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Environmental profile of Sardinian sheep milk cheese supply chain: A comparison between two contrasting dairy systems

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ABSTRACT

Despite the significant role of small ruminant sector in the global trends of livestock productions, little research has been conducted on the environmental implications of dairy sheep production systems. Dairy sheep systems are relevant for the economy of many areas of the Mediterranean Basin and the environmental and economic optimization of their productive factors is considered an effective strategy for promoting the innovation and increasing the competitiveness of Mediterranean dairy sheep systems. Therefore, scientific studies are needed in order to propose specific greening strategies and to improve the environmental performances of dairy sheep systems. The main objective of this study was to define a preliminary characterization of the environmental profile of sheep milk ("Pecorino") cheese chain in Sardinia (Italy), using a Life Cycle Assessment (LCA) approach, with the following specific goals: i) comparing the environmental impacts caused by both the artisanal and the industrial manufacturing processes of "Pecorino" cheese and ii) identifying the hotspots to reduce the environmental impacts of the Sardinian dairy sheep sector. The analysis was based on the functional unit of 1 kg of artisanal "Pecorino di Osilo" cheese, and 1 kg of the industrial manufacturing cheese "Pecorino Romano PDO" cheese. The LCA highlighted that the GHG emissions of the two cheeses were similar, with an average value equal to 17 kg CO_2-eq, largely due to enteric fermentation. The main differences between the two environmental profiles were found for human toxicity, ecotoxicity and eutrophication potential impact categories. Enteric methane emissions, feed supply chain, electricity, equipment and wastewater management seemed to be the hotspots where the environmental performances can be improved.

1. Introduction

The significant role of the animal production in the global climate change scenario has been clearly assessed by international organizations and environmental advocacy groups oriented by several scientific research on greenhouse gas (GHG) emissions of livestock sector (FAO, 2006; Galloway et al., 2010; Garnett, 2009; Gerber et al., 2013; O'Mara, 2011). In particular, the main studies have been concentrated in beef and dairy cattle systems (de Boer, 2003; de Vries et al., 2015; Soteriades et al., 2016) because of their essential function as protein food source and for their relevant contribution in global methane and nitrogen dioxide emissions. Less attention has been dedicated to the analysis of the environmental implications of sheep and goat systems despite their increasingly significance in the current and near future environmental and socio-economic dynamics. At global level, the GHG emissions of small ruminant sector account around 0.5 Gt CO_2-eq, representing 6.5% of overall livestock emissions. In particular, the enteric methane emissions from the entire world sheep population represent over 6.5% of the whole livestock sector. Moreover, correlating the total emission of CO_2-eq to the unit of protein produced, the milk and the meat produced by small ruminants (with 165 and 112 kg CO_2-eq kg^{-1} protein, respectively) represent the second and third animal products, respectively, for emission intensity (amount of GHG emitted per unit of product) (Gerber et al., 2013; Opio et al., 2013). On the other hand, the world goats and sheep population is increasing since 2001 and exceeded 2200 million heads in 2014 (+22% compared to 2000) (FAOSTAT, 2017). In addition, within the positive trend of livestock productions estimated by OECD-FAO in the Agricultural Outlook 2015-2024 (OECD-FAO, 2015), the sheep sector occupies a key position with an increase in production larger than 20% compared to the previous

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decade. Europe, with about 147 million heads, is the third continent for sheep and goat number (FAOSTAT, 2017). However, the sheep and goat farming represents a minor agricultural activity, accounting less than 4% of the total value of animal production in EU-27. In particular, the sheep sector, which represents close to 89% of total European sheep and goat population, is characterized by a decreasing in ewe number (−1% per year in the 1990s and −3% per year in 2005) but with contrasting trends for meat and milk supply chains: negative for the meat sector (−33% of meat ewes number from 2000 to 2009; −47% of meat consumption between 2001 and 2010), and positive for the milk one (+43% of the milking ewes number and a steadily increasing of milk production) (AND International, 2011). Moreover, the sheep farming covers an important portion of the agricultural land in some European countries (31% in the UK, about 20% in Ireland, Spain, Romania and Italy) and plays a crucial role, both in economic and environmental terms, in many less favoured zones of the Mediterranean region (Zygoyiannis, 2006). Italy is the third countries in EU-28 for sheep population, with more than 7 million sheep heads in about 68 thousand farms (IZS, 2016). More than 45% of Italian sheep population is found in Sardinia where about 13 thousand farms (ISTAT, 2016), spread all over the island, shares 25% of total EU-27 sheep milk production (Rural Development Programme of Sardinia - RDP, 2014-2020). Basically, the whole Sardinian sheep milk production (more than 300,000 t year^{-1}) is destined for cheese production, manufactured both in semi-artisanal and industrial manner. The Sardinian sheep milk cheese production is composed by three Protected Designation of Origin (PDO) cheeses (“Pecorino Romano”, “Fiore Sardo”, “Pecorino Sardo”) and several minor productions, all strong linked with the local traditions and natural resources (Piredda et al., 2006). Among them, the most important is by far the Pecorino Romano PDO, which represents more than 90% of the total Sardinian PDO cheese production (Osservatorio Regionale della filiera ovicaprina, 2012). Pecorino Romano PDO is one of the most exported Italian cheeses in the world (Pirisi and Pes, 2011), more than 97% is made in Sardinia and in large part sold in US as grating cheese type (Consorzio per la tutela del formaggio Pecorino Romano DOP, 2017). However, the fluctuating dynamics of the Pecorino Romano PDO international price and the dominant role played by few industries (the first five cheese-makers transform 45% of total production) represent structural limitations and serious threats for the whole Sardinian agri-food system (RPD, 2014-2020). It is an established opinion that the Sardinian sheep milk sector needs a robust innovation process where the integration and optimization of economic and environmental perspectives are key factors in order to maximize efficiency and to minimize risk of jeopardizing sustainability (Atzori et al., 2015). Therefore, it is essential to valorise the environmental quality of sheep milk productions with the purpose of improving the Sardinian dairy sector competitiveness and keeping the opportunity represented by i) the continuous expansion of green international markets, and ii) the increasing effort of EC on support greening Europe's agriculture. As mentioned above, little research has been conducted on environmental implications of small ruminant systems with a life cycle perspective, and even less focused on sheep milk cheese (Roma et al., 2015). Therefore, more specific data are needed in order to promote effective greening strategies at both territorial and dairy farm/plant level. The main international scientific literature concerns the identification and quantification of the environmental effects of sheep milk production in the Mediterranean context (Atzori et al., 2015; Batalla et al., 2015; Marino et al., 2016; Vagnoni et al., 2015), assessed with the Life Cycle Assessment (LCA) method (ISO, 2006a). Only two studies investigated both the production phases (agriculture and industry): i) Favilli et al. (2008) carried out a “from cradle to gate” LCA study of Pecorino Toscano PDO cheese. In this study 7 impact categories (among them Global Warming Potential, Acidification, Eutrophication and Photochemical ozone creation potentials) were considered in order to define the eco-profile of a Pecorino Toscano PDO produced in a family-run farm located in Larderello (Italy). Pecorino Toscano PDO is a soft or semi-hard sheep milk cheese typical of Tuscany region; ii) Conte et al., 2015 used an eco-indicator to analyze the environmental impacts of 24 packaging systems, in terms of potential food loss of Canestrato di Moliterno PDO (an Italian ripened cheese obtained from sheep milk). In particular, this paper compared different cheese packaging scenarios, using an LCA approach where shelf life and food loss probability were included.

