtracting from the total intake of dry matter (DMI) the amount of other feeds consumed by the ewe. DMI was calculated using Small Ruminant Nutrition System Software (SRNS - Tedeschi et al., 2008; www.nutritionmodels.tamu.edu). Feed composition was assessed by the analysis of samples from case study farms, or estimated using a local feed database (Sardegna Agricoltura, 2013). Fodder consumption from animal diets was also recorded and the biomass yields of forage crops and natural pastures produced on-farm were compared with the amount eaten by the flocks, as estimated using SRNS for each animal category (according to sex, age, weight, physiological and production level of animals). On-farm feed production was modeled according to farm-specific data on crop yields, agricultural operations, sowing seeds, agrochemicals, and water use, etc. In particular, the dataset of each agricultural operation (sowing, harrowing, baling, etc.) was modeled modifying the corresponding Ecoinvent datasets according to the primary data on working time and diesel consumption (Table S1, Supplementary Material). The allocation criteria used for modeling On-farm feed were consistent with the FAO (2016) guidelines. Emissions related to the use of pesticides and fertilizers were evaluated using the following methodologies (see also Table S2, Supplementary Material): (i) the equations reported in Ecoinvent report no.15 (Nemecek and Kägi 2007) for NH_3 and NOx emissions to the atmosphere, release of heavy metals and P into the water, and release of heavy metals to soil; (ii) IPCC Tier 1 approach (IPCC, 2019) for both N_2O direct and indirect emissions to the atmosphere; (iii) EPIC model (Williams, 1995) as applied in Demurtas et al. (2016) for NO_3- emissions to water.

The enteric methane (CH_4) emissions were estimated as approached by Atzori et al. (2013), thus estimating the Metabolizable Energy Intake (MEI) and Digestible Energy (DE) of each animal category with the software SRNS and applying the CH_4 emission factor (Ym), calculated as a function of DE (Vermorel et al., 2008). In particular:

$$F_{CH4} = MEI \cdot Ym/55.65$$

where:

F_{CH4} represents the amount (kg) of CH_4 emitted per head per day; MEI is expressed in MJ per head per day; the coefficient 55.65 reflects the energy content of 1 kg of CH_4 and is expressed in MJ; the methane conversion factor Ym (%), which indicates the percentage of gross energy of the ration lost as CH_4, is calculated as follows:

$$Ym = -0.15 \cdot DE + 21.89$$

where DE is expressed in percentage (%).

Because in all farming systems sheep were not confined in small pens or sheltered areas, manure management impacts did not include CH_4 emissions but only N_2O released through animal excreta. These animal emissions were calculated using the IPCC (2019) approach and the standard emission factor for sheep and 'other animals' [0.003 kg N_2O–N (kg N)$^{-1}$]. In addition, the daily N excretion of each animal category was estimated using empirical equations elaborated by Decandia et al. (2011).

Electricity consumption for irrigation, milking, milk cooling, and water heating was estimated based on the installed power, and the results were cross-checked with data from existing literature (Pazzona et al., 2015; Todde et al., 2018a, 2018b). After removing household and external uses, electricity use was compared to the average annual consumption listed in the electric company's bills. Electricity data were based on the Ecoinvent process "Electricity, medium voltage {IT}| electricity voltage transformation from high to medium|Cut-off, U" adjusted to the energy mix declared by the energy supplier companies in the reporting year. In particular: (i) firstly, the "Electricity, high voltage {IT}| market for | Cut-off, U" Ecoinvent dataset was modified including as inputs from technosphere the specific high voltage electricity production mix declared by each operator on the website. Renewable energy mix and hydro-electrical mix were selected according to the annual average mix declared by Terna, the Italian operator for national transmission grid for high and extra-high voltage electricity. Air emissions were not modified; (ii) then, a new dataset was created from the previous one (in order to move from high to medium voltage), using the unit process "Electricity, medium voltage {IT}| electricity voltage transformation from high to medium voltage | Cut-off, U" and applying a transformation ratio equal to 1.0055 kWh. Because of the lack of water counters in most of the sheep farms surveyed, direct water consumption was based on simplified calculation models and with inaccurate allocation of water use among farm activities. In particular, water use for milking machine and refrigeration tank cleaning was calculated according to Pazzona et al. (2015), while the consumption for flock watering was calculated according to the ratio between [L of water intake] and [kg of DM intake], estimated by Pulina and Nudda (2002). Final and intermediate transportations were accounted for through the means of transport (modeled according to the relevant Ecoinvent processes), the distances, and the transported mass. Primary data were used to calculate distances when available (online searches were done to locate the production plants and identify the logistic chain). In the absence of primary data, logistics and distances were traced using the Searates website (https://www.searates.com). Impact assessment related to the production of tractors and machineries (e.g. pipes, boilers, pumps, etc.) was based on the Ecoinvent datasets, using the mass of the machinery as input to the technosphere. As recommended by PEFCR for Dairy Products (EDA, 2018), other capital goods, such as sheds, reservoirs, etc., were inventoried but not included within the system boundaries.

The allocation of impacts between sheep farming products (milk, meat, and wool) was performed using biophysical (energy content) and economic criteria. A sensitivity analysis revealed small differences in the environmental performance of milk calculated using different allocation methods (Tables S3 and S4, Supplementary Material). Finally, given that milk was by far the most important driver of production, accounting for around 75% of farm income, and in line with the international literature on the dairy sector (Baldini et al., 2017; Salou et al., 2017), in this paper, only LCA results pertaining to economic allocation are presented. The unit prices of sheep products considered for the economic allocation were referred to the 2016/2017 production year (average annual values recorded in the Sardinian markets of Cagliari, Macomer, and Sassari - ISMEA, 2018) and were 0.65, 2.75, 0.52, and 0.32 € kg^{-1} for milk, lamb meat, sheep meat, and wool, respectively.

For LCA calculations, SimaPro Analyst Software v9.3 (PRé Sustainability, 2021) and Environmental Footprint 3.0 (version 1.02) (EF) evaluation method (Fazio et al., 2018) were utilized. Moreover, within the Climate Change (CC) impact category of the EF method we replaced the default characterization factors for fossil and biogenic CH_4, and N_2O with the following values according to the Sixth IPCC Assessment Report: 29.8 and 27.0 CO_2eq/kg CH_4, and 273 CO_2eq/kg N_2O, respectively (Forster et al., 2021). In order to identify the main relevant impact categories, the results for each of the sixteen impact categories included in the EF method were normalized and weighted, and those that cumulatively contributed to at least 80% of each single EF score of the product-based FU were selected and discussed.

