Journal of Cleaner Production 351; 131518*,* DOI:10.1016/j.jclepro.2022.131518.

Influence of precision livestock farming on the environmental performance of intensive dairy goat farms

Guillermo Pardo[a], Agustín del Prado[a], Javier Fernández-Álvarez[b], David R. Yáñez-Ruiz[c], Alejandro Belanche[c,d]

[a]Basque Centre for Climate Change (BC3), 48940, Leioa, Spain.

[b]Caprigran, Corgijo Peinado, 18340, Fuente Vaqueros, Granda, Spain.

[c]Estación Experimental del Zaidín (CSIC), Profesor Albareda 1, 18008 Granada, Spain.

[d]Departamento de Producción Animal y Ciencia de los Alimentos, Instituto Agroalimentario de Aragón (IA2), Universidad de Zaragoza-CITA, Miguel Servet 177, 50013 Zaragoza, Spain

*Corresponding author: guillermo.pardo@bc3research.org

Abstract

The implementation of Precision Livestock Farming (PLF) concepts has been pointed out as an indirect strategy that could potentially help to optimize farm management and mitigating the environmental impacts of livestock production systems. However, to date, few studies have focused on analyzing specifically the relationship among PLF adoption and environmental performance, so sustainability benefits have not yet been quantified for many technologies. Moreover, studies evaluating the environmental impact of dairy production have traditionally focused on cattle, and when exploring sheep or goats, they have often involved extensive, low-productive systems, providing an incomplete picture of the sector. Within this context, in this study we apply life cycle assessment (LCA) to analyze the environmental impact associated to intensive dairy goat production, and to explore the influence of adopting a smart-farming PLF platform on the environmental performance of a group of dairy goat farms in Spain.

The proposed PLF-platform, relies on systematic on-farm monitoring of individual animal data, coupled with big data processing and interpretation, which supports farmers to take adequate - and timely- farm management decisions. In order to capture its influence, two different periods were analyzed in five selected farms: a baseline year just before innovation was implemented (2014) and four years after (2018), when most of the effect of improved management was reflected. Results after the PLF-platform implementation showed significant reductions (-11%) in GHG emissions and similar trends in other impact categories (9-16% reductions). This PLF platform provided a precise monitoring of the productivity, genetic merit and physiological state of each animal, allowing adequate criteria for a number of decision-making processes, such as selecting animals for breeding, replacement or culling. This optimization led to an increase in the genetic selection progress, ultimately reflected on milk productivity. Moreover, a reduction of unproductive periods such as first partum age or dry period length was often achieved. As a result of this general improvement, the efficiency of resource usage in relation to milk (and meat) production was increased, with positive effect on the environmental performance. Production of 1 kg of fat and protein corrected milk (FPCM) resulted in 1.53-1.71 kg CO_2 eq. Results in other impacts categories were also in a similar range than previously reported values for highly productive dairy systems, including dairy cattle, which stresses the important role that small ruminant farming can play on environmentally sustainable livestock production, particularly in the Mediterranean context.

Keywords: LCA, smart-farming, PLF, carbon footprint, small ruminants

1 Introduction

In Europe, most of the goat populations are concentrated in the Mediterranean countries where they have traditionally played an important role both, socio-economically and ecologically, providing a source of high value protein, and contributing to food and financial security of households in less favored rural areas (Aziz, 2010). The Spanish goat milk sector is the second largest in the EU region, with about 2 million goats and a milk production of more than 530,000 t/year –approximately 22% of the EU-28 total (FAOSTAT 2021). During the last decades, market demands for increasing productivity and reducing seasonality, have driven livestock husbandry in this area to intensify their production. Consequently, many dairy goat farms have evolved, from traditional low producing grazing systems to more intensive production systems with high-dependence on external feeds, scaling up their size, and implementing a number of innovations (e.g. automated milking, milk control, artificial insemination, health programs) in order to increase their productivity (Castel et al., 2011).

Despite its relative importance, studies evaluating the environmental impact of dairy production have traditionally focused on cattle, providing an incomplete picture of the sector, especially in those areas where small ruminant farming plays an important role (e.g. Mediterranean basin). To date, the amount of specific life cycle assessment (LCA) studies of dairy goat -or sheep- systems is still scarce, and they often involve low-productive systems which are not always representative of the state-of-the-art in the sector.

In the current context, characterized by livestock systems with a high level of organization and efficiency, the application of smart-farming through the implementation of Precision Livestock Farming (PLF) concepts, could represent an opportunity to support farmers in order to optimize farm management and meet market demands. PLF is based on measuring variables and analyzing collected data so providing support for animal/herd monitoring and management (Berckmans, 2017). However, while the application of PLF tools in other livestock sectors (e.g.

dairy cattle) has been successfully tested and it is of widespread use, the incorporation in small ruminant dairy systems has been limited so far (Belanche et al., 2021).

Approaches for implementing PLF concepts to small ruminants were recently reviewed by Caja et al., (2020) and Odintsonv Vaintrub et al., (2021). They are based on wearable (e.g. ear tag, rumen bolus, collar) and non-wearable devices (e.g. camera, electronic scale) which are used for collecting data and monitoring the performance, health or behavior of the animals. Some of them have focused on specific aspects, like the use of automatic devices for goat milking (Alejandro et al., 2016), or the detection of estrus phases (Odintsonv Vaintrub et al., 2021). Among them, devices for electronic identification, and particularly ear tags, already in use in many regions (i.e. EU), have been pointed out as a very promising option, triggering the possibilities for data gathering and processing through PLF platforms (Caja et al., 2020). This allows farmers to have a more precise monitoring of herd data, which provides a base for management decisions (breeding, culling, selection, dry off, feeding) (Belanche et al., 2019).

In a previous study we demonstrated that the implementation of a PLF platform (Figure 1) based on a systematic individual animal data collection and interpretation, had positive effects on overall performance of dairy goat farms (Belanche et al., 2019). As the main advantages, this PLF platform allows the integration of individual animal data (e.g. milk yield, lactation length, health, genetic merit) which helps farmers during the decision-making processes at different levels, mainly: 1) customize the lactation length for each individual animal to optimize the individual revenue (long lactations for high productive animals and vice-versa), 2) minimize the unproductive periods such as first partum and dry period length 3) improve the breeding management by selecting high merit females for artificial insemination; 4) improve genetic selection by identifying the best newborn animals for replacement, 5) detect animals with health issues or poor productive and reproductive performance for selective culling, and 6) increased traceability of each individual animal (including filiation test) to better implement the selection program and accelerate the genetic progress.

