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ENVIRONMENTAL IMPLICATIONS OF DAIRY SHEEP SUPPLY CHAIN AND EVALUATION OF CLIMATE CHANGE MITIGATION ACTIONS FOR SARDINIAN SHEEP FARMING SYSTEMS

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A mi querido amigo Angel,
quien me enseñó que el deseo de saber
es la mejor forma de ser libre.

SUMMARY

INTRODUCTION

The IPCC Fifth Assessment Report on Climate Change (2014) confirms the agro-forestry sector as a significant source of greenhouse gases emissions (GHG): with a contribution equal to 24%: it is the second most impacting economic activity, after the energy industry (35% of total emissions). Excluding carbon dioxide emissions (CO_2), agriculture ranks as the largest contributor with 56% of 2005 global GHG emissions (U.S. EPA, 2011), mainly due to methane (CH_4) and nitrous oxide (N_2O), which determine a radiative forcing 23 and 300 times higher than CO_2, respectively. In more recent years, FAO has estimated that emissions of non-CO_2 from agriculture amount to 5.2–5.8 Gt CO_{2eq} yr^{-1}, corresponding to 10-12% of total anthropogenic GHG emissions. Under this scenario, the livestock sector plays a relevant role. The report 'Tackling climate change through livestock' (Gerber et al., 2013) estimates that the livestock sector is responsible for 14.5% of all anthropogenic GHG emissions, with a significant impact of CH_4 emissions (44% of sector's emissions). In particular, livestock supply chains emit 5%, 44% and 53% of CO_2, CH_4 and N_2O anthropogenic emissions, respectively. Within the livestock sector, cattle breeding is responsible for the most emissions. Small ruminants farming is an important contributor too (just under 0.5 Gt CO_{2eq}, 1/3 of GHG emissions of bovine milk production), representing around 6.5% of GHG sector's emissions (Gerber et al., 2013; Opio et al., 2013). In particular, enteric CH_4 emissions from world sheep population represent more than 6.5% of similar emissions from the global livestock sector (FAOSTAT, 2012). Furthermore, when emissions are expressed on a per protein basis, meat and milk from small ruminants represent the second and third highest emission intensities (165 e 112 kg CO_{2eq} per kg protein, respectively) among the overall food of animal origin (amount of GHG emitted per unit of output produced) (Gerber et al., 2013). The role of small ruminants' livestock in tackling climate change and its environmental implications are also more relevant considering that goat and sheep population is growing steadily worldwide: increasing from 876 to 1,043 million heads over the period 2007-2011(OECD-FAO, 2015) and exceeding 2,200 million heads in 2014 (FAOSTAT, 2017). Moreover, within the positive trend of livestock productions foreseen for 2015-2024, the sheep sector occupies a key position with an expected production increasing more than 20% compared to the past decade (OECD-FAO, 2015).

With about 147 million heads, Europe is the world's third region in terms of number of sheep (FAOSTAT, 2017). In spite of sheep and goat farming representing a minor agricultural activity, accounting for less than 4% of the total value of animal production in EU-27, these activities play a crucial role, both in economic and environmental terms, in particular in many disadvantages areas of the Mediterranean Basin (Zygoyiannis, 2006). Most livestock farms are located in Great Britain (27%), Spain (18%), Romania (11%), Greece (11%), Italy (9%), France (9%) and Ireland (4%). Although in Europe sheep are raised mainly for meat production, a stable growth has been registered in sheep milk production since 2003 (+2.1% from 2003 to 2013), despite a drop in head number and meat production (respectively by -4% e -10.5%) (FAOSTAT, 2013). In particular, over 70% of the sheep bred in Romania, Greece and Italy – which together hold approximately 30.5% of the entire European sheep population – are milking ewes (EUROSTAT, 2014).

Italy, with more than 7 million sheep heads in about 68 thousand farms, is the third country in EU-28 for sheep population (IZS, 2016). According to FAO (FAOSTAT, 2012), Italian sheep farming is responsible for more than 6% of the total enteric methane emissions by the European agricultural sector. Within the Italian sheep sector, Sardinia is by far the main region, with more than 45% of Italian sheep ewes and about 13 thousand farms (ISTAT, 2016), spread all-over the island. In fact, 25% of total EU-27 sheep milk production came from Sardinia (Rural Development Programme of Sardinia - RDP, 2014-2020). Basically, the whole Sardinian sheep milk production (more than 300,000 t year-1) is transformed in cheese, produced with a semi-artisanal or industrial process. Sardinian milk sheep cheese production has three Protected Designation of Origin cheeses (PDO), i.e. “Pecorino Romano” (mainly intended for export, represents more than 90% of the total Sardinian PDO cheeses) (Osservatorio Regionale della filiera ovicaprina, 2012), “Fiore Sardo”, “Pecorino Sardo” and several minor productions, all closely linked to the territory and local traditions (Piredda et al., 2006). 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 the total production) represent a structural weakness and a serious threat for the whole Sardinian agro-food system (RPD, 2014-2020). As well as in others Mediterranean regions, the Sardinian sheep sector is characterized by a strong farm fragmentation, with a predominance of small family-run farms (herds below 300 heads). Only in the more fertile and irrigated plains medium/big farms are found. Therefore, contrasting dairy sheep farming systems coexist in Sardinia, with differences in input utilization, land use and intensification level which depend on geographical location of farms, specific economic conditions and other external factors such as public incentives policies and local or global market trends (Biala et al., 2007). In order to contrast the deep structural crisis (i.e. the high dependency on external markets, the limited generational change of the sector and the on-going abandonment of rural areas) mainly related to the cyclic collapse of Pecorino Romano PDO international price, the Sardinian dairy sheep sector needs a robust innovation process where the integration and optimization of economic and environmental productive factors are key actions (Atzori et al., 2015). The eco-innovation of production processes and the valorisation of pasture-based systems could represent an effective strategy to improve farms competitiveness and to promote Sardinian dairy sheep products as well as the whole Mediterranean livestock chains. On the other hand, assessing environmental implications of sheep farming and improving its environmental performance could have effects both on combating climate change (GHG emissions mitigation and ecosystem services optimization) and on rural development policies. At present, greening of agriculture and farming practices supported by EU policies and driven by the increasing demand of eco-sustainable food, as well as the circular economy rising, place even more emphasis on the need to incorporate knowledge about the environmental implications of production systems into management farming strategies.

Several studies have been dedicated to the environmental assessment of cow systems (Baldini et al., 2017; de Boer, I.J.M, 2003; de Vries et al., 2015; Soteriades et al., 2016), because they have a worldwide economic relevance, they play an essential role in human diet as protein food source and they largely contribute to global CH_4 and N_2O emissions. All authors estimated the environmental performances using a Life Cycle Assessment (LCA) approach, the widely accepted, complete and standardized computational tool for providing a widespread knowledge on the environmental aspects associated with products, services or activities (Hayashi et al., 2006). The LCA analysis represents also the first step towards sustainability of production systems, identifying where environmental impacts and damages take place (Chen et al., 2005). On the other hand, little research has been focused on the environmental implications of dairy sheep systems from a life cycle perspective, despite their significance in the global trends of livestock productions. The most relevant research studies on the environmental performances of small ruminant systems using an LCA approach have been conducted mainly in Australia, New Zealand and in the United Kingdom. As a consequence, these LCA studies concerned wool and meat, the main products of global sheep farming systems (Biswas et al., 2010; Brock et al., 2013; Browne et al., 2011; Ledgard et al., 2011; Peters et al., 2011; Williams et al., 2012). In addition, a LCA study on Spanish sheep meat production was quite recently published by Ripoll-Bosch et al. (2013). To our knowledge, the main scientific papers on the environmental implications of sheep milk production regarded a LCA study of an Australian intensive farming system (Michael, 2011) and four works carried out on the European context, including the first chapter of this doctoral thesis (Atzori et al., 2015; Batalla et al., 2015; Marino et al., 2016; Vagnoni et al., 2015). Moreover, only two LCA studies investigated the environmental implications of the sheep milk cheese production chain (Favilli et al., 2008; Conte et al., 2016). If GHG mitigation actions in the sheep sector are to be achieved, there is not clear scientific evidence showing that, for example, extensive farming systems are less impacting than more intensive ones. Extensive agriculture may help in mitigating some negative environmental impacts caused by intensive livestock systems, such as consumption of fossil energy resources, use of macroelements, global warming potential, loss of biodiversity, degradation of soil quality (Biala et al., 2007). On the other side, the introduction of some low-input techniques, i.e. manure fertilisation, mechanical weeding, no-tillage cultivation and so on, was demonstrated to have sometimes the opposite effect (Basset-Mens and Van Der Werf, 2005; Brentrup et al., 2004; Michael, 2011).

Therefore, more research studies are needed in order to i) better assess the environmental implications of Mediterranean sheep systems with a comprehensive and site-specific approach, and ii) to evaluate the effectiveness and efficacy of climate change mitigation actions.

The present thesis deals with these knowledge gaps and is intended to contribute to the environmental profile characterization of the Sardinian dairy sheep chain. The thesis is structured in three chapters developed following a common logical and scientific framework, each having specific objectives and its own independence:

1. LCA analysis of sheep milk obtained with three different production systems (high, mid, and low input), already published in Science of the Total Environment, Vol. 502, 1 January 2015, pp 354-361.
2. Comparison of the environmental performances of two contrasting management systems within the same dairy sheep farm, currently under submission to Journal of Small Ruminant Research.
3. Preliminary evaluation of the environmental profile of the Sardinian milk sheep cheese chain, at present under submission to Journal of Cleaner Production.

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CHAPTER 1 - ENVIRONMENTAL PERFORMANCES OF SARDINIAN DAIRY SHEEP PRODUCTION SYSTEMS AT DIFFERENT INPUT LEVELS

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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).

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.