The main scope of this study was to improve our knowledge and understanding on the environmental implications of small ruminant systems under a life cycle perspective, with a specific focus on the Sardinian sheep milk cheese supply chain. Specific goals were: i) comparing the environmental implications of two contrasting dairy sheep systems and ii) identifying the hotspots to improve the environmental performances of the Sardinian dairy sheep sector.

2. Materials and methods

2.1. Sheep milk cheeses under study

Two different types of sheep milk cheese were considered: 1) a “Pecorino Romano” PDO produced at industrial scale and destined for the international market (mainly grating use); 2) a “Pecorino di Osilo” manufactured on-farm with a semi-artisanal system and sold in the local market.

Pecorino Romano PDO is the best known Italian dairy product obtained from sheep milk. According to the PDO protocol (Commission Regulation (EC) N. 1030/2009, 2009), Pecorino Romano is a hard cheese, cooked, made with fresh whole sheep's milk, derived exclusively from farms located in Sardinia and Lazio region and in province of Grosseto (Tuscany). It may be inoculated with indigenous natural cultures of lactic ferments, then coagulated with lamb's rennet in a paste derived exclusively from animals raised in the same production area. The rounds are cylindrical with flat top and bottom, the height of the side is between 25 and 40 cm and the diameter of top and bottom between 25 and 35 cm. The weight of the rounds can vary between 20 and 35 kg. After a minimum maturation period of 5 or 8 months, Pecorino Romano PDO can be used as a table or grating cheese, respectively. The taste is aromatic, lightly spicy and tangy in the table cheese, intensely spicy in the grated cheese.

Pecorino di Osilo is a typical cheese of a small area of the North-Western Sardinia. It is a semi-cooked, soft or hard cheese, included in the list of typical Italian agri-food products (18/07/2000 Ministerial Decree of the Italian Ministry for Agricultural, Food and Forestry). The essential characteristic of the Pecorino di Osilo cheese-making is the pressing for 5/6 hours after the curd cutting into small granules. The shape is cylindrical, with a height between 9 and 13 cm, a diameter between 14 and 22 cm and a weight in the range 1.5–3.0 kg. The cheese taste is sweet, or savoury and slightly spicy when seasoning exceeds 6 months. It is used mainly as table cheese but also for grating.

2.2. Case studies

Data were collected during 2013 in two cheese factories representative of each production system: “Allevatori di Mores Società Cooperativa” (“Coop. Mores”) for Pecorino Romano PDO (PR) produced at industrial scale; “Azienda Agricola Truvunittu” (“Truvunittu”) for Pecorino di Osilo (PO) manufactured on-farm in a semi-artisanal manner. The two dairy sheep factories are quite contrasting in all items (Table 1).

“Coop. Mores” is a medium-large dairy sheep industry located in Mores, a small town in the Central-North Sardinia placed in a strategic position to collect the milk from a large part of Sardinia and well connected with the main ports and airports of the island. The “Coop. Mores” dairy plant is provided with a system for recycling pressurized hot water from heating production processes. In this study, we considered the PR export type, called “Duca di Mores”, weighting 27 kg and with an average fat and protein content of 32% and 22% per 100 g, respectively.

“Truvunittu” is located in the countryside of Osilo municipality, a small town in the North-Western Sardinia. “Truvunittu” is a typical sheep farm operating in Sardinian hilly areas, in terms of size, productivity and capital good. This farm was selected also by having a small scale dairy plant annexed. The 2013 “Truvunittu” PO production was equal to 10,549 kg (around 6,000 rounds) and the fat and protein content was on average 30% and 28% per 100 g of cheese, respectively.

2.3. LCA methodology

The study was conducted in agreement with ISO 14040-44 compliant LCA methodology (ISO, 2006a,b). The functional unit (FU) considered was 1 kg of cheese packaged and distributed to the first customer (a trader most of times for PO, a retailer in the rest of the cases), according to other LCA cheese studies (Berlin, 2002; González-García et al., 2013). Therefore, the LCA followed a “from cradle to retailer” approach, including all inputs to the dairy plant, from crop farming to livestock operations, from refrigerated milk to the final disposition of the cheese packaging at the first customer. The LCA system boundaries were divided into the following main phases (Fig. 1): a) milk production at the sheep farm (from cradle to gate), b) milk collection and cheese-making at the dairy plant (from farm gate to dairy plant gate, taking into account cheese packaging and cleaning of equipment too), and c) cheese distribution (from dairy plant to retailer). A previous work we conducted on the environmental life cycle assessment of Sardinian dairy sheep production systems at three different input levels (Vagnoni et al., 2015) was used as background for milk production at farm gate. For PR we considered the milk received at the plant as a combination of the milk provided by production systems at three different input levels, with percentages of contribution that reflect the type of farms that belong to the “Coop. Mores”. In particular, the 188 sheep farms that delivered the milk to “Coop. Mores” dairy plant in 2013 were grouped according to the three above-mentioned different farming systems. The technical information about the milk providing farms were gathered from the “Coop. Mores” farm's dataset. Finally, 60% of total processed milk derived from the mid-input farming system, 30% from the high-input system and 10% from low-input system. For PO, we considered the milk produced by the “Truvunittu” farm, which is a mid-input farm. In addition, this LCA milk model was updated with respect to i) enteric methane emissions, that were quantified using a detailed approach based on Vermorel et al. (2008) and considering the total metabolizable energy ingested with the specific animal category diet, and ii) emissions related to pesticide and fertilizer use that were estimated with the IPCC method (IPCC, 2006). Similarly to milk production scheme, the cheese-making phase includes all input linked with the plant structure (buildings, machinery, cheese-making equipment and tools, etc.). Energy consumption was referred to farm and dairy plant phase but without assigning a specific value of consumption for each single stage or unit operations. Rather, the water consumption was detailed for specific operations, such as cleaning processes at both the farm and the dairy plant step, crop irrigation, livestock watering and general use. Regarding wastewater treatment for PR, a municipal wastewater treatment plant process by Ecoinvent v3.1 (Weidema et al., 2013) was used. In the case of PO, since the wastewater was directly applied on field (without any treatment), organic and inorganic compounds emissions in soil were estimated according to Bonari et al. (2007) emission factors.

The impact partitioning between the production process outputs was performed using an economic allocation procedure (Table 2), according with several LCA investigations on dairy sector (Baldini et al., 2017; Berlin, 2002; Castanheira et al., 2010; Pirlo et al., 2014) and given the large price difference between the “main product” and the other co-products. In particular, the following co-products were considered: meat and wool for sheep farm; ricotta cheese for “Coop. Mores” (which has a specific production line for PR); ricotta cheese (fresh and smoked) and fresh cheese for “Truvunittu”.

Primary data were collected through company's register examination, several visits in situ and employees' interviews. The survey requested both farm and plant level data regarding purchases (materials and energy), production (milk, cheese and other products), and emissions (solid and liquid waste streams). Data collected were checked for validity by ensuring consistency with theoretical or average values described in sectoral reference for similar contexts. Secondary data were taken from the three following database: Ecoinvent v3.1 (more than 60% of secondary data) (Weidema et al., 2013); Agri-footprint 2.0 (2015) (about 39% of secondary data); and USLCI (less than 1% of secondary data) (US LCI, 2015). SimaPro software (PRé Consultants, 2016) was used to model the life cycle and for the impact analysis. In order to assess in a more comprehensive way the environmental performances of sheep milk cheeses, and with the purpose of considering a wide range of impact categories, two different evaluation methods were used: 1) IPCC (IPCC, 2013), for the Carbon Footprint (CF) estimates, expressed in kg of CO_2-eq, and 2) CML-IA version 3.3 (Guinée et al., 2002), which considers, besides the GHG emissions, other 10 categories of environmental impact, i.e.: Stratospheric Ozone

Table 1
Main characteristics of the two dairy sheep factories.

