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Environmental performances of Sardinian dairy sheep production systems at different input levels

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HIGHLIGHTS

- Similar trends in the environmental performances of the sheep farming systems.
- No significant difference in 1 kg FPCM Carbon Footprint between farms.
- ReCiPe end-point score of the low-impact farm is significantly different.
- Little range of variation of the Carbon Footprint scores (from 2.0 to 2.3 kg CO_2-eq per kg FPCM).
- Relevant role of enteric methane emissions, field operations, electricity and machineries.

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ABSTRACT

Although sheep milk production is a significant sector for the European Mediterranean countries, it shows serious competitiveness gaps. Minimizing the ecological impacts of dairy sheep farming systems could represent a key factor for farmers to bridging the gaps in competitiveness of such systems and also obtaining public incentives. However, scarce is the knowledge about the environmental performance of Mediterranean dairy sheep farms. The main objectives of this paper were (i) to compare the environmental impacts of sheep milk production from three dairy farms in Sardinia (Italy), characterized by different input levels, and (ii) to identify the hotspots for improving the environmental performances of each farm, by using a Life Cycle Assessment (LCA) approach. The LCA was conducted using two different assessment methods: Carbon Footprint-IPCC and ReCiPe end-point. The analysis, conducted "from cradle to gate", was based on the functional unit 1 kg of Fat and Protein Corrected Milk (FPCM). The observed trends of the environmental performances of the studied farming systems were similar for both evaluation methods. The GHG emissions revealed a little range of variation (from 2.0 to 2.3 kg CO_2-eq per kg of FPCM) with differences between farming systems being not significant. The ReCiPe end-point analysis showed a larger range of values and environmental performances of the low-input farm were significantly different compared to the medium- and high-input farms. In general, enteric methane emissions, field operations, electricity and production of agricultural machineries were the most relevant processes in determining the overall environmental performances of farms.
Future research will be dedicated to (i) explore and better define the environmental implications of the land use impact category in the Mediterranean sheep farming systems, and (ii) contribute to revising and improving the existing LCA dataset for Mediterranean farming systems.

1. Introduction

The dairy sheep production is a significant sector for the European Mediterranean countries. It is the most important production coming from the extensive and semi-intensive livestock systems typical of the Mediterranean pastoralism (Abdelguerfi and Ameziane, 2011). These systems of livestock production often represent the only possible economic activities in inland areas and play a crucial role in maintaining both the vitality and the traditions of rural communities, as well as in preventing environmental issues (*i.e.*, soil erosion, desertification, wildfire, *etc.*).

Sardinia (Italy) is the most important EU region for sheep milk production, with more than 3.2 million ewes — about 3.5% of the EU total (EUROSTAT, 2012) — and a milk production of about 330.000 t year^{-1}

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(Osservatorio Regionale per l'Agricoltura, 2012), which represents more than 12% of the total European production (EUROSTAT, 2012). More than half of Sardinian sheep milk production is addressed to cheese industry for "Pecorino Romano PDO" (Protected Designation of Origin, European quality label) production (Furesi et al., 2013). "Pecorino Romano PDO" is one of the main Italian PDO products (ISMEA, 2012) and 95% of its production derives from Sardinian cheese factories (Idda et al., 2010).

The dairy sheep farming systems in Sardinia are considered to be pasture-based and quite extensive, but large differences in input utilization, land use and intensification level exist. This different degree of intensification basically depends on the geographical location of farms, which affects key traits such as arable land availability, soil fertility and possibility for irrigation (Caballero et al., 2009; Pirisi et al., 2001; Porqueddu et al., 1998; Porqueddu, 2008). In the last decades, Sardinian sheep production systems suffered a serious and continuous loss of competitiveness, due to several internal and external factors that caused a deep structural crisis in this traditional sector. As a consequence, Sardinian sheep farms have been realizing low profit margins with negative impacts on both farms' productivity and Sardinian economy (Furesi et al., 2013). As a matter of fact, the economic sustainability of Sardinian sheep farms is based on CAP (Common Agricultural Policy) payments, which account for more than 20% of their gross receipts (Idda et al., 2010).

As production systems' eco-sustainability and climate change mitigation are on top of the European agenda, minimizing the ecological impacts of farms represent a key factor for farmers to obtaining public incentives and for enhancing the multifunctionality of agricultural systems expressed as services to society (*e.g.* public goods such as biodiversity and landscape conservation). Therefore, the optimization of environmental performances could be a crucial factor to improve competitiveness of sheep farming, in particular when located in marginal lands. For this purpose it is essential to assess the environmental performances of these livestock systems and to identify the weak points of the production chain where to take actions for reducing the overall environmental impact of farms (FAO, 2010). The environmental impacts (including greenhouse gas emissions) of animal production systems can be evaluated by using the Life Cycle Assessment (LCA) approach (De Boer, 2003). LCA is a widely accepted, complete and standardized computational tool for providing a widespread knowledge on the environmental aspects associated with products or production processes (Hayashi et al., 2006). It represents also the first step towards sustainability of production systems, identifying where environmental impacts and damages take place (Chen et al., 2005). However, when applied to agriculture, the method presents some challenges due to the intensive nature of required data, their limited availability and the multiple-output nature of production (FAO, 2010).

The most relevant research studies carried out to evaluate the environmental implications of small ruminant livestock systems using an LCA approach have been conducted mainly in Australia, New Zealand and United Kingdom. It is clear that the majority of LCA studies focused on the main products of sheep livestock systems: wool and meat (Biswas et al., 2010; Brock et al., 2013; Browne et al., 2011; Ledgard et al., 2011; Peters et al., 2011; Williams et al., 2012). To our knowledge very little research has been conducted on the environmental implications of sheep milk production (Michael, 2011). Moreover, very few research studies on LCA of sheep farming systems have been carried out in the Mediterranean context focusing again on meat production (Ripoll-Bosch et al., 2013).

This study was conducted with the main aim of contributing to fill in these knowledge and data gaps and with the following specific objectives of: (i) comparing the environmental impacts of sheep milk production from three Sardinian dairy farms at different input levels; (ii) identifying the hotspots to improve the environmental performances of each farm, by using an LCA analysis.