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%

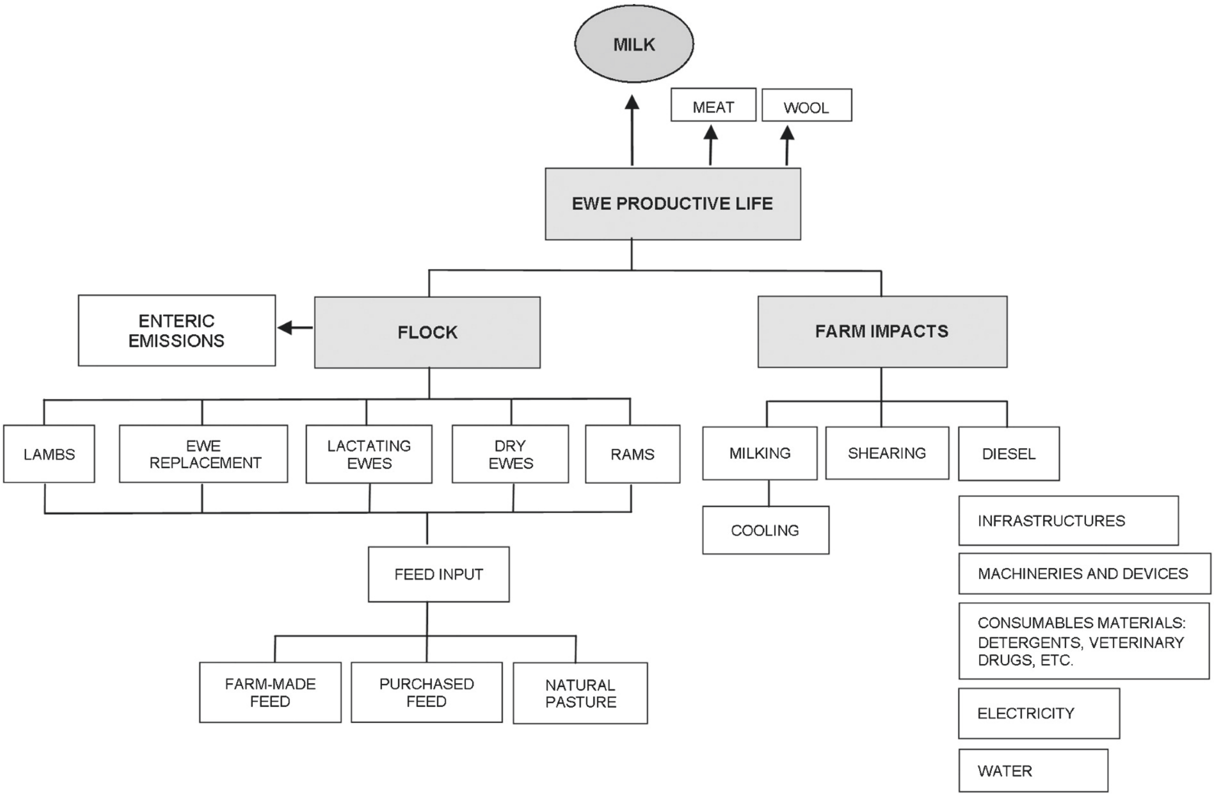

Fig. 1. Flow chart of sheep milk production.

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

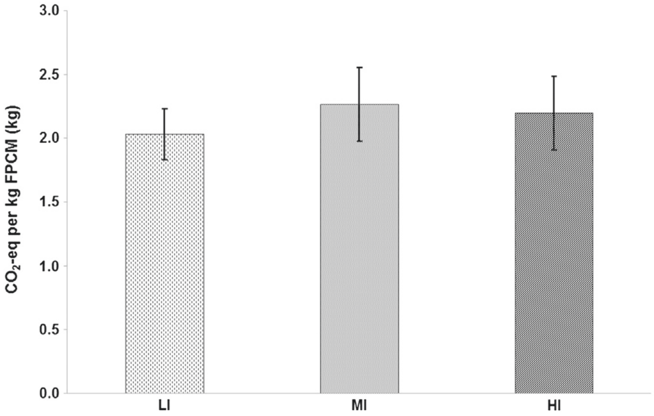

Fig. 2. Mean values and standard errors of the Carbon Footprint (IPCC, 2006) of low- (LI), mid- (MI), and high-input level (HI) farms. The functional unit (FU) is 1 kg of FPCM (Fat and Protein Corrected Milk).

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.

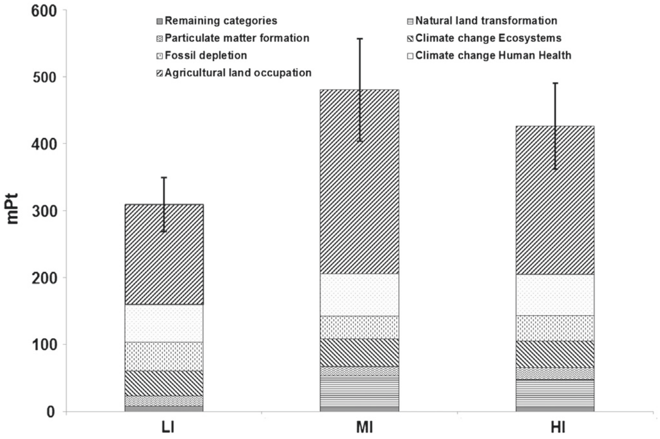

Fig. 3. Mean values and standard errors obtained using the ReCiPe end-point impact assessment method for the functional unit 1 kg of FPCM for low- (LI), mid- (MI), and high-input level (HI) farms. Impact effects are expressed in milli-ecopoints (mPt). Impact categories with scores lower than 10 mPt are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

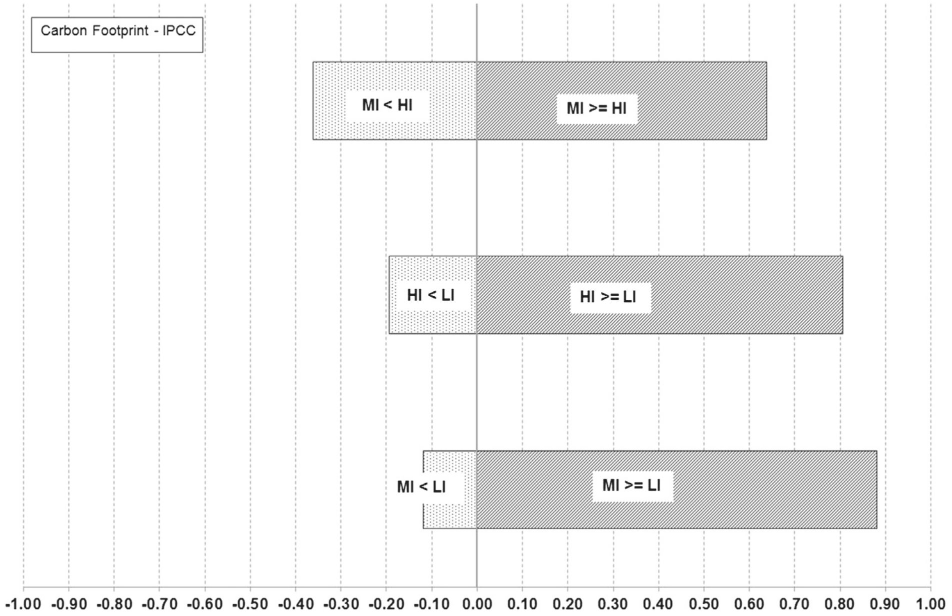

Fig. 4. Monte Carlo results of the comparisons between Carbon Footprints from low- (LI), mid- (MI), and high-input level (HI) farms. The analysis consisted in multiple comparisons involving each pair of mean values.

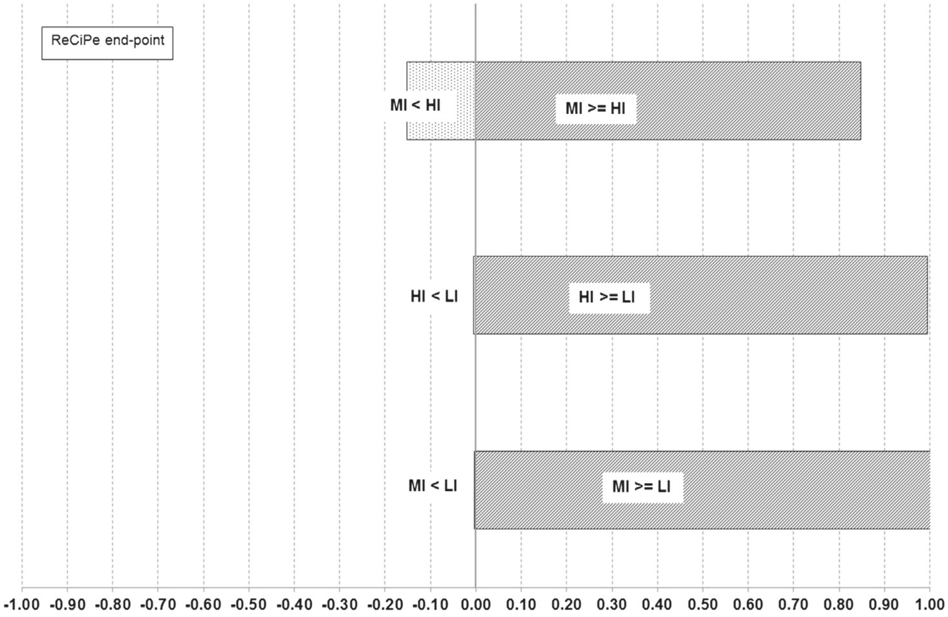

Fig. 5. Monte Carlo results of the comparisons between ReCiPe endpoint results from low- (LI), mid- (MI), and high-input level (HI) farms. The analysis consisted in multiple comparisons involving each pair of mean values.

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.

Acknowledgments

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CHAPTER 2 - ENVIRONMENTAL IMPLICATIONS OF DIFFERENT PRODUCTION SYSTEMS IN A SARDINIAN DAIRY SHEEP FARM

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ABSTRACT

Sardinia (Italy) plays a relevant role on EU sheep milk production. As well as in others Mediterranean regions, contrasting dairy sheep farming systems coexist in Sardinia and an effective renovation process is needed in order to contrast the deep structural crisis. Eco-innovation of production processes and the valorisation of pasture-based livestock systems can be a key strategy to improve the farms competitiveness and to promote the typical Mediterranean dairy sheep products in a green way. For this purpose, research studies are needed in order to assess the environmental implications of Mediterranean sheep systems with a holistic and site-specific approach. The main objective of this study was to compare the environmental performances of two contrasting sheep milk production systems, by using a Life Cycle Assessment (LCA) approach. The LCA was carried out in a farm where, along ten years, a conversion from arable and irrigated crops to native and artificial pastures and a reduction of total mineral fertilizers supply occurred. The analysis was conducted using 1 kg of Fat and Protein Corrected Milk (FPCM) as functional unit and Carbon Footprint-IPCC and ReCiPe Endpoint as evaluation methods. The LCA study highlighted that the change from a semi-intensive to a semi-extensive production system had a slight effect on the overall environmental performances of 1 kg FPCM, because of the dominant impact of enteric fermentation in both systems. The Carbon Footprint was on average 3.12 kg CO2eq per kg FPCM and the average score of the ReCiPe Endpoint was 461 mPt per kg FPCM. Methane enteric emissions and the use of imported soybean meal resulted the main environmental hot spots.