	Coop. Mores	Truvunittu
Legal entity	Cooperative company with 270 members	Family-run company
Manpower (number of workers)	38	2
Dairy plant area (m^2)	3,500	130
Energy consumption, dairy plant (kW $year^{-1}$)	593,669	18,803
Water consumption, dairy plant (m^3 $year^{-1}$)	5,011	301
Wastewater treatment, dairy plant	Municipal wastewater treatment plant	Application on field
Milk origin	Purchased from Sardinian farmers	Produced on-farm
Milk processed (kg $year^{-1}$)	5,953,871	92,880
Products, total quantity (t/$year^{-1}$)	498	21
Products, type	Pecorino Romano PDO; 8 semi-cooked cheese types; Ricotta cheese	Pecorino di Osilo, Ricotta cheese, Fresh cheese
Products destination (% of total quantity)	55% USA; 45% Italy	100% Local market

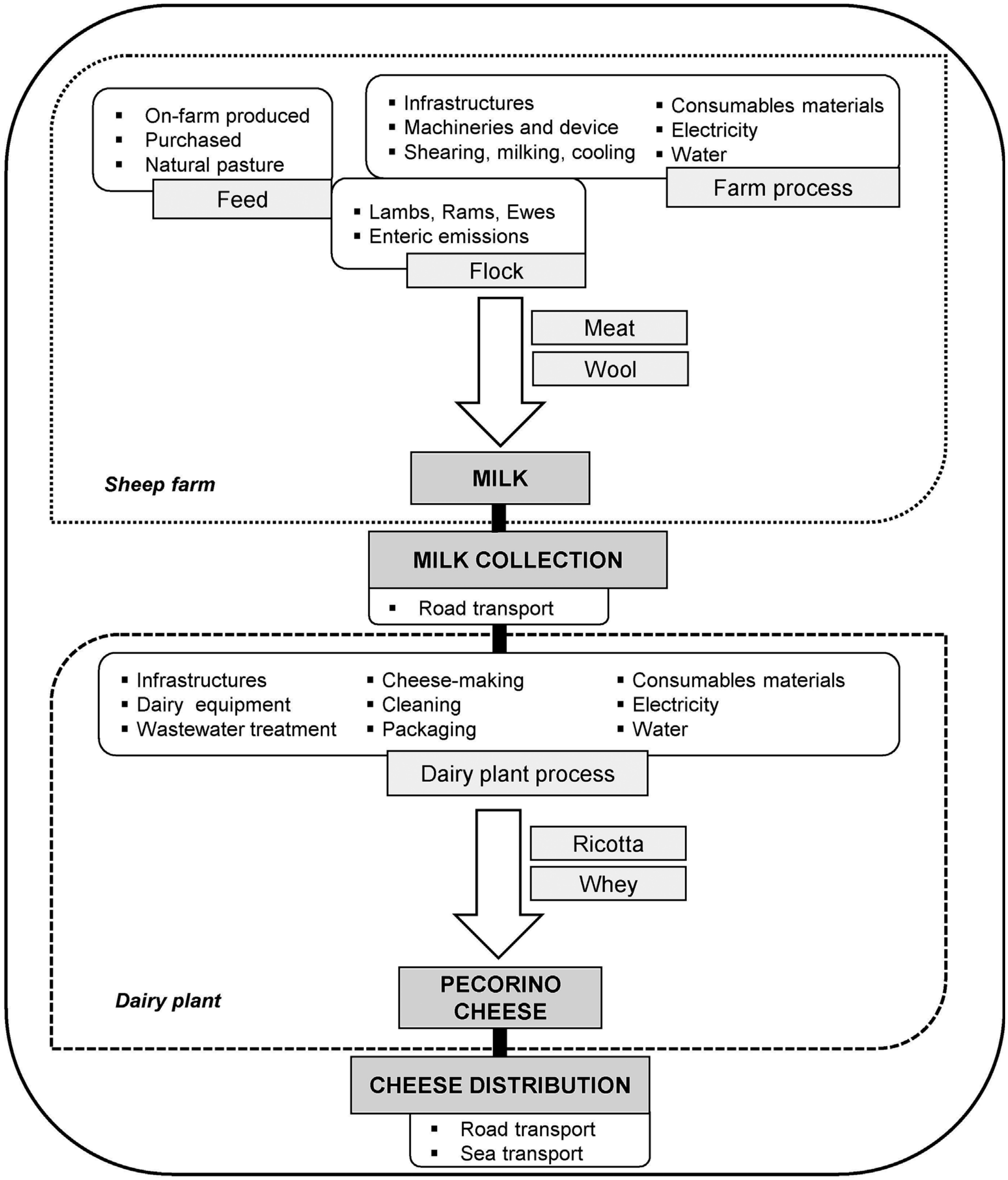

Fig. 1. System boundaries of the two Sardinian Pecorino cheese LCA case studies.

Table 2
Percentages of economic allocation of co-products from "Allevatori di Mores Soc. Coop." (Coop. Mores) and "Azienda Agricola Truvunittu" (Truvunittu) dairy plants.

	Percentage of allocation	
	Coop. Mores	Truvunittu
Sheep farm		
Milk	88.9	91.0
Lamb meat	8.8	6.7
Sheep meat	1.7	1.7
Wool	0.6	0.6
Dairy plant		
Pecorino Romano PDO	91.4	–
Pecorino di Osilo	–	62.7
Ricotta, fresh	8.6	21.0
Ricotta, smoked	–	12.7
Fresh cheese	–	3.6

depletion (expressed in kg of Trichlorofluoromethane equivalent, kg CFC-11-eq); Human toxicity (expressed as kg 1,4-dichlorobenzene equivalent, kg 1,4-DB-eq); Fresh-water aquatic ecotoxicity (kg 1,4-DB-eq); Marine ecotoxicity (kg 1,4-DB-eq); Terrestrial ecotoxicity (kg 1,4-DB-eq); Photochemical oxidation potential (POCP, expressed in kg of ethylene equivalent, kg C_2H_4-eq); Acidification potential (AP, expressed in kg of sulfur dioxide equivalent, kg SO_2-eq); Eutrophication potential (EP, expressed as kg of phosphate equivalent, kg PO_4^{3-}-eq); Abiotic depletion (elements, ultimate reserve) (expressed as kg antimony equivalent, kg Sb-eq); Abiotic depletion (fossil fuel) (expressed in MJ per m^3 of fossil fuel, MJ).

2.4. Statistical analysis on simulation scenarios

Moving from the identification of farm and dairy plant environmental hotspots and in order to assess alternative production system scenarios, we constructed four simulation scenarios both at sheep farm and dairy plant stage, based on different diet and more efficient/green power supply, respectively. In particular, the farming system scenarios were defined for mid-input farming system, since it is by far the most important sheep milk source for both cheeses (PR and PO). In addition, this case study is highly representative, in terms of size, productivity and capital good, of sheep farms in Sardinian hilly areas. For each simulation scenario, we estimated the CF (IPCC, 2013) of 1 kg of normalized milk (Fat Protein Corrected Milk - FPCM). In the case of dairy plant stage, the parameter used to evaluate the new scenarios was the CF (IPCC, 2013) of 1 kg of PR (from cradle to retailer). The statistical significance of the differences between CF mean values of actual and simulated scenarios was tested as follows: i) a population of 20 simulated CFs within each scenario was obtained using a Monte Carlo propagation test (Henriksson et al., 2015), ii) a one-way analysis of variance (ANOVA) with Tukey test post-hoc testing for $p < 0.05$ was performed using the R software (R Core Team, 2015). In addition, box-and-whisker plot was constructed to provide a graphical view of the results.