2. Materials and methods

2.1. Case studies

During 2011, data were collected from three different dairy farms located in the Province of Sassari (40°43′36″N 8°33′33″E), Northwestern Sardinia, Italy. The three studied farms fall into a homogeneous agro-climatic area, with climate conditions typical of the central Mediterranean area, an average annual rainfall of approximately 550 mm, mean monthly temperatures varying from 10 to 26 °C, and elevation ranging from 60 to 350 m a.s.l. Rural landscape is characterized by dairy sheep farms with a mosaic of feed resources mainly represented by annual forage crops, cereal crops, improved and natural pastures.

The three farms differed mainly in stocking rate, size of grazing areas and concentrates consumption (Table 1), mostly covering the range of input levels for Sardinian sheep livestock (ARAS, 2013). We considered as low input farm (LI), the farm with the lowest stocking rate (1 ewe ha^{-1}), the largest grazing area (95 ha) and the lowest consumption of concentrates (1 t per year). On the opposite, the high input farm (HI) showed the highest stocking rate (5.5 ewes ha^{-1}), the smallest grazing area (12 ha) and an annual consumption of concentrates of about 200 t. Mid-input farm (MI) was characterized by intermediate levels of input. Farms had also different market strategy: LI and HI farms sold the milk to the cheese industry for "Pecorino Romano PDO" production, while MI uses its own milk for small-scale on farm cheese production, "Pecorino di Osilo", which is included in the Italian list of

Table 1
Main characteristics of production system in low- (LI), mid- (MI), and high-input (HI) dairy farms. Data refer to 2011.

	Low-input (LI)	Mid-input (MI)	High-input (HI)
Heads (number)	120	320	370
Stocking rate (ewes ha^{-1})	1.0	4.6	5.5
Milk production (kg $year^{-1}$)	25,000	79,655	110,000
Milk pro-capita annual production (kg ewe^{-1} $year^{-1}$)	208	249	297
Pastures — grazing area (ha)	95	52	12
Arable land — cereals and annual forage crops (ha)	30[a]	18	55
Total utilized agricultural area (ha)	125	70	67
Concentrate feed annual consumption (t) [b]	1	121	204
Mineral N-fertilizing (kg ha^{-1})	0	21	45
Mineral P_2O_5-fertilizing (kg ha^{-1})	0	72	32
Irrigation	No	Yes	No
Milking system	Manual	Mechanical	Mechanical
Manpower	2 part-time workers	3 full-time and 1 temporary workers	3 full-time and 1 temporary workers

[a] 10% of the arable land production is used for sheep feeding; the remaining part is sold as hay and grain.
[b] LI produces all concentrates on farm, MI imports all concentrate feed needed, and HI imports about 86% of total requirements.

typical agri-food products. Moreover, MI was the only farm that used the aseasonal lambing technique, which leads to an extension of the lactation ewe period, needing a specific feed strategy and farm management with relevant influences on the farm input level.

2.2. Life Cycle Assessment methodology

The methodology used to carry out the LCA study is consistent with the international standards ISO 14040–14044 (2006a,b). The analysis was conducted using 1 kg of Fat and Protein Corrected Milk (FPCM) as functional unit (FU), as suggested by the FAO (2010) and IDF (2010) for dairy sector Carbon Footprint assessment. FPCM amounts expressed in kg were calculated using the equation by Pulina and Nudda (2002):

$$\mathrm{FPCM} = \mathrm{RM}(0.25 + 0.085\,\mathrm{FC} + 0.035\mathrm{PC})$$

where RM, FC, and PC indicate raw milk amount (kg), fat content (%), and protein content (%) of the raw milk, respectively.

Since all three farms in addition to milk produced also meat and wool, all inputs and outputs were partitioned (impact allocation) between milk and the other co-products, on the basis of the economic value of products. The economic allocation procedure was preferred to other criteria indicated by ISO prescriptions (*e.g.* system expansion/substitution or physical allocation) considering the large economic value differences between the “main product” (milk) and the other co-products (wool and meat) (Table 2). When co-products were obtained from the same field (*e.g.*, triticale-barley grain and stubble), mass-based allocation was applied, since the amounts of the individual co-products are interdependent in a physical relationship and an increase in the output of each specific co-product causes an increase in production in direct proportion.

The life cycle was assessed “from cradle to gate”, including in the system boundaries all the input and output related to sheep milk production (Fig. 1). All modes of transportation and distances covered within the system were also taken into account. In addition, all the emissions into the soil, air and water from the use of fertilizers were included. The emissions from pesticides, which were used in very small quantities just in HI farm, were also included. The emissions from the livestock manure were excluded from the system's boundaries. The model system was divided into two subsystems: a) Flock, and b) Farm Impact.

a) Flock — Processes linked with the productive life of livestock.
They include all the processes related to i) the land use and all the other inputs and agricultural operations required for feed production (*e.g.* seeds, fertilizers, pesticides, fuel, *etc.*, and plowing, sowing, harrowing, irrigation, haymaking, threshing, *etc.*; ii) the whole consumption of feed from pastures and concentrates; iii) livestock operations such as shearing (once a year) and milking (performed twice a day if mechanical, once a day if manual). Each of these processes has been applied to the different categories of sheep, depending on the breeding techniques adopted by each farm, having as primary reference points the quantity and quality of sheep diet. Therefore, LCA model includes ewes and rams, each subdivided into lambs, replacement animals and adults. The ewes were grouped by physiological and productive phase (maintenance, dry and lactation).

Table 2
Economic allocation of co-products from dairy farm case studies, low- (LI), mid- (MI), and high-level input (HI) farms.