INTRODUCTION

The dairy products scenario described by the last OECD-FAO (2015) baseline projection attributes to the sheep sector the most dynamic trend with an expected production increase of 23%, 2024 relative to 2012-14. Europe with a contribution of 34.8% is the second continent in the world for sheep milk production, after Asia that contributes for 44.4%. Considering the per capita sheep milk annual production, Europe is by far the world's biggest producer: 3.9 kg per inhabitant versus a worldwide production of 1.3 kg per inhabitants (Zygoyiannis, 2006). The European sheep milk production is concentrated in Central and Southern regions (Czech and Slovak Republics, Hungary, Romania, Greece, France, Spain and Italy) where the dairy sheep farming plays a crucial cultural, economic and ecological role, in particular in marginal rural areas. Structural data indicate Sardinia (Italy) among the leading regions for the sheep milk production: 3.2 million ewes and 14,000 dairy sheep farms (Anagrafe Nazionale Zootecnica, 2016) provide about 330,000 t year^{-1} of milk, and a surprising per capita annual production of 201.2 kg of sheep milk per inhabitants (ISTAT, 2012). In fact, the dairy sheep breeding, driven by the export of Pecorino Romano PDO cheese, represents one of the main sector of the whole Sardinian economy. Similarly to other Mediterranean regions, contrasting dairy sheep farming systems coexist in Sardinia, with differences in input utilization, land use and intensification level. These differences depend on several factors, such as geographical location of farms, specific market conditions and others external factors such as public incentive policies and local or global market trends (Biala et al., 2007). For instance, during the 80's, in order to increase the farm productivity, the development of intensified production systems occurred especially in Sardinian lowlands, where the possibility of irrigation contributed to the spread of highly-yield forage crops like maize (for silage), lucerne and hybrid forage sorghum (Fois et al., 2001). Afterwards, since the early 2000s - when the Sardinian dairy sheep farming sector suffered a deep structural crisis, following the collapse of Pecorino Romano PDO price - many farmers tried new ways to reduce production's costs and the main solution was an overall production system extensification (i.e. lower use of concentrates, agrochemicals, agricultural machines, etc.) (Porqueddu, 2008). Nowadays, the greening process of agriculture and livestock supply chain, supported by EU climate change policies and driven by the increasing demand of environmental-friendly agri-food products, gives an additional importance to the environmental implications of production systems into marketing and production farming strategies. In this scenario, the Sardinian dairy sheep sector and the whole Mediterranean livestock supply chain can find new opportunities to improve their competitiveness through the eco-innovation of production processes and the valorisation of typical livestock products. Therefore, more research is needed in order i) to assess and improve the environmental performances of dairy sheep systems with a comprehensive approach (Vagnoni et al., 2015) and ii) to better explore the relationship between sheep farming and climate change (Marino et al., 2016; Wiedemann et al., 2015). FAO showed several differences in greenhouse gases (GHG) emissions from small ruminant sector, according to the geographical regions, the agro-ecological zones and the grassland/mixed-based production systems. Regarding milk production, Africa and Asia were identified as the bigger GHG emitters per kg of milk, thus suggesting that the highest productivity of most intensive farming systems adopted in the industrialized countries would lead to better environmental performances (Opio et al., 2013). However, there is not clear scientific evidence showing that extensive systems, at least at farm scale, are really preferable to more intensive one from an environmental point of view. Several studies showed lower environmental impact of extensive over intensive farming systems, focusing on complex processes that affect yield, resource consumption and emissions (Bailey et al., 2003; Casey and Holden, 2006; Haas et al., 2001; Nemecek, 2011, Vagnoni et al., 2015). Extensive agriculture may help in mitigating some negative environmental impacts caused by intensive livestock systems, such as consumption of fossil energy resources, demand for macroelements, global potential warming, loss of biodiversity, degradation of soil quality (Biala et al., 2007). On the other side, the introduction of various low-input techniques, i.e. manure fertilisation, mechanical weeding, no-till agriculture and so on, in some cases was demonstrated to have the opposite effect (Basset-Mens and Van Der Werf, 2005; Brentrup et al., 2004; Michael, 2011). This work is intended to serve to fill these knowledge gap, investigating with a Life Cycle Assessment (LCA) approach (De Boer, 2003; Hayashi et al., 2006) if and how the adoption of a low input production system may result in an effective variation of environmental impacts at farm level. In particular, the main scope of this study was to compare the environmental impacts of two contrasting sheep milk production systems carried out in the same farm in different years.

METHODS

Characteristics of the two production systems

The case study was a dairy sheep farm located in Osilo (latitude and longitude, elevation) (Province of Sassari), North-western Sardinia. In terms of dimension, productivity and capital good, the farm is representative of sheep farms operating in Sardinian hilly areas. The climate is Mediterranean with an average annual rainfall amount of 550 mm, and mean monthly temperatures ranging from 10 to 26 °C. The data refer to 2001 and 2011 years when the two different farming systems were adopted. The experimental data, collected using a specific questionnaire, derived from farm records, several visits *in situ* and farmer interviews. In 2001, the farm was characterized by a foraging system based on cereal crops (wheat and barley grain), annual forage crops (ryegrass/oat mixture, mainly) and irrigated maize for silage. From 2008 to 2011, a radical change in the farm management strategy occurred, facing the very low sheep milk price payed by the Sardinian cheese industries that seriously threaten the farm profitability. Therefore, the whole farm milk production was destined to on-farm "Pecorino di Osilo" cheese (included in the list of typical Italian agri-food products) manufacturing, instead of cheese industry. In addition, with the aim of reducing the production costs, the farm management moved to an extensification of forage production, with a larger use of natural and artificial pastures, valorising the role of native legumes-grasses mixtures and adopting low-input farming practices (minimum tillage, reduced use of fertilizers, etc.). Despite of many similar characteristics among the two different production systems (Table 1), such as number of heads, stocking rate, total utilized agricultural area and concentrates consumption, the 2001 production system was characterized by the use of irrigation for the maize crop (7 ha), a largest arable land area (73 ha) and a higher use of mineral fertilizers (182 kg ha^{-1}).

Regarding the farm milk productivity, the lower Feed Unit for Lactation (FUL) consumption in 2011 than in 2001 (-19%) led to a similar decrease (-16%) in milk per capita annual production: 257 and 307 kg ewe^{-1} year^{-1} in 2011 and 2001, respectively. Moreover, in 2011 production system, 75% of the total utilized agricultural area was destined to native and artificial pastures, on-farm maize production was interrupted and total mineral fertilizers were strongly reduced (about 80% less). At the same time, the farm no longer carried out the production of selected rams that, until 2001, represented an additional farm output. Starting from these features and focusing on farm forage production system, the farm production systems can be assumed as "semi-intensive" and "semi-extensive" in 2001 and 2011, respectively.

Table 1: Main characteristics of the two different production systems adopted by the same farm in 2001 and 2011.

	2001	2011
Heads (number)	340	320
Stocking rate (ewes ha^{-1})	4,6	4,6
Milk total annual production (kg)	104,234	82,214
Milk pro-capite annual production (kg ewe^{-1} year^{-1})	307	257
Feed Unit for Lactation, UFL (UFL ewe^{-1} year^{-1})	478	387
Pastures — grazing area (ha)	3	52
Arable land — cereals and annual forage crops (ha)	70	18
Total utilized agricultural area (ha)	73	70
Concentrate feed annual consumption (t)	105	98
Mineral N-fertilizing (kg ha^{-1})	72	8
Mineral P_2O_5-fertilizing (kg ha^{-1})	110	29
Irrigated maize (ha)	7	0
Irrigated lucerne (ha)	0	2.7
Milk destination	Cheese industry	On-farm cheese manufacture
Power source	Diesel generator	Electricity

LCA methodological issues

The LCA study was conducted in coherence with the international standards ISO 14040–14044, adopting a "from cradle to gate" approach and using 1 kg of Fat and Protein Corrected Milk (FPCM) as functional unit. The system boundaries included all inputs and outputs related to sheep milk production (Figure 1). Since the dairy sheep farm in addition to milk produced also meat, wool and rams (the latter only in 2001), an impact allocation of all inputs and outputs was performed by partitioning them between milk and the other co-products, on the basis of their economic value (Table 2). The economic allocation procedure was chosen considering the large economic value differences between the “main product” (milk) and the other co-products (wool and meat). This allocation method applied to sheep milk production tends to be similar to mass-based methods and to estimate a higher environmental impact than protein-based and energy-based methods (Mondello et al., 2016). All data were organized into a Life Cycle Inventory (LCI), the process that quantifies energy and raw material requirements, atmospheric and waterborne emissions, solid wastes and other releases for the entire life cycle of a product (SAIC, 2006).

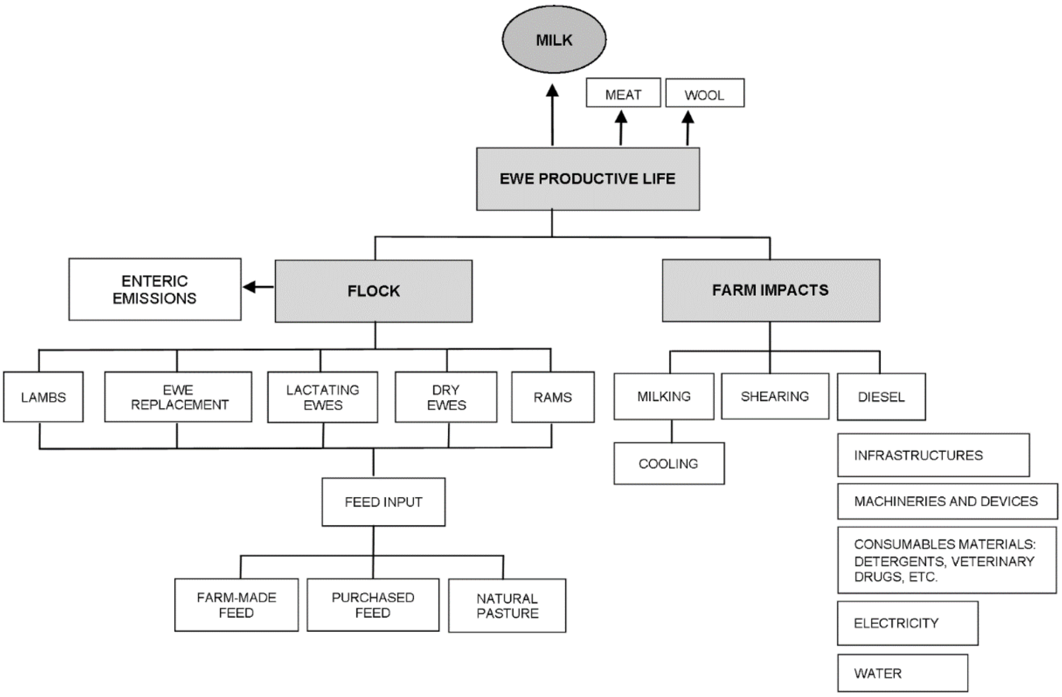

Fig. 1: Flow chart of sheep milk production (from Vagnoni et al., 2015).

Table 2: Percentages of economic allocation of co-products from 2001 and 2011 dairy farm's production systems.