3. Results and discussion

3.1. Carbon Footprint

A small difference in 1 kg of cheese GHG emissions between dairy systems was found, with the PO CF higher than PR CF by 1.4% (Fig. 2). As expected, the milk production phase was by far the most impacting one, reaching about 92% of total GHG emissions in both case studies. The second largest contributor to the total CF was the cheese-making phase, with a percentage contribution of about 7% and 5% for PR and PO, respectively. The dominant contribution of milk production and cheese-making phase to the total GHG emissions was in agreement with several studies on global warming potential of dairy sector (Berlin, 2002; Kim et al., 2013; González-García et al., 2013; van Middelaar et al., 2011). The CF results of the PR and PO differed for milk collection, cheese-making and cheese distribution phases, reflecting the contrasting production scale and technology level of the two dairy systems. In particular, the main difference was obtained for cheese distribution phase, where the PO emissions of CO_2-eq per kg of cheese was 5 time greater than PR. As a consequence, the distribution phase represented about 3% of the total PO GHG emissions, and contributed only to about 0.6% in PR CF. This result can be explained by the fact that, in general, the PO distribution implies small quantities and higher frequency, leading to a much less efficient transportation phase. In fact, 10.5 t of PO was distributed using a van car, covering about 21,700 km. Therefore, the relationship between amount of product transported and distance covered was equal to about 0.5 kg km^{-1}. On the other hand, the PR distribution concerned the transportation of about 757 t of cheese for about 11,000 km using lorry (mostly >32 t gross vehicle weight size class) and transoceanic freight ship, which corresponds to about 69 kg of cheese per km of covered distance. GHG emissions of PR manufacturing process was 45% largest than PO that required few production input in addition to manpower. Similarly, milk collection had a tangible effect only for PR total GHG emissions (with a contribution of about 0.7%) since the milk transformed by “Truvunittu” was entirely produced on-farm.

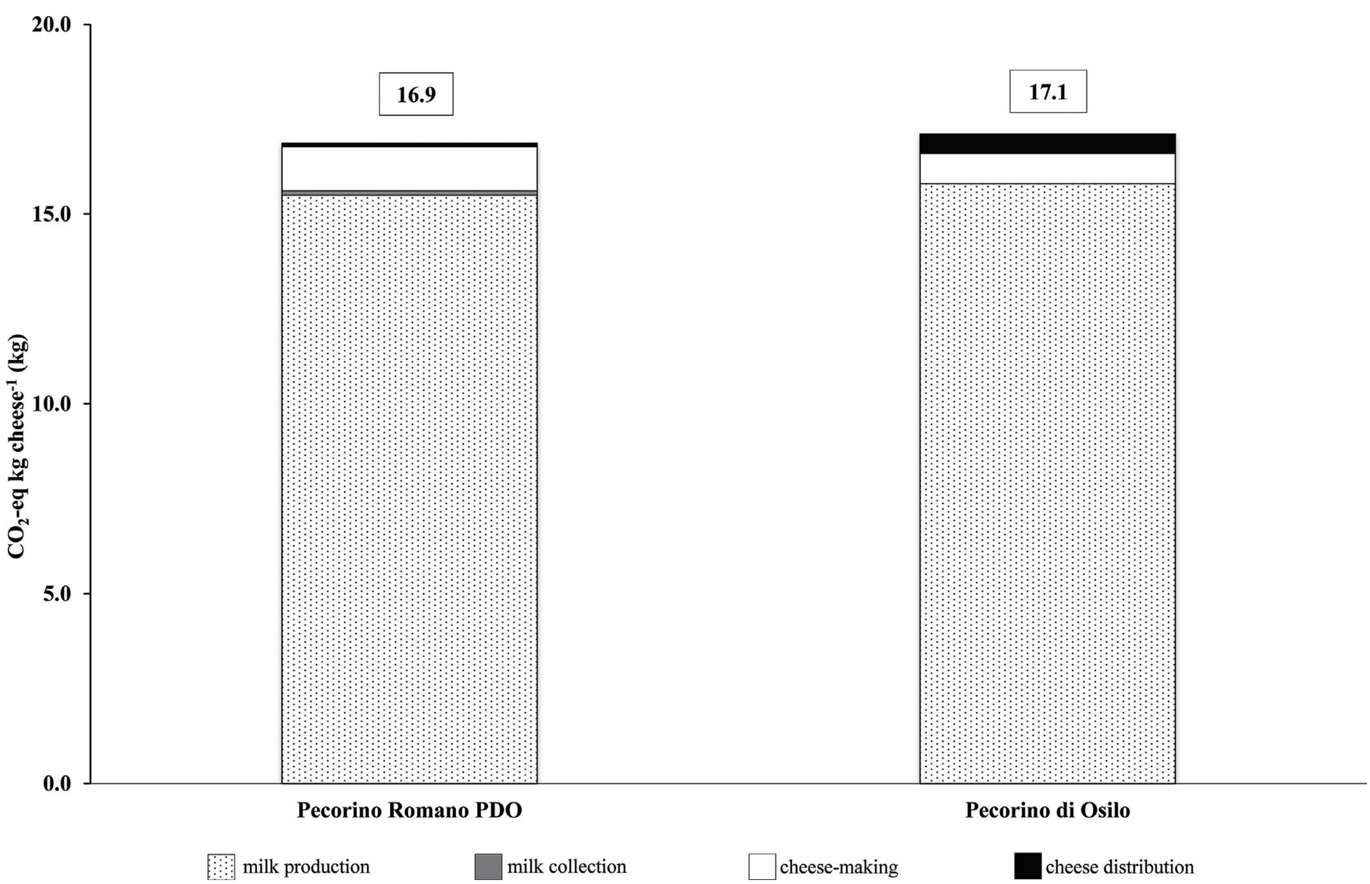

Fig. 2. Carbon Footprint (kg CO_2-eq) for 1 kg of Pecorino Romano PDO and Pecorino di Osilo life cycle.

Table 3
Percentage contribution of processes to the total GHG emissions of Pecorino Romano PDO (PR) and Pecorino di Osilo (PO) life cycle, using IPCC evaluation method and 1 kg of cheese as functional unit. The process category "Remaining processes" includes all the processes with a percentage contribution lower than 0.25% for both production systems.

Process	Percentage contribution to the total GHG emissions	
	PR	PO
Methane enteric emissions	53.4	52.6
Soybean meal, feed purchased	12.0	13.8
Cereal grain, feed purchased	7.5	10.2
Electricity, medium voltage	5.5	6.6
Transport, lorry	4.5	6.8
Transport, transoceanic freight ship	1.7	1.5
Dairy plant equipment	3.5	0.1
Tractor and agricultural machinery	3.5	2.9
Field crop operations	1.1	1.0
Dinitrogen oxide enteric emissions	0.8	0.7
Milking parlour, construction	0.4	0.5
Hay, from natural grassland	0.2	0.3
Remaining processes	5.8	3.2

Table 3 illustrates all individual processes that contributed with more than 0.25% to the total GHG emissions of each cheese and indicates that the three first largest processes were the same in both dairy systems. For instance, enteric methane emissions, soybean and cereal feed purchased summarized about 73% and about 77% of the total PR and PO CF, respectively. This result is consistent with the above-mentioned studies on the environmental profile of the dairy sector. On the other hand, the relevant role played by feed production and enteric fermentation in the global warming scenario was also highlighted by FAO, which estimated in about 85% the contribution of these emission sources to global emissions from livestock supply chains (Gerber et al., 2013). The main emissions from cheese life cycle was enteric methane, with a percentage contribution equal to 53% in both case studies. The sum of contributions by soybean meal and cereal grains ranged from 20% to 24% of the total PR and PO CF, respectively. Considering that on-farm produced feed contribution was less than 2% in both systems, this result demonstrated the dominant effect of purchased feed with respect to on-farm production. Dairy plant equipment played a quite different role in the CF composition of the two dairy supply chain, highlighting that the semi-artisanal manufacturing of PO required a smaller equipment stock. Otherwise, the road transportation contribution showed that milk collection and PR distribution was more eco-efficient than PO distribution, due to the largest work capacity of the large vehicles utilized in PR logistic management.