	LI	MI	HI
Milk	86.5%	91.0%	87.6%
Lamb meat	12.5%	6.7%	9.9%
Sheep meat	0.4%	1.7%	2.0%
Wool	0.6%	0.6%	0.5%

b) Farm Impact — Processes linked with the farm structure.
They include infrastructures (milking parlor, barns, *etc.*), agriculture machineries and devices (tractors, plows, milk cooler, pumps, *etc.*), water and energy consumption, and consumable materials like detergents, veterinary drugs, spare parts, *etc.*

All data were organized into a life cycle inventory, the process that quantifies energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product. Primary data collection was carried out through 12 visits *in situ*, interviews and a specific questionnaire, and included data on utilized agricultural area and forage crop yield, characteristics of farm infrastructures (milking parlor, barns, silos, *etc.*), processes directly related to flock (*e.g.* quality and quantity of production, number of heads, flock diet, *etc.*), characteristics and consumptions of fuel, power, *etc.* from equipment and machinery, and consumptions of raw materials and chemicals. The remaining data were collected from available literature (in particular enteric methane emissions and forages consumptions) and databases (mostly Ecoinvent v. 2.2 developed by Swiss Centre for Life Cycle Inventories). Ecoinvent database was mainly used for quantifying the environmental impacts involved in the following elements of the productive system: power production, equipment and agricultural machinery, field operations, crops, chemicals, raw materials and consumables, heat production from boiler and power generators, transportation. However, the sum of primary and representative secondary data was never below 98% of the overall data collected for each farm.

The LCA analysis was conducted using two evaluation methods: 1) IPCC, Intergovernmental Panel on Climate Change (2006), which provides estimates on greenhouse gases emitted in the life cycle of products (Carbon Footprint), expressed in kilograms of CO_2-equivalents, using a 100-year time horizon; and 2) ReCiPe end-point method (ReCiPe Endpoint (H) V1.06/Europe ReCiPe H/A), that provides a wider assessment of life cycle environmental performances compared to IPCC (2006), considering 18 different categories of environmental impact (Goedkoop et al., 2009). Over the past years, the Carbon Footprint has become one of the most important environmental protection indicators. It is widely used in agricultural LCA analysis and represents a reliable tool for comparing results from different research studies. We used also the ReCiPe end-point method for taking into account a larger range of impact categories and for assessing in a more comprehensive way the environmental performances of sheep farming systems. In addition, the choice of the end-point approach provides the most appropriate and understandable level of aggregation for comparing the environmental impacts of production systems, since our study does not need to deal separately with the environmental relevance of the category indicators.

The life-cycle analysis was performed under the following simplified assumptions: the analysis included only the amount of forage (fodder crops and pastures) consumed by flocks, after cross-checking estimated and/or measured forage production and estimated nutritional needs based on gender, age, weight, physiological stage and production level of animals. Enteric methane emissions were quantified using the national emission factor proposed by ISPRA (2011) and based on the simplified IPCC's Tier 1 approach (IPCC, 2006). N_2O enteric emission estimates were based on the methodology proposed by IPCC (2006).

LCA calculation was made using LCA software SimaPro 7.3.3 (PRé Consultants, 2011), which contains various LCA databases.

A Monte Carlo analysis was also performed using the SimaPro software to quantify the effects of the data uncertainties on the final results and to evaluate the significance of the difference between the environmental performances of the three farms based on both LCA methods (Carbon Footprint and ReCiPe). The analysis consisted in multiple comparisons involving each pair of farm environmental scores.

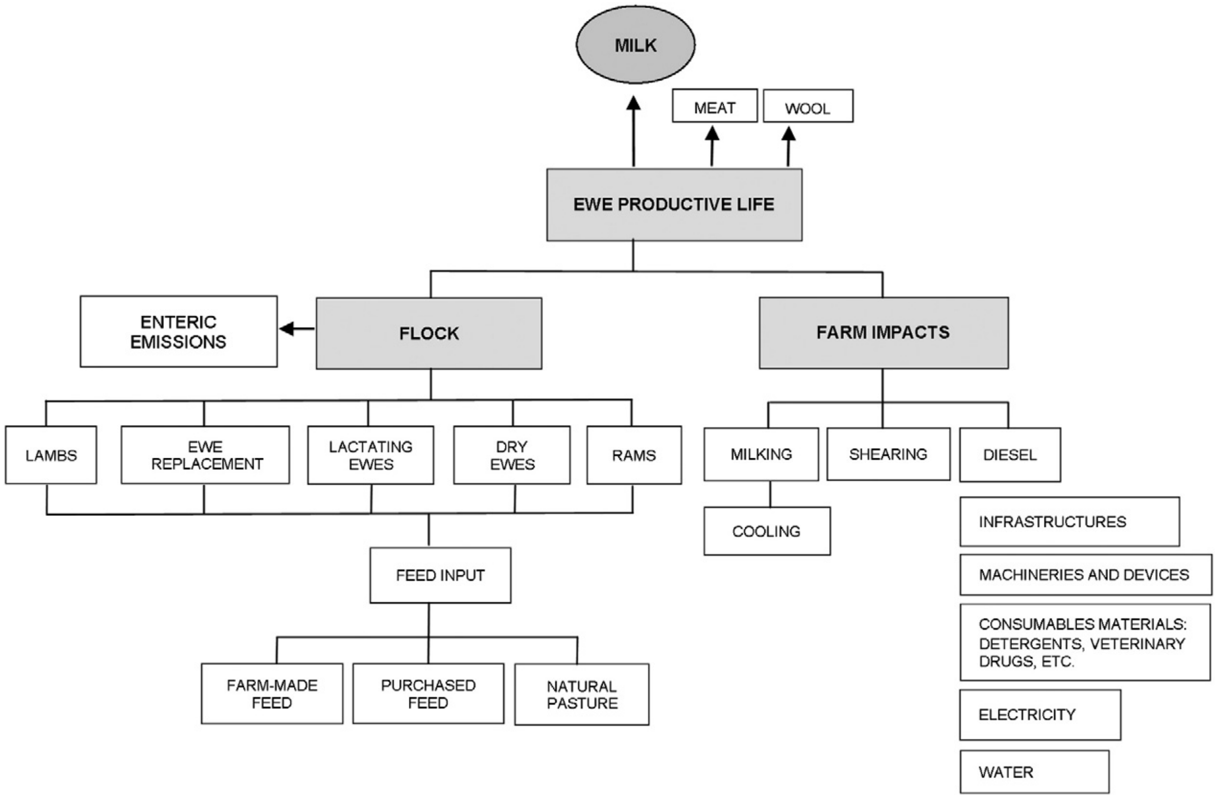

Fig. 1. Flow chart of sheep milk production.

3. Results and discussion

3.1. Inventory analysis

The life cycle inventory of the main impact categories for the total annual production of FPCM by farm is reported in Table 3. The variability of the input/output values reflects the differences between the three productive systems: LI farm showed the lowest values for all the impact categories while HI farm showed the highest, with the exception of water and cypermethrin (a synthetic pyrethroid used as an insecticide), which appeared to be the largest impact categories for MI farm compared to LI and HI.