While PLF tools are not primarily designed for improving the environmental sustainability of livestock systems, this has often been pointed out as a potential side-effect of increased productivity by several authors (Berckmans, 2017; Hristov et al., 2013). However, to date, few studies have focused on analyzing the PLF efficacy in reducing the environmental impact of livestock products, and the need of further studies to estimate their actual effect as a mitigation strategy has been stressed in recent reviews (Lovarelli et al 2020, Tullo et al 2019).

For these reasons, the objectives of this study were 1) to estimate through LCA the environmental impact associated to intensive dairy goat production, in order to contextualize the results with regards to other dairy systems; and 2) to explore if the utilization of a PLF platform could involve a reduction in the environmental impact of the dairy goat farms that have incorporated its use.

2 Material and methods

2.1 Scope of the study

2.1.1 *Description of the PLF platform*

Cabrandalucía Federation, which comprises the main goat breeding associations in Andalusia (Spain), has recently implemented a concept of smart farming relying on a PLF platform (Web-App RUMIA), which incorporates PLF-like principles based on the integration of individual animal data to optimize decision making through a smart phone-based terminal.

Briefly, this platform relies on three principles (Figure 1): 1) systematic on-farm individual data recording (e.g. partum data, physiological stage, health status, reproductive data, etc.) together with remote data acquisition as a result of the milk control, morphologic evaluation and genetic selection program, ii) data storage, processing and interpretation by a supercomputer placed at Cabrandalucía headquarters, and 3) interactive feedback of processed data to the farmer in order to optimize farm management. The main inputs and outputs of this PLF platform, along with the farm management implications are summarized in Table 1.

The effectiveness of the platform has been recently evaluated by monitoring the shift in the performance indicators of a group of dairy goat farms after it was implemented (Belanche et al., 2019). A sub-group of 5 farms involved in that experiment was randomly selected in our study in order to analyze the evolution in their environmental performance. All the farms implemented the PLF platform in late 2014 and the only filter criterion was that, during the studied period (2014-2018) they did not introduce substantial changes in terms of existing facilities or feeding strategies, which could have affected aspects like energy consumption or concentrate composition. By avoiding modifications on those operational conditions, we aimed at analyzing specifically how changes in the herd management could influence the environmental performance of the farm, therefore exploring the optimization potential obtained through the PLF platform.

2.1.2 *Data collection and sample description*

Five dairy goat farms of Murciano-Granadina breed were selected randomly from a group of farms belonging to Cabrandalucia association, representing the typical intensive management system in the region based on absence of grazing and high dependence on off-farm feeds (self-sufficiency 0-3%). The farms were located in Andalusia (Southern Spain), an area with Mediterranean climate, characterized by mild winters and very warm and dry summers. All farms had similar management based on intensive reproduction, two milking per day and the same monthly milk monitoring scheme. Key characteristics of the farms involved in the study are provided in Table 2.

2.1.3 *Functional unit (FU)*

Life cycle assessment is an internationally accepted method to assess quantitatively the environmental impacts related to all the stages of a production cycle, from raw material extraction to the end products. The present study followed the principles described in the international standards ISO 14044 (ISO, 2006) and specifically in FAO (2016) guidelines, which establishes a harmonized methodological framework to conduct LCAs of small ruminant systems.

In the present study, the functional unit (FU) considered is 1kg of fat and protein corrected milk (FPCM). According to FAO (2016), milk yield was corrected at 4.0% fat and 3.3% protein to provide comparison with dairy cow milk. The following equation was applied:

$$Kg\ FPCM = kg\ milk \times (0.1226 \times Fat\% + 0.0722 \times Crude\ Protein\% + 0.0621 \times Lactose\%) \quad (1)$$

2.1.4 *System boundaries*

The time boundary selected was a period of 12 months, covering all life stages of the animal, and representing the average environmental impacts for goat milk production during 1 year. As all the analyzed farms had an intensive production system, small influence of seasonality or inter-annual variability was expected. In order to capture the effect of the PLF platform implementation, two different 12-month periods were analyzed for each farm: a baseline year just before the platform was incorporated (2014) and four years after (2018), when most of the influence of improved management was reflected.

A “cradle to farm-gate” perspective was considered for defining the boundaries of the goat milk production system, involving all processes until the milk leaves the farm, and excluding milk transport and processing afterwards (see Figure 2). This involves the aspects related to on-farm activity, such as fuel and electricity consumption, animal housing, ruminant digestion and manure management, but also off-farm activities like crop production, feed processing and transport to the farm. Capital goods (e.g. equipment, machinery, buildings) and inputs for ancillary activities (e.g. medicines) were excluded of the final analysis as they were considered not relevant for this case study.

2.1.5 *Allocation of co-products*

Dairy goat farms are multifunctional systems which produce more than one product. The main purpose is milk production, although meat from kids (and culled goats) is also obtained as a co-product. In order to estimate the environmental impacts of the single product analyzed in the study (i.e. milk), the overall impacts have to be partitioned among the various outputs of the system. To do so, we followed FAO (2016) guidelines for LCA studies on small ruminant systems, recommending to prioritize allocation based on biophysical causality over other allocation criteria.

Accordingly, a biophysical allocation based on the partitioning of the animal energy requirements was applied. Energy requirements for the different metabolic functions of the animals in the farm were estimated following IPCC (2019) Tier-2 methodology. The allocation ratio for milk, was calculated from the ratio of the energy requirements for milk production to the energy requirements for the production of milk and meat (growth):

$$R = \text{energy req. milk production} / (\text{energy req. milk production} + \text{energy req. growth}) \qquad (2)$$

Applying more than one allocation method is recommended for dairy LCAs though, in order to show the potential effect of allocation method through a sensitivity analysis. To do so, two additional procedures for allocation were explored: one based on economic value and other based on protein content. Details are provided in Supplementary Material.