Product	2001	2011
Milk	76%	91%
Lamb meat	10%	7%
Ewe meat	0%	1%
Wool	1%	1%
Rams	13%	--

The LCA methodology was detailed in Vagnoni et al. (2015). In summary, the analysis included the amount of fodder crops and pastures consumed by flocks, after crosschecking forage production and nutritional needs based on gender, age, weight, physiological stage and production level of animals. Enteric methane emissions were quantified using a detailed approach (IPCC Tier 2/3) based on Vermorel et al. (2008) and considering the total metabolizable energy ingested with the specific animal category diet. Moreover, soil carbon sequestration from natural grassland was not taken into account for lack of specific data. In order to consider a wide range of impact categories, two evaluation methods were utilized:

IPCC (IPCC, 2013), for the Carbon Footprint (CF) estimates, expressed in kg of CO_2-equivalents, and ReCiPe Endpoint (H) V1.12, which considers, besides the GHG emissions, others 17 categories of environmental impact (Goedkoop et al., 2009). LCA calculation was made using LCA software SimaPro 8.1.1 (Consultants PRé, 2016), which contains various LCA databases (Ecoinvent, Agri-footprint, etc.).

RESULTS AND DISCUSSION

LCI analysis

The LCI analysis of the total annual production of FPCM can give a first picture of the environmental implications and the main differences of the two production systems (Table 3).

Table 3: Inventory of the impact categories for the total annual production of FPCM for the two production systems.

Impact category	Unit	2001	2011
Water	m^3	13,409.9	6,595.2
CO_2	t	109.5	55.4
CO_2 biogenic	t	5.2	3.6
Methane	kg	236.0	128.9
Methane biogenic	t	5.6	4.8
Dinitrogen monoxide	kg	101.0	74.9
Phosphorus, in water	kg	15.6	14.6
Phosphate	kg	91.2	70.2
Sulphur Dioxide	kg	367.2	226.7
Isoproturon	kg	2.6	2.0
Nitrogen oxides	kg	560.3	270.5
Particulates	kg	113.9	79.4
Coal	t	16.1	9.8
Occupation industrial area	m^2year^{-1}	788.2	931.8
Occupation, arable, non-irrigated	ha	21.0	10.0
Occupation, arable, irrigated	ha	4.6	3.0
Occupation, grassland, natural	ha	9.9	28.9
Transformation from forest	m^2	80.8	126.8

The 2001 production system showed highest values for all considered impact categories, except for "Land transformation from forest", "Occupation of industrial area" and "Natural grassland use". The difference in "Land transformation from forest" may be explained by the different percentage contribution attributed to "soybean meal" process: 87% in 2011 instead of 57% in 2001 (Table 4). In particular, the 2011 animal diet was characterized by a greater use of soybean-based feed than in 2001. In our LCI construction, according to Ecoinvent database, we utilized for this process a soybean produced in Brazil, which has a strong impact on forest transformation into agricultural land (Moreno Ruiz et al., 2013). Similarly, the diet composition affected both the "Occupation of industrial area" and "Natural grassland use" impact categories. In the first case, the total impact was principally related to "cereals grain feed" production. In the second one, the total impact was influenced by the effect of a high utilization of natural pastures for the animal direct grazing.

Table 4: Percentage contribution of processes to the total value of "Transformation from forest" and "Occupation industrial area" impact categories related to Life Cycle Inventory of total FPCM annual production by 2001 and 2011 production system. The process category "Remaining processes" includes all the processes with a percentage contribution lower than 0.3%.

Impact category	Transformation from forest		Occupation industrial area	
Process/production system	2001	2011	2001	2011
Soybean meal	57	87	3	7
Protein pea	11	0	8	0
Cereals grain (barley, maize, wheat)	4	3	77	87
Machine operation, diesel	9	0	2	0
Transport (lorry and/or transoceanic freight ship)	6	4	2	2
Diammonium phosphate	3	0	2	0
Milking parlour	2	1	1	0
Urea	1	0	-	-
Tillage, ploughing	1	0	-	-
Electricity, medium voltage	0	1	-	-
Remaining processes	6	4	5	4

As shown in Table 5, the contribution of the direct grazing to this impact category is around

50% in 2011, while is only 23% in 2001, when the contribution to "Natural grassland use" was mainly due to the straw production for animal bedding (77%). On the other hand, "Water", "Nitrogen oxides" and "CO_2" were the impact categories that showed relevant differences (about twice) between 2001 and 2011 production systems. These results were consistent with the different overall input consumption of the two contrasting production systems.

Table 5: Percentage contribution of processes to the total value of Occupation natural grassland impact category related to Life Cycle Inventory of total FPCM annual production by 2001 and 2011 production system.

Impact category	Occupation natural grassland	
Process/production system	2001	2011
Natural grassland (hay and sheep grazing)	23%	69%
Straw (sheep bedding)	77%	31%

Carbon Footprint

The CF of 1 kg of FPCM was quite similar in 2001 and 2011 production systems, with values equal to 2.99 and 3.25 kg CO_{2eq}, respectively (Figure 2 and 3). Nevertheless, this result seems to agree with some findings reported in literature (Batalla et al., 2016; Gerber, 2013), where more intensive systems had a lower environmental impact per kg of product than extensive one.

Figures 2 and 3 show a detailed contribution analysis, which illustrates the main processes that contributed to total CF of each production system. IPCC method indicated that, for both production systems, enteric methane emissions was the most relevant process, representing up to 50% and more of the total GHG emissions. This result was consistent with FAO (2006) and several others studies, which clearly indicate enteric methane emissions as the main environmental hot spot in ruminant livestock sector. Thus, the reduction of methanogenesis from rumen fermentation represents a key factor for mitigation strategies in ruminants (Marino et al., 2016).

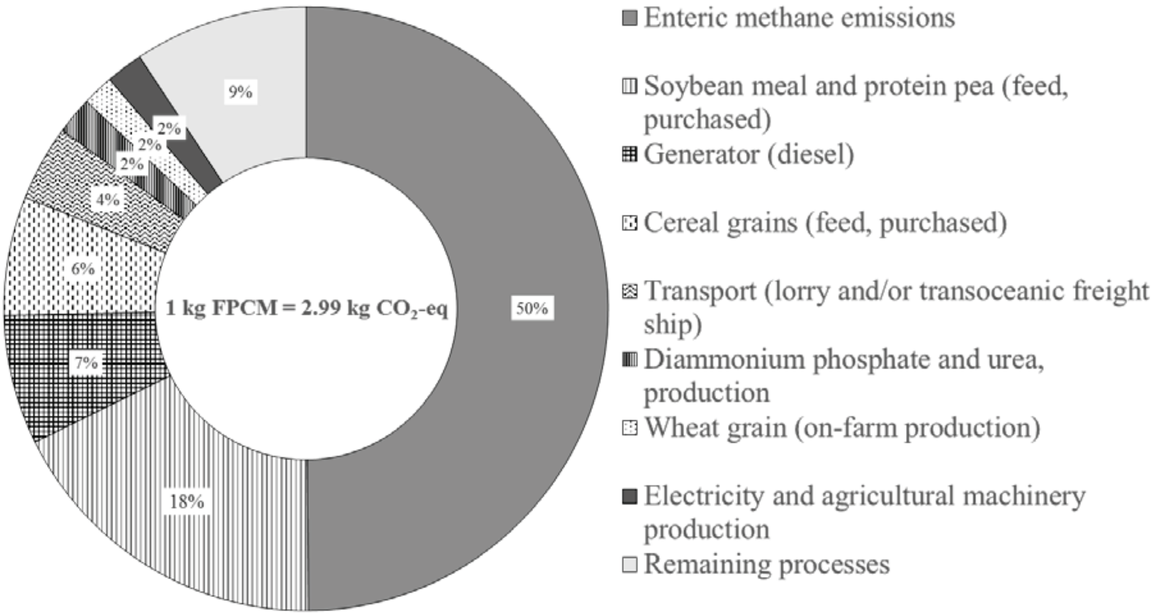

Fig. 2: Carbon Footprint (kg CO_{2eq}) and percentage contribution of inputs to GHG emissions for 1 kg of FPCM in 2001 production system.

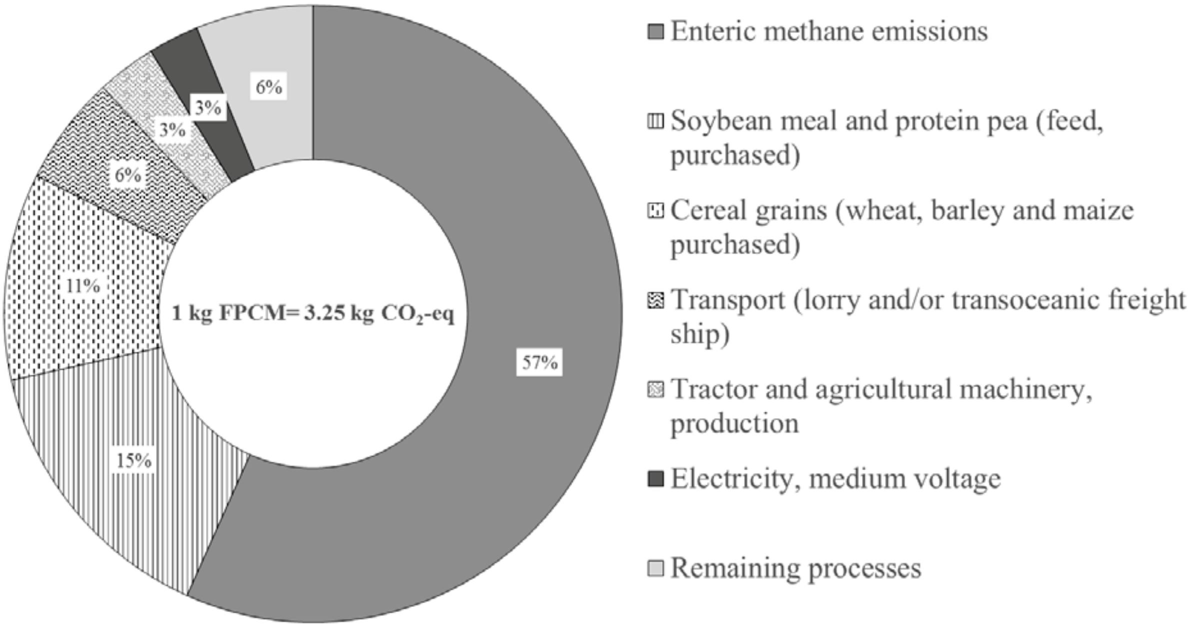

Fig. 3: Carbon Footprint (kg CO_{2eq}) and percentage contribution of inputs to GHG emissions for 1 kg of FPCM in 2011 production system.