2.3. Soil carbon sequestration estimation

Following the approach proposed by Petersen et al. (2013), we calculated soil Cseq, expressed as kg of CO_2 per kg of FPCM and per ha of UAA. This model was developed just for LCA studies in agriculture to figure out how the carbon in the soil changes due to crop residues and manure added to the soil. This approach was based on the modeling of two carbon fluxes: (i) from the soil to the atmosphere, where the soil organic matter mineralization was modeled using the C-TOOL model (Petersen, 2010); and (ii) from the atmosphere to the soil, where atmospheric CO_2 decay was modeled using the Bern Carbon Cycle model (IPCC, 2007). According to the Global Warming Potential (GWP) indicator, 9.7% of the carbon added to the soil as organic carbon in the first year would be sequestered in a 100-year perspective, as observed by Petersen et al. (2013). Although this method can be considered simplistic, it has the advantage of relying on site-specific data on soil carbon inputs and field conditions, whereas other models for agricultural LCA of Cseq use preset values per ha. In LCA investigations on dairy systems under Mediterranean conditions (Batalla et al., 2015; Escribano et al., 2020; Gutiérrez-Peña et al., 2019), as well as in regions of Western Europe (Knudsen et al., 2019), other authors have used this method to estimate soil Cseq. To estimate soil Cseq, the same coefficient (9.7%) was used on the amount of carbon remaining in the soil at the end of the study year, which was composed of two different fractions: (i) carbon from crop residues and (ii) carbon from manure deposited onto pasture from grazing sheep (Batalla et al., 2015). Both above- and below-ground residues contributed to the carbon from crop residues. Yields of grain, hay, silage, and removed straw were quantified by farmers, while green and stubble grazed biomasses were estimated by attributing available data on hay yields of crops on the same farm under the same pedoclimatic conditions. To estimate the grazed biomass of crops managed with different agronomic techniques (irrigation and fertilizers adoption) or used for different purposes (i.e., hay and green forage), adjustment factors from literature were applied to the reference crop (Table S5, Supplementary Material). The estimation of above-ground residues was based on the available crop yields data, expressed in Mg of dry matter (DM) ha^{-1}, by applying specific equations and using coefficients from the literature (Table S6, Supplementary Material). Below-ground residue estimation (Table S7, Supplementary Material) included root and rhizodeposition biomass, estimated by: (i) applying, for root biomass, a specific shoot-root or root-shoot ratio to the relative total above-ground biomass, calculated as the sum of yield and above-ground residues; (ii) applying, for rhizodeposition biomass, an index of 0.65 to the estimated root biomass of each crop (Bolinder et al., 2007). In addition, root biomass of permanent grasslands was estimated as an annual biomass increase and rhizodeposition was estimated as a fraction of the entire root system; in contrast, the root and rhizodeposition of annual crops were estimated as annual biomass production (Arca et al., 2021). Residue amounts were converted to C using a C content coefficient of 0.40 (Burle et al., 1997; dos Santos et al., 2011), with the exception of silage maize, for which C from crop residues was estimated as a percentage (11%) of harvested DM (Lai et al., 2017). The amount of C derived from sheep manure was calculated by applying a C:N ratio index equal to 13.4 (Escudero et al., 2012) to the total fecal N, estimated, for each animal category, according to the model of Decandia et al. (2011), and using the emission factors recommended by IPCC (2019).

In summary, soil Cseq was calculated by using the following steps: (i) estimation of DM yield from grazed green biomass and stubble; (ii) estimation of above- and below-ground dry matter residues; (iii) conversion of total crop residues (sum of above- and below-ground residues) from DM to C; (iv) estimation of the amount of C derived from sheep manure; (v) calculation of total soil C input by summing the C input from crops and that from sheep manure; (vi) conversion of total soil C input from C to CO_2 (using the C–CO_2 conversion factor of 3.67); (vii) estimation of soil Cseq by applying the coefficient of 9.7% to total soil C input (Petersen et al., 2013).

Finally, we calculated the net GWP for both FUs, subtracting the soil Cseq values from the GWP, in line with similar studies (Arca et al., 2021; Batalla et al., 2015).

2.4. Statistical analysis

The distribution of the sample population of each group and the homogeneity of variance between groups were checked by preliminary tests. Normality was tested using the "Shapiro-Wilk normality test" and homogeneity of variance was tested by the "Classical Leven's test" (for normal samples) or by the "rank-based (Kruskal-Wallis) classical Leven's test" (for non-normal samples). Differences between the two groups for each variable were evaluated using appropriate statistical tests at $P < 0.05$. One-way ANOVA test was used for normal samples with homogeneous variance; (ii) Welch's ANOVA test was used for normal samples with non-homogeneous variance; (iii) Kruskal-Wallis and Wilcox Mann-Whitney tests were used for non-normal samples.

To determine the significance level (P-value <0.05) and the direction of each correlation, correlation matrices were used, including the farm characteristics parameters and both variables of the LCA impact categories related to 1 kg of FPCM and 1 ha of UAA.

All statistical analyses were conducted using the R programming language (R Core Team, 2015).

3. Results

3.1. Meteorological conditions of the study year

According to the meteorological analysis annually provided by the Sardinian Regional Agency for the Protection of the Environment (ARPAS, 2018), weather conditions during the first quarter (October to December 2016) of the study period were characterised by above-average temperatures, especially highs (+0.5 °C to +1.0 °C compared to the 1995–2014 average), and by low rainfall (from 100 to 300 mm in central and western Sardinia) over the entire island, with the exception of some areas in the central-eastern Sardinia, which received heavy rainfall in December, with a cumulative maximum up to 600 mm. February and March were characterised by dry periods with maximum temperatures well above the 1971–2000 climatological mean, while low temperatures were characterised by an increasing gradient from the north-west to the south-east. The spring season was warm and particularly dry. July and August had also little rainfall, and September was particularly dry in the north and mid-western areas. With the exception of September, when values were unusually low across most of Sardinia, summer temperatures were particularly high (6 heat waves of varying intensity were recorded during the period July–August).