2.2 Life cycle inventory (LCI)

2.2.1 *Farm inputs and outputs*

To obtain a detailed inventory, the farms were analyzed by field investigation and through a survey which provided details about farm structure, management applied, and main input and output flows. Structured farmer surveys were conducted to quantify farm inputs such as feeds, water, electricity or fuel consumption, as well as to identify some management practices, like manure treatment. Farm outputs such us milk, goat kids sold and culled goats were obtained from the information gathered by the PLF platform. Additionally, feed suppliers were consulted to collect concentrate composition. An overview of the collected data is shown in Table 3. Specific details about feed ingredients and concentrate composition can be found in Table S1.

Based on the collected details, a farm model was built describing the farm structure, according to technical parameters and animal management practices reported. All the animal classes present in the farm along the year were accounted together with their respective excreta and emissions (Figure 3) estimated through IPCC (2019) guidelines.

2.2.2 *Estimation of emissions*

Methane (CH_4) emissions from enteric fermentation were estimated according to Tier 2 of the most recent IPCC (2019) guidelines. Gross energy was calculated from estimations of energy requirements and diet digestibility, and CH_4 emissions from enteric fermentation were calculated by applying a Y_m of 5.5% for dairy goats. Emissions from manure management were also estimated based on IPCC (2019) guidelines. Specific values for high productivity goats were applied when considering maximum methane producing capacity (Bo) ($0.18 m^3 CH_4/kgVS$). Manure management types under the studied farms were solid storage and passive composting with infrequent turning. Accordingly, methane conversion factors (MCFs) of 4% and 2% were considered for solid storage and composting respectively, both under warm temperate dry climate.

Similarly, nitrous oxide (N_2O) emissions were estimated based on excretion rate of nitrogen (N) estimated following IPCC (2019) and applying emission factors for direct N_2O of 1% for solid storage and 0.5% for composting in passive windrow. For estimating indirect N_2O emissions and ammonia (NH_3) and nitrate (NO_3^-) losses, the Tier1 from IPCC (2019) was applied. The estimation of off-farm emissions from purchased feeds (i.e. concentrates, grains and forages) and bedding materials, involving the stages from agricultural production, processing and transport to the farm, was conducted based on Agri-footprint v4.1 database (Blonk Agri-footprint BV, 2019). Emissions related to fuels (diesel and biomass (olive husks)) consumed on-farm, and electricity from Spanish national grid, were estimated from Ecoinvent 3.3 database (Ecoinvent, 2016).

2.3 Impact categories and characterisation

Different methods were chosen to conduct the life cycle impact assessment (LCIA) stage. The IPCC 2013 (Mhyre et al. 2013) method was selected to assess the climate change (CC) impact, considering the global warming potential factors of IPCC with a timeframe of 100 years. Beyond CC, other five impact categories were selected among the so-called “baseline impact categories” in the ReCiPe 2016 midpoint method: stratospheric ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), land use (LU), and water consumption (WC). Additionally, cumulative energy demand (CED) was included as an indicator of the energy use throughout the life cycle of the product. SimaPro 9.1 LCA software (PRé Sustainability, 2020) was used to conduct the calculations.

2.4 Statistical analysis

To determine the effect of the PLF platform on the environmental performance, each farm was considered as an experimental unit and data were analyzed by ANOVA using the R software (version 3.6.2 R Core Team 2020) as follows:

$$Y_{ijk} = \mu + T_i + F_j + e_{ijk}$$

Where Y_{ijk} is the dependent, continuous variable, μ is the overall mean, T_i is the fixed effect of the PLF platform based on the differences between times (I = 2014 vs 2018), F_j is the random effect of the farm considered as a block (j = 1 to 5) and e_{ijk} is the residual error. Pearson's simple correlation analysis was carried out between estimated environmental impact, annual milk production and the physiological parameters obtained from the farms monitored.

3 Results

3.1 Environmental impact of goat milk

Impact assessment results for all the impact categories involved in the study are detailed in Table 4 and Figure 4, showing results referred per FU (1 kg of FPCM) and relative to highest contribution, respectively. Results from the sensitivity analysis using different allocation rules (biophysical, economic and protein content) are shown in Table S2. Allocation based on protein content resulted on the highest impact estimations (4-9% higher than biophysical), while economic allocation tended to attribute less environmental load to the goat's milk (2-4% lower). Independently of allocation method, some differences can be observed between the farms when compared on the same year basis, with milk from Farm 5 consistently showing the lowest environmental impact for most of the categories, except for water consumption (Figure 4).

Focusing on the carbon footprint (CF) of goat milk, GHG emissions per kg of FPCM for the five dairy goat farms analyzed are shown in Figure 5, together with the contribution from different GHG sources. The larger proportion of total GHG emissions was associated with feed production, which comes from cropland areas outside the farm. This involves emissions from crop cultivation and feed transport stages, with grains and concentrates contributing on average 48.5%, and forages 9.4%. Approximately, a third of these emissions are linked to CO_2 released through direct land use change (LUC) processes, while the remaining are mainly associated to N_2O emissions from fertilization and CO_2 emissions from agricultural and feed processing activities, involving fossil fuel consumption.

Enteric CH_4 emissions were identified as the second largest GHG source accounting for 28.0% of the total goat milk CF on average, followed by manure management (6.3%) and cereal straw usage for bedding purposes (3.3%). Finally, other GHG sources were also identified, most of them related to the energy use on-farm, although their contribution to the CF was on a lesser extent, mainly in the form of electricity (2.5%), diesel (1.7%) and biomass combustion (0.3%).

3.2 Effect of the PLF platform

Effect of PLF on the farm productive performance

The implementation of the PLF platform promoted an intensification of the production system at different levels (Table 2). The number of reproductive goats per farm tended to increase from 2014 to 2018 (*P*=0.060) and the reproductive intensification led to an increase in the prolificacy (*P*=0.031) and number of kids sold per goat (*P*=0.056). The FPCM yield per lactation tended to increase (*P*=0.098) being this increment more obvious when expressed as FPCM per year per goat (*P*=0.006). This platform also tended to decrease the unproductive periods such as the dry period length (*P*=0.051) or first partum age (-2.8%) and the replacement rate (*P*=0.048).

