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Management options to reduce the environmental impact of dairy goat milk production

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ABSTRACT

Although numbers are still low compared to cattle rearing, intensive dairy goat farms have been widely spreading in the Italian livestock systems. Since goats are quite rustic, they can easily adapt to different management practices; however, improving the efficiency can make the difference, both in productivity and on the environmental impact attributed to goat milk production.

In the present study, the Life Cycle Assessment (LCA) approach was used to quantify the potential environmental impact of goat milk production system in 17 farms in Lombardy (Northern Italy). Together with the environmental assessment, statistical analysis was carried out in order to determine whether it was possible to identify any relation among the variables that characterise this farming system.

From an environmental point of view, it has been shown that the lower the individual milk production, the more it affects the environmental impact: specifically, the carbon footprint appears higher than the one emitted by cattle milk production. Climate Change resulted, on average, equal to 2.67 kg CO_2 eq/kg Fat and Protein Corrected Milk (FPCM) with a wide variability (min: 1.12 kg CO_2 eq/kg FPCM; max: 5.05 kg CO_2 eq/kg FPCM). Purchased feed was the main hotspot for several environmental impact categories (such as freshwater eutrophication, land use and mineral, fossil and renewable resources depletion). Enteric emissions and emissions from manure storage were hotspots for climate change, particulate matter and terrestrial acidification. The C sequestration during crop cultivation was not considered. As shown by the statistical analysis, the main driver which influenced the 6 main impact categories was, in fact, individual milk production. The environmental assessment was also performed considering a second Functional Unit (FU) (i.e. 1 ha of land) and the statistical analysis conducted on this FU showed the relevance of livestock intensity. In addition to this, the statistical analysis also showed how a restricted land availability can negatively affect the environmental outcome. This study represents one of the first studies on the environmental impact assessment of dairy goat milk production. Additionally, studying two FUs and using a statistical analysis approach helped to identify the main management options to which farmers should pay attention to improve goat milk production from an environmental point of view.

1. Introduction

The livestock sector is responsible for 12% of greenhouse gas (GHG) emissions attributable to human activity (Havlík et al., 2014; IPCC, 2007). Dairy goats contribution to these emissions is of minor importance compared to the major livestock sectors of dairy cattle, beef, sheep and deer, due to the low numbers of goat farms and reared animals. Nevertheless, since climate change needs to stay within acceptable limits, every single production sector must reduce its carbon footprint (Robertson et al., 2015; O'Mara, 2011), and, more generally, its environmental impact.

In ruminants, it is widely known that improving animal and herd efficiency can lead to mitigate the environmental impact (Beukes et al., 2010; Marino et al., 2016) because several issues affect its sustainability; of these, the ruminal enteric methane is one of the main drivers. Moreover, the environmental sustainability of both extensive and intensive livestock production systems, characterised by a large availability of pasture and yearly confined animals, is a complex topic that includes environmental, economic, social, and institutional involvements (Peacock and Sherman, 2010). In particular, acidification and eutrophication of soils, water and air cannot be disregarded, especially

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in intensive livestock areas (Bacenetti et al., 2016). In addition, livestock farming is also characterised by problems related to particulate matter formation in the facilities (Tullo et al., 2019) as well as to the high use of feed concentrate mixes that affect the environmental sustainability, among which the land use (Bava et al., 2014; Stanley et al., 2018). among these, also goat farming is included.

The sustainable intensification of livestock systems can decrease GHG emissions (Bava et al., 2014) and improve food availability (Havlík et al., 2014; Udo et al., 2011). In recent decades, the interest on this topic has been increasing widely due to the concerns about environmentally sustainable production, the growth of population worldwide, and the consequent need of increasing food productions. Intensification can bring positive effects on the environment (Steinfeld and Gerber, 2010). However, some researchers identified positive externalities also in extensive systems that should be taken into consideration as a factor of mitigation of environmental impact, such as fire prevention and enhancement of biodiversity. Moreover, grazing leads to positive social implications, such as the maintenance of local traditions (Gelasakis et al., 2017; Gutiérrez-Peña et al., 2019). Nevertheless, the most popular method to quantify the environmental sustainability of processes or services is the Life Cycle Assessment (LCA). This method has spread worldwide in the last decades, however, for the agricultural assessments it still shows some gaps, such as the absence of metrics to assess benefits of biodiversity (Winter et al., 2017) and the still uncertain methodology on C sequestration evaluation (Stanley et al., 2018).

In 2011, sheep and goats produced more than 5 million tonnes of meat and 24 million tonnes of milk. Production has increased by 1.7% and 1.3% per year, respectively, during the past 20 years (FAOSTAT, 2013). Developing countries in Africa and Asia drove this increase, however, Oceania (mainly for meat) and Europe still contribute significantly to animal production.

Goat farming can be commonly found in less productive areas, where reduced attention to efficient productions is paid, and where low inputs availability is present (i.e. areas where high-income crops cannot be cultivated, or high-income animals cannot be reared). In particular, goats do not require high inputs in terms of feed and housing, therefore, they are generally spread in disadvantaged areas. In Italy, most of goat farms are reared in extensive or semi-intensive systems (Pulina et al., 2018). In recent years, however, they have started spreading in lowland areas with intensive farming systems (Sevi et al., 2009). The widest and most productive lowland area in Italy is located in the northern regions. Among these, Lombardy region has shown a great increase in the number of dairy goats in the last 10 years and produces nearly 16.5% of the total Italian goat milk production. This reflects the high specialisation of this region in milk production, both in cattle and goat rearing (Istat, 2017).

In this context, there still is plenty of room for improvement on efficient dairy goat production, most of all in terms of breeding and herd management, milk production and environmental sustainability.

In literature, there are still few studies about the environmental impact of small ruminant milk systems (McClelland et al., 2018) and most of them adopted gas estimation models (Weiss and Leip, 2012) for the environmental analysis. Robertson et al. (2015) showed that the average carbon footprint for indoor (intensive) dairy goat farms was lower than that of outdoor (extensive) dairy goat farming systems. Similarly, Batalla et al. (2015) showed that in the ovine species, milk production in semi-intensive systems was characterised by lower carbon footprint than the one emitted by semi-extensive systems. One of the main differences between the two livestock systems was also related to the higher milk production in the semi-intensive one. Nevertheless, authors also analysed a case in which soil carbon sequestration was considered, and the results showed no difference in the carbon footprint of sheep milk from different systems and breeds.