On the other side, the estimates of enteric methane emissions per kg of FPCM represented an important difference between the two production systems. These estimates represented the ratio between FUL supply, from which enteric methane emissions are calculated, and milk pro-capite annual production. Therefore, the difference in enteric methane emissions reflected the contrasting management strategies adopted in the two considered periods. In 2001, the main scope of the farm was the maximization of productivity supported by a strong energetic feed supply; on the other hand, the input reduction was the farm priority in 2011. Summarizing the percentage contributions to total CF of each feed production process, we obtained the same value for the two production systems (26%), with a predominant influence of purchased feed (soybean meal, protein pea and cereals grain) with respect to on-farm feed production. This suggested that the increase of the locally produced feed supply may represent a step ahead towards a more eco-sustainable sheep farming system. The percentage contributions of the other processes reflected, in general, the contrasting technological context and farm management strategy, which characterized the two farming systems, such as power source (diesel generator in 2001 and public electricity in 2011), fertiliser use and agricultural machineries supply.

Recently, Batalla et al. (2015) and Vagnoni et al. (2015) assessed the CF of 1 kg of FPCM produced by semi-intensive and semi-extensive dairy sheep farming systems comparable with ours in terms of stocking rate and feed supply management. Batalla et al. (2015) estimated a CF ranging from 2.87 to 3.19 kg CO_{2eq} kg^{-1} FPCM in three semi-intensive systems with Laxta bred, and ranging from 2.76 to 5.17 kg CO_{2eq} kg^{-1} FPCM in six semi-extensive systems. In Vagnoni et al. (2015) the CF was equal to 2.2 CO_{2eq} kg^{-1} FPCM and to 2.3 CO_{2eq} kg^{-1} FPCM in a semi-intensive and a semi-extensive system, respectively. , These studies showed also a similar trend for IPCC method assessment results. However, it is important to highlight that the difference in global warming potential between semi-intensive and semi-extensive production system was statistically significant only in study conducted by Batalla et al. (2015). In addition, all case studies indicated that the largest contributor to the CF was the methane enteric emissions, although the present study indicates a larger contribution compared to Batalla et al. (2015) and Vagnoni et al. (2015), where the average percentage contribution was equal to 34% and 40%, respectively. This variability may be explained by the attribution of the different emission factors for enteric methane emission estimate. Vagnoni et al. (2015) adopted the methane emission rates for Italian sheep livestock fixed by ISPRA (2011) in 8.0 kg CH_4 ewe^{-1} $year^{-1}$. A similar rate, equal to 8.2 kg CH_4 ewe^{-1} $year^{-1}$ was used by Batalla et al. (2015) according to values estimated by Merino et al. (2011) for methane emissions from ruminant livestock in the Basque Country. In our study, an average of 22.6 kg CH_4 ewe^{-1}year^{-1} was estimated with a more farm-specific approach. In addition, in this study the average percentage contribution of purchased feed to total CF was lower than in Batalla et al. (2015) (25% and 34%, respectively).

ReCiPe Endpoint method

The ReCiPe Endpoint method results confirmed a small difference between the environmental performances of the two production systems. The semi-extensive (2011) production system resulted the most impacting one, with an environmental score 7% higher than the semi-intensive (2001) (Figure 4). For both production systems, the most relevant impact category was represented by "Agricultural land occupation", which resulted responsible of about 56% of the total estimated impact. In ReCiPe Endpoint method, "Agricultural land occupation" impact category expresses the amount of agricultural land occupied for a certain period of time, considering the effects of the land use, the amount of area involved and the duration of its occupation (de Roest et al., 2014). In our case study, the two production systems were very similar in terms of total agricultural land and duration, but different when considering land use. The semi-intensive production system (2001) destined the whole total utilized agricultural area to arable crops, while the semi-extensive destined 75% of the total utilized agricultural area destined to extensive grazed pastureland, characterized by native pastures and low-input artificial pastures. The ReCiPe Endpoint method simply translates the switching from arable land to extensive grazed pastureland in the 2011 as a change of land occupation and transformation, as evidenced by LCI (Table 3), attributing a consequent environmental impact, without ascribing any differentiation between high input crops (i.e. annual forage crops) and extensive grasslands. These results confirm that LCA analysis in the agricultural sector may emphasize critical aspects when agricultural land occupation and, more generally, land use impact categories are investigated (Schmidinger and Stehfest, 2012). Other relevant impact categories for both production systems were "Climate change — Human Health", with an average value equal to about 17%, and "Climate change – Ecosystems", which was responsible in average for about 11% of the overall impact (Figure 4). Other impact categories were responsible for less than 10% of the total score. The impact categories with scores less than 1 mPt ("Remaining categories") represented less than 1% of the overall scores.

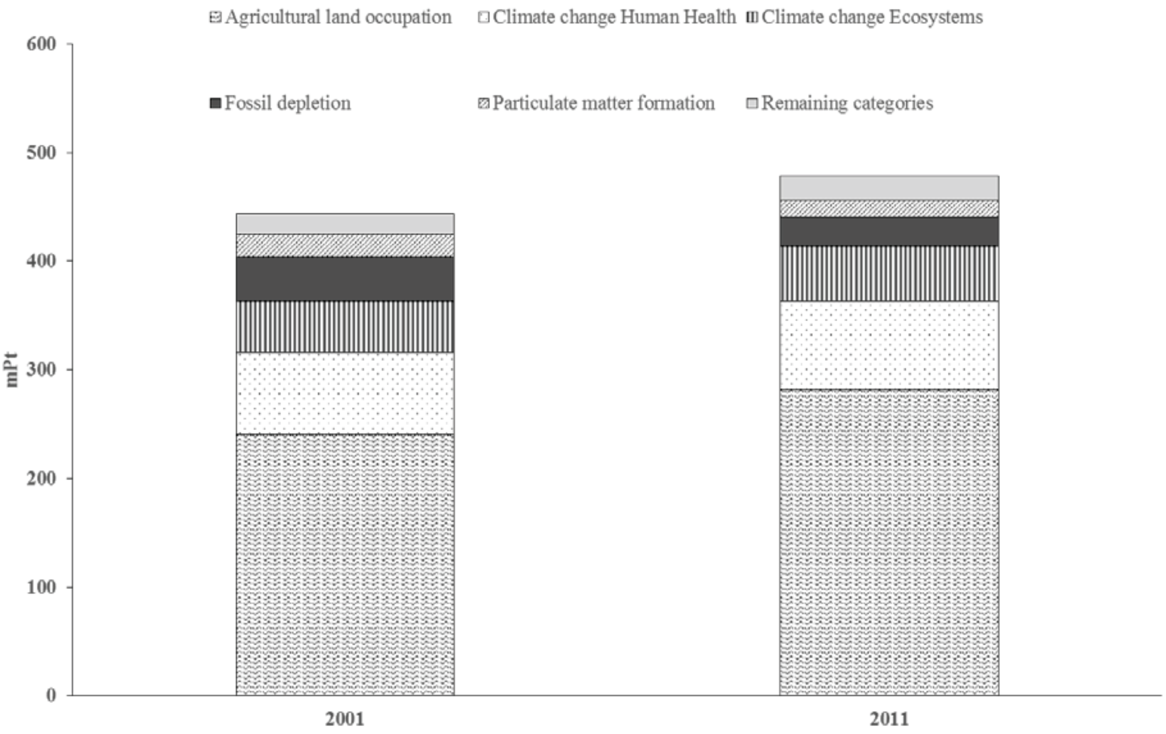

Fig. 4: Mean values obtained using the ReCiPe end-point impact assessment method for the functional unit 1 kg of FPCM for 2001 and 2011 production systems. Impact effects are expressed in milli-ecopoints (mPt). Impact categories with scores lower than 10mPt are included in the group ”Remaining categories”.

Regarding the percentage contributions to the environmental impact of 1 kg of FPCM, in the 2001 production system, when farm forage production was characterized by a more intensive management, ReCiPe Endpoint method highlighted the relevant role played by protein feed purchased (soybean meal and pea), which represented 30% of the total impact (Table 6). On the other hand, for 2011 production system the percentage contributions were shared in several processes such as soybean meal (17%), cereals grain (15%), improved pastures (15%) and enteric methane emissions (14%).

None of recent LCA studies regarding dairy sheep sector (Biswas et al., 2010; Ripoll-Bosch et al., 2013; Jones et al., 2014; Wiedemann et al., 2015; Zonderland-Tomassen et al., 2014), have explored the environmental performances following the changing of production inputs in dairy sheep farms. Anyway, a few studies discussed some results facing the topic of extensification of dairy sheep farms. For example, Janssens et al. (2005), studying the effects of switching arable soils to pasture and grassland adoption, showed an enhance of carbon inputs to the soil and a reduction of soil disturbance, estimating a carbon sink and soil carbon sequestration of improved pasture of about 1 t CO_2 ha^{-1} y^{-1}. Also, Batalla et al. (2015) reported the importance of the reseeding of legume-based mixture for grassland preservation purposes.

In our case study the substitution of irrigated maize and wheat with low input forage crops, such as oat/ryegrass forage crops and legume-based artificial pastures, only slightly improved the overall environmental performances of the farm, as demonstrated by ReCiPe Endpoint method results. These findings are consistent with Soteriades (2016), who stated that average eco-efficiency of dairy farms enhances when the percentage of maize for silage in the total forage area is reduced. According to Basset-Mens et al. (2009) and Rotz et al. (2010), the low input techniques related to grassland, requiring less fertilization and field operations than arable land, have lower environmental impacts from eutrophication, acidification, greenhouse gas emissions and non-renewable energy use on grass-based farms.

Table 6: Percentage contribution of processes to the total environmental impact of 2001 and 2011 production system, using ReCiPe Endpoint evaluation method 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 both production system.

Process/production system	2001	2011
Soybean meal and protein pea (feed purchased)	30	17
Wheat (on-farm production)	13	0
Enteric methane emissions	12	14
Improved pastures	8	15
Straw (sheep bedding)	5	8
Cereals grain (maize, barley and wheat purchased)	9	15
Generator (diesel)	5	0
Maize silage (on-farm production)	4	0
Natural grassland (hay and sheep grazing)	2	17
Diammonium phosphate, production	1	0
Transport (lorry and/or transoceanic freight ship)	2	4
Tractor and agricultural machinery, production	1	3
Electricity, medium voltage	0	2
Remaining processes	8	5

Finally, combining IPCC and ReCiPe Endpoint methods, our study gives some interesting information on the environmental consequences of adopting low input/extensive foraging strategies. For instance, the methane enteric emissions and the use of imported soybean meal resulted the main environmental hot spots considering both evaluation methods. As a consequence, the environmental performances of the analysed sheep milk production systems could be improved by moving along two main directions: i) on a major extent, by operating on livestock diet and metabolism, in view of using forage species capable to reduce animal methanogenesis (Hopkins and Del Prado, 2008; Puchala et al., 2005; Piluzza et al., 2013; Tavendale et al. 2005; Woodward et al., 2001), ii) by increasing the acreage of low input and high quality pasture and amount of the self-produced feed in the flock diet (Franca et al., 2008; Porqueddu and Maltoni, 2005). Moreover, in a further perspective of farm management, the conversion of arable crop to grasslands may be facilitated by the current EU agricultural policy, in relation to the funding of greening measures (Matthews, 2013).