The observed increase in the number of reproductive animals and milk yield per goat observed from 2014 to 2018 tended to increase the consumption of concentrate (*P*=0.076), water (*P*=0.072) and electricity (*P*=0.087) (Table 3), whereas other relevant inputs such as forage, bedding, diesel or biomass fuel consumption were not significantly affected by the PLF implementation. The intensification observed from 2014 to 2018 promoted a substantial increase in the farm outputs such as the sales of FPCM (*P*=0.028) and the goat kids (*P*=0.017). On the contrary, the PLF implementation decreased the number of culled goats sold as meat (*P*=0.042) due to the lower replacement rate as a result of a higher functional longevity (Table 3).

Effect of PLF on the farm environmental performance

Across all the farms, the implementation of this PLF platform had a substantial and multi-factorial effect on the environmental impact per FU (1kg of FPCM) which ranged from -9% to -16% depending on the impact category considered (Table 4). As a result, from 2014 to 2018, all the impact categories were significantly reduced ($P<0.05$). Moreover, the environmental impact of milk production was significantly correlated ($p<0.05$) with several physiological and productivity variables, as affected by the PLF platform implementation (Table S3). Specifically, for the CF, a negative correlation was found with annual milk yield ($r^2=0.47$), lactation milk yield ($r^2=0.55$) and prolificacy ($r^2=0.47$), while a positive correlation was found with first partum age ($r^2=0.58$) and dry period length ($r^2=0.56$ – excluding farm 5) (Figure 6).

4 Discussion

4.1 Environmental impact of goat milk

Methodological choices applied in LCA studies of dairy products (e.g. FU, allocation method) have a strong influence on the results, making difficult to establish comparisons among studies, and therefore, among different production systems (Baldini et al, 2017). LCA studies on small ruminant dairy systems have often corrected milk according to the equation of Pulina et al (2005) for sheep milk, based on a fat and protein content of 6.5% and 5.8%, respectively. This approach makes difficult the comparison among dairy systems, and it seems especially inadequate for goat milk, which rarely reach those values. In view of this, the recommendation by FAO guidelines (FAO, 2016) seems a sensible approach, providing a common basis for comparison among dairy systems. In an attempt to harmonize results, the reported values from previous LCA works on small ruminants have been converted into a common FU (1 kg FPCM) following the equation indicated by FAO guidelines (FAO, 2016). Still, a number of methodological aspects like allocation method, or including LUC emissions and carbon sequestration in the estimation, will add strong variability in the reported values, but at least it allows to extract, with caution, some general trends that may help to contextualize the results from this study.

Traditionally, LCA approaches have attributed to goat -and sheep- milk a higher environmental impact compared to predominant milk production systems from dairy cattle (Gerber et al 2013). For example, Weiss et al (2012) estimated GHG fluxes of cow milk at 1.3–1.7 kg CO_2eq/FPCM on EU-27 average, while sheep and goat milk at 2.6–4.1 kg CO_2/kg FPCM. However, from the results of this study, and after reviewing data of previous literature on small ruminant LCAs, it does not seem that such differences exist when dairy production systems are compared under an equivalent FU (i.e. similar content of %fat and %protein) or when produced in a similar intensive manner. The importance of the FU on dairy goat systems, and in particular of the FPCM basis applied, was previously noted by Gutiérrez-Peña et al (2019). They reported an estimation 41% lower of the CF when milk correction was based on cow's milk vs sheep's milk. A similar trend can be observed in this study for other reviewed studies (Table 5).

When harmonized into the same FU (Table 5), the results of the CF in this work (1.53-1.71 kg CO_2 eq/kg FPCM) seem to be within the range observed for other high-productivity dairy goats in the same area (1.41-2.17 kg CO_2 eq/kg FPCM; Pardo et al 2016; Gutiérrez-Peña et al 2020) and values generally reported for dairy sheep systems (1.18-2.72 kg CO_2 eq/kg FPCM; Batalla et al 2015, Escribano et al 2020, Vagnoni et al 2015, 2017). In contrast to low productive small ruminant systems, where enteric CH_4 has been identified as the main source of GHG emissions, the CF of intensive dairy systems is often dominated by feed production activities. This is due to the use of supplementary feeds with greater quality and digestibility which enhance milk productivity per animal, and also results on lower enteric CH_4 emissions per kg DM ingested. As a trade-off, increased use of grains and concentrates usually involves a higher intensity of CO_2 and N_2O emissions per kg of feed, mainly linked to the use of fertilizers and fossil fuels during the cultivation stage. Moreover, some of these feed sources (e.g. soy, palm) are associated to direct

LUC processes (i.e. deforestation) which can lead to crucial changes in the CF of dairy systems when accounted. For example, when Battini et al (2014) included LUC emissions from soybean meal in the CF of cow's milk, they estimated a remarkable increase by 0.53 kg CO_2 eq/kg FPCM.

In our study, for the farms analyzed during 2018, forage and concentrate production contributed up to 57.9% of GHG emissions, of which 14.5% were attributed to direct LUC, mainly due to soybean expansion in South America. As previously stated, feed production is often the dominant GHG source of high-productive small ruminant systems, even though they often result in the lower emission intensity per kg of FPCM (Table 5). For that reason, it becomes especially important to look for potential mitigation strategies related to feed consumption in these systems.

From the data revised in this work, the lowest CF estimated for goat milk is reported by Robertson et al (2015) in indoor farms in New Zealand (NZ). A number of factors can explain that result, from the high milk productivity level observed, to the use of a specific method for estimating enteric CH_4 emissions. But interestingly, despite a large amount of supplementary feed was consumed in the indoor NZ dairy goat farms, they had a very low GHG associated, because many of them were food by-products (e.g. brewers grain). The benefits of exploiting available agri-food residues in the Mediterranean basin was also highlighted by Pardo et al (2016), with estimated GHG reductions among 12-19% in the CF of goat milk, and it has been stressed as a key adaptation opportunity for the small ruminant systems against expected CC effects in the region (Pardo et al 2020).