The goal of the present study is to analyse intensive dairy goat farming systems without grazing activity of Northern Italy, and to evaluate the environmental impact of goat milk production by means of the LCA approach in order to identify, through statistical analysis, the main management options to mitigate milk production impact.

2. Materials and methods

In this study, Life Cycle Assessment (LCA) approach was applied to assess the environmental impact of a sample of Italian intensive dairy goat farms, that is farms in which goats have no access to pasture. Finally, using statistical analysis, the linkages among farm management options and environmental impact were identified.

2.1. Life cycle assessment

LCA is the most widely applied method for quantifying the potential environmental impact of products and/or services and consists of four standardised phases (ISO 14040–14044, 2006), all of which are explained in the following paragraphs.

2.1.1. Goal and scope definition, functional units, system boundary and allocation procedure

The goal of this LCA study was to quantify the potential environmental impact of goat milk production in milk goat farms without pasture and evaluating the possible improvements on the herd management to make milk goat production more environmentally sustainable.

The Functional Unit (FU) selected was 1 kg of Fat and Protein Corrected Milk (FPCM) (3.5% fat and 3.4% protein) produced by the lactating goats. An equation modified by INRA (2018) was used to quantify goat FPCM. This choice was made in order to have standardised milk quality, and thus comparable results (IDF, 2015).

The equation by INRA (2018) that quantifies FPCM was modified for what regards the protein content of corrected milk. In the French system, true protein is the selected variable, while here it is substituted by crude protein content. In more detail, the equation is the following:

$$FPCM = Milk_{DEL}(0.26 + 0.1352fat\% + 0.079prot\%) \quad (1)$$

Where:

$Milk_{DEL}$ is the total delivered milk per year per farm (kg/y), fat% is the percentage of fat in the delivered milk (%), prot% is the percentage of crude protein in the delivered milk (%).

Additionally, given the huge variability in dairy goat farming and in the wide presence of both intensive and extensive farming systems, a second FU was considered. As second FU was selected 1 ha of land. This evaluation considered the total land of the studied farms for the production of forages and concentrate feed, as well as the land for the purchased feed that was included as secondary data for the land use assessment. This choice allowed comparing results with more studies such as Gutiérrez-Peña et al. (2019). However, the second FU was applied only to the studied farms with at least 1 ha of farm area ($n = 14$).

An attributional approach with a "cradle to farm gate" system boundary was adopted. All inputs (e.g., off farm feed and bedding, machinery, fuel, lubricant, organic and mineral fertilisers, pesticides and water) and outputs (emissions to air, soil and water, milk and meat) included in the system boundary are reported in Fig. 1.

Allocation between goat milk and meat was calculated following the recommendations by IDF (2015) and adopting Eq. (2). This is valid for any milking farm in which both milk and meat are produced, therefore, it can be applied to any animal category producing milk.

$$Allocatedmilk = 1 - 6.04(MT/ML)/100 \quad (2)$$

Where:

MT = mass of live weight (kg);
ML = mass of fat and protein corrected milk (kg).

2.1.2. Description of the system and inventory data collection

Seventeen intensive dairy goat farms were identified in Lombardy region, in Northern Italy. These farms were characterised by rearing a high number of heads (on average, 200 dairy goats) of cosmopolitan breeds (i.e. Saanen and Alpine) on a restrained lowland area (on average, 11.8 ha of Usable Agricultural Area, UAA) and they sold the

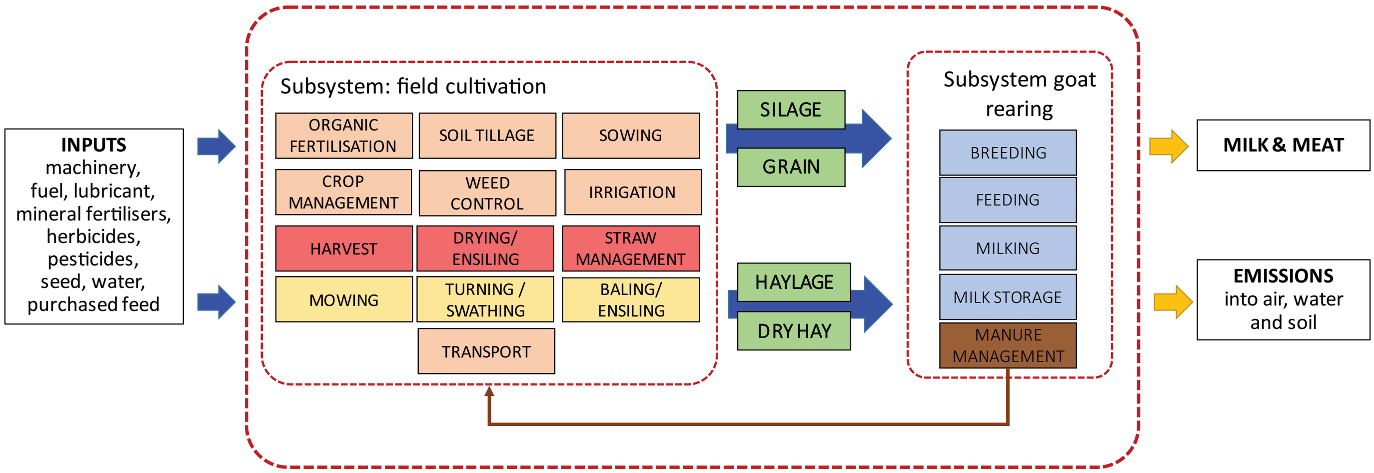

Fig. 1. System boundary.

total milk produced to the same cheese-factory. All of these farms were located in lowland areas, and animals were kept along the whole year in livestock holdings with no pasture. Three of the studied farms did not own any agricultural land, so feed was totally purchased from the market and manure was assigned to other neighbouring farms.