Table 3
Inventory of the impact categories for the total annual production of FPCM of three farms at different level of input consumption (low — LI, mid — MI, and high — HI).

Category	Unit	LI	MI	HI
Water	m^3	188	4959	3652
CO_2	kg	25,372	54,346	93,651
CO_2 biogenic	kg	639	1496	2452
Methane	kg	42	90	153
Methane biogenic	kg	1043	3339	3679
Occupation, pasture and meadow	ha $year^{-1}$	12	47	53
Occupation, arable, non-irrigated	ha $year^{-1}$	0.1	8	10
Dinitrogen monoxide	kg	6	85	176
Transformation from forest	m^2	25	833	1125
Phosphorus, in water	kg	1.7	9.6	11.8
Nitrogen oxide	kg	158	337	673
Isoproturon	kg	0.1	1.4	3.0
Occupation industrial area	m^2	42	748	1024
Phosphate	kg	26	72	128
Sulphur dioxide	kg	56	149	240
Methane, tetrafluoride	g	7	12	22
Sulphur hexafluoride	g	1	2	3
Phosphorus, in ground	g	6	17	28
Ethan, hexafluoride	g	0.7	1.4	2.5
Cypermethrin	mg	31	673	624
Nitrogen oxides	kg	158	337	673
Particulates	kg	29	53	102
Oil crude in ground	kg	4707	10,746	18,979
Gas natural in ground	m^3	2266	4949	8282
Coal	kg	4388	7935	13,321

3.2. Evaluation of the environmental performances

The environmental impact assessment of each farm (LI, MI, and HI), conducted using the IPCC and ReCiPe methods is presented in the following paragraphs.

3.2.1. IPCC

The estimated life-cycle greenhouse gas (GHG) emissions of 1 kg of FPCM were slightly higher in MI (Fig. 2). The GHG emissions per kg of FPCM from the observed production systems showed a little range of

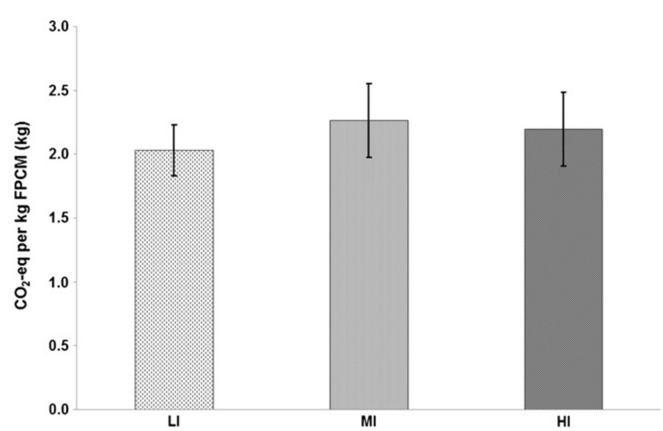

Fig. 2. Mean values and standard errors of the Carbon Footprint (IPCC, 2006) of low- (LI), mid- (MI), and high-input level (HI) farms. The functional unit (FU) is 1 kg of FPCM (Fat and Protein Corrected Milk).

variation with values approximately equal to 2.0 (LI), 2.2 (HI) and 2.3 (MI) kg of CO_2-eq, and standard errors ranging from 0.20 (LI) to 0.29 (MI and HI) kg of CO_2-eq. Differences between farming systems in GHG emissions were not significant, as illustrated in Section 3.4 dedicated to the Monte Carlo analysis results. The lowest Carbon Footprint of LI compared to the more intensified farming systems of MI and HI can be explained by different factors which are crucial in determining the relation between inputs and outputs. The most critical advantages of LI compared to MI and HI were (i) its lower use of agricultural machinery for field operations, and (ii) its lower power consumptions. In addition, LI milk production showed larger values of fat and protein contents compared to both MI and HI, which implied a relevant improvement of the productive performance when the raw milk production was expressed in FPCM.

The comparison of the Carbon Footprint of MI and HI, which adopted more homogeneous farm management models, indicated similar performance results with a light advantage for the more intensified farming system HI. This result is in line with the findings reported in previous research studies (FAO, 2010; Hayashi et al., 2006; Michael, 2011), where it was shown that more intensive systems have a lower environmental impact per kg product than extensive one.

When we compared our study with the little research studies conducted on sheep milk, our LCA results showed that the average Carbon Footprint of our three farm systems (2.17 kg CO_2-eq/kg FPCM) was about 39% lower than that estimated by Michael (2011) on a typical Australian dairy farm, where the Carbon Footprint was equal to 3.57 kg CO_2-eq/kg FPCM.

The study of Michael (2011) was conducted on an intensive dairy sheep farming system characterized by East Friesian sheep bred with very high productivity (421 kg ewe^{-1} $year^{-1}$ of milk) and feed requirements, a stocking rate equal to 8 ewes ha^{-1}, a phosphate fertilizer use of 200 kg ha^{-1} $year^{-1}$, a potash fertilizer use of 100 kg ha^{-1} $year^{-1}$ and a concentrate feed annual consumption of about 190 kg ewe^{-1} t. The enteric emission factor for methane emission estimate (16.9 kg CH_4 ewe^{-1} $year^{-1}$) was based on the methodology proposed by the Department of Climate Change (2006), which adopted a more detailed approach than the IPCC's Tier 2 (IPCC, 2006). This source of GHG emissions represented the largest contributor (82%) to the total global warming potential, followed by fertilizer (9%).

Beyond the structural differences between Australian and Sardinian case studies, a relevant element that can likely explain what we obtained comparing our Carbon Footprint results with Michael (2011) findings is the enteric methane emission factor we used. We adopted the methodology proposed by ISPRA (2011), which is based on the more simplified IPCC's Tier 1 approach (IPCC, 2006), and has fixed methane emission rates for sheep livestock in Italy (8.0 kg CH_4 ewe^{-1} $year^{-1}$). In other terms, the value of the methane emission factor used in our study is more than 50% lower than the emission factor used by Michael (2011). However, also in our case studies the largest contributor to the total global warming potential was the methane enteric emission, which contributed to a lesser extent (42% on average) than in the case study illustrated by Michael (2011).