3.2. Technical and productive performances

The size of the farms of both groups were comparable in terms of the total average number of ewes and the average UAA (Table 1). Consequently, no significant differences in the stocking rates were observed. However, significant differences were observed for many other farm characteristics. The CS group of farms showed a percentage of UAA occupied by natural pasture more than three times higher than the N-SS group of farms, where the majority of the area was occupied by annual forage crops (P-value <0.01). The first group included two farms (F8 and F10) with 100% of natural pasture, while the second group included four farms (F14, F16, F17, and F18) without natural pasture (Table S8, Supplementary Material). The feed self-sufficiency of the two groups

Table 1
Technical and productive characteristics of the Central Sardinia and Northern and Southern Sardinia farm groups.

Farm group	Total ewes	UAA	Natural pasture	Stocking rate	Feed self-sufficiency	FPCM production		DMI	FE	N	P_2O_5	Water
Unit	n.	ha	% UAA	n. heads ha^{-1} of UAA	%	kg ewe^{-1} $year^{-1}$	kg ha^{-1} of UAA $year^{-1}$	kg ewe^{-1} $year^{-1}$	%	kg ha^{-1} of UAA $year^{-1}$	kg ha^{-1} of UAA $year^{-1}$	m^3 ha^{-1} of UAA $year^{-1}$
CS	505	89	75	6.3	62	117	580	446	0.24	4	7	26
N-SS	554	85	21	6.6	74	188	969	508	0.34	43	23	236
Coefficient of variation (%)	*57*	*53*	*78*	*35*	*16*	*33*	*44*	*11*	*27*	*132*	*140*	*194*
P-value	*n.s.*	*n.s.*	*< 0.01*	*n.s.*	*< 0.01*	*< 0.01*	*< 0.01*	*< 0.01*	*< 0.01*	*< 0.01*	*n.s.*	*< 0.05*

UAA: Utilized Agricultural Area; FPCM: Fat and Protein Corrected Milk; DMI: Dry Matter Intake; FE: Feed efficiency (kg of FPCM kg^{-1} DMI of productive ewes). CS: Central Sardinia farm group; N-SS: Northern and Southern Sardinia farm group.

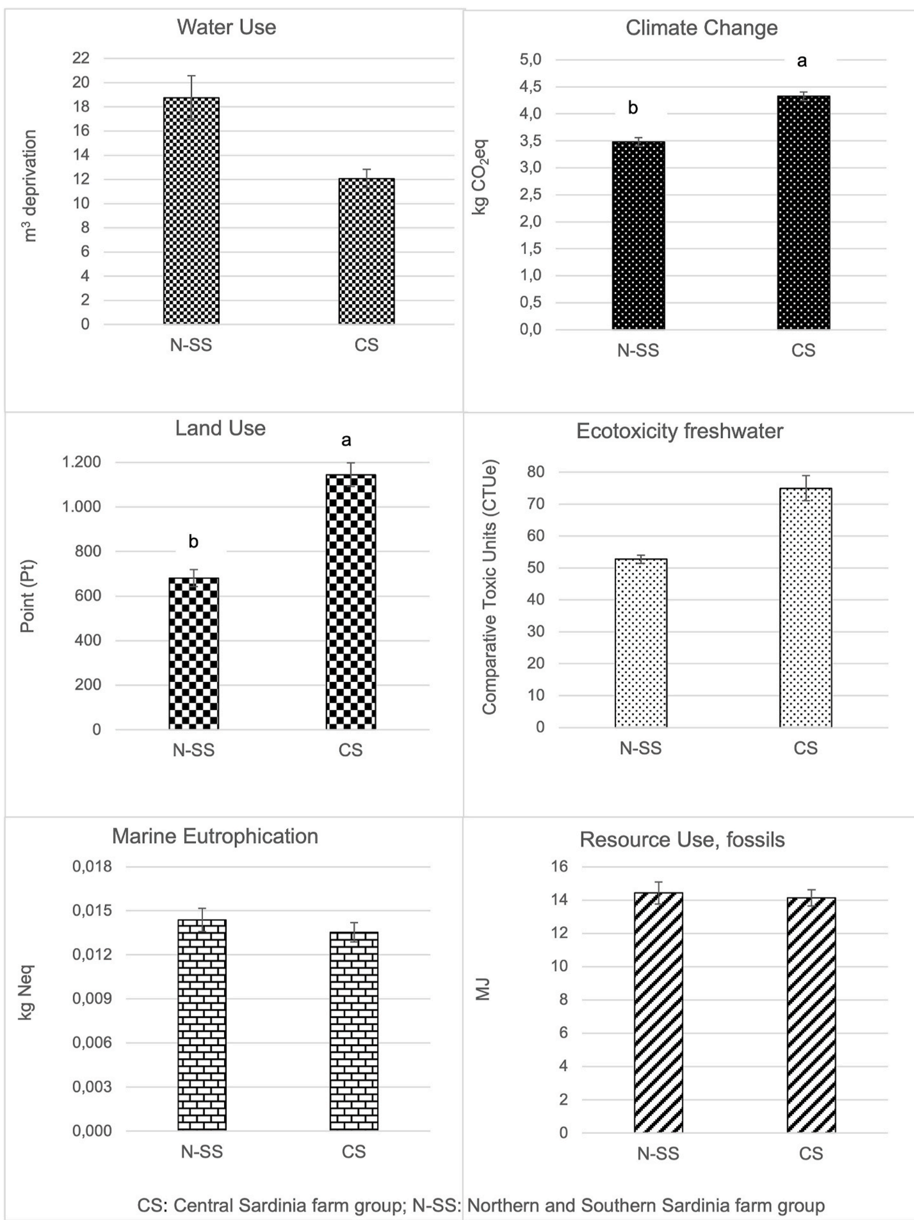

Fig. 2. Environmental footprint of dairy sheep farming systems in Central Sardinia and Northern and Southern Sardinia, expressed per kg of Fat and Protein Corrected Milk. Only the most relevant impact categories are displayed, as determined by those that cumulatively contributed to at least 80% of the total environmental impact. Different letters indicate significant differences between the means (P-value < 0.05). Vertical bars indicate ± standard error.