In order to collect information about management practices, farmers were directly interviewed filling in questionnaires about multiple aspects of their farming system. Information about cultivated crops and field cropping system, herd composition and management, manure management, rations, purchased feed and milk production and quality per year was asked. Inventory data are presented in Table 1.

The farm structures and construction, maintenance and disposal of milking parlour were excluded from the system boundary.

The goats breeding out of season, which happens when goats are mated out of the normal season (i.e. during spring), is a common practice. Additionally, the long lactation, quantified as a lactation that lasts longer than the usual 300 lactating days per year, is widespread.

The feed Dry Matter (DM) produced on farm was quantified per year to obtain information about the feed self-sufficiency of the farms with UAA ($n = 14$). Feed self-sufficiency (%) was quantified as the ratio between the dry matter produced on farm and the total dry matter needed for feeding goats. Lucerne and grass hay were both produced on farm and purchased, whereas the concentrate feed as raw material or commercial mixed compounds was totally purchased from the market. The composition of mixed concentrates was obtained using an adapted version of the INRA software for goat rations (INRA, 2018) that defines a ration starting from

Table 1
Main inventory data of the studied farms.

Variable	Unit	Mean	SD	Min	Max
Input					
Dairy goats	n	200	108	62	450
Straw purchased	t DM/year	33.3	21.9	0	80
Forages purchased	t DM /year	80.1	112.5	0	380
Concentrate feed purchased	t DM /year	78.7	75.3	0	330
Mineral fertiliser	t/year	2.54	6.92	0	27
Diesel	l/year	4993	4932	0	18,000
LPG	l/year	612.5	2021	0	8000
Electricity	kWh/year	31,676	13,950	15,000	60,000
Output					
Milk sold	kg FPCM/year	138,506	81,088	28,245	363,971
Individual milk sold	kg FPCM/year	711	269	302	1144
Fat	%	3.85	0.22	3.4	4.38
Protein	%	3.60	0.24	3.15	4.00
Meat sold	kg/year	2842	1496	540	5400

the nutritive value of the commercial mixed compounds as declared on the formulation. Dried forages (mainly Italian ryegrass, grass and lucerne hay) and concentrate-based feed (mainly composed of maize and barley flours, soybean meal and molasses) characterised the goats' ration.

The number of Livestock Units (LU) was quantified adopting the European Directive 91/676/CEE, according to which the following coefficients are used: for adult goats 0.15, for kids and billygoats 0.07 and 0.2, respectively. Production intensity depends on the available land on farm, thus it was quantified as LU/ha only for farms with UAA ($n = 14$).

Concerning the emissions from the application of mineral (mainly urea) and organic (mainly manure) fertilisers, for each farm ammonia (NH_3), nitrous oxide (N_2O), nitric oxide (NO) and nitrates (NO_3) related to fertiliser spreading were quantified using the equations proposed by IPCC (2006a) and EEA (2009). Similarly, phosphate (PO_4) emissions were quantified following Nemecek and Kägi (2007) focusing on dairy goats. Commonly, mineral fertilisers were used when fertilising the maize cultivated on farm, while for other crops (mainly Italian ryegrass, grass and lucerne) either no mineral fertiliser or goat manure were used.

Additionally, when farms had no UAA for the spreading and gave manure to other farms, emissions related to the spreading of manure on field were quantified by assuming that these farms had 2 ha of UAA, of which 1 ha of arable land and the second ha of meadow. This assumption was made in order to consider that even if farms do not have UAA, the emissions related to the spreading of manure must be attributed to the livestock system. In all other calculations, instead, the effective amount of land was taken into account.

The CH_4 and N_2O storage emissions were quantified following IPCC (2006b) Tier 1, depending on farm dimension (number of bred goats) and manure produced, while NH_3 and NO emissions were estimated following EEA (2009). The animal emissions were assessed depending on the number of bred goats and their rations. More in detail, enteric CH_4 emissions were quantified following INRA (2018) with Tier 2 level taking into account the body weight, the feeding level, the concentrate level of the diet, the digestibility of organic matter and some correction factors.

Background data from the Ecoinvent v.3.5 database (Weidema et al., 2013) were used in regard of the production of seeds, diesel fuel, fertilisers and pesticides, and for the production, maintenance and disposal of capital goods such as field machinery. Agri-footprint database was used for purchased forages and for crops that were the raw materials for the concentrate feed, considering their production origin. Direct land use change (LUC) for soybean meal production was considered in the assessment using the value reported by the Agri-footprint database (soybean at farm/BR Economic) (Blonk Consultants, 2017).

Although Gutiérrez-Peña et al. (2019) suggest that, especially for extensive systems with pasture, C sequestration is an important aspect to consider because of the amount of C added to soils from grazing, to C residues from crops and C from manure, in this study C sequestration during crops cultivation was not considered because of the lack of information and the still uncertain methodology available.

2.1.3. Life cycle impact assessment

To quantify the environmental impacts, the inventory data need to be transformed into potential environmental impacts through characterisation factors. Every input data is multiplied by the specific factor to get the impact expressed in equivalent units. In this study, for the translation of the inventory data into potential environmental impacts, the ILCD characterisation method (ILCD Handbook 2011) was used. The following 11 environmental impact categories were quantified: Climate Change (CC), Ozone Depletion (OD), Particulate matter (PM), Photochemical Oxidant Formation (POF), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Eutrophication (TE), Land Use (LUse), Water resource depletion (WD) and Mineral, Fossil and Renewable resources Depletion (MFRD).

In more detail, CC refers to the emissions of GHG released in the atmosphere, OD, POF and MFRD are dependent on the fuel consumption and related emissions during mechanical operations and MFRD also considers the consumption of resources and materials of fossil and renewable origin. PM mainly derives from particulate matter emitted to the air and it is a precursor of ammonia, which is the main responsible for TA. Eutrophication impact categories mainly depend on the excess of nutrients such as nitrogen and phosphorous. WD refers to the local water consumption taking into account availability and withdrawals, whereas LUse refers to the occupation and transformation of land.