In general, the CF results of our investigation were quite similar to the results obtained by Favilli et al. (2008). The Pecorino Toscano PDO analysed by Favilli et al. (2008) was produced i) by a family-run dairy farm that had a production scale intermediate between PO (10 time lowest in number of rounds per year) and PR (6 time largest in cheese mass production) assessed in the present work, ii) with milk collected from several farms, and iii) utilizing geothermal steam during the thermal cheese-making operations. The global warming potential of 1 kg of Pecorino Toscano PDO analysed "from cradle to gate" by Favilli et al. (2008) was equal to 15.5 kg CO_2-eq, with the largest contribution of enteric fermentation. Excluding the distribution phase, the CF of the two Sardinian cheeses was equal to 16.7 kg CO_2-eq, on average. Moreover, the contribution analysis of Pecorino Toscano PDO production phases showed also a similar trend to the two Sardinian cheeses, namely: milk production 92%, cheese-making 5%, milking and transportation 3%.

3.2. CML-IA

The CML-IA evaluation method results indicated that PO showed lower environmental impacts than PR for 7 of the 10 considered impact categories (Table 4). The difference between the environmental performances of the two dairy systems was more accentuated (a difference larger than 15% with respect to the lowest value indicator) for the following 6 impact categories: Human toxicity, +160%; Terrestrial ecotoxicity, +42%; Fresh water aquatic ecotoxicity, +39%; Eutrophication, +36%; Marine aquatic ecotoxicity, +22%; Ozone layer depletion, +16%.

The mineral elements depletion impact was very low in both dairy systems, with a slightly difference between them. This can be explained by the fact that the considered farming systems are pasture-based and quite extensive in feed input utilization (González-García et al., 2013).

The energy demand of the two dairy systems was quite similar, with an average value of 73.4 MJ per kg of cheese. For both cheese supply chains the largest consumption of fossil fuel took place during the production of milk (76% of total fossil fuel depletion score, in both cases) and the main difference between diary systems occurred, as expected considering the above reported CF results, for cheese distribution phase (Table 5). Therefore, the transportation was the individual process that determined the main difference on fossil fuel depletion composition of the two dairy systems, which presented, in general, a quite similar trend (Figs. 3 and 4). The energy requirements estimated by Favilli et al. (2008) for Pecorino Toscano PDO was equal to 21.6 MJ kg cheese^{-1}, a value significantly lower than the values calculated for the two Sardinian cheeses. However, taking into account that Pecorino Toscano PDO was produced using geothermal heat (saving an important quantity of fossil fuel) and that the Sardinian cheese LCA included also the distribution phase, this difference seems reasonable.

In general, the ozone layer depletion impact was very low (10^{-7}

Table 4
Environmental impact results associated to the production of 1 kg of Pecorino Romano PDO (PR) and Pecorino di Osilo (PO), using the CML-IA evaluation method. Column AVG represents the average values between PR and PO.

Impact category	Unit	PR	AVG	PO
Abiotic depletion (minerals)	kg Sb-eq	$5.64 \cdot 10^{-5}$	$5.43 \cdot 10^{-5}$	$5.24 \cdot 10^{-5}$
Abiotic depletion (fossil fuels)	MJ	73.06	73.39	73.73
Ozone layer depletion (ODP)	kg CFC-11-eq	$8.41 \cdot 10^{-7}$	$7.82 \cdot 10^{-7}$	$7.22 \cdot 10^{-7}$
Human toxicity	kg 1,4-DB-eq	10.74	7.44	4.14
Fresh water aquatic ecotoxicity	kg 1,4-DB-eq	3.59	3.08	2.58
Marine aquatic ecotoxicity	kg 1,4-DB-eq	5,928	5,402	4,876
Terrestrial ecotoxicity	kg 1,4-DB-eq	0.05	0.04	0.03
Photochemical oxidation	kg C_2H_4-eq	0.005	0.005	0.005
Acidification	kg SO_2-eq	0.05	0.045	0.04
Eutrophication	kg PO_4^{3-}-eq	0.04	0.042	0.05

Table 5
Percentage contribution of production phases to the environmental impacts of Pecorino Romano PDO (PR) and Pecorino di Osilo (PO) life cycle, using CML-IA evaluation method and 1 kg of cheese as functional unit. Columns AVG represent the averages values between PR and PO.

Impact category	Percentage contribution of production phases to the environmental impacts									
	milk collection[a]	milk production			cheese-making			cheese distribution		
	PR	PR	AVG	PO	PR	AVG	PO	PR	AVG	PO
Abiotic depletion (fossil fuels)	2	76	76	76	19	17	14	2	6	10
Human toxicity	0	32	55	79	68	38	9	0	6	12
Fresh water aquatic ecotoxicity	0	58	69	80	42	25	8	0	6	12
Marine aquatic ecotoxicity	1	63	71	79	36	24	12	0	5	9
Terrestrial ecotoxicity	0	80	86	92	20	13	5	0	2	3
Photochemical oxidation	0	92	93	95	7	5	3	1	2	2
Acidification	1	83	85	88	13	11	8	3	4	4
Eutrophication	0	95	86	78	5	13	21	0	1	1

[a] The milk utilized for the PO cheese was directly produced on-farm.

order of magnitude). However, data on leakage of cooling equipment, which mainly contributes to the depletion of the ozone layer (Berlin, 2002), were not taken into account because of the level of uncertainty. For this reason, detailed information and results discussion about that are omitted.

The human- and eco- (fresh water, marine aquatic and terrestrial) toxicity profile of the two dairy systems were quite different and highlighted how the contrasting production scale affected distinct impact categories (Tables 4 and 5; Figs. 3 and 4). For PO, the largest toxic emissions were related to milk production, with a very high contribution for all impact categories. For PR, the cheese-making phase had also a relevant role, especially for Human toxicity and Fresh water aquatic ecotoxicity where represented the largest contributor. Toxic emissions related to dairy infrastructures and equipment were dominant in the industrial dairy system. Toxic emissions from transportation characterized the semi-artisanal system. Regarding the toxic emissions at farm level, fertilizer and pesticide use on crop cultivation underlined the feed contribution on the total environmental profile, as founded by others LCA studies on dairy sector (Berlin, 2002; de Boer, 2003).

The photochemical oxidation potential results were very similar. The average POCP value for the two dairy systems was equal to 4.69 g C_2H_4-eq kg^{-1} cheese. The lowest POCP value was estimated for PR, with a difference less than 1% with respect to PO. In agreement with several dairy LCA studies (Berlin, 2002; Castanheira et al., 2010; González-García et al., 2013; Pirlo et al., 2014), the POCP was mainly correlated to on-farm emissions (Table 5). In particular, the largest contributor was enteric fermentation (Figs. 3 and 4) closely followed by feed purchased. These processes summarized jointly 71% and 76% of the total POCP for PR and PO, respectively.