ranged from 45% to 86%, and mean value in the N-SS group was significantly higher than that in the CS group of farms (P-value <0.01). The N-SS group showed the highest milk production performance. Three farms in the N-SS group (F11, F16, and F18) showed milk production values higher than 220 kg of FPCM per milking ewe, with the highest value being 255 kg of FPCM (F16). In contrast, two farms of the CS group (F5 and F10) showed values below 100 kg of FPCM per milking ewe. Those values do not include the milk suckled by the weaned lambs. Milk production per hectare of UAA ranged from 349 to 1523 kg of FPCM, with three farms (F11, F14, and F18) producing more than 1000 kg of FPCM and four farms (F1, F2, F4, and F8) producing less than 400 kg of FPCM, in the N-SS and CS groups, respectively. As a ratio between milk production per ewe and DMI of productive ewes (excluding rams and replacement), feed efficiency (FE) ranged from 0.25 to 0.43 in the N-SS farm group and from 0.17 to 0.35 in the CS farm group. The mean value of FE was 1.4 times greater in the N-SS than in the CS group (P-value <0.01). In addition, the level of DMI per ewe was greater in the N-SS than in the CS group (P-value <0.01), and the difference between the two groups was 62 kg of DMI ewe^{-1} year^{-1}. Finally, inputs per unit surface area, in particular kg of N fertilizer ha^{-1} of UAA and m^3 of water ha^{-1} of UAA (primarily for irrigation), were significantly greater in the N-SS group (P-value <0.01 and 0.05, respectively). Values greater than 50 kg N ha^{-1} were observed in five different farms belonging to the N-SS group, while five farms of the CS group did not use nitrogen fertilization. The N-SS farm group utilized in average 9 times more water per hectare than the CS farm group.

3.3. Environmental performances

Listed in decreasing order of magnitude, the main relevant impact categories were Water Use (WU), CC, Land Use (LU), Ecotoxicity Freshwater (ECOTOX), Marine Eutrophication (ME) and Resource Use,

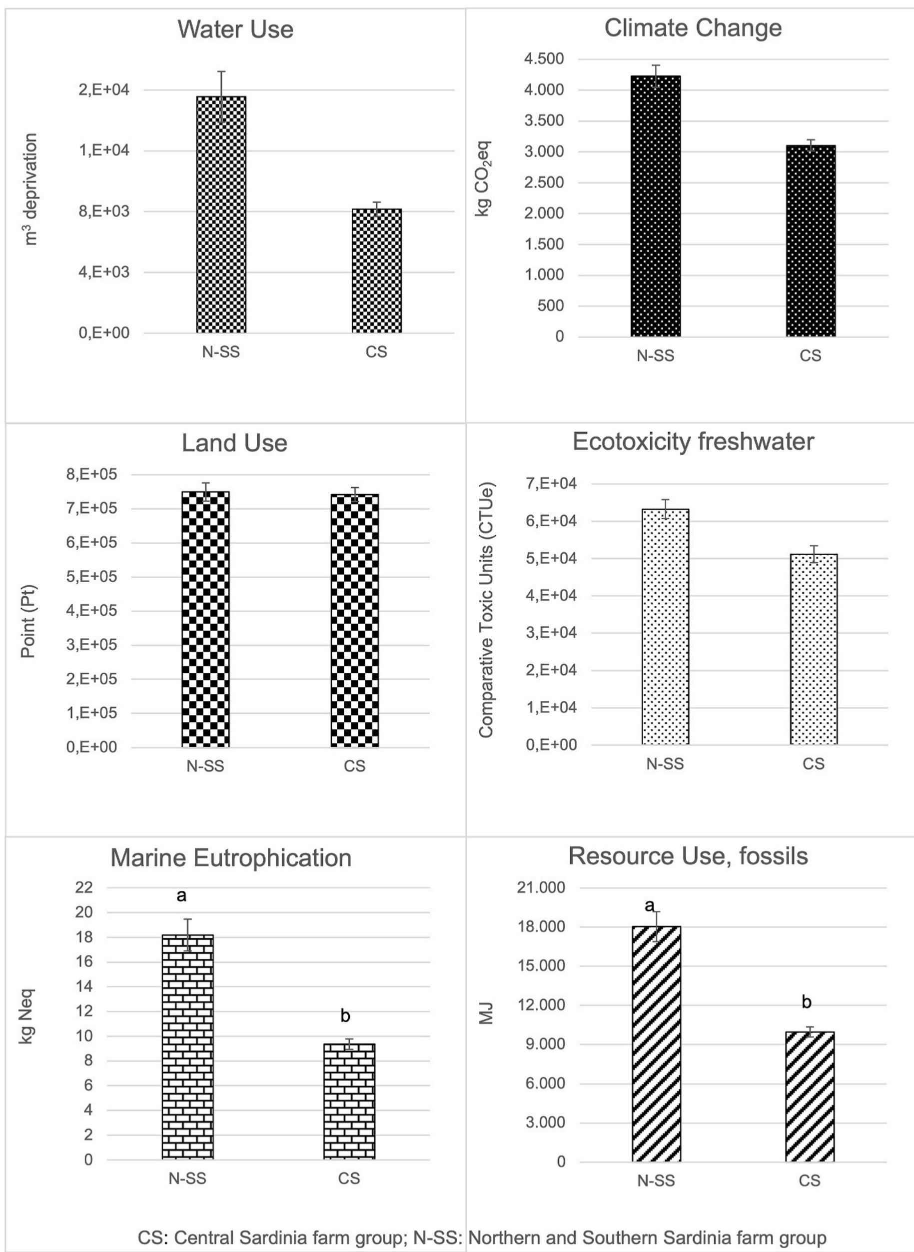

Fig. 3. Environmental footprint of dairy sheep farming systems in Central Sardinia and Northern and Southern Sardinia, expressed per ha of Utilized Agricultural Area. Only the most relevant impact categories are displayed, as determined by those that cumulatively contributed to at least 80% of the total environmental impact. Different letters indicate significant differences between the means (P-value < 0.05). Vertical bars indicate ± standard error.

fossils (RU-f), that contributed to the EF single score 26%, 22%, 19%, 6%, 5% and 4%, respectively.