2.2. Statistical analysis

SAS 9.4 (SAS, 2012) software was used for the statistical analysis. The GLMSELECT procedure was performed in order select the most impactful variables that influence the main environmental impact categories for dairy production (i.e. CC, PM, AC, FE, MFRD). The analysis was performed both for the impact assessment expressed per 1 kg of FPCM and per 1 ha. Class and continuous variables were included in the models in order to understand the effects of different management choices on the environmental impact evaluation.

The variables included in the models were: lactating goats (n); milk production per goat (kg/year); breeding out-of-season (yes vs no); replacement rate (%); concentrate feed intake per goat (kg DM/day); farm land (ha); livestock intensity (LU/ha); feed produced per year (kg DM/head); lucerne land (yes). The MODEL AVERAGE option was selected to combine the variable selection methods with the model averaging in order to build parsimonious predictive models. A variable with a relative importance value equal to 100 is present in 100% of all the 20 fitted models and can be interpreted as having high relative importance to the predictive model.

MEAN procedure was used to compare groups of farms with different level (high vs low) of the following variables: milk per goat sold ($<$710 kg/year vs $>$710 kg/year); replacement rate ($<$30% vs $>$30%); feed produced per year ($<$323 kg DM/head vs $>$323 kg DM/head). These levels were defined in accordance with the calculated mean values of the sample farms.

3. Results and discussion

3.1. Farm description

All the 17 dairy goat farms were located in intensive milk production areas, where there is also a high concentration of dairy cow farms. The average number of goats per farm (200) was higher than the average of Italian farms (45.2 goats/farm; ISTAT, 2016) and higher than data reported by Sandrucci et al. (2019) in a study on 173 dairy goat farms located in the same Italian region. Saanen was the most frequent breed, followed by Alpine. All producers sold milk to a cheese factory.

As underlined by Pulina et al. (2018), the amount of goat milk transformed in Italy by the dairy industry increased over time due to the increasing demand for goat cheese.The demand for cheese factories to produce cheese all year round has led farmers to tackle the seasonality of milk production by applying two management practices: a long lactation period and out-of-season milk production. This condition affects the goat milk production per year, as well as the farm management and animal rations. As shown in Table 2, about a third of dairy goats (29.8%, found in 11 farms) was milked out-of-season, while 64.2% (7 farms) of dairy goats were milked in a long lactation that is greater than one year (on average 18 ± 3.6 months).

Table 2
Dairy goats farms traits.

Variables	Unit	Mean	SD	CV	Min	Max
Livestock intensity *	LU/ha	4.46	3.75	84%	1.23	15.35
Out-of-season bred heads	%	29.8	28.5	96%	0.0	100
Heads in long lactation	%	64.2	35.0	55%	30.0	100
Age at first birth	month	13.1	2.7	21%	11.0	20.0
Kids per goat	n	1.75	0.39	22%	1.20	3.00
Length of lactation	d	382	130	34%	300	720
Replacement rate	%	28.2	13.3	47%	0.0	53.6
Total area	ha	11.8	11.6	98%	0.0	40.0
Meadow area*	% total area	31.1	36.6	118%	0.0	100
Lucerne area *	% total area	20.0	21.9	110%	0.0	54.0
Feed produced at farm *	kg DM/head per year	392	319	81%	4	1295
Feed self-sufficiency	%	45.5	32.9	72%	0.0	100
Estimated dry matter intake	kg DMI/head d	2.07	0.29	14%	1.64	2.59
Dairy efficiency	kg FPCM/kg DMI	0.95	0.36	38%	0.46	1.63

Note: * parameters quantified on 14 farms (3 farms with no UAA were excluded). + calculated on 11 farms that performed out-of-season breeding.

Continuous milk production is only possible due to the highly concentrate feed that supports the high levels of energy and protein required for milk production. Moreover, Todaro et al. (2015) suggested that for a correct application of these management practices (i.e. long lactation and out-of-season breeding) it is important to have adequate housing density and airspace, as well as proper indoor ventilation to sustain the production performance and the udder health. The long lactation milk production resulted in a higher production per goat: 818 ± 268 kg FPCM/year. This value is higher if compared to the individual production in the farms (636 ± 269 kg FPCM/year) where long lactation milk production was not performed, although the daily production resulted lower in the goats that had been continuously milked (1.79 ± 0.88 vs 2.12 kg ± 0.85 kg FPCM/day, respectively).

Goats milked out-of-season produced slightly more milk per day (2.02 ± 0.84 kg FPCM/day) than the goats that were milked in season (1.92 ± 0.95 kg FPCM/day) but the total production per year was higher in the last case (744 ± 300 vs 693 ± 264 kg FPCM/goat for in season and out-of-season goats, respectively). Also Sandrucci et al. (2019) found a low production per milking in goats that kidded at the beginning of the summer season.

The total farm area was small (11.8 ha on average) and three farms had no UAA at all, hence, they did not produce feed for goats and were characterised by 0% feed self-sufficiency. About half of the UAA was utilised for grass and lucerne hay, which were entirely used for the forage fraction of goats' rations. The average feed produced on farm for each goat (lactating and non-lactating) was 392 kg DM per year. In fact, only few farms could meet the feed requirements for the flock, while the others purchased the mixed feed and forages – either entirely or extensively – from the market. The low feed self-sufficiency of dairy goat farms is a typical feature of intensive farms: for example, in France, during the last decades, farms gradually turned into intensive farming with more purchased inputs (Brocard et al., 2016) also due to a decrease in the ratio between areas and herd size. The share of cultivated area dedicated to lucerne was also an important aspect regarding the protein supply in the ration, and the amount of concentrates represented a key data to quantify the average ratio between forages and concentrates in goats' rations.

In almost 60% of farms, lactating goats were fed with forages and concentrates distributed separately, while 7 farms used a total mixed ration that included maize silage or sorghum silage. The average amount of concentrate intake was 1.27 ± 0.32 kg/d per goat, while forages were distributed ad libitum. The average dairy efficiency, intended as ratio between FPCM produced and dry matter intake, was 0.95 ± 0.35, which is lower than the average results obtained in an experimental farm analysed by Rapetti et al. (2014), where high producing Saanen goats were reared.