CONCLUSIONS

In this paper, the environmental impacts of two different sheep milk production systems carried out in the same farm but in different time were compared using the LCA methodology. The IPCC and ReCiPe Endpoint evaluation methods highlighted that the change from a semi-intensive to a semi-extensive production system had a negligible effect on the overall environmental performances of 1 kg FPCM. The Carbon Footprint was on average 3.12 kg CO_{2eq} per kg FPCM and the average score of the ReCiPe Endpoint was 461 mPt per kg FPCM. For both production systems and evaluation methods, the methane enteric emissions and the use of imported soybean meal resulted the main environmental hot spots. The LCA approach demonstrated that the reduction of farm input level related to the forage supply system of a Mediterranean dairy sheep farm did not directly translate towards an environmental performance improvement because of the predominant effect of enteric fermentation with respect to others impact factors. However, more information and data from future research studies is needed to better assess and define the environmental implications related to i) the relationship between sheep breed, diet composition and methanogenesis, and ii) land use in the Mediterranean sheep farming systems.

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CHAPTER 3 - ENVIRONMENTAL PERFORMANCES OF SARDINIAN DAIRY SHEEP PRODUCTION SYSTEMS AT DIFFERENT INPUT LEVELS

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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 CO2eq, largely due to enteric fermentation. The main difference 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.

INTRODUCTION

The significant role of the animal production in the global climate change scenario has been clearly assessed by international organization and environmental advocacy groups oriented by several scientific research on livestock sector GHG emissions (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 cow systems (de Boer, I.J.M, 2003; de Vries et al., 2015; Soteriades et al., 2016) because of its essential function as protein food source and for their relevant contribution in global methane and nitrogen dioxide emissions. Otherwise, less attention has been dedicate to the environmental implications analysis of sheep and goats systems despite its increasingly significance in the current and near future environmental and socio-economic dynamics. At global level, the greenhouse gas (GHG) emissions of small ruminant sector account around 0.5 Gt CO_{2eq}, representing 6.5% of overall livestock emissions. In particular, the enteric methane emissions from world sheep population represent over 6.5% of the whole livestock sector. Moreover, correlating the total emission of CO_{2eq} to the unit of protein produced, the milk and the meat produced by small ruminants (with 165 and 112 kg CO_{2eq} kg protein^{-1}, 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 2,200 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 expected production increasing more than 20% compared to the previous 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 cover an important portion of the agricultural land in some European countries (31% in the UK, about 20% in Ireland, Spain, Romania and Italy) and play a crucial role, both in economic and environmental terms, in many disadvantages zones of Mediterranean regions (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 the 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 in industrial manner. The Sardinian milk sheep 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 cheeses 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 industry (the first five cheese-makers transform 45% of total production) represent a structural weakness and a serious threat for the whole Sardinian agro-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. Therefore, more specific data are needed in order to promote effective greening strategies at both territorial and dairy farm/plant level. The main works published in the international literature concern the identification and quantification of the environmental effects of sheep milk production in 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 they 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. (2016) analysed using an eco-indicator 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 a LCA approach in which shelf life and food loss probability were included.

The main scope of this study was to develop environmental knowledge about the Sardinian sheep milk cheese supply chain, using a life cycle approach with the following specific goals: 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.

MATERIALS AND METHODS

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 natural cultures of lactic ferments indigenous to the area of production, 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 25-40 cm and the diameter of top and bottom between 25-35 cm. The weight of the rounds can vary between 20-35 kg. The taste of the Pecorino Romano PDO is aromatic, lightly spicy and tangy in the table cheese, intensely spicy in the grated cheese. After a minimum maturation period of 5 or 8 months, Pecorino Romano PDO can be used as a table or grating cheese, respectively.

Pecorino di Osilo is a typical cheese of a small area of the province of Sassari (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 9-13 cm, a diameter between 14-22 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. Is used mainly as table cheese but also for grating. Pecorino di Osilo is quite similar to Pecorino Toscano PDO in main product and cheese-making features.

Case studies

Data were collected during 2013 in the following cheese factories, which can be considered representative of each production system: “Allevatori di Mores Società Cooperativa” (“Coop. Mores”) for Pecorino Romano PDO produced at industrial scale; “Azienda Agricola Truvunittu” (“Truvunittu”) for Pecorino di Osilo manufactured on-farm in a semi-artisanal manner. The two dairy sheep factories are quite contrasting in all items (Table 1). They represent, in fact, the main crossroad on farm management that every Sardinian sheep breeder have to deal with: sold the whole farm milk production to cheese industries accepting the price set by them or transforming on-farm the milk in order to increase the valued added of own production.

“Coop. Mores” is a medium-large dairy sheep industry located in Mores (province of Sassari), 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 Pecorino Romano PDO 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 (Province of Sassari), 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” Pecorino di Osilo 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.

Table 1: Main characteristics of the two dairy sheep factories.

	Allevatori di Mores Soc. Coop	Azienda agricola 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 $year^{-1}$)	5,011.5	301
Wastewater treatment, dairy plant	Municipal wastewater treatment plant	Application on field
Milk origin	Purchased from members and others Sardinian farmers	On-farm production
Milk processed (kg $year^{-1}$)	5,953,871	92,880
Products, total quantity (kg $year^{-1}$)	498,207	20,549
Products, type	Pecorino Romano PDO; 8 sheep milk cheese semi-coocked types; Ricotta cheese)	Pecorino di Osilo, Ricotta cheese, Fresh cheese type
Products destination (% of total quantity)	55% USA; 45% Italy	100% Local market

LCA methodology

The study has been 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 Pecorino Romano PDO, 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 was 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).

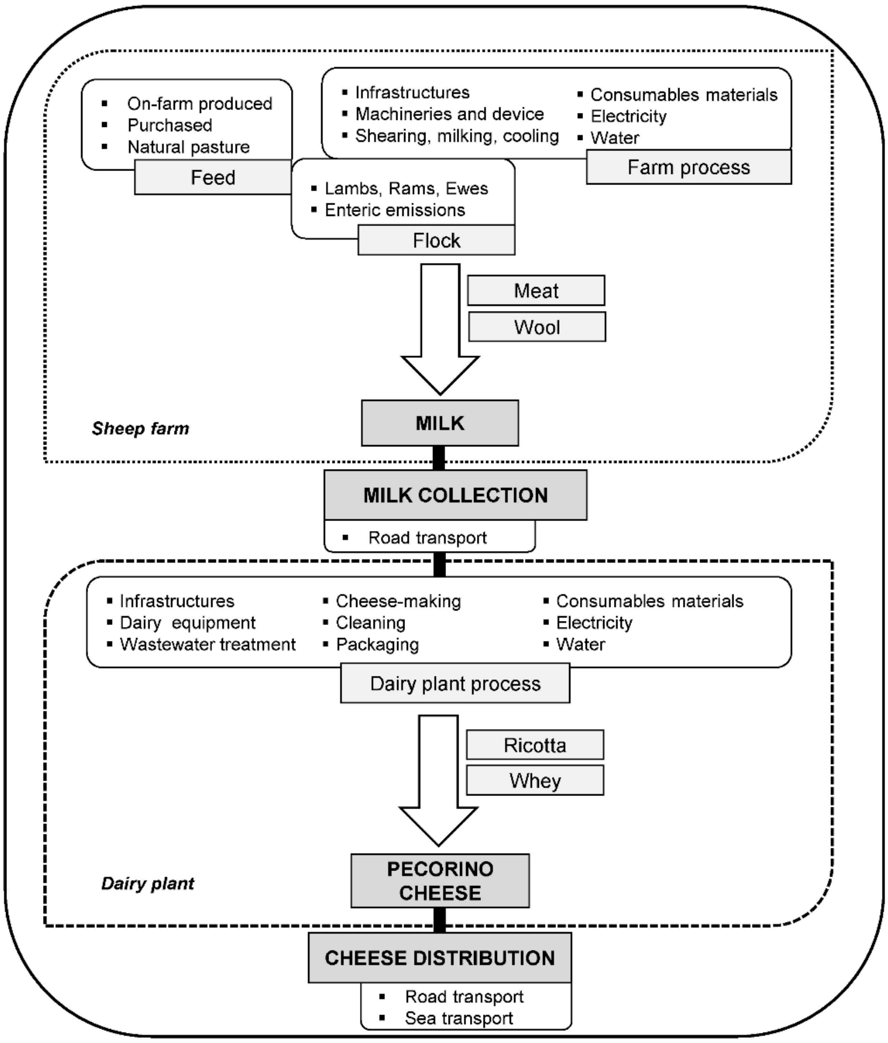

Fig. 1: System boundaries of the two Sardinian Pecorino cheese LCA study.

A previous work conducted by the same authors for 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. In particular, for Pecorino Romano PDO we considered a combination between milk produced with the three systems by applying a percentage that reflects the type of farms that belong to the “Coop. Mores” (at that time, the three farms studied in Vagnoni et al. (2015) were Cooperative’s members), namely: 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 Pecorino di Osilo we considered the milk produced by the mid-input farm because it is precisely the “Truvunittu” one. 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 step 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 Pecorino Romano PDO, a municipal wastewater treatment plant process by Ecoinvent v3.1 (Weidema et al., 2013) was used. In the case of Pecorino di Osilo, 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) emissions 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 for “Coop. Mores” (which has a specific production line for Pecorino Romano PDO); ricotta (fresh and smoked) and fresh cheese for “Truvunittu”.

Primary data were collected through company’s archive 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. Records were then organized in a specific questionnaire to facilitate the data incorporation. 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 impacts analysis. In order to assess in a more comprehensive way the environmental performances of sheep milk cheeses, 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-equivalents, and 2) CML-IA version 3.3 (Guinée et al., 2002) which consider, besides the GHG emissions, others 10 categories of environmental impact, i.e.: Stratospheric Ozone 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 eco-toxicity (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_{4eq}); Acidification potential (AP, expressed in kg of sulfur dioxide equivalent, kg SO_{2eq}); 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) .

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

	Allevatori di Mores Soc. Coop	Azienda agricola 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%

RESULTS AND DISCUSSION

Carbon Footprint

A small difference in 1 kg of cheese GHG emissions between dairy systems was founded, with the Pecorino di Osilo CF higher than Pecorino Romano PDO 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 Pecorino Romano PDO and Pecorino di Osilo, 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 Pecorino Romano PDO and Pecorino di Osilo 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 estimated for cheese distribution phase, for which the CO_{2eq} per kg of cheese calculated for Pecorino di Osilo was 5 time greater than Pecorino Romano PDO. As a consequence, the distribution phase represented about 3% of the total Pecorino di Osilo GHG emissions, and contributed only to about 0.6% in Pecorino Romano PDO CF. This result can be explained by the fact that the Pecorino di Osilo distribution concerned small quantities of product for several times, making the transporting operation less efficient, in general. In fact, 10.5 t of Pecorino di Osilo was distributed using a van car, covering 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 Pecorino Romano PDO distribution concerned the transport 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 Pecorino Romano PDO manufacturing process was 45% largest than Pecorino di Osilo that required few production input in addition to manpower. Similarly, milk collection had a tangible effect only for Pecorino Romano PDO total GHG emissions (with a contribution of about 0.7%) since the milk transformed by “Truvunittu” was entirely produced on-farm.