3.3.1. Environmental footprint of 1 kg of Fat and Protein Corrected Milk

The farms of the CS group showed significantly worse environmental performance than N-SS farms for the impact categories CC and LU (P-value <0.05 for both cases), whereas there were no significant differences between the two groups for the impact categories WU, ECOTOX, ME and RU-f (Fig. 2).

In the CS and N-SS groups, GHG emissions ranged from 2.8 to 5.3 and from 2.7 to 4.6 kg CO_2eq kg^{-1} of FPCM, respectively, with an average value 24% higher in the CS group compared to the N-SS group (4.3 and 3.5 kg CO_2eq kg^{-1} of FPCM, respectively).

The average LU value of CS farms was nearly double the average value of N-SS farms (1145 and 681 Pt kg^{-1} of FPCM, respectively). LU ranged from 395 to 1990 Pt kg^{-1} of FPCM in the CS group, and from 284 to 1227 Pt kg^{-1} of FPCM in the N-SS group.

WU values in the CS and N-SS groups averaged 12.1 and 18.7 m^3 depriv. kg^{-1} of FPCM, respectively, and ranged from 4.9 to 49.7 m^3 depriv. kg^{-1} of FPCM in the entire sampled population.

The mean values of ECOTOX in the CS and N-SS groups were 75 and 53 CTUe kg^{-1} of FPCM, respectively. The lowest and highest values (31 and 144 CTUe kg^{-1} of FPCM, respectively) were observed for the CS group, resulting in a greater variability compared to the N-SS group.

The ME and RU-f average values were similar for the two farm groups, resulting equal to 1.35E-02 kg Neq kg^{-1} of FPCM (ME) and 14.1 MJ kg^{-1} of FPCM (RU-f) in CS, and 1.44E-02 kg Neq kg^{-1} of FPCM (ME) and 14.4 kg Neq kg^{-1} of FPCM (RU-f) in N-SS. The values of the whole sampled population ranged from 7.0E-03 to 2.7E-02 Neq kg^{-1} of FPCM, and from 7.3 to 25.5 MJ kg^{-1} of FPCM, for ME and RU-f, respectively.

3.3.2. Environmental footprint of 1 ha of Utilized Agricultural Area

Considering the area-based FU, the ranking of environmental performance values between the two groups was substantially the opposite to that observed for the product-based FU: N-SS resulted more impacting than CS farms (Fig. 3). In particular, a significantly greater impact in the N-SS than in the CS group was observed for ME and RU-f impact categories (P-value <0.05), with the following values: 18.2 vs. 9.4 kg Neq ha^{-1} of UAA, and 1.8E+04 vs. 1.0E+04 MJ ha^{-1} of UAA, respectively. ME values ranged from 5.4 to 37.1 and from 4.6 to 17.2 kg Neq ha^{-1} of UAA, while RU-f values ranged from 5.9E+03 to 3.5E+04 and from 5.1E+03 to 1.8E+04 MJ ha^{-1} of UAA, in the N-SS and CS groups, respectively.

For the CC impact category, a trend (P-value <0.1) towards higher mean values in the N-SS than CS group was found (4226 and 3105 kg CO_2eq ha^{-1} of UAA, respectively). GWP values ranged from 1616 to 6425 kg CO_2eq ha^{-1} of UAA in the entire sampled population.

For WU, LU and ECOTOX impact categories, no significant differences between the two farm groups were observed. The mean values of WU in the N-SS and CS groups were equal to 1.6E+04 and 8.2E+03 m^3 depriv. ha^{-1} of UAA, respectively. The lowest value was found in a non-irrigated CS farm (2.4E+03 m^3 depriv. ha^{-1} of UAA, in F2 farm) with 67% of UAA covered by natural pasture and with the highest feed self-sufficiency percentage (74%) within the CS group. The highest value was observed for an irrigated N-SS farm (4.6E+04 m^3 depriv. ha^{-1} of UAA, in F14 farm), where the total UAA was annually tilled for feed production and irrigated silage-maize was cultivated in an intercropping system. High variability in WU was observed within the two farm groups, with a coefficient of variation equal to 86% and 57% for N-SS and CS group, respectively. The average LU values were very similar between the two groups, with 7.5E+05 and 7.4E+05 Pt ha^{-1} of UAA in N-SS and CS farms, respectively. Considering the entire sampled population, LU values ranged from 3.3E+05 to 1.1E+06 Pt ha^{-1} of UAA. For the ECOTOX impact category, the average score of N-SS group was 24% higher than this of the CS one (6.3E+04 vs. 5.1E+04 CTUe ha^{-1} of UAA). The ECOTOX values of the whole sampled population ranged from 1.6E+04 to 1.0E+05 CTUe ha^{-1} of UAA, and the greatest variability was observed for the N-SS group (coefficient of variation of 92% and 36%, for N-SS and CS group, respectively).

3.3.3. Contribution analysis

For the WU impact category, Off-farm feed represented the dominant process in both farm groups (61% and 79% in N-SS and CS, respectively), while On-farm feed accounted for 31% of contribution in the N-SS group and only 6% in the CS one.

Animal emissions (enteric CH_4 and N_2O) represented for both groups the largest source of impact for CC, accounting for 59% and 68% in the N-SS and CS farms, respectively (Table 2). The second impactful process was On-farm feed (18%) for N-SS group, while Off-farm feed (23%) for CS group.

On-farm feed represented the main impacting process for LU impact category (87% and 78% in the N-SS and CS group, respectively), followed by Off-farm feed (11% and 19% on average in N-SS and CS farms, respectively).

For ECOTOX impact category, the processes related to the feed supply chain represented the main source of impact for both groups (near to 90% of contribution, in total). In particular, Off-farm feed contributed for 58% and 83% in N-SS and CS group, while On-farm feed accounted for 30% and 8%, respectively.

Feed supply represented the main impact source for both groups for the ME and RU-f impact categories as well, although the first process was On-farm feed for N-SS (51% and 47% for ME and RU-f, respectively) and Off-farm feed for CS (74% and 65% for ME and RU-f, respectively).

3.3.4. Soil carbon sequestration

Farms belonging to the CS group sequestered the highest amount of C in the soil, regardless of the FU considered (Table 3).