3.2. Environmental impact indicators

3.2.1. Results per milk production unit

Table 3 shows the environmental results for 1 kg of FPCM goat milk. Goat milk shows a higher impact compared to other milk production systems such as dairy cattle (Kanyarushoki et al., 2008). This result is affected by the individual milk production level and by the rearing system. A wide variability in the results can be noticed: the coefficient of variation varied from 36% to 52%. This variability could be due to different management choices such as the herd dimension, breed, feed type, and length of the lactation period. All of them deeply affect the environmental outcomes.

Studies available in literature on the environmental impact evaluation of goat milk production are scarce, and only focus on CC impact category. In this study, CC resulted higher than the values found by Gutiérrez-Peña et al. (2019) and Robertson et al. (2015). Gutiérrez-Peña et al. (2019) conducted a study on dairy goat production systems with different grazing levels, and C sequestration was estimated and deducted from the total estimated value of climate change. This would explain why the values in their research resulted lower compared to the ones in the present study. Additionally, different methodological choices can also explain the different results obtained in different studies. For example, the FU adopted in this study is not the same adopted by others, as there is not a recommended equation to calculate FPCM for goat milk. Hence, other different FUs can be found in literature (e.g., Fat Corrected Milk, Protein Corrected Milk, Energy Corrected Milk, raw milk at 7% fat content). In both Gutiérrez-Peña et al. (2019) and in Robertson et al. (2015), the FU were 1 ha UAA and 1 kg FPCM. The allocation method used in these two studies was based on the economic values of milk and meat, so the result is influenced by their price, and, in particular, the year and location to which they are referred. Selecting a physical allocation method, instead, allows stability in the outcomes and in the comparability with other studies.

Regarding the estimation of terrestrial acidification and freshwater eutrophication, no other studies were found in literature, to the best of the authors' knowledge. Therefore, no comparison can be made for dairy goat systems on this aspect. However, comparing the results for cow milk production reported in other studies (de Boer, 2003; Lovarelli et al., 2019) with the results of the present study, goat milk production had a higher environmental impact. The farms involved in this study were characterised by a very low UAA that brought to a low crop production at farm level; they also had a high livestock intensity and, as a consequence, the nitrogen and phosphorous produced by animals had a relevant contribution to acidification and eutrophication impact categories.

Six out of the 11 categories calculated with the ILCD characterisation method were selected for the statistical analysis. The selected categories were climate change, particular matter, terrestrial acidification, freshwater eutrophication, land use and mineral, fossil and renewable resources depletion. These categories are the most important for the livestock systems, as also reported by Fantin et al. (2012), Santos et al. (2017), and Cederberg and Mattsson (2000). Focusing on these 6 categories, the processes that mainly contributed to the environmental impact of goat milk production are shown in Fig. 2.

These processes, known as hotspots, were grouped as follows: (i) field emissions, including all emissions from mineral and organic fertilisers spread on field; (ii) animal emissions, which include emissions deriving from ruminal activity; (iii) storage emissions, which include emissions related to the storage of manure on farm; (iv) field crops that include all processes related to the cultivation of crops (forages and concentrates) on farm; (v) purchased feed, including the production and transport of commercial mixed feed and forages produced off-farm (purchased from the market); (vi) energy, including the electricity, natural gas and methane for the livestock facilities at farm level.

Contrary to what was found for dairy cow milk production, the main contributors to CC were the processes connected with the production and transport of the purchased feed and not animal emissions. In fact, for the production of cow milk, the emission of methane is the main hotspot of CC (Kristensen et al., 2011; O'Brien et al., 2012), contributing about 40–50% to the total impact. In the present study on goat milk production, methane emissions contributed to 25.2 ± 7.47% of CC, hence not resulting the hotspot of CC, as reported by Silanikove and Koluman (2015).

Purchased feed production contributed to CC by 44.3 ± 16.1%, similarly to the results obtained by Batalla et al. (2015). This interesting result is most of all related to the specific management choices of farmers, and adds weight to the urgency of efficiency improvements and to the farmers decisional approach. In particular, the high level of concentrate feed in the diet (1.27 ± 0.32 kg/day) and the low feed self-sufficiency (45.5 ± 32.9 %) result from the purchasing of most of the feed.

Regarding particulate matter and terrestrial acidification, a big share of the environmental impact is attributed to the emissions related to animals, manure storage and field spreading of fertilisers; thus, it was necessary to highlight the relevance of ammonia (NH_3) and the importance of the storing system adopted for manure. In particular, NH_3 is the main contributor to TA and a precursor of particulate matter formation. Feed purchase was the main hotspot to FE (56% of the impact), MFRD (70% of the impact) and LUse (73% of the impact). Hence, the field practises and the feed transport played a major role.

FE and MFRD resulted mostly influenced by the production, transport and application of mineral fertilisers and manure used for the purchased feed production.

Table 3
Environmental impact assessment of 1 kg of FPCM.

Impact categories	Unit	Mean	SD	Min	Max
Climate change (CC)	kg CO_2 eq	2.67	0.88	1.12	5.05
Ozone depletion (OD)	kg CFC-11 eq	$8.78 \cdot 10^{-8}$	$3.57 \cdot 10^{-8}$	$3.11 \cdot 10^{-8}$	$1.90 \cdot 10^{-7}$
Particulate matter (PM)	kg PM2.5 eq	0.0016	0.0006	0.0009	0.0031
Photochemical ozone formation (POF)	kg NMVOC eq	0.003	0.001	0.001	0.006
Terrestrial Acidification (TA)	molc H+ eq	0.065	0.026	0.035	0.126
Terrestrial eutrophication (TE)	molc N eq	0.286	0.113	0.153	0.555
Freshwater eutrophication (FE)	kg P eq	0.0002	0.0001	0.0001	0.0003
Marine eutrophication (ME)	kg N eq	0.0240	0.0101	0.0055	0.0481
Land use (LUse)	kg C deficit	41.6	19.6	12.5	94.2
Water resource depletion (WD)	m^3 water eq	0.39	0.15	0.11	0.71
Mineral, fossil & ren resource depletion (MFRD)	kg Sb eq	$1.08 \cdot 10^{-5}$	$4.18 \cdot 10^{-6}$	$2.69 \cdot 10^{-6}$	$2.03 \cdot 10^{-5}$