Table 3 illustrates all individual processes that contributed with more than 0.25% to the total GHG emissions of each cheese, i.e. the contribution analysis. This Table 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 Pecorino Romano PDO and Pecorino di Osilo 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 emissions 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% and 24% of the total Pecorino Romano PDO and Pecorino di Osilo 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 method adopted for Pecorino di Osilo required a small equipment stock. Otherwise, the road transportation contribution showed that milk collection and Pecorino Romano PDO distribution was more eco-efficient than Pecorino di Osilo distribution, due to the largest work capacity of the large vehicles utilized in Pecorino Romano PDO logistic management.

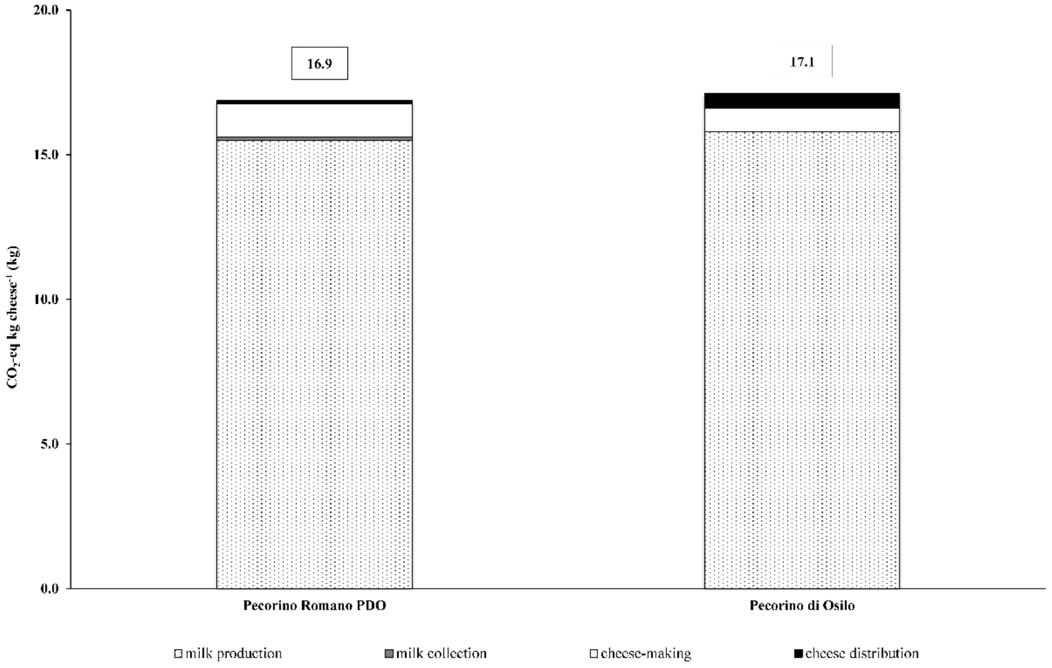

Fig.2: Carbon Footprint (kg CO_{2eq}) for 1 kg of Pecorino Romano PDO and Pecorino di Osilo life cycle.

Table 3: Percentage contribution of processes to the total GHG emissions of Pecorino Romano PDO and Pecorino di Osilo 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 system.

	Pecorino Romano PDO	Pecorino di Osilo
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 (mowing, baling, etc.)	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

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 Pecorino di Osilo (10 time lowest in number of rounds per year) and Pecorino Romano PDO (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_{2eq}, with the largest contribution of enteric fermentation. Excluding the distribution phase, the Sardinian cheese CF was equal to 16.7 kg CO_{2eq}, 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%.

CML-IA

The CML-IA evaluation method results indicated that Pecorino di Osilo showed lower environmental impacts than Pecorino Romano PDO for 7 of the 10 considered impact categories (Table 4). The difference between the environmental performances of the two dairy systems were more accentuated (a difference larger more 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%.

Table 4: Environmental impacts results associated to the production of 1 kg of Pecorino Romano PDO and Pecorino di Osilo, using the CML-IA evaluation method.

Impact category	Unit	Pecorino Romano PDO	Pecorino di Osilo
Abiotic depletion (minerals)	kg Sb eq	$5.64 \cdot 10^{-5}$	$5.24 \cdot 10^{-5}$
Abiotic depletion (fossil fuels)	MJ	73.06	73.73
Ozone layer depletion (ODP)	kg CFC-11 eq	$8.41 \cdot 10^{-7}$	$7.22 \cdot 10^{-7}$
Human toxicity	kg 1,4-DB eq	10.74	4.14
Fresh water aquatic ecotox.	kg 1,4-DB eq	3.59	2.58
Marine aquatic ecotoxicity	kg 1,4-DB eq	5,928	4,876
Terrestrial ecotoxicity	kg 1,4-DB eq	0.05	0.03
Photochemical oxidation	kg C_2H_4 eq	0.005	0.005
Acidification	kg SO_2 eq	0.05	0.04
Eutrophication	kg PO_4--- eq	0.04	0.05

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 two 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 chain 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 (Fig. 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}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 was quite different and highlighted how the contrasting production scale affected distinct impact categories (Table 4 and 5; Fig. 3 and 4). For Pecorino di Osilo, the largest toxic emissions were related to milk production, with a very high contribution for all impact categories. For Pecorino Romano PDO, 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_{4eq} kg cheese^{-1}. The lowest POCP value was estimated for PDO Pecorino Romano, with a difference less than 1% with respect to Pecorino di Osilo POCP score. 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 (Fig. 3 and 4) closely followed by feed purchased. These processes summarized jointly 71% and 76% of the total POCP for Pecorino Romano PDO and Pecorino di Osilo, respectively.

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

Acidification potential results indicated that Pecorino Romano PDO was slightly more impacting because of the largest SO_{2eq} kg cheese^{-1} emission compared to Pecorino di Osilo 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 Pecorino Romano PDO and Pecorino di Osilo AP, respectively - also represented key factors (Fig. 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 AD of 1 kg of cheese was strongly lower (about 390 g SO_{2eq} versus about 45 g SO_{2eq} 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 Pecorino Romano PDO, with a margin of about 13 g PO_4^{3-} (which represent about 27% of Pecorino di Osilo 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 Pecorino Romano PDO and equal to 69% for Pecorino di Osilo (Fig. 3 and 4). However, the direct wastewater on field application and the large use of purchased feed by "Truvunittu", determined that the EP of Pecorino di Osilo was higher than Pecorino Romano PDO. The main role of milk production phase was consistent with the considered references (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 PO_4^{3-} which was very similar to this obtained in our study, in particular for Pecorino Romano PDO.

Table 5: Percentage contribution of production phases to the environmental impacts of Pecorino Romano PDO and Pecorino di Osilo life cycle, using CML-IA evaluation method and 1 kg of cheese as functional unit.

Impact category	**milk collection**	**milk production**		**cheese-making**		**cheese distribution**	
	Pecorino Romano PDO	Pecorino Romano PDO	Pecorino di Osilo	Pecorino Romano PDO	Pecorino di Osilo	Pecorino Romano PDO	Pecorino di Osilo
Abiotic depletion (fossil fuels)	2	76	76	19	14	2	10
Human toxicity	0	32	79	68	9	0	12
Fresh water aquatic ecotox.	0	58	80	42	8	0	12
Marine aquatic ecotoxicity	1	63	79	36	12	0	9
Terrestrial ecotoxicity	0	80	92	20	5	0	3
Photochemical oxidation	0	92	95	7	3	1	2
Acidification	1	83	88	13	8	3	4
Eutrophication	0	95	78	5	21	0	1

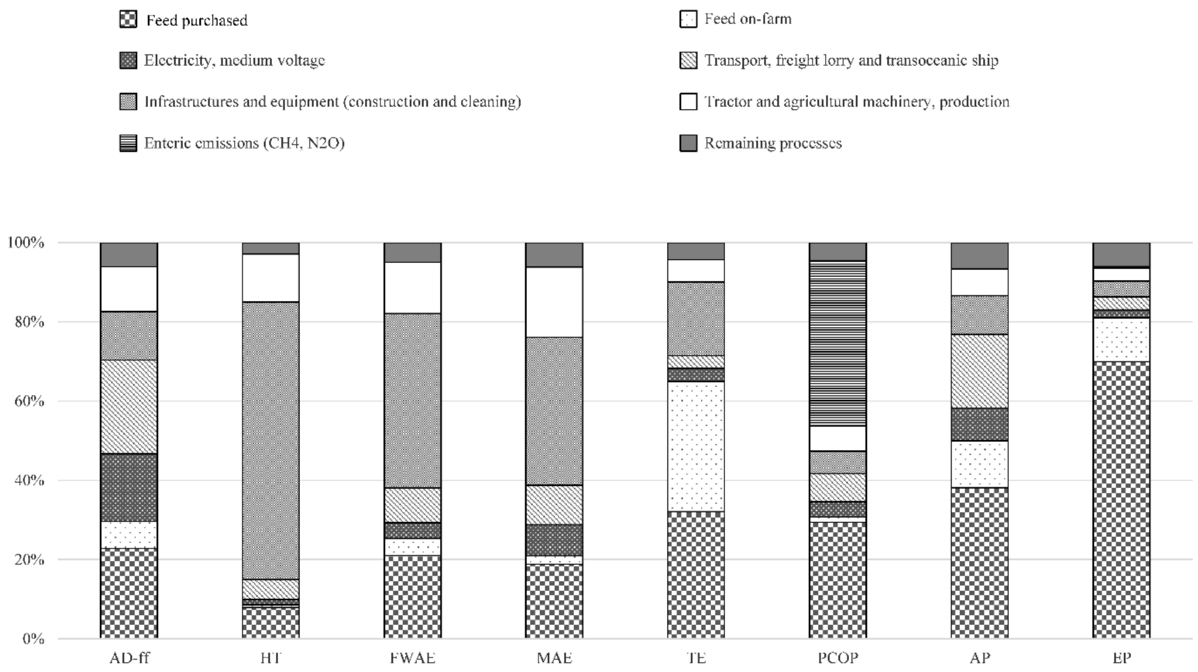

Fig.3: CML-IA evaluation method results (in %) for each impact category and process involved in the Pecorino Romano PDO life cycle. Impact category acronyms: AD-ff =Abiotic Depletion fossil fuel, HT = Human Toxicity; FWAE = Fresh Water Aquatic Eco-toxicity, MAE = Marine Aquatic Ecotoxicity, TE = Terrestrial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