The average POCP value of our study was 1.4 time greater than

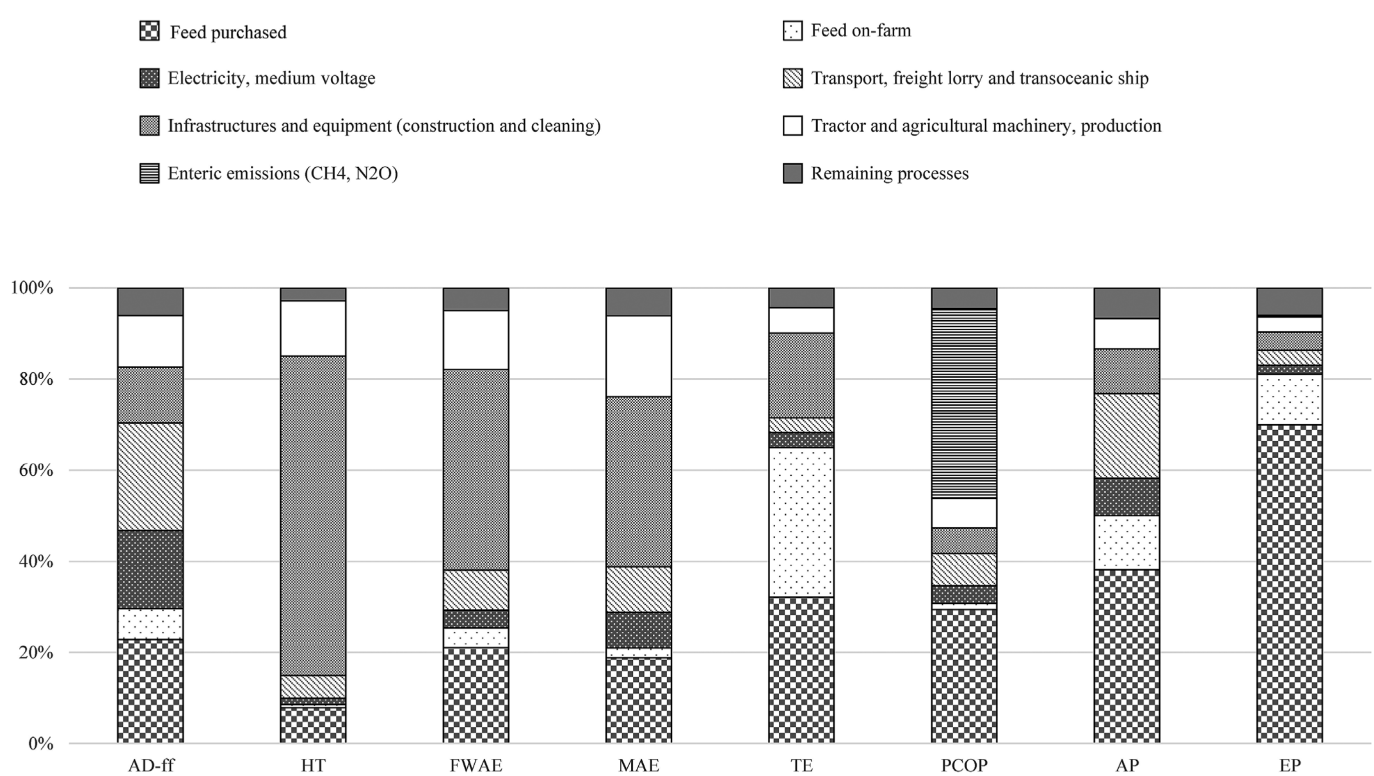

Fig. 3. CML-IA evaluation method results (in %) for each impact category and process involved in the Pecorino Romano PDO life cycle. Impact categories: AD-ff = Abiotic Depletion fossil fuel, HT = Human Toxicity; FWAE = Fresh Water Aquatic Ecotoxicity, MAE = Marine Aquatic Ecotoxicity, TE = Terrestrial Ecotoxicity, PCOP = PhotoChemical Oxidation Potential, AP = Acidification Potential, EP = Eutrophication potential.

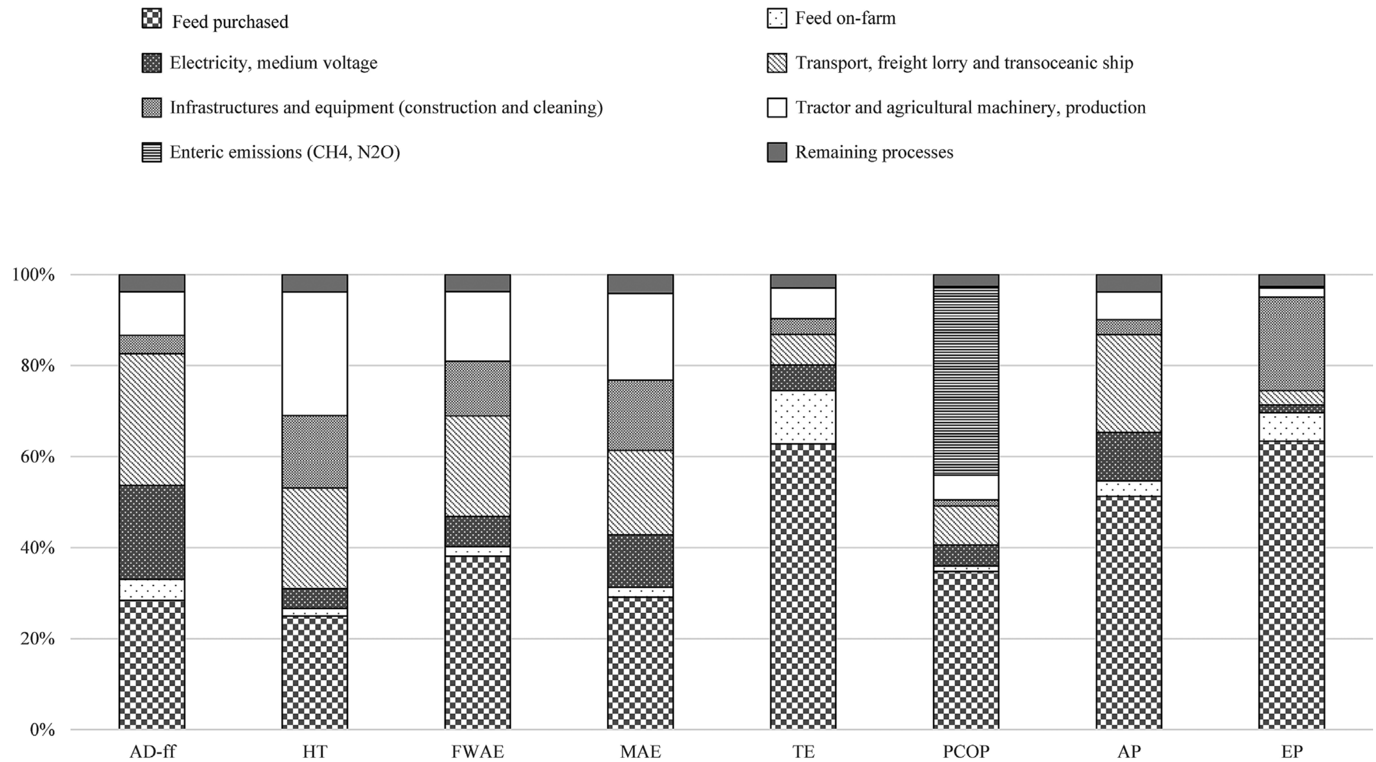

Fig. 4. CML-IA evaluation method results (in %) for each impact category and process involved in the Pecorino di Osilo life cycle. Impact categories: AD-ff = Abiotic Depletion fossil fuel, HT = Human Toxicity; FWAE = Fresh Water Aquatic Ecotoxicity, MAE = Marine Aquatic Ecotoxicity, TE = Terrestrial Ecotoxicity, PCOP = PhotoChemical Oxidation Potential, AP = Acidification Potential, EP = Eutrophication potential.

the POCP value obtained by Favilli et al. (2008). However, more data on Favilli et al. (2008) sheep diet and methane enteric emissions estimates are needed to better understand the differences between the Sardinian and Tuscany cheese LCA studies. Despite that, the consideration about the different LCA system boundaries and power source remains valid.