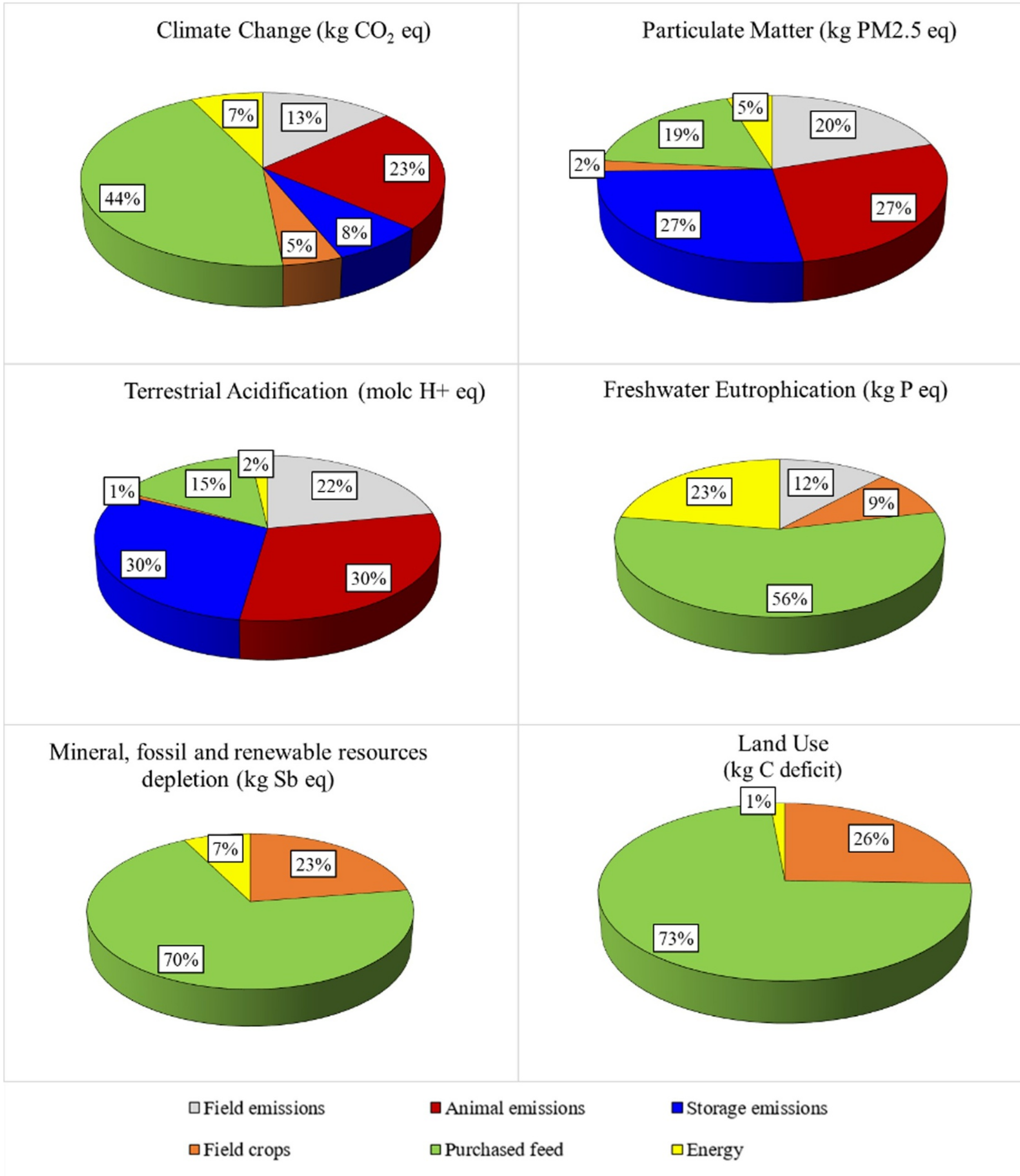

Fig. 2. Main process contributors on the 6 environmental impact categories.

Statistical analysis was used to identify the variables and their relative weight, which influenced these 6 main impact categories (Table 4).

As expected, milk production per head was the main driver of the environmental impact and it was inversely related with impacts per kg of milk (Table 5): when milk production increased, environmental impacts decreased. In addition, CC, LUse, MFRD and FE were significantly ($P < 0.01$) influenced by the percentage of replacement rate, showing that the more the rate increases, the more the environmental impact increases.

In any case, a high replacement rate involves a high number of unproductive heads, which affects the emissions of CH_4 and N from farm. As suggested by Salou et al. (2017), in fact, the replacement rate is an index of intensification rate per unit area. These authors also found a positive correlation among all impact categories expressed per unit of land and replacement rate, while a negative correlation was found when the impact was expressed per milk unit. Baldini et al. (2018) found that calves and non-productive animals contributed up to 50% to the environmental impact of dairy cow farms, so the reduction of the number of kids, together with a good management of adults' fertility and health, could be considered a successful mitigation strategy.

In this study, the amount of feed produced by farms (expressed as kg DM/head) was positively correlated with all impact categories (table 5), and had a significant role on CC, PM and FE. The results obtained clearly showed that although a high feed self-production reduces the feed purchase, it does not always mitigate the environmental impact of milk production, at least for some of the evaluated environmental impact categories. This is due to the fact that, from the LCA point of view, the location where the production takes place is not compelling. As reported by Guerci et al. (2013) in a study about dairy cow milk production, feed self-sufficiency was not clearly related to all the environmental impact categories.

3.2.2. *Results per land unit*

As it occurs in this study, adopting the unit of land as FU can be interesting in particular when the UAA is a limiting factor (Robertson et al., 2015). When expressed per 1 ha (Table 6), the environmental impact results highlight the peculiar characteristics of most of the farms included in the study: the scarce land availability. The results of CC were much higher in the present study than in Gutiérrez-Peña et al. (2019) in extensive and semi-extensive dairy goat systems.

Table 4
Relative importance values of farm characteristics for the 6 environmental impact categories (expressed per kg of FPCM).