Although enteric CH_4 emissions is not the largest hot-spot in the CF, in our study its relative contribution is still quite relevant (28%). This observation agrees with estimates from previous studies on intensive dairy goat systems. However, it contrasts with estimations from global LCA approaches that often attribute a dominant role for enteric CH_4 emissions on sheep and goat milk (Gerber et al 2013; Leip et al, 2010), which could be due to the use of unrefined methodologies unspecific for small ruminants. The implementation of enteric methane mitigation strategies (e.g.

use of feed additives) is helping to decrease these emissions, despite they are not still considered neither in this study nor in most national inventories. Activities related to management practices contribute to a lesser extent to the CF, such as manure treatment (6.3%) and bedding material utilization (3.3%). Manure in goat farms is predominantly handled in solid form, often through composting treatment. This tends to produce significantly less CH_4 emissions in comparison to manure systems in liquid form (i.e. slurry), which are typical in intensive dairy cattle farms. Energy demand in goat farms is mainly linked to electricity consumption and fuel use for heating purposes. Although it is just a small part of the CF (4.6%), some actions can be taken in this aspect. Interestingly, two of the studied farms produced their heating from biomass by-products (i.e. olive husk), which contributed to reduce slightly their GHG emissions.

Comparing results of all impact categories with other studies is particularly difficult, due to heterogeneity of methodologies and impact assessment methods applied. Despite this, in general the results seem in the same range of previous LCAs (Zucali et al 2020, Battini et al 2014) with impacts on FE close to values reported by Zucali et al (2020) for dairy goats, while WC is slightly lower in our case.

In contrast to the CF, emissions produced on-farm tend to have a high relevance for some impact categories. For example, TA and FE were caused mainly by emissions of NH_3 (and leaching or run-off of NO_3^- and PO_4^-), which resulted directly from manure management, and additionally, from fertilizer application during off-farm feed production stages. In the case of OD, N_2O is the main substance involved, mainly associated to crop cultivation activities, but with a relevant role of N losses from manure management too (about 20%).

When comparing farms on the same year basis, milk from Farm 5 consistently showed the lowest environmental impact for most of the categories (Figure 4). Main reason behind this is the feed efficiency ratio, which is the highest (1.17 kg DM/kg FPCM) among all the analyzed farms, but also the feed resources utilized. Farm 5 shows the lowest forage proportion in the diet, but it includes an important share of grains' mix, which replaces the consumption of concentrates that tend to have a higher environmental impact.

Interestingly, the use of some specific ingredients in the animal feed seems to have a crucial influence in the WC category. In particular, maize and oats production contributed the most to this category. They are both crops with high water demands in comparison to other cereals, and its cultivation under Mediterranean climate conditions often involves important irrigation needs. Their use explains why Farm 5 did not performed especially well in this category, despite showing the highest feed efficiency.

4.2 Effect of the PLF platform

From the main findings of this work, it can be underlined that the incorporation of this PLF platform promoted a significant improvement in the environmental sustainability of dairy goat farms, mainly as a result of a substantial increase in the milk yield (Tables 2 and 3). Previous studies have highlighted individual milk production as a key parameter influencing the environmental impact of goat milk (e.g. Zucali et al 2020). This trend was also observed in the present study, with a consistent negative correlation observed among environmental impact and annual milk yield (Figure 6a, Figure S1, Table S3).

Depending on the impact category, reductions among 9 to 16% on the environmental impact were estimated after three years from the implementation of the PLF platform. These figures are relevant taking into account that they come exclusively from changes in aspects directly related to the farm management during a limited time period. Intensive livestock farming involves managing large numbers of animals, which makes difficult a detailed control of all of them by simple human observation. In this context, PLF platforms for data collection and management can be particularly helpful, allowing the integration of individual animal data. As a result of this individual monitoring, a number of farm management decisions can be affected (as described in Table 1), which leads to increase farm productivity through 3 main mechanisms that involve i) an accelerated genetic progress relying on more knowledgeable selection of high merit goats, ii) an improved breeding and culling management based on the records of productive, reproductive and health parameters from each animal, and iii) a decrease of unproductive periods through the optimization of first conception date, and lactation and dry periods lengths according to animal's physiological state and milk yield prospects.

In our study, the optimization of breeding and culling selection, together with the accelerated genetic progress, led in the mid-term to a general improvement of the animal´s performance. This PLF platform facilitated these strategies by enabling a better data integration which allowed, for example, to identify top (and bottom) productive animals, whose offspring to be selected for replacement; or to detect individuals prone to suffer physiological or reproductive insufficiencies for culling. The improvement in both strategies obtained through the PLF platform implementation was reflected on the positive impact on various productive and reproductive parameters across the studied period, like the increments observed of milk produced per lactation (+7.9%) and prolificacy (+9.4%) (Table 2). Both parameters were positively correlated with the annual milk productivity (lactation milk yield: r^2 =0.80, prolificacy: r^2=0.36) (Figure S2) and inversely correlated with the environmental impact at the farm level (lactation milk yield: r^2 =0.55, prolificacy: r^2=0.47) (Figure 6b,c).

Moreover, the optimization of breeding and culling selection was also associated to the observed decrease in the replacement rate (-20%) during the studied period. The shift towards more resilient animals, together with a more accurate monitoring of health programs, allowed to decrease the culled goats and to increase the number of kids sold (+33%) as a result of lower replacement needs. These aspects affect positively both, milk and meat production, with implications for the allocation between co-products, leading to more effective reductions of the environmental impact on the milk side.

A decrease of first partum age (-15 days) and dry period length (-9 days) was also noted in our study after farms implemented the PLF platform. This is associated to a more precise monitoring of each animal, which allows i) an optimization of first conception date according to its particular physiological stage and individual records, and ii) a customization of lactation and dry period lengths based on specific milk yield prospects. Both parameters were found positively correlated with annual milk productivity (Figure S2, Table S3) and negatively correlated with CF (first birth age: r^2 =0.58, dry period length: r^2=0.56) (Figure 6d,e).