3.2.2. ReCiPe

The results from the ReCiPe end-point method assessment followed a trend similar to IPCC method (Fig. 3). To facilitate the interpretation of results, only impact categories with scores higher than 10 milli-ecopoint (mPt) per 1 kg of FPCM are shown. The ReCiPe end-point results indicate scores for each farm equal to 309 (LI), 480 (MI), and 426 (HI) mPt, with standard errors approximately equal to 40, 77, and 64 mPt, respectively. The overall environmental performances of LI showed to be significantly different compared to the other farms (see also Section 3.4). The comparison between MI and HI scores confirms the results obtained using the IPCC method: performances are similar, not significantly different, with a light advantage for the more intensified farming system HI.

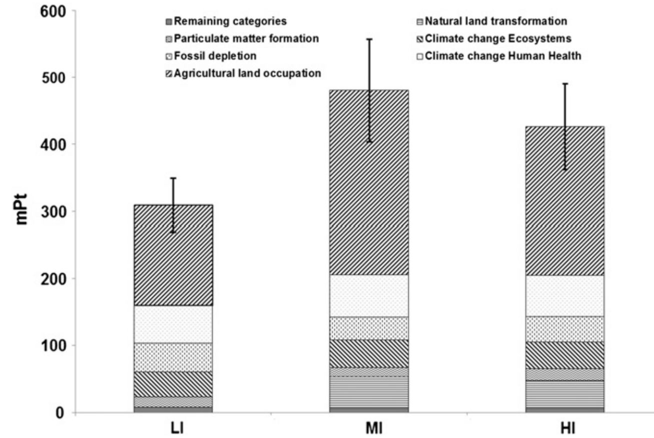

Fig. 3. Mean values and standard errors obtained using the ReCiPe end-point impact assessment method for the functional unit 1 kg of FPCM for low- (LI), mid- (MI), and high-input level (HI) farms. Impact effects are expressed in milli-ecopoints (mPt). Impact categories with scores lower than 10 mPt are included in the group 'Remaining categories'.

For all farms, the most relevant impact category is represented by 'Agricultural land occupation', which resulted responsible of about 50% of the total estimated impact (from 48% for LI to 57% for MI). The impact category 'Climate change — Human Health' contributed to the overall scores with values ranging from 13% to 18%, representing the second impact category for all farms. Other relevant impact categories for all farms were 'Fossil depletion', and 'Climate change — Ecosystems', with an average value equal to about 10%, and 'Particulate matter formation', which was responsible in average for about 4% of the overall impact. In the case of MI and HI, a further impact category significantly responsible for their overall scores was 'Natural land transformation', with values around 10% of the total score.

The impact categories with scores less than 10 mPt (Remaining categories) represented less than 2.5% of the overall scores. For MI and HI farms, 94% of the impact determined by the 'Remaining categories' was due to the categories 'Human toxicity' (more than 60%), 'Urban land occupation', and 'Terrestrial ecotoxicity'. For LI, the majority (94%) of the impacts determined by the 'Remaining categories' was due to 'Human toxicity' (more than 55%), 'Urban land occupation', and 'Natural land transformation'.

The possible explanations of the results obtained using the ReCiPe method are similar to the reasons that explained the IPCC method findings. However, the ReCiPe method analysis revealed considerable differences between the farm with the lowest input level and the other farms, and indicated that a large part of this differences can be attributed to the impact category 'Agricultural land occupation', which showed absolute scores approximately equal to 149, 278, and 222 for LI, MI, and HI, respectively, contributing to the 50% of the overall impact of each farm.

These results confirm that agricultural land occupation and, more generally, land use impact category are critical aspects of LCA analysis, in particular when the agricultural sector is investigated (Schmidinger and Stehfest, 2012).

3.3. Contribution analysis

A detailed contribution analysis is reported in Table 4, which illustrates all processes that contributed with more than 1% to the total environmental impact of all farms for the two different evaluation methods adopted. In general, the analysis of the contributions of individual processes for the three farming systems and both evaluation methods showed a relevant role of enteric methane emissions, field operations (mainly tillage), electricity and production of agricultural machineries. In MI and HI, feed concentrates in the diet (in particular soy production) showed a relevant contribution, with percentages

Table 4
Percentage contribution of processes to the total environmental impact of low- (LI), mid- (MI) and high-input level (HI) farms, using two evaluation methods (IPCC and ReCiPe endpoint) and 1 kg of FPCM as functional unit. The process category "Remaining processes" includes all the processes with a percentage contribution lower than 1% for all methods and farms.

Method	IPCC			ReCiPe endpoint		
Process/farm	LI	MI	HI	LI	MI	HI
Enteric methane emissions	45	46	34	14	10	8
Field operations (tillage and sowing)	27	8	16	21	4	8
Electricity, medium voltage	13	5	3	8	2	1
Natural pastures	1	2	0	31	24	9
Improved pastures	0	2	16	17	21	36
Concentrate feed	1	21	16	1	30	26
Lactating ewes (feed consumption and animal excretion)	1	1	1	0	0	0
Infrastructures (milking parlor, barn, *etc.*)	0	2	1	0	0	0
Irrigating (infrastructure and water consumption)	–	0	0	–	0	0
Tractor, production	4	2	2	3	1	1
Pick-up vehicle, production	1	0	0	1	0	0
Agricultural machinery, production	5	3	2	4	1	2
Transport (lorry and/or transoceanic freight ship)	0	5	4	0	1	1
Water consumption (milking and irrigating excluded)	0	0	0	0	0	0
Agrochemicals (urea, glyphosate, *etc.*)	–	0	3	–	0	2
Consumable materials (detergent, veterinary drugs, *etc.*)	0	0	0	0	0	0
Remaining processes	2	3	2	0	6	6

ranging from 16% for HI (IPCC method) to 30% for MI (ReCiPe method). The natural and improved pastures utilization resulted in relevant contribution only for the ReCiPe assessment method (48% in LI, 45% in MI and 45% in HI), essentially for the effect of the Agricultural Land Occupation impact category. The contribution of agrochemicals was generally low (always less than 3%), due to their very limited use in all the three farms. However, the incidence of contribution of each process varied with the evaluation method utilized. For example, the enteric methane emission is the most important impact (an overall average of 42% of total impacts) for the IPCC method, which estimates the amount of GHG produced by each process and the relative contribution to global warming, but when the estimate is performed using the ReCiPe method, which takes into account 16 additional impact categories, the impact of the enteric methane emissions amounted on average to 11%, representing only the fifth highest-ranked impact. The combined use of the two methods provided a balanced picture that resulted in a more comprehensive assessment of impacts.