Acidification potential (AP) results indicated that PR was slightly more impacting because of the largest SO_2-eq kg^{-1} cheese emission compared to PO during the cheese-making phase. For both dairy systems, the largest contributor was the milk production phase, with a contribution to the total AP more than 80% (Table 5). NH_3, NO_x and SO_2 emissions related to a different use of concentrate feed (purchased) on sheep diet supply - which represented 38% and 51% of total PR and PO AP, respectively - also represented key factors (Figs. 3 and 4). The observed dominant role of milk production was in agreement with other environmental studies on dairy sector (Berlin, 2002; González-García et al., 2013), including the Pecorino Toscano PDO LCA study conducted by Favilli et al. (2008). However, in the latter study, the AP of 1 kg of cheese was strongly lower (about 390 g SO_2-eq versus about 45 g SO_2-eq obtained, on average, for the two Sardinian cheeses in our study). This inconsistency can be explained by the farmyard manure use and the largest fertilizer use in Pecorino Toscano PDO production process, where NH_3 emissions from fertilizing system represented the largest contributor to the AP.

Eutrophication potential of 1 kg of cheese was quite lower in PR, with a margin of about 13 g PO_4^{3-}-eq (which represents about 27% of PO EP value) (Table 4). As occurred in AP impact category, feed was the largest source of eutrophication with a percentage contribution equal to 81% for PR and equal to 69% for PO (Figs. 3 and 4). However, the direct wastewater on field application and the large use of purchased feed by “Truvunittu”, determined that the EP of PO was higher than PR. The main role of milk production phase was consistent with other studies (Berlin, 2002; González-García et al., 2013). Moreover, Favilli et al. (2008) founded an EP value for 1 kg of Pecorino Toscano PDO equal to 35 g PO43- which was very similar to this obtained in our study, in particular for PR.

3.3. Remarks on model performance improvement

In order to propose substantial improvements in the environmental performances of each dairy farm/plant, the hotspots identified through the contribution analysis for the two evaluation methods were considered.

The environmental improvement of production activities should be addressed firstly to farm practices, since, as discussed earlier, milk production represented the most critical phase in determining the overall environmental performances.

Reduction of the main GHG emissions by ruminant sector has been the focus of several initiatives (such as LEAP Partnership by FAO (2017) and LIFE Programme by EU (2017)) and investigations (Alcocka and Hegartyb, 2011; Kumar et al., 2014; Gerber et al., 2013; McAllister et al., 2011). Recently, Marino et al. (2016) in their review on the effect of climate change on small ruminant production and health, classified the strategies to decrease GHG emissions into the following categories: 1) options related to flock diet, feed supplements and feed/feeding management (for CH_4 only); 2) options for rumen control and modifiers; 3) genetics options and intensiveness of production. In our case studies, strategies to reduce enteric fermentation emissions and to improve the eco-efficiency of the feed supply chain seem the key challenges. In particular, the environmental performances of the analysed sheep farming systems could be improved according to the following practical solutions: i) using forage species that can decrease the methane production in sheep rumen (Hopkins and Del Prado, 2007; Puchala et al., 2005; Tavendale et al., 2005), ii) increasing the amount of on-farm produced feed, especially forage legumes (Melis et al., 2016), instead of soybean and others protein-based feed imported from distant countries, and iii) increasing low-input and high-quality pasture acreage and adopting sustainable grazing management techniques (Becoña et al., 2014; Picasso et al., 2014; Porqueddu et al., 2016). Moving from these criteria, four alternative scenarios based on different diet and feed supply chain were constructed. The progressive replacement in lactating ewe diet of soybean-based feed (soybean meal and concentrate) with high-quality on-farm produced forage species was applied (Table 6). The feeding rate of the four simulated scenarios was adjusted in a manner that the milk productivity resulted always equal to the actual level (1.0 l ewe^{-1} day^{-1}). Specifically, we introduced sulla (*Hedysarum coronarium* L.), a native drought tolerant and high quality forage legume species, recognized as particularly rich in condensed tannins, which are relevant compounds for reducing rumen fermentation (Piluzza et al., 2014). Also, we introduced on-farm produced oat grain, as concentrate feed. Finally, the improved pasture contribution to diet varied in relation with the supply of sulla, because it has a lower FUL (Feed Unit for Lactation) content compared to sulla. All the rest of feed quality and quantity did not change compared to the actual diet.

All the simulated scenarios determined a significant reduction of GHG emissions per 1 kg FPCM compared to the actual one (Table 7 and Fig. 5). Carbon Footprint ranged from 3.27 kg CO_2-eq kg^{-1} FPCM in the actual scenario to 2.80 kg CO_2-eq kg^{-1} FPCM obtained in FS4 scenario (total substitution of soybean meal and concentrate feed with on-farm produced forage). All the four diet and feed supply chain scenarios determined a relevant reduction of the CF values, from a minimum of approximately 9% (FS1) to a maximum up to 15% (FS4). This is a clear confirmation of the findings of several authors (for example, Tavendale et al., 2005; Puchala et al., 2005) suggesting that enteric fermentation can be greatly reduced using forage species that can decrease the methane production and/or increasing the amount of on-farm produced feed, especially forage legumes.

Considering that milk production represented on average about 92% of the total cheese CF, we can consider these solutions viable and promising towards the environmental profile improvement of the considered cheese supply chains.

At dairy plant level, the main environmental improvement can be addressed to energy use. The “Coop. Mores” electricity consumption was equal to 0.71 kWh kg^{-1} of PR. This performance was consistent with some dairy systems, as reported by González-García et al. (2013), where electricity consumption was equal to 0.71 kWh kg^{-1} of cheese, and ENEA (2007), which calculated an average consumption for the Central Sardinia dairy sector equal to 0.76 kWh kg^{-1} of cheese. However, the results we obtained can be considered quite high when compared with Berlin (2002), where electricity consumption was equal to 0.36 kWh kg^{-1} of cheese. For “Truvunittu” dairy farm, characterized by a low cheese production amount, the electricity use per FU was even higher than “Coop. Mores” and reached 1.12 kWh kg^{-1} of PO. Therefore, an effective power supply strategy based on an accurate energy audit is recommended, in particular for the semi-artisanal dairy system. Similarly to farm stage, we constructed four simulation scenarios in relation to the dairy plant of PR:

- DS1) 10% of the actual consumed electricity derived from a photovoltaic plant. This percentage is in line with a similar case study reported by Cambuli et al. (2013) in their study about the energy management of the Sardinian dairy sector, and aimed to evaluating the possible technical-economic solutions for improving energy efficiency;
- DS2) 30% of the actual consumed electricity derived from a wind power plant. Again, this percentage was established according to Cambuli et al. (2013);
- DS3) 20% reduction of actual consumed electricity (provided by the Italian power grid), according to a mix of technological improvements defined by ENEA (2007);
- DS4) combination of the second and third scenario.

The simulation of new power supply scenarios for PR dairy plant did not lead to an effective environmental performance improvement compared to the actual scenario (Table 8): DS1 did not show any difference compared to the actual scenario; DS2 and DS3 determined a little decrease, just 0.1 kg CO_2-eq per kg of cheese; DS4 saved 0.2 kg CO_2-eq per kg of cheese. In any case, differences were not statistically significant (data not shown). These results reflect the percentage contribution of electric power consumption (never higher than 5.5%) to the total PR CF (Table 8).