Considering 1 kg of FPCM, the average soil Cseq amount per FU in CS group was 2.1 times greater than in N-SS group, with values equal to 2.2 and 1.1 kg CO_2 kg^{-1} of FPCM, respectively (P-value <0.01). In the first group, the soil Cseq ranged between 1.2 and 3.3 kg CO_2 kg^{-1} of FPCM (coefficient of variation = 35%), whereas in the second group the range was between 0.5 and 2.9 CO_2 kg^{-1} of FPCM (coefficient of variation = 76%). Two farms in the CS group (F1 and F8), with a high proportion of natural pasture (97 and 100%, respectively), had soil Cseq levels above 3 kg kg^{-1} of FPCM (Table S9, Supplementary Material). In contrast, only two farms in the N-SS group had soil Cseq values greater than 1 kg CO_2 kg^{-1} of FPCM (F12 and F13, with 85 and 50% of the farmland occupied by natural pasture, respectively).

Using 1 ha of UAA as FU, CS group confirmed a better performance in terms of soil Cseq, although the difference was less than that observed for the product-based FU (P-value <0.05). In fact, the estimated amount of soil Cseq for CS group was 29% greater than in N-SS group (1129 vs. 872 kg CO_2 ha^{-1} of UAA, respectively). However, the maximum value of soil Cseq (1398 kg CO_2 ha^{-1} of UAA) was observed in a farm with 67% of natural pasture (F12) belonging to the N-SS group. The lowest value (514 kg CO_2 ha^{-1} of UAA) was also found in the same group, on a farm (F16) with 100% of UAA devoted to annual crops. As a result, the coefficient of variation for soil Cseq values in N-SS group was greater than in CS group (34% and 12%, respectively). In CS group, soil Cseq ranged from 927 to 1375 kg CO_2 ha^{-1} of UAA, and only two farms (F3 and F6, with 15% and 65% of UAA covered by natural pasture, respectively) had soil Cseq values below 1000 kg CO_2 per unit area.

The GWP and soil Cseq results for both groups, considering the two FUs, are summarized in Fig. 4. Comparing the values of the two environmental indicators referred to 1 kg of FPCM, CS group performed worse in terms of GWP and better in terms of Cseq than the other group. In CS group, the soil Cseq was 51% of GWP, with values ranging from 32% to 82%. In contrast, in N-SS group the ratio of average soil Cseq to average GWP was lower, and equal to 31%. Furthermore, values ranged from 13% to 86%, with only two farms (F12 and F13) showing percentages higher than the group mean value. As a result, the variability of

Table 2
Contribution analysis (%) of principal processes to the main impact categories for the dairy sheep farming groups of Central and Northern and Southern Sardinia.

Impact category	CH_4	N_2O	On-farm feed	Off-farm feed	Power	Tractors and machineries	Remaining processes
Water Use							
CS	–	–	6	79	–	–	15
N-SS	–	–	31	61	–	–	8
Climate Change							
CS	65	3	5	23	1	1	2
N-SS	56	3	18	16	2	2	3
Land use							
CS	–	–	78	19	–	–	3
N-SS	–	–	87	11	–	–	2
Ecotoxicity freshwater							
CS	–	–	8	83	1	2	6
N-SS	–	–	30	58	1	4	7
Marine Eutrophication							
CS	–	–	21	74	–	–	5
N-SS	–	–	51	43	–	1	5
Resource Use, fossils							
CS	–	–	15	65	6	3	11
N-SS	–	–	47	35	3	6	9

CH_4 emission from enteric fermentation; N_2O emission from animal excreta.
CS: Central Sardinia farm group.
N-SS: Northern and Southern Sardinia farm group.

Table 3
Soil C sequestration amounts for the Central Sardinia and Northern and Southern Sardinia farm groups, estimated according to Petersen et al. (2013) and expressed in kg of CO_2 sequestered in soil per kg of Fat and Protein Corrected Milk, and per ha of Utilized Agricultural Area.

Farm group	Soil Cseq	
	kg CO_2 kg^{-1} of FPCM	kg CO_2 ha^{-1} of UAA
CS	2.2	1,129
N-SS	1.1	872
Coefficient of variation (%)	56	25
P-value	<0.01	<0.05

Soil Cseq: soil carbon sequestration.
FPCM: Fat and Protein Corrected Milk; UAA: Utilized Agricultural Area.
CS: Central Sardinia farm group; N-SS: Northern and Southern Sardinia farm group.

the N-SS group was higher than that of the CS group (coefficients of variation of 77% vs. 30%, respectively). Including soil Cseq in GWP calculations, the average net GWP values resulted equal to 2.4 kg and 2.1 CO_2eq kg^{-1} of FPCM for the N-SS and CS groups, respectively, with the highest and lowest values observed for the N-SS group (4.0 and 0.5 kg CO_2eq kg^{-1} of FPCM). When 1 ha of UAA was used as FU, the ratio between average soil Cseq and average GWP in CS group was equal to 36%, with values ranging from 23% to 65%. On the other hand, the range for N-SS group varied from 11% to 68%, with an average value of 22%, and more than twice the variability of the other group (coefficients of variation of 92% vs. 36%, respectively). When soil Cseq was included in the GWP calculations, the average net GWP values were equal to 1976 and 3354 kg CO_2eq ha^{-1} of UAA for CS and N-SS group, respectively. In this case, the lowest value was observed in CS group (F2 farm) while the highest value was observed in N-SS group (F14 farm) with 599 and 5724 kg CO_2eq ha^{-1} of UAA, respectively.