The analysis of contributions has been also useful for identifying more specific strengths and weaknesses of each dairy sheep farming system, in order to improve their environmental performances.

Enteric methane emissions represented the most important environmental impact factor for all the farms when the IPCC method was used. This result is consistent with the actual knowledge about the role played by the enteric methane fermentation in ruminant livestock emissions, which are estimated to represent approximately 18% of the global anthropogenic GHG emissions (FAO, 2006). Few practical strategies can be followed for reducing enteric methane emissions of grazing animals (Hegarty et al., 2007), mainly by regulating the quantity and quality of feed consumed (Pelchen and Peters, 1998) or utilizing inhibitors of enteric fermentation (Martin et al., 2010; Nolan et al., 2010; Puchala et al., 2005; Tiemann et al., 2008; Wallace et al., 2006). However, further research studies are needed to carefully analyze the complexity of relations among breeding techniques and enteric gas emissions (*e.g.*, methane and nitrous oxide).

For ReCiPe method, the major contributions to the environmental impact of LI are due to land use on natural and improved pastures (48%), field operations (21%), enteric methane emissions (14%), and electricity (8%). The power consumption of LI depended mainly on milk cooling and therefore an improvement of the environmental performance of this farm could be achieved choosing the proper size of the cooling tank and/or adopting a more efficient cooling system, possibly powered by renewable sources. In addition, LI showed a relevant contribution to the overall impact determined by tractor and other devices, such as pick-up and generator diesel (10% and 8% for IPCC and ReCiPe methods, respectively). This contribution is at least double compared to the contribution observed in the other farms and it can be likely due to the use of over-dimensional and power-consuming equipment compared to the farm needs.

The contribution of field operations (tillage and sowing) to the total environmental impact of the productive cycle of 1 kg of FPCM was largely lower in MI (with values never exceeding 8%) than in the other farms, for both methods. This result could be probably due to the minimum tillage practice used by MI for sowing of pasture mixtures. However, the environmental performances of MI could be improved by reducing the purchase of feed concentrates and consequently increasing the

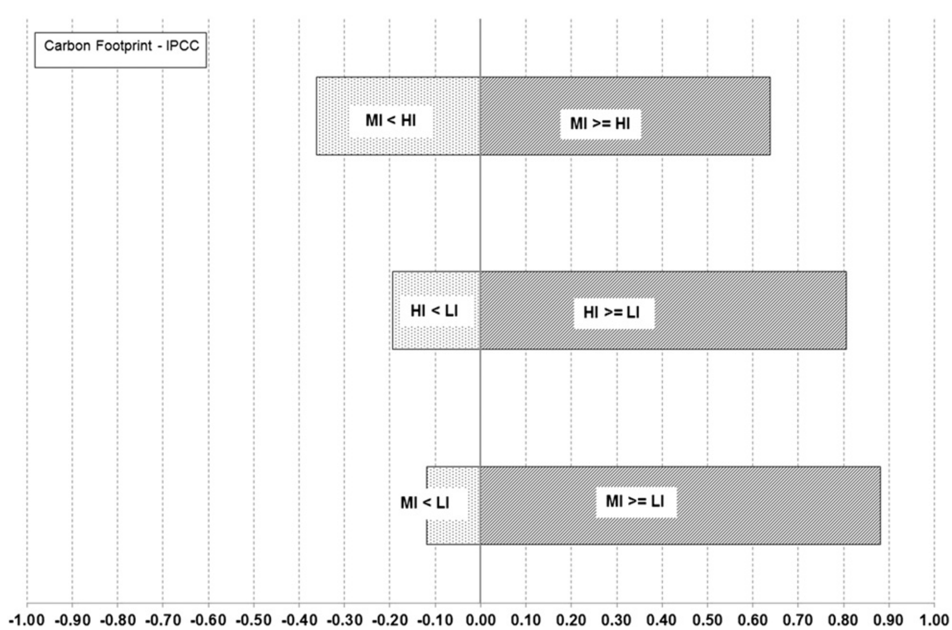

Fig. 4. Monte Carlo results of the comparisons between Carbon Footprints from low- (LI), mid- (MI), and high-input level (HI) farms. The analysis consisted in multiple comparisons involving each pair of mean values.

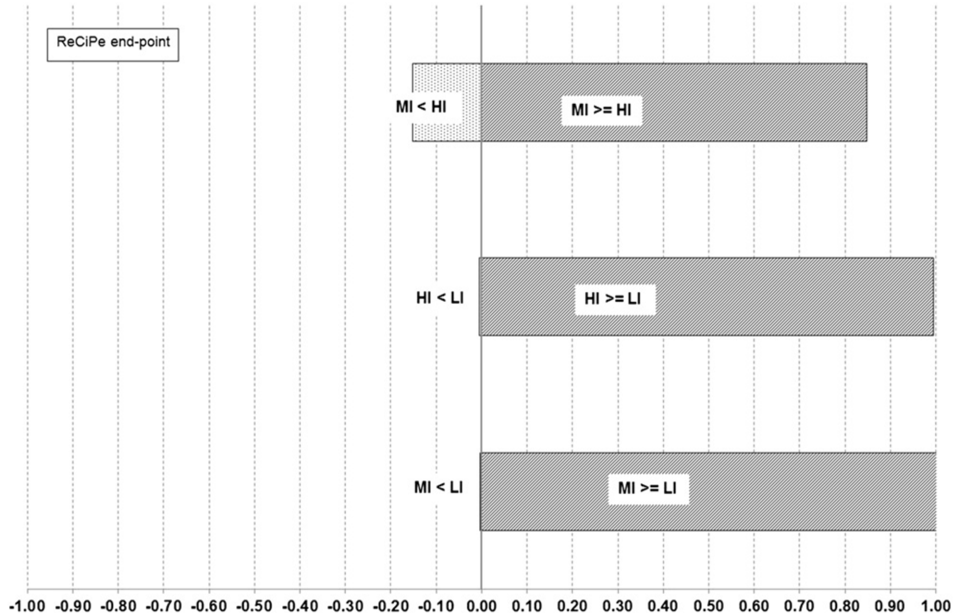

Fig. 5. Monte Carlo results of the comparisons between ReCiPe endpoint results from low- (LI), mid- (MI), and high-input level (HI) farms. The analysis consisted in multiple comparisons involving each pair of mean values.