Variables	CC	PM	FE	TA	LUse	MFRD
Lactating goats (n)	**71**	**76**	69	**80**	68	69
Individual milk production (kg FPCM/year)	**99**	**99**	**100**	**98**	**93**	**93**
Breeding out of season (yes)	**73**	63	63	62	**72**	69
Replacement rate (%)	**93**	**76**	**93**	**73**	**92**	**83**
Concentrate feed intake (kg DM/head)	68	67	58	65	67	**78**
Farm land (ha)	69	66	**77**	58	62	**71**
Feed produced per year (kg DM/head)	**84**	**81**	**90**	**81**	**77**	**90**
Livestock intensity (LU/ha)	50	**71**	58	61	**82**	**73**
Land for lucerne (yes)	58	62	56	64	67	**71**

Note: Red: selection percentage (SP) >90%; orange: SP 80–90%; yellow: SP 70–80%; white: SP <70%. The values mean the weight that every variable has on the prevision model developed to predict the environmental impact of dairy goat milk production.

Table 5
Effects included in the estimation models for different environmental categories.

Variables	CC	PM	FE	TA	LUse	MFRD
Lactating goats (n)	ns	ns	ns	+	ns	ns
Individual milk production (kg FPCM/year)	−	−	−	−	−	−
Breeding out of season (yes)	ns	ns	ns	ns	ns	ns
Replacement rate (%)	+ + +	+	+ +	+	+ + +	+ + +
Concentrate feed intake (kg DM/head)	ns	ns	ns	ns	ns	ns
Farm land (ha)	ns	ns	ns	ns	ns	ns
Feed produced per year (kg DM/head)	+	+	+ + +	ns	ns	ns
Livestock intensity (LU/ha)	ns	ns	ns	ns	ns	ns
Land for lucerne (yes)	ns	ns	ns	ns	ns	ns

Note: +/− <= 0.01; ++/− < 0.05; +++/− < 0.01; ns: no significance +: direct relation between variables; -: inverse relation between variables

Moreover, all the environmental impacts were higher than those shown by Salou et al. (2017), who used the unit of land as FU for the environmental impact evaluation of dairy cow systems (intensive-organic-highland). Also Robertson et al. (2015) used 1 ha as FU and they found a higher CC for the indoor goat rearing system than for the outdoor one.

The statistical analysis was also performed considering the environmental impact results expressed per ha. The results showed that the most important variable that influenced the impact categories was the livestock unit, with a positive and significant ($P < 0.01$) relation. A farm characterised by high livestock units and low UAA is also characterised by a reduced land availability for the spreading of organic fertilisers, which has dramatic consequences on a local level in terms of nutrients (i.e. N and P) leaching and run-off. This leads to increasing acidification and eutrophication. Since farms are characterised by a high livestock intensity, the environmental results of CC per ha increased because of the increase in enteric emissions. Moreover, the availability of a limited area on farm forces farmers to increase the amount of purchased feed. The intensification level, implying high inclusion of concentrate feed in the diet and no grazing period, negatively affects all the environmental categories also in the dairy cow production system (Salou et al., 2017).

Following these results, it is advisable to use both mass-based and area-based functional units in life cycle assessments of agricultural goods to better describe the environmental impact of the production system. In fact, it must be taken into account that the livestock breeding fulfils two functions even in the areas with an intensive production system: the production and the territorial preservation. These two functions are particularly important for goats production systems, in which is important to make an appropriate use of the natural resources and to reach an optimum level of milk productivity, as suggested by Gutiérrez-Peña et al. (2019).

3.2.3. Results for farms classification

The farms involved in the study were classified based on high and low levels of the following variables: (i) milk production per goat, (ii) replacement rate and (iii) feed production at farm (Table 7). The obtained results confirm the data previously discussed. Results (expressed per 1 kg of FPCM) for all impact categories, except for MFRD, were lower (from 17% to 34%) for the farms with a higher milk production per goat than for those with a lower milk production. Also farms with a low replacement rate achieved interesting results, showing a reduction of the environmental impact for 8 of the evaluated categories and, in particular, for FE that decreased by 34% compared to farms with a higher replacement rate. As shown in Fig. 2, the main hotspot process of FE is the feed purchase (56%). Therefore, the chance of reducing the amount of feed purchased from the market by increasing self-sufficiency is an appropriate option to reduce FE and the related supply of nutrients to fields.

A high capacity of farms to produce feed for goats reduced CC, TA, TE, ME and MRFD, with an amplitude from -1% to -3.8%; while, as reported in Table 5, for PM and FE, the high capacity of feed production at farm can increase the environmental impacts by 1% to 32%.

When the environmental impact performance expressed per unit of land is considered, the results show that the increase of milk production can produce a small mitigation of CC (-9.5%). On the other hand, the farms with a high level of feed production at farm can reduce CC by -30.4% and ME by -33.2%; these farms have more land availability and they efficiently maximise the crop yield. The farms characterised by a high replacement rate result more sustainable than those with a low replacement rate, because this group of farms includes the farms with the highest land availability; in this case, the most evident environmental effect for the impacts expressed per land unit is shown for CC (-18.5%), ME (-16.6%) and MRFD (-7.14%).

4. Conclusions

This study deals with a particularly innovative field, as it represents one of the first studies on the environmental impact of dairy goat milk production. Additionally, by means of statistical analysis, it helps to identify the management options that can improve goat milk production from an environmental point of view.

Table 6
Environmental impact assessment per unit of land (1 ha) (n = 14).

Impact categories	Unit	Mean	Dev.st	Min	Max
CC	kg CO_2 eq	39,199	26,771	11,091	90,220
OD	kg CFC-11 eq	0.0012884	0.000909563	0.000450062	0.0031765
PM	kg PM2.5 eq	24.1	16.1	6.0	49.1
POF	kg NMVOC eq	44.9	31.5	12.5	112.0
TA	molc H^+ eq	998	680	235	2028
TE	molc N eq	4376	2994	1028	8915
FE	kg P eq	2.09	1.48	0.67	5.47
ME	kg N eq	361	264	91.4	807
LUse	kg C deficit	617,422	492,080	124,453	1,856,282
WD	m^3 water eq	5545	3715	1713	12,550
MFRD	kg Sb eq	0.14	0.10	0.03	0.35

Note: Climate Change = CC, Ozone Depletion = OD, Particulate Matter = PM, Photochemical Oxidant Formation = POF, Terrestrial Acidification = TA, Terrestrial Eutrophication = TE, Freshwater Eutrophication = FE, Marine Eutrophication = ME, Land Use = LUse, Water Depletion = WD, Mineral, fossil and renewable resources depletion = MFRD.