4. Discussion

The different geo-pedological conditions of the two production areas clearly influenced the structure and characteristics of both farm groups. The N-SS production systems achieved 74% feed self-sufficiency by taking advantage of orography and soil depth and using fertilizers and irrigation for maximizing forage production. The hilly and mountainous

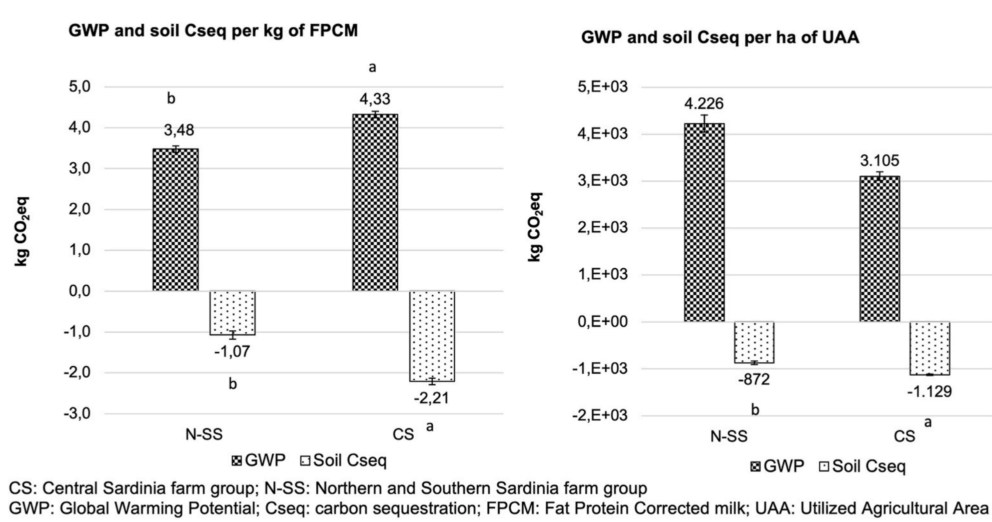

Fig. 4. Global Warming Potential and soil carbon sequestration referring to 1 kg of Fat and Protein Corrected Milk and 1 ha of Utilized Agricultural Area in Central Sardinia and Northern-Southern Sardinia dairy sheep farming groups.

morphology with reduced soil fertility limited the potential for soil tillage of CS farms (75% of the farm's agricultural area was occupied by sheep-grazed natural pasture), which achieved only 62% of feed self-sufficiency.

The better performance of the N-SS compared to the CS farm group, particularly for the FE indicator, can be attributed to the following: (i) the higher flock fertility, which results in fewer non-productive ewes; (ii) the better quality of forage from arable crops compared to natural pasture (Table S10, Supplementary Material), likely due to a greater contribution of legume species to the total biomass (Hernández-Esteban et al., 2018). In addition, the higher milk production both per ewe (+61%) and per ha of UAA (+67%) of N-SS compared to the CS group can be mainly explained by the higher level of DMI ewe^{-1}, which was approximately 14% higher than in the CS group, and by the above quoted higher nutritive value of grazed forage crops as compared to many natural pastures in Sardinia. This, in its turn, explains why FE was higher by 42% in N-SS than CS farms.

As expected, GWP values per kg of FPCM were negatively correlated (P-value <0,01) with production performance, such as milk production (kg of FPCM ewe^{-1} and ha^{-1} of UAA) and FE (Table S11, Supplementary Material), confirming that the most intensive and productive farming systems had the best environmental performance (Escribano et al., 2020; Vagnoni et al., 2015). It seems that agricultural areas with natural pastures indirectly increased GWP kg^{-1} of FPCM compared to arable crops, albeit the positive correlation between GWP per kg of FPCM and natural pasture percentage was weak (P-value <0.1). Similarly, the lower impact in terms of LU per kg of FPCM in N-SS farms compared to CS farms can be explained by their better production efficiency and animal performance, as indicated by the negative correlation with production parameters (P-value <0.05), and considering that the average UAA was very similar between groups. WU per kg of FPCM was not significantly different between the two farm groups, despite it was positively correlated with water consumption (P-value <0.01). That means the higher water use of N-SS farms was partially offset by the higher normalized milk production. Moreover, the lower use of Off-farm feeds (the main hotspot for WU) in N-SS than in CS finally balanced the effect of water consumption by N-SS farms.

The higher impact showed by N-SS compared to CS group in RU-f and ME referred to the area-based FU, can be explained by the higher N fertilizer use in arable crops than in natural pastures, as confirmed by the positive correlation between N inputs and RU-f and ME (P-vale <0,001; Table S12, Supplementary Material). Consequently, RU-f and ME results were negatively correlated with the extent of natural pasture areas, which were managed with low N fertilizer input. In general, the higher use of inputs per unit of UAA to boost milk production in N-SS than CS farms resulted in greater environmental impact, as suggested by the positive correlation (P-value <0.01) between RU-f and ME results and FPCM production per ha of UAA. The overall trend of N-SS farms to have a higher GWP per ha of UAA than CS ones was in line with the literature (Arca et al., 2021; Escribano et al., 2020), but it is important to highlight that the observed environmental benefits associated with extensive farming had a weak statistically significance and were strongly correlated with specific production performances. Moreover, the tendential differences (P-value <0.1) in terms of GWP per ha of UAA between the two farm groups were probably influenced by the wide variability within the sampled population (coefficient of variation greater than 30%).

Consistent with previous studies on the water footprint of sheep farming (Dougherty et al., 2019; Ibidhi and Ben Salem, 2019), the feed chain was by far the main source of impact also for WU. Differences in soil management and, therefore, in diet compositions between farm groups were reflected in the contrasting contributions of Off-farm feed and On-farm feed to WU. However, it is important to emphasize that direct water consumption was based on simplified estimate models and inaccurate allocation among farm activities, which suggests caution in interpreting the WU results. On the other hand, very little studies on water use in sheep farms have been conducted, and main literature is focused on water quality degradation caused by farm activities (including sheep farm) as a potential WU threat (Monaghan et al., 2021).

Enteric emissions were confirmed to be the largest source of GHG emissions from dairy sheep systems (Marino et al., 2016; O'Brien et al., 2016; Vagnoni et al., 2015), as well as from other ruminant species (Hristov et al., 2013). However, methodological issues and considered hotspots can cause large differences on final outcomes of different LCA studies even when performed on similar farming systems. In particular, misperceptions on the relevance of enteric contribution to total emissions could be caused by differences in inputs, animal productivity and soil management. For instance, Batalla et al. (2015) reported contribution of enteric emissions that ranged from 19% to 45% within study (Atzori et al., 2017). The higher percentage contribution of CH_4 emissions in the CS than in the N-SS farming systems was in line with the lower FE value. Conversely, the lower percentage contribution of enteric emissions observed in the N-SS group aligns with their high production efficiency that is favoured by the high forage quality. The higher frequency of soil tillage in the N-SS than in the CS farm group for on-farm feeds production resulted in a larger contribution by On-farm feed process to the total GWP of N-SS group. In contrast, the lower feed self-sufficiency capacity of CS farms resulted in higher use of off-farm feeds, which contributed more to the total GWP compared to N-SS farms.