amount of pasture and self-produced hay in the diet of flock. To achieve this result, an increase of the total surface sown with well adapted and high quality pasture mixtures may be suggested (Franca et al., 2008; Porqueddu and Maltoni, 2005). The overall high consumption of electricity suggests to introduce a farm strategy based on renewable source power supply. Finally, it may be appropriate to assess a proper sizing of the machinery stock, in relation to the needs of MI.

The contribution of concentrate feed was particularly large in MI, despite lower annual consumption per capita compared to HI (0.38 t ewe^{-1} *versus* 0.55 t ewe^{-1}). It is important to note that HI produced about 24% of its concentrate needs on-farm and had a larger annual milk yield per ewe compared to MI, which imported all concentrate. In HI, improved pastures and concentrate feed contributed largely to its overall environmental impact. Taking this result into account, a possible strategy to reduce the environmental performances of HI could consist in increasing the agricultural surface area utilized for permanent semi-natural pastures and finding proper pasture management strategies (*i.e.*, deferred grazing during spring to allow self-reseeding). Moreover, improving power supply strategy could represent an effective way to enhance the HI environmental performance, as well as for the other farms.

3.4. Monte Carlo analysis

Figs. 4 and 5 show the graphical results of the uncertainty analysis for the multiple comparisons between the farm environmental performances estimated using both the IPCC (2006) and the ReCiPe end-point methods.

Differences between the Carbon Footprint of farms (Fig. 4) were in general not significant with the higher level of statistical significance obtained for the comparison MI ≥ LI ($p > 85\%$). When the uncertainty analysis was performed using the ReCiPe end-point single scores (Fig. 5), the low-input farming system resulted significantly lower than the medium- and high-input systems with a level of statistical significance always higher than 99%. As discussed above, the relevant differences between the LI farm and the other farms when using the ReCiPe end-point single score can be largely attributed to the impact category 'Agricultural land occupation'.

4. Conclusions

In this work, LCA approach was used for comparing dairy sheep production systems at different input levels and for identifying the hotspots to improve their environmental performances. The LCA analysis, conducted using 1 kg of Fat Protein Corrected Milk as functional unit and two different assessment methods (IPCC and ReCiPe), provided a balanced picture of the environmental performances of the sheep farming systems, resulting in a more comprehensive assessment of impacts.

The trends of the environmental performances of the studied farming systems were similar for both evaluation methods. The low-input and medium-input farms showed the lowest and highest scores, respectively. Further, the GHG emissions revealed a little range of variation (from 2.0 to 2.3 kg CO_2-eq per kg of FPCM) with differences between farming systems being not significant. The ReCiPe end-point results showed scores ranging from 309 (LI) to 480 mPt (MI) and environmental performances of LI significantly different compared to MI and HI farms.

In general, this study shows the relevant role played by enteric methane emissions, field operations, electricity and production of agricultural machineries in the overall environmental performances estimated by both evaluation methods. However, for ReCiPe end-point method the major contributions to the environmental impact are due to land use on natural and improved pastures.

In conclusion, future research will be devoted to (i) explore and better define the environmental implications of the land use impact category in the Mediterranean sheep farming systems, and (ii) contribute to revise and improve existing LCA dataset for Mediterranean farming systems.

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References

Abdelguerfi A, Ameziane TE. Interactions between cereal cropping systems and pastoral areas as the basis for sustainable agricultural development in Mediterranean countries. In: Lemaire G, Hodgson J, Chabbi A, editors. Grassland productivity and ecosystem services. UK: CAB International Oxfordshire; 2011. p. 261–70.

ARAS. Data Warehouse of the Regional Association of Sardinian Farmers. Available on internet at www.ara.sardegna.it, 2013. [last access: Jan 15, 2014].

Biswas WK, Graham J, Kelly K, John MB. Global warming contributions from wheat, sheep meat and wool production in Victoria, Australia, a life cycle assessment. J Clean Prod 2010;18(14):1386–92.

Brock P, Graham P, Madden P, Douglas JA. Greenhouse gas emissions profile for 1 kg of wool produced in the Yass Region, New South Wales: A Life Cycle Assessment approach. Anim Prod Sci 2013;53:445–508.

Browne NA, Eckard RJ, Behrendt R, Kingwell RS. A comparative analysis of on-farm greenhouse gas emissions from agricultural enterprises in south eastern Australia. Anim Feed Sci Technol 2011;166–167:641–52.

Caballero R, Fernández-Gonzáles F, Pérez Badia R, Molle G, Roggero PP, Bagella S, et al. Grazing systems and biodiversity in Mediterranean areas: Spain, Italy and Greece. Pastos 2009;39:3–154.

Chen G, Orphant S, Kenman SJ, Chataway RG. Life cycle assessment of a representative dairy farm with limited irrigation pastures. Proceedings of the 4th Australian Conference on Life Cycle Assessment — Sustainability Measures for Decision Support; 2005. p. 1–11. [23–25 February 2005, Sydney, Australia].

Consultants PRé. Software LCA SimaPro 7.3; 2011 [Netherlands (www.pre.nl)].

De Boer IJM. Environmental impact assessment of conventional and organic milk production. Livest Prod Sci 2003;80:69–77.

Department of Climate Change. Methodology for the estimation of greenhouse as emissions and sinks: agriculture. Department of Climate Change. Canberra, Australia: National Circuit; 2006.

Database available at EUROSTAThttp://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tag00017, 2012. [last access: 10 Sep 2013].

FAO. Livestock's long shadow: environmental issues and options. Rome, Italy: Food and Agriculture Organization of the United Nations; 2006.

FAO. Greenhouse gas emissions from the dairy sector. A Life Cycle Assessment. Rome, Italy: Food and Agriculture Organization of the United Nations; 2010.