Similarly to cows rearing systems, the annual milk production per head is the main driver of the environmental impact of milk production in dairy goat systems, when the impact is expressed per unit of milk. High producing farms show a lower impact for all the evaluated categories. Consequently, all management options that increase production, such as the long lactation, are promising. Reducing the number of replacement heads had a positive effect on the most important environmental categories. Moreover, the amount of purchased feed is a hotspot affecting negatively most of the environmental results. However, increasing the feed production on farm is only possible through the improvement of crop yield and increase of farm agricultural area. This suggests that, when the environmental impact is expressed per unit of land, the increase of livestock units, with the same UAA, means scarce land availability for spreading organic fertilisers and for feed production, which has dramatic consequences at local level in terms of nutrients released to soil, water and air. C sequestration was not considered in this study so its hypothetic effect of mitigation of CC was not included. The evaluation of C sequestration was not considered in this study because no livestock grazing systems were included; however, this aspect should be taken into consideration for studies that take into account extensive livestock farms, as C sequestration can affect the results in terms of Climate Change assessment.

The environmental impact assessment carried out with the unit of land as FU suggests that the increase of feed production on farm is the most promising mitigation that can be achieved. On the other hand, the unit of product as FU allows to compare easily different livestock systems and different studies.

The results of this study suggest that increasing milk production per head, increasing feed production on farm and reducing the replacement rate are the most interesting and achievable management options that farmers can adopt to reduce the environmental impact of milk production in intensive goat rearing systems.

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Table 7
Average environmental impact of milk production (per 1 kg FPCM) obtained from the grouping of farms in different classes (low/high milk production, replacement rate and feed produced at farm).

Impact categories	Unit	Low individual milk production	High individual milk production	Low replacement rate	High replacement rate	Low feed produced at farm	High feed produced at farm
		< 710 kg FPCM/ year	> 710 kg FPCM/ year	< 30%	> 30%	< 323 kg DM/head	> 323 kg DM/head
	N farms	8	9	10	7	8	9
CC	kg CO2 eq	3.26 (21.9%)	2.05 (-23.3%)	2.52 (-5.55%)	2.75 (3.04%)	2.67 (0.04%)	2.57 (-3.83%)
OD	kg CFC-11 eq	$1.10 \cdot 10^{-7}$ (25.4%)	$6.27 \cdot 10^{-8}$ (-28.5%)	$8.16 \cdot 10^{-8}$ (-7.04%)	$8.99 \cdot 10^{-8}$ (2.40%)	$7.60 \cdot 10^{-8}$ (-13.4%)	$9.30 \cdot 10^{-8}$ (5.94%)
PM	kg PM2.5 eq	0.0021 (32.7%)	0.0012 (-24.2%)	0.0016 (1.08%)	0.0016 (1.08%)	0.0016 (1.08%)	0.0016 (1.08%)
POF	kg NMVOC eq	0.004 (18.6%)	0.002 (-23%)	0.003 (-7.04%)	0.003 (2.57%)	0.0028 (-10.3%)	0.0032 (2.57%)
TA	molc H+ eq	0.086 (31.3%)	0.048 (-26.8%)	0.066 (1.42%)	0.065 (-0.57%)	0.0668 (2.34%)	0.0646 (-1.03%)
TE	molc N eq	0.376 (31.6%)	0.210 (-26.8%)	0.290 (1.49%)	0.285 (-0.50%)	0.294 (2.74%)	0.2827 (-1.20%)
FE	kg P eq	0.0002 (32.1%)	0.0001 (-33.9%)	0.0001 (-33.9%)	0.0002 (32.1%)	0.0001 (-33.9%)	0.0002 (32.1%)
ME	kg N eq	0.0319 (33%)	0.0170 (-29.2%)	0.0234 (-2.47%)	0.0249 (3.78%)	0.0247 (2.94%)	0.0233 (-2.89%)
LUse	kg C deficit	52.8 (26.7%)	31.1 (-25.4%)	36.9 (-11.5%)	47.6 (14.3%)	37.0 (-11.1%)	45.1 (8.28%)
WD	m3 water eq	0.43 (10.7%)	0.33 (-16.8%)	0.39 (-0.74%)	0.36 (-8.34%)	0.33 (-14.8%)	0.42 (5.81%)
MRFD	kg Sb eq	$1.21 \cdot 10^{-5}$ (11.9%)	$8.92 \cdot 10^{-6}$ (17.8%)	$9.49 \cdot 10^{-6}$ (-12.5%)	$1.18 \cdot 10^{-5}$ (8.68%)	$1.00 \cdot 10^{-5}$ (-7.55%)	$1.08 \cdot 10^{-5}$ (-0.45%)

Note: The values in brackets refer to the improvement or worsening of the environmental impact (expressed as %) of the classified farms compared to the average impact values of the farms involved in the study.

CRediT authorship contribution statement

Maddalena Zucali: Writing - review & editing, Data curation, Conceptualization, Visualization, Writing - original draft, Formal analysis, Methodology, Investigation. **Daniela Lovarelli:** Writing - original draft, Writing - review & editing, Data curation, Conceptualization, Visualization, Formal analysis, Investigation, Methodology. **Stefania Celozzi:** Writing - review & editing, Data curation, Visualization, Conceptualization, Investigation, Writing - original draft, Formal analysis, Methodology. **Jacopo Bacenetti:** Writing - review & editing, Data curation, Conceptualization, Investigation. **Anna Sandrucci:** Data curation, Conceptualization, Writing - review & editing. **Luciana Bava:** Writing - original draft, Data curation, Project administration, Visualization, Supervision, Methodology, Conceptualization, Funding acquisition, Formal analysis, Investigation.

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