Table 6
Changes in lactating ewe diet, expressed as daily intake (kg d^{-1}), deriving from the actual (T) and four simulated farm scenarios (FS). Diet and feed supply chain scenarios were constructed to reduce enteric fermentation emissions and to improve the eco-efficiency of the farming system.

Feed	Actual and simulated scenarios				
	T	FS1	FS2	FS3	FS4
Actual					
Soybean meal	0.125	0.125	–	–	–
Concentrate feed	0.100	0.100	0.100	0.100	–
Improved pasture	4	4.5	2.1	0.9	0.9
Introduced					
Sulla (*Hedysarum coronarium*) herbage	–	–	2.0	3.0	3.0
Oat grain	–	–	–	–	0.1

Table 7
Carbon Footprint (CF) mean values of the actual (T) and four simulated scenarios (FS), based on different lactating ewe diet and feed supply chain. The functional unit is 1 kg of Fat Protein Corrected Milk.

Scenario	Mean CF
T	3.27 a
FS1	2.97 b
FS2	2.91 c
FS3	2.88 d
FS4	2.80 e

Means followed by different letters indicate significant differences at $p < 0.05$.

4. Conclusions

This work contributes to improve our knowledge and understanding on the environmental implications of small ruminant systems, with a specific attention to the Sardinian dairy sheep supply chain. In particular, the present study compared the environmental profile of two contrasting sheep milk cheese supply systems. A semi-artisanal typical cheese (Pecorino di Osilo) produced by a family-run dairy farm, and a popular industrial manufacturing cheese (Pecorino Romano PDO) were assessed using an LCA approach (“from cradle to retailer” and with IPCC and CML-IA evaluation methods). The CF of 1 kg of each cheese were similar, with an average value equal to 17 kg CO_2-eq. The main difference between the two dairy system environmental performances were founded for human- and eco-toxicity, as well as eutrophication impact categories.

According with several LCA studies on dairy sector, the farm

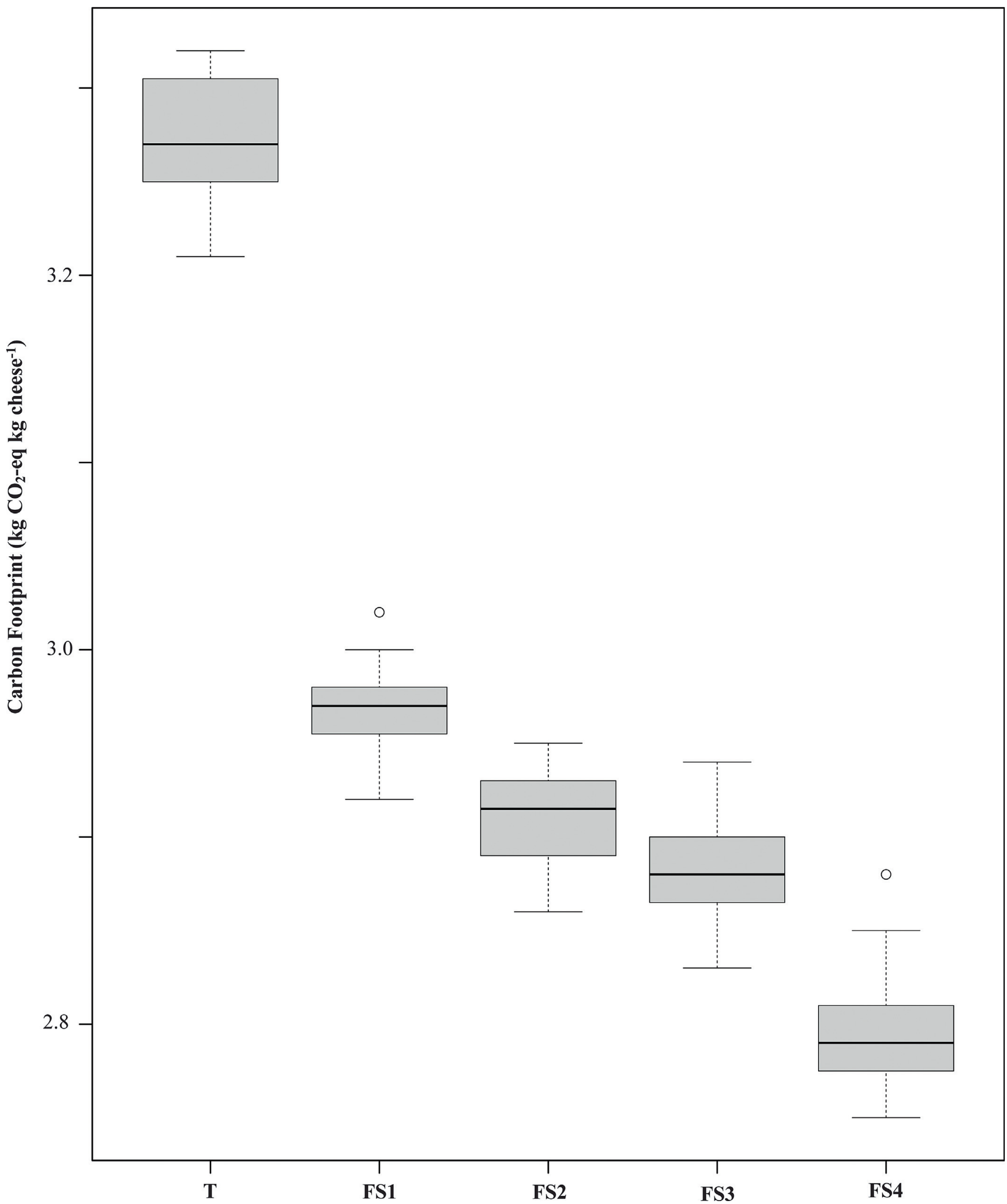

Fig. 5. Box and whisker plot of the Carbon Footprint values from the actual (T) and four simulated scenarios (FS) based on different lactating ewe diet and feed supply chain. The horizontal line within the boxes indicates the median, boundaries of the box indicate the 25th- and 75th-percentile, whiskers indicate the lowest datum still within 1.5 interquartile range (IQR) of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile, and individual points (small circle) indicate outliers.

Table 8
Carbon Footprint (CF) values and electricity percentage contribution to the total CF (E/CF) of 1 kg of Pecorino Romano PDO (PR), for the actual (T) and four simulated scenarios (DS) at dairy plant level, based on different green and/or more efficient power supply.

Scenario	CF (kg CO_2-eq kg^{-1} PR)	E/CF (%)
T	16.9	5.5
DS1	16.9	5.3
DS2	16.8	5.0
DS3	16.8	5.2
DS4	16.7	4.7

activities played the most relevant role in the overall environmental performances, with the only exception of human toxicity category for Pecorino Romano PDO. Therefore, looking for the environmental profile improvement of the Sardinian sheep milk cheese sector, enteric fermentation reduction and feed supply chain optimization seem as clear priorities. Moreover, a high efficient and/or more green-energy based power supply, a proper sizing of the equipment stock, the use of less pollutants cleaning agents, as well as the adoption of a more cleaner wastewater management in small dairy farms, are key improvements at the dairy plant and represent further important steps towards a more eco-sustainable dairy system. Scenario simulations based on alternative diet/feed supply chain and more efficient/green power supply combined with statistical analysis of scenario results confirmed the potential for the environmental profile improvement of Sardinian sheep milk cheese sector. However, this study involved only two case studies for one year and the conclusions about the environmental comparison between industrial and semi-artisanal dairy systems should be considered as preliminary. Concluding, future research studies are needed to better assess the environmental implications related to i) the relationship between sheep breed, diet composition and enteric methane emissions, and ii) the externalities (ecosystem services) produced by the pasture-based farming systems.

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