Franca A, Caredda S, Dettori D, Sanna F. Introducing new grass–legume mixtures for pasture improvement in agro-pastoral farming systems. Options Méditerr, Ser A 2008;79:203–6.

Furesi R, Madau FA, Pulina P. Technical efficiency in the sheep dairy industry: an application on the Sardinian (Italy) sector. Agric Food Econ 2013;1(4):1–11.

Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, van Zelm R. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint levelFirst ed. ; 2009 [Report I: Characterisation, NL. www.lcia-recipe.net/last access: Jan 20, 2013].

Hayashi K, Gaillard G, Nemecek T. Life cycle assessment of agricultural production systems: current issues and future perspectives. Proceedings of the International Seminar on Technology Development for Good Agriculture Practice in Asia and Oceania; 2006. p. 98–109. [Taipei, Taiwan].

Hegarty RS, Goopy JP, Herd RM, McCorkell B. Cattle selected for lower residual feed intake have reduced daily methane production. J Anim Sci 2007;85:1479–86.

Idda L, Furesi R, Pulina P. Economia dell'allevamento ovino da latte. Franco Angeli Milano; 2010.

IDF. A common carbon footprint approach for dairy: the IDF guide to standard lifecycle assessment methodology for the dairy sector. Bull Int Dairy Fed 2010:445.

IPCC. 2006 IPCC guidelines for national greenhouse gas inventories: volume 4: agriculture, forestry and other land use. Paris, France: Intergovernmental Panel on Climate Change; 2006 [http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.htm].

ISMEA. Italian institute for food and agricultural products. Database available at http://www.ismea.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/4173, 2012. [last access: Dec 8, 2013].

ISO. ISO 14040 international standard. Environmental management — life cycle assessment — principles and framework. Geneva, Switzerland: International Organisation for Standardization; 2006a.

ISO. ISO 14044 international standard. Environmental management — life cycle assessment — requirements and guidelines. Geneva, Switzerland: International Organisation for Standardisation; 2006b.

ISPRA. National greenhouse gas inventory system in Italy. Year 2011. Rome: Istituto Superiore per la Protezione e la Ricerca Ambientale; 2011.

Ledgard SF, Lieffering M, Coup D, O'Brien B. Carbon footprinting of New Zealand lamb from the perspective of an exporting nation. Anim Front 2011;1(1):40–5.

Martin C, Morgavi DP, Doreau M. Methane mitigation in ruminants: from microbe to the farm scale. Anim 2010;4:351–65.

Michael D. Carbon reduction benchmarks and strategies: new animal products. Australian Government, rural industries research and development corporation. RIRDC Publication No. 11/063, RIRDC Project No. PRJ-003369; 2011. p. 115.

Nolan JV, Hegarty RS, Hegarty J, Godwin IR, Woodgate R. Effects of dietary nitrate on fermentation, methane production and digesta kinetics in sheep. Anim Prod Sci 2010;50:801–6.

Osservatorio Regionale per l'Agricoltura. La filiera ovicaprina in Sardegna. Report available at http://www.sardegnaagricoltura.it/documenti/14_43_20131220133546.pdf, 2012.

Pelchen A, Peters KJ. Methane emissions from sheep. Small Rumin Res 1998;27:37–150.

Peters GM, Wiedemann S, Rowley HV, Tucker R, Feitz AJ, Schulz M. Assessing agricultural soil acidification and nutrient management in life cycle assessment. Int. J. Life Cycle Assess. 2011;16:431–41.

Pirisi A, Piredda G, Scintu MF, Fois N. Effect of feeding diets on quality characteristics of milk and cheese produced from Sarda dairy ewes. Options Méditerr, Sér A 2001;46:115–9.

Porqueddu C. Low-input farming systems in Southern Europe: the role of grasslands for sustainable livestock production. Proc. of the JRC Summer University: low input farming systems: an opportunity to develop sustainable agriculture; 2008. p. 52–8. [Ranco, 2–5 July 2007].

Porqueddu C, Maltoni S. Evaluation of a range of rainfed grass–legume mixtures in a Mediterranean environment. Proceedings of COST 852 WG1 and WG2 meeting; 2005. p. 113. [Ystad, Sweden].

Porqueddu C, Fara G, Caredda S, Busu F, Sechi R, Pintus G. Sardinian cereal–dairy sheep farming systems: evaluation of the potential environmental impact using nutrients surplus estimation. Proceedings of the 17th General Meeting of the European Grassland Federation; 1998. p. 369–72. [Debrecen, Hungary, 18–21 May 1998].

Puchala R, Min BR, Goetsch AL, Sahlu T. The effect of a condensed tannin-containing forage on methane emission by goats. J Anim Sci 2005;83:182–6.

Pulina G, Nudda A. Milk production. In: Pulina G, editor. Dairy sheep feeding and nutrition; 2002. p. 11–3. [Edizioni Avenue media (Bologna)].

Ripoll-Bosch R, de Boer IJM, Bernués A, Vellinga TV. Accounting for multi-functionality of sheep farming in the carbon footprint of lamb: a comparison of three contrasting Mediterranean systems. Agr Syst 2013;116:60–8.

Schmidinger K, Stehfest E. Including CO_2 implications of land occupation in LCAs-method and example for livestock products. Int J Life Cycle Ass 2012;17(8):962–72.

Tiemann TT, Lascano CE, Wettstein HR, Mayer AC, Kreuzer M, Hess HD. Effect of the tropical tannin-rich shrub legumes *Calliandra calothyrsus* and *Flemingia macrophylla* on methane emission and nitrogen and energy balance in growing lambs. Anim 2008;2:790–9.

Wallace RJ, Wood TA, Rowe A, Price J, Yanez DR, Williams SP, et al. Encapsulated fumaric acid as a means of decreasing ruminal methane emissions. In: Soliva CR, Takahashi J, Kreuzer M, editors. Greenhouse gases and animal agriculture: an update, International Congress Series No. 1293. The Netherlands: Elsevier; 2006. p. 148–51.

Williams A, Audsley E, Sandars D. A systems-LCA model of the stratified UK sheep industry. Proc. 8th Intl. Conference on LCA in the Agri-Food Sector; 2012. [October 1–4, 2012, Saint Malo. France].