Interestingly, total feed intake (kg DM/goat/year) was not correlated with CF or annual milk yield although, a negative relationship was observed between forage/concentrate ratio with CF (r^2=0.39) (Figure 6f) and other parameters like milk yield per lactation (r^2=0.35). This could imply that the transition towards more intensive systems may involve an increase in the use of concentrates. This could be a result of shortened unproductive periods, when higher proportion of forage is used in the diet, but also a consequence of the shift towards more productive animals, in order to satisfice the energy requirement of high yielding goats, as noted in this study (+9.1%). This trend has been adverted by previous works, as it could lead to relevant changes in the self-sufficiency of dairy systems (Gutiérrez-Peña et al 2019; Zucali et al 2020) and also in their GHG emissions profile (del Prado et al 2021). Increased feed efficiency has been often linked with the ingestion of feed more suitable for human consumption, but this involves negative impacts in relation to land competition, biodiversity and global food system sustainability (del Prado et al., 2013). Moreover, increased use of concentrates often leads to less enteric CH_4 emissions (through improved nutrient utilization) but sometimes at the expense of increasing CO_2 and N_2O contribution from crop cultivation activities. This kind of dynamics are typical of intensification processes, but their implications in terms of global warming must be carefully analyzed due to the different behavior of long-lived pollutants (i.e. CO_2, N_2O) versus short-lived (i.e. CH_4) (Del Prado et al 2021, Ridoutt, 2021).

In our study, a generalized reduction was observed in all GHG sources, due to a combination of PLF-led improvements that affect efficiency at animal and farm level. In relative terms, the greater reductions were observed on activities related to fixed resource utilization for farm operations, such as fuels (-34%), electricity (-16%) and use of bedding materials (-25%). However, when analyzing results in absolute terms, the major contribution to the CF reduction was associated to concentrates consumption (-51%) (Table S4). Although some improvements achieved from the PLF platform implementation (i.e. animal milk productivity) may involve an increase in the proportion of concentrate used, ultimately there is an overall decrease (-17%) on the consumption of concentrates per kg of FPCM produced. This optimization in the concentrates use was also the major factor behind the mitigation observed in other environmental impacts, dominating especially the reduction achieved in impact categories such as WC (67%), LU (51%), FE (48%) and OD (44%) (Table S4).

Despite the known benefits of PLF tools to optimize farm management (Lovarelli et al 2020, Tullo et al 2019), their implementation is not a widespread practice in small ruminant dairy systems. Cost for investment often represents an obstacle in small farms, but a number of specific reasons may have also constraint the incorporation of PLF concepts in these systems, such as low net margin per animal, the additional labor required for data collection, structural insufficiencies (e.g. aged milking parlor and infrastructures) or difficulties on the adoption of new technology (Belanche et al., 2019; Caja et al., 2020). In the face of challenges like CC, the incorporation of PLF tools in small ruminant systems should be promoted, as they provide opportunities, not only for mitigation purposes but for CC adaptation too. Small ruminant systems are particularly relevant in Mediterranean areas, where severe impacts of CC are expected in the next years (Pardo et al., 2020). In this context, a precise monitoring of animal's physiological state and productive parameters, together with weather variables (e.g. temperature-humidity data loggers), could give farmers the possibility to cope better with heat stress risks, by timely taking appropriate adaptation measures, like adjusting ambient conditions or feeding. Moreover, the use of platforms for data gathering and interpretation open up the possibilities for incorporating other PLF tools into the farm management. In this context, the proposed PLF platform is in constant development and over the last two years has incorporated open and scalable computing resources in order allow a greater versatility on the integration of new elements. This evolution appears as a repose to the growing demand from the users to better monitor individual animals and farm parameters, as well as to improve the product traceability and information to satisfice the consumer demand for healthy, nutritious and environmentally friendly products. The new elements focus on a better monitoring of the animals´ health and wellbeing, farm expenses (e.g. feeds, medicines, animals, labor, etc.) and farm outputs (e.g. milk, meat, culled animals, manure, etc.) in order to generate reliable technical-economic indicators. Future research is needed in the years to come in order to evaluate the effects of these new elements on the farm environmental performance and overall farm sustainability.

5 Conclusions

From our analysis it seems clear that small ruminant dairy production does not necessarily imply a higher environmental impact in comparison to cow milk. Moreover, our study showed that when smart-farming concepts are applied through the implementation of a PLF platform, significant increases in the productivity are achieved together with reductions in the environmental impact of goat milk. These findings stress the importance of harmonizing methodological choices in dairy LCAs, but also that PLF platforms for data management could play an important role for the sustainability of small ruminant dairy production. However, technology should not aim at substituting farmers in decision-making but to support them through an effective data processing and interpretation system. In this sense, the farmers´ capacity building based on the adoption of new technologies and increasing the technical and business management training has been identified as top priority for the sustainability of the small ruminant systems in Europe (Belanche et al., 2021).

Future actions in the sector should promote the adoption of PLF concepts, but a successful implementation will probably require support in terms of financial instruments, knowledge transfer activities and research of technological innovations like tools and sensors that can adapt to the existent diversity of small ruminant production systems. This acquires particular relevance in the Mediterranean region, where sheep and goats farming plays a key role, from both socio-economic and environmental perspectives, providing not only protein-rich products from harsh environments, but also a number of eco-services (e.g. fire prevention, landscape and biodiversity preservation) that should also be preserved or enhanced through PLF tools implementation.

6 Acknowledgements

This research is supported by the Spanish Government through María de Maeztu excellence accreditation 2018-2022 (Ref. MDM-2017-0714) and by the Basque Government through the BERC 2018-2021 program. This work was also supported by the Horizon2020 SFS-01c-2015 project entitled “Innovation of sustainable sheep and goat production in Europe (iSAGE)” (grant number 679302). Alejandro Belanche and Agustin del Prado are funded by the Ramon y Cajal program from the Ministry of Sciences and Innovation (RYC2019-027764 and RYC-2017-22143, respectively).

7 References

Alejandro, M., 2016. Automation devices in sheep and goat machine milking. Small Rumin. Res. 142, 48–50. doi:10.1016/j.smallrumres.2016.04.004

Aziz, M.A., 2010. Present status of the world goat populations and their productivity. World 861, 1.