The feed chain represented the main source of impact for LU, ECOTOX, ME and RU-f impact categories, with distinct roles of on- and off-farm feeds according to the different cropping and soil management systems adopted by each farm group.

Soil Cseq capacity of both farm groups, strongly influenced by land management strategy, varied according to the different geo-pedological conditions and production potential of the two production areas. Regardless of the FU to which the soil Cseq values were referenced, the most productive farms in the Southern and Northern Sardinia sequestered less carbon in soil than the least productive farms in the Central Sardinia. As expected, natural pastures of more extensive farming systems favoured higher soil Cseq level despite their low feed productivity and quality. The lower intensity of soil tillage on extensive farms favoured the preservation of SOC, whereas the frequent tillage typical of arable crops promoted mineralization (Acar et al., 2018; Six et al., 2004). Moreover, in terms of root biomass turnover and rhizodeposition, the amount of crop residue left on the soil by natural pasture was considerable (Beniston et al., 2014; Lorenz and Lal, 2018). However, some farms showed distinct performances compared to the group's average, and it is worth analysing them as individual case studies. For instance, within the N-SS group for both specific land management approach and environmental conditions (F12 and F13 farms, specifically) an effective feed supply strategy allowed to combine high soil Cseq performance (by a large use of natural pasture) with good milk production level. From our point of view, these specific case studies deserve attention and further investigations because they represent interesting demonstrative farms that should be promoted as best practices within the policies for the ecological transition of the Mediterranean sheep farming systems. Accounting for soil Cseq, a significant GWP decrease was observed for both farm groups. In particular, the GWP reduction was greater in CS than in N-SS farms, for both FUs. This indicates that soil Cseq has the potential to mitigate the GHG emissions per unit of FPCM of the pasture-based farms, usually less productive and less efficient farming systems.

The statistical findings and the contribution analysis of this LCA study outlined the main critical environmental issues to be addressed in order to implement effective improvement strategies, which can be summarized in the following area of intervention: (i) *Animal management*, implementation of innovative reproduction and management protocols to improve herd production efficiency. Effective reproduction management is a key to reduce the CH_4 emissions as highlighted by several studies and reviews (Harrison et al., 2014; Hristov et al., 2013;

Zucali et al., 2020); (ii) *Feed supply*, reducing off-farm feeds use (Zucali et al., 2020) and improving sheep diet digestibility. The increase of diet digestibility represents a key improvement solution to reduce CH_4 emissions, while the mitigation effect of increasing the level of intake is limited and inconsistent (Hegarty et al., 2010; Hristov et al., 2013). In particular, improving forage quality by selecting high-quality forage such as legumes (Waghorn et al., 2002), and managing under cutting and grazing regimens aimed at keeping quality for as long as possible, can contribute to limit emissions (Zhao et al., 2016). Conservation techniques may potentially have a role, but likely to a lesser extent (Atzori et al., 2017); (iii) *Field management*, introducing native self-reseeding species as an option for arable crops and adopting low-input agricultural practices (e.g. minimum tillage, direct sowing, etc.). As reported by Bernués et al. (2017), the reducing of mechanical soil tillage, grazing management and maintaining semi-natural silvopastoral systems and grasslands represent agricultural practices that may contribute to reduce the GHG emissions thanks to the soil Cseq potential of managed grassland; (iv) *Energy consumption*, minimizing cropping operations and using more renewable energy sources (Todde et al., 2018a). However, the evaluation of the environmental benefits determined by LCA-based improvement solutions implemented in field have not been fully explored by the scientific literature, and this represents a relevant knowledge gap within the global ecological transition effort in agriculture systems (Hellweg et al., 2023).

From a theoretical perspective, to achieve a rapid reduction in emissions at the territorial level, mitigation strategies need to focus on the single farm hotspots that have high emission intensities per functional unit (low performances) and also have high cumulative impact in the system being considered (Batalla et al., 2015). In practice, an efficient mitigation strategy can effectively reduce the overall impact of a given product when applied to a large process that actually shows low performances (Atzori et al., 2017).

5. Conclusions

The geo-pedological conditions that characterize the different production areas of Sardinian island influenced the structure, productivity and environmental profiles of the analysed sheep farming systems. Environmental performances were closely related to the structure of the farming system and production level, and significantly varied according to the different geo-pedological and production areas. Regardless of the functional unit used, the positive impact of soil carbon sequestration capacity compensated the high GHG emission intensity (especially when expressed per kg of normalized milk) of grassland-based extensive farms such as those of CS group, despite the limited nutritional value of natural pasture. At territorial level, effective mitigation actions should prioritize the targeting of inefficient farm hotspots over inefficient farms themselves. This requires the implementation of regional policies that integrate good practices into the activities of both institutions and stakeholders. In particular, environmental strategies should aim to enhance the efficiency of farms that have the greatest potential for milk production and feed self-sufficiency (i.e. N-SS farms), as well as farms with significant potential for non-marketable goods, by promoting the enhancement of ecosystem services like soil Cseq.

Finally, further research is needed to (i) reduce the uncertainty associated with the estimation methodology for soil Cseq as well as considering the role of tree component, (ii) increase our comprehension of the interdependencies and trade-offs between productivity and environmental burden, (iii) refine the data quality pertaining to water utilization in sheep farming, and (iv) evaluate the effective benefits of science-based mitigation solutions by conducting specific field experiments and by using an LCA approach.

CRediT authorship contribution statement

Enrico Vagnoni: Writing – review & editing, Visualization, Validation, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Pasquale Arca:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Mauro Decandia:** Writing – review & editing, Conceptualization. **Giovanni Molle:** Writing – review & editing, Conceptualization. **Gabriella Serra:** Data curation. **Paola Sau:** Data curation. **Mondina Francesca Lunesu:** Data curation. **Claudio Porqueddu:** Writing – review & editing, Conceptualization. **Delia Cossu:** Data curation. **Alberto Stanislao Atzori:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Antonello Franca:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Pierpaolo Duce:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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