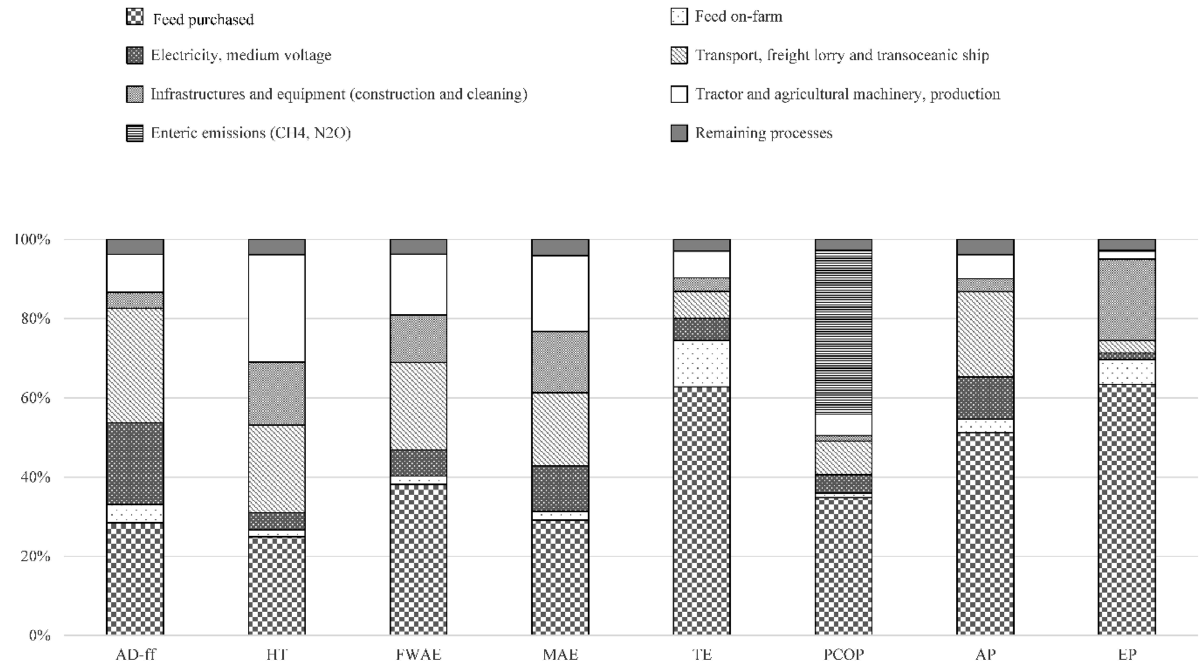

Fig.4: CML-IA evaluation method results (in %) for each impact category and process involved in the Pecorino di Osilo life cycle. Impact category acronyms: AD-ff =Abiotic Depletion fossil fuel, HT = Human Toxicity; FWAE = Fresh Water Aquatic Eco-toxicity, MAE = Marine Aquatic Ecotoxicity, TE = Terrestrial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

Performances improvement remarks

In order to propose substantial improvements in the environmental performances of each dairy farm/plant, the hot spot identified through the contribution analysis for the two evaluation method were considered. The discussion about solutions dealing with the increasing of productivity and yield of production processes was avoided.

The improvement of 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.

Mitigation of 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 mitigation strategies 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. The authors finally concluded that it will be necessary to focus on both mitigation and adaptation actions. In our case studies, strategies to mitigate 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) use of forage species that can mitigate the methane production in sheep rumen (Hopkins and Del Prado, 2007; Puchala et al., 2005; Tavendale et al., 2005), ii) increase the amount of on-farm produced feed instead of soybean and others protein based products imported from distant countries, and iii) grazing system intensification by increasing low input and high quality pasture surfaces and by improving grazing management (Becoña et al, 2014; Franca et al., 2008; Picasso et al., 2014). Moreover, for “Truvunittu” dairy farm is suggested to adopt a wastewater treatment process in order to reduce pollutants emissions.

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 Pecorino Romano PDO^{-1}. This performance was consistent with some dairy systems, i.e. as reported by González-García et al. (2013), where electricity consumption was equal to 0.71 kWh kg cheese^{-1}, and ENEA (2007), which calculated an average consumption for the Central Sardinia dairy sector equal to 0.76 kWh kg^{-1}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 cheese^{-1}. For “Trunuvittu” dairy farm, characterized by a low cheese production amount, the electricity use per FU was even more higher than “Coop. Mores” and reached 1.12 kWh kg Pecorino di Osilo^{-1}. Therefore, an effective power supply strategy based on an accurate energy audit is recommended, in particular for the semi-artisanal dairy system. In addition, the equipment stock of the industrial system seemed underexploited or oversized considering their relevant role in the environmental performance of Pecorino Romano PDO.

CONCLUSIONS

This work provided some environmental knowledge about the Sardinian dairy sheep supply chain, comparing 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 a 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_{2eq}. For both dairy systems the main source of GHG emissions was milk production phase within a dominant role of enteric methane and a relevant contribution by imported feed, electricity and transportation. The main difference between the two dairy systems environmental performances were founded for human- and eco- toxicity, as well as eutrophication impact categories. Toxic emissions by the semi-artisanal cheese production process were mainly related to fertilizer and pesticide used for feed production (milk production phase). Otherwise, for Pecorino Romano PDO dairy infrastructures and equipment (cheese-making phase) were also relevant sources of toxics emissions. Feed production was the largest source of eutrophication in both systems and the lack of wastewater treatment indicated Pecorino di Osilo as the most impacting one.

According with several LCA studies on dairy sector, the farm activities played the most relevant role in the overall environmental performances, with the only exception in human toxicity category for Pecorino Romano PDO. Therefore, looking for the environmental profile improvement of the Sardinian sheep milk cheese sector, enteric fermentation mitigation and feed supply chain optimization seem as clear priorities. Moreover, a power supply high efficient and/or more green-energy based, 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 improvement at the dairy plant and represent further important steps towards a more eco-sustainable dairy system. However, this study involved only two case studies 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 (environmental services) produced by the pasture-based farming systems.

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CONCLUSIONS AND FUTURE PERSPECTIVES

As climate change mitigation and circular economy promotion are at the top of the European agenda, agriculture is required to reduce GHG emissions and to satisfy the growing food global demand with a minimal environmental impact. In particular, the livestock sector has come into spotlight because of it is universally acknowledged its contribution to climate change and, at the same time, it is a crucial source of protein based food. Within several research initiatives, the environmental implications of small ruminant systems gained less attention than the cattle farming sector, even though sheep and goat population is increasing worldwide over the past decade and its contribution to overall livestock GHG emissions seems quite significant. Moreover, sheep production is an important sector for many European countries, where it often represents the only feasible economic activity in inland areas and plays a crucial role in socio-economic and environmental terms. Detailed scientific knowledge is needed in order to promote effective GHG mitigation strategies and to optimize the environmental performances of sheep systems. The major contribution of this thesis lies in filling in these knowledge and data gaps, allowing for a preliminary characterization of the environmental profile of the Sardinian dairy sheep supply chain. Three studies were conducted using a LCA approach, with the following specific goals: i) comparing the environmental implications of contrasting dairy sheep systems and ii) identifying the hotspots to improve the environmental performances of the Sardinian dairy sheep sector.

Three sheep milk farming systems at different input levels (Low-input, LI; Mid-input, MI; High-input, HI) were compared and their environmental hot spots were identified. The LCA analysis, conducted using 1 kg of Fat Protein Corrected Milk as functional unit and two different assessment methods (Carbon Footprint-IPCC and ReCiPe Endpoint), provided a comprehensive picture of the environmental impacts of sheep farming systems. The environmental performance trends 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_{2eq} per kg of FPCM) with not significant differences among farming systems. The ReCiPe Endpoint results showed scores ranging from 309 (LI) to 480 mPt (MI) and environmental performances of LI were significantly different compared to MI and HI farms. In general, this study showed 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 the ReCiPe Endpoint method the main factor determining the environmental impact was land use on natural and improved pastures.

The environmental impacts of two different sheep milk production systems adopted by the same farm were also compared using the LCA methodology. The IPCC and ReCiPe Endpoint evaluation methods highlighted that the transition from a semi-intensive to a semi-extensive production system had a negligible effect on the overall environmental performances of 1 kg FPCM. The average Carbon Footprint of 1 kg FPCM was equal to 3.12 kg CO_{2eq} and the average score of the ReCiPe Endpoint was 461 mPt per kg FPCM. For both production systems and evaluation methods, the methane enteric emissions (estimated using a more detailed approach than the *tier* 1 adopted in the previous study) and the use of imported soybean meal were found to be the main environmental hotspots. The LCA approach demonstrated that the reduction of farm input level related to the forage supply chain did not immediately result in improvement of environmental performances, because of the dominant role of enteric fermentation.

Finally, the environmental profile of 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 compared using the LCA method ("from cradle to retailer" approach and Carbon Footprint-IPCC and CML-IA evaluation methods). The Carbon Footprint of 1 kg of the two cheeses were similar, with an average CF value equal to 17 kg CO_{2eq}. For both diary systems, the milk production phase was the largest contributor to total GHG emissions. In particular, enteric methane was the main GHG emissions source and imported feed, electricity and transportation represented other relevant processes. The main difference between the two dairy system environmental profiles were founded for human toxicity, ecotoxicity and eutrophication potential impact categories. Toxic emissions by Pecorino di Osilo life cycle were mainly related to fertilizer and pesticide used for feed production (milk production phase). As far as the Pecorino Romano PDO, dairy infrastructures and equipment (cheese-making phase) were also important sources of toxics emissions. Feed production was the largest source of eutrophication in both systems and the lack of wastewater treatment indicated Pecorino di Osilo as the most impacting one.

In line with several LCA studies on dairy sector, the farm activities played the most relevant role in the overall environmental performances, with the only exception of the human toxicity category for Pecorino Romano PDO.

In conclusion, with a view to achieving climate change mitigation targets and higher environmental performances of the Sardinian dairy sheep sector, enteric fermentation reduction and feed supply chain optimization appear to be the most viable solutions. In addition, a power supply more efficient and/or more green-energy based, a proper sizing of the equipment stock, the use of less pollutants cleaning agents, as well as the adoption of cleaner wastewater management in small dairy farms, are strategic improvements at dairy plant level. On the other hand, additional studies are needed to better assess the environmental implications of Mediterranean sheep systems with a solid site-specific approach. In particular, future research will be addressed to i) explore in detail the relationship between sheep breed, diet composition and enteric methane emissions, ii) estimate carbon sequestration from crops and grasslands, and iii) assess the ecosystems services of pasture-based farming systems (biodiversity and landscape maintaining, environmental risks reduction, etc.).

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