Baldini, C., Gardoni, D., Guarino, M., 2017. A critical review of the recent evolution of Life Cycle Assessment applied to milk production. J. Clean. Prod. 140, 421–435. doi:10.1016/j.jclepro.2016.06.078

Batalla, I., Knudsen, M.T., Mogensen, L., Hierro, Ó. Del, Pinto, M., Hermansen, J.E., 2015. Carbon footprint of milk from sheep farming systems in Northern Spain including soil carbon sequestration in grasslands. J. Clean. Prod. 104, 121–129. doi:10.1016/j.jclepro.2015.05.043

Battini, F., Agostini, A., Boulamanti, A.K., Giuntoli, J., Amaducci, S., 2014. Mitigating the environmental impacts of milk production via anaerobic digestion of manure: Case study of a dairy farm in the Po Valley. Sci. Total Environ. 481, 196–208. doi:10.1016/j.scitotenv.2014.02.038

Belanche, A., Martín-Collado, D., Rose, G., Yáñez-Ruiz, D.R., 2021. A multi-stakeholder participatory study identifies the priorities for the sustainability of the small ruminants farming sector in Europe. Animal 15, 100131.

Belanche, A., Martín-García, A.I., Fernández-Álvarez, J., Pleguezuelos, J., Mantecón, Á.R., Yáñez-Ruiz, D.R., 2019. Optimizing management of dairy goat farms through individual animal data interpretation: A case study of smart farming in Spain. Agric. Syst. 173, 27–38. doi:10.1016/j.agsy.2019.02.002

Berckmans, D., 2017. General introduction to precision livestock farming. Anim. Front. 7, 6–11. https://doi.org/10.2527/af.2017.0102

Blonk Agri-footprint BV, 2019. Agri-Footprint 4.1 database

Caja, G., Castro-Costa, A., Salama, A.A.K., Oliver, J., Baratta, M., Ferrer, C., Knight, C.H., 2020. Sensing solutions for improving the performance, health and wellbeing of small ruminants. J. Dairy Res. 87, 34–46. doi:10.1017/S0022029920000667

Castel, J. M., Mena, Y., Ruiz, F. A., Camúñez-Ruiz, J., Sánchez-Rodríguez, M, 2011. Changes occurring in dairy goat production systems in less favoured areas of Spain. Small Rumin. Res, 96(2-3), 83-92.

Del Prado, A., Manzano, P., Pardo, G., 2021. The role of the European small ruminant dairy sector in stabilising global temperatures: lessons from GWP* warming-equivalent emission metrics. J. Dairy Res. 88, 8–15.

Del Prado, A., Mas, K., Pardo, G., Gallejones, P., 2013. Modelling the interactions between C and N farm balances and GHG emissions from confinement dairy farms in northern Spain. Sci. Total Environ. 465, 156–165. doi:10.1016/j.scitotenv.2013.03.064

Ecoinvent® 3.3 Database, 2016. Ecoinvent® Swiss Center for Life Cycle Inventories. Available at http://www.ecoinvent.org/database/ecoinvent-33/ecoinvent-33.html

Escribano, M., Elghannam, A., Mesias, F.J., 2020. Dairy sheep farms in semi-arid rangelands: A carbon footprint dilemma between intensification and land-based grazing. Land use policy 95. doi:10.1016/j.landusepol.2020.104600

FAO, 2016. Greenhouse gas emissions and fossil energy use from small ruminant supply chains: Guidelines for assessment. Livestock Environmental Assessment and Performance Partnership. FAO, Rome, Italy.

FAOSTAT, 2021. Statistical databases. in Food and Agriculture Organization of the United Nations. Rome.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO).

Gutiérrez-Peña, R., Mena, Y., Batalla, I., Mancilla-Leytón, J.M., 2019. Carbon footprint of dairy goat production systems: A comparison of three contrasting grazing levels in the Sierra de Grazalema Natural Park (Southern Spain). J. Environ. Manage. 232, 993–998. doi:10.1016/j.jenvman.2018.12.005

Hristov, A.N., Ott, T., Tricarico, J., Rotz, A., Waghorn, G., Adesogan, A., Dijkstra, J., Montes, F., Oh, J., Kebreab, E., 2013. Special topics—Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options. J. Anim. Sci. 91, 5095–5113.

IPCC, 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories available at: www.ipcc-nggip.iges.or.jp/public/2019rf

ISO, 2006. ISO 14044. Environmental Management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization.

Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S., Biala, K., 2010. Evaluation of the livestock sector’s contribution to the EU greenhouse gas emissions (GGELS).

Lovarelli, D., Bacenetti, J., Guarino, M., 2020. A review on dairy cattle farming: Is precision livestock farming the compromise for an environmental, economic and social sustainable production? J. Clean. Prod. 262, 121409. doi:10.1016/j.jclepro.2020.121409

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B. and Nakajima, T., 2013. Climate change 2013: the physical science basis.

Odintsov Vaintrub, M., Levit, H., Chincarini, M., Fusaro, I., Giammarco, M., Vignola, G., 2021. Review: Precision livestock farming, automats and new technologies: possible applications in extensive dairy sheep farming. Animal 15, 100143. doi:10.1016/j.animal.2020.100143

Pardo, G., del Prado, A., 2020. Guidelines for small ruminant production systems under climate emergency in Europe. Small Rumin. Res. 193. doi:10.1016/j.smallrumres.2020.106261

Pardo, G., Martin-Garcia, I., Arco, A., Yañez-Ruiz, D.R., Moral, R., Del Prado, A., 2016. Greenhouse-gas mitigation potential of agro-industrial by-products in the diet of dairy goats in Spain: A life-cycle perspective. Anim. Prod. Sci. 56. doi:10.1071/AN15620

PRé Sustainability, 2020. Software LCA SimaPro 9.1 http://www.pre.nl

Pulina, G., Macciotta, N., Nudda, A., 2005. Milk composition and feeding in the Italian dairy sheep. Ital. J. Anim. Sci. 4, 5–14.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Ridoutt, B., 2021. Climate impact of Australian livestock production assessed using the GWP* climate metric. Livest. Sci. 246, 104459.

Robertson, K., Symes, W., Garnham, M., 2015. Carbon footprint of dairy goat milk production in New Zealand. J. Dairy Sci. 98, 4279–4293. doi:10.3168/jds.2014-9104

Sabia, E., Gauly, M., Napolitano, F., Serrapica, F., Cifuni, G.F., Claps, S., 2020. Dairy sheep carbon footprint and ReCiPe end-point study. Small Rumin. Res. 185, 106085. doi:10.1016/j.smallrumres.2020.106085

Tullo, E., Finzi, A., Guarino, M., 2019. Review: Environmental impact of livestock farming and Precision Livestock Farming as a mitigation strategy. Sci. Total Environ. 650, 2751–2760. doi:10.1016/j.scitotenv.2018.10.018

Vagnoni, E., Franca, A., Breedveld, L., Porqueddu, C., Ferrara, R., Duce, P., 2015. Environmental performances of Sardinian dairy sheep production systems at different input levels. Sci. Total Environ. 502, 354–361. doi:10.1016/j.scitotenv.2014.09.020

Vagnoni, E., Franca, A., Porqueddu, C., Duce, P., 2017. Environmental profile of Sardinian sheep milk cheese supply chain: A comparison between two contrasting dairy systems. J. Clean. Prod. 165, 1078–1089. doi:10.1016/j.jclepro.2017.07.115

Vandermeulen, J., Bahr, C., Johnston, D., Earley, B., Tullo, E., Fontana, I., Guarino, M., Exadaktylos, V., Berckmans, D., 2016. Early recognition of bovine respiratory disease in calves using automated continuous monitoring of cough sounds. Comput. Electron. Agric. 129, 15–26.

Weiss, F., Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: a life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149, 124–134.

Zucali, M., Lovarelli, D., Celozzi, S., Bacenetti, J., Sandrucci, A., Bava, L., 2020. Management options to reduce the environmental impact of dairy goat milk production. Livest. Sci. 231, 103888. doi:10.1016/j.livsci.2019.103888

Table captions

Table 1 - Summary of the input and output information in the implemented PLF platform.

Table 2 – Main characteristics of the dairy goat farms analyzed in the study

Table 3 –Main outputs and inputs flows of the farms during the analyzed period (2014-2018).

Table 4 – Environmental impact of goat milk of the analyzed farms (1 kg FPCM).

Table 5 – Comparison of studies analyzing the carbon footprint (CF) of small ruminant dairy systems. Original CF estimates have been converted into FPCM according to FAO, 2016.

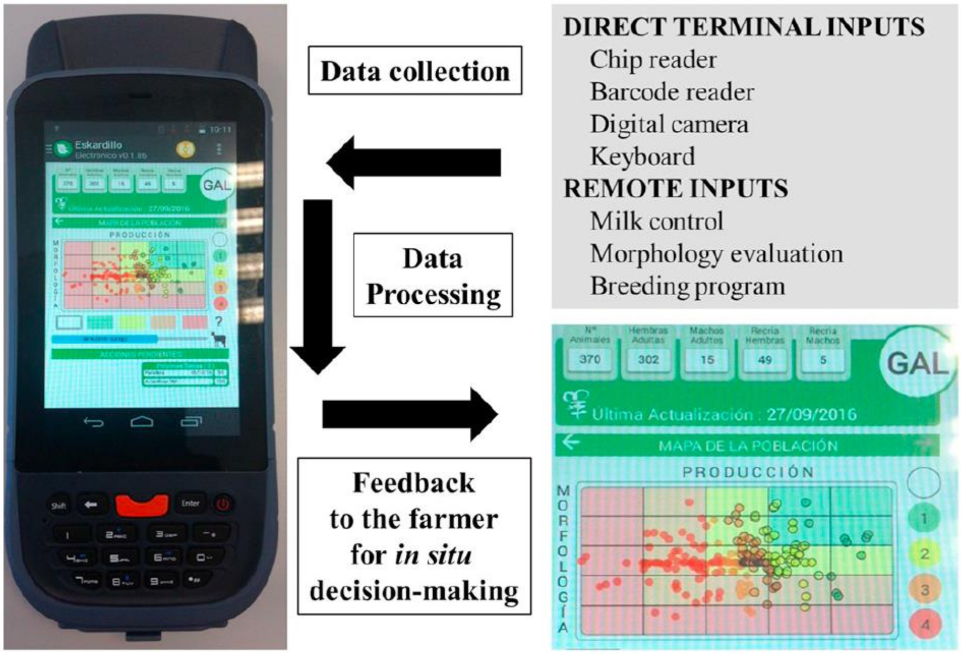

Figure 1. Image of the PLF platform terminal (left), data flows and a screenshot describing the population map of the goats in the farm according to their physiological stage, morphology and productivity (right) (from Belanche et al., 2019).

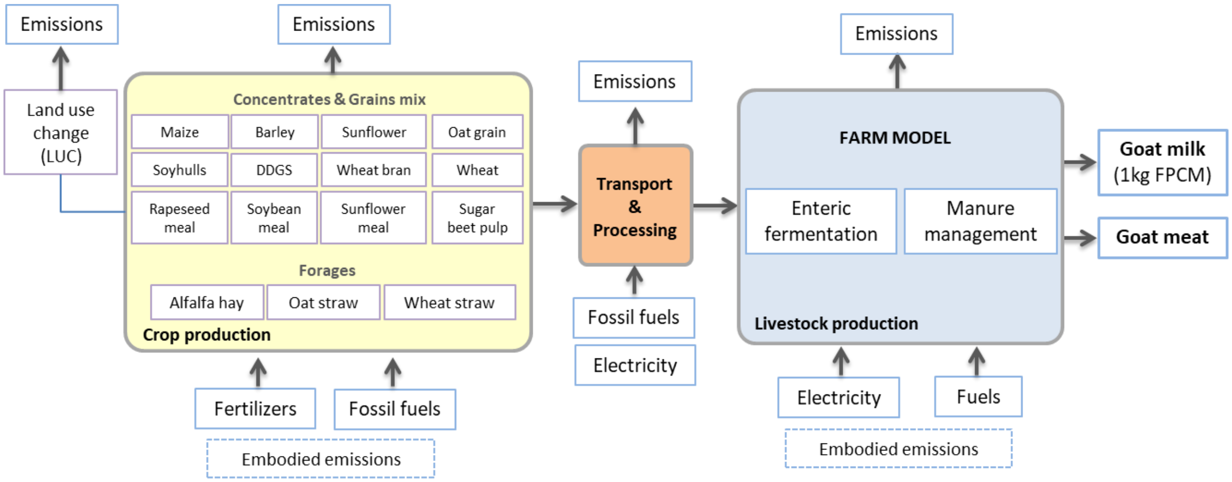

Figure 2 – System boundaries for dairy goat production system and main sources of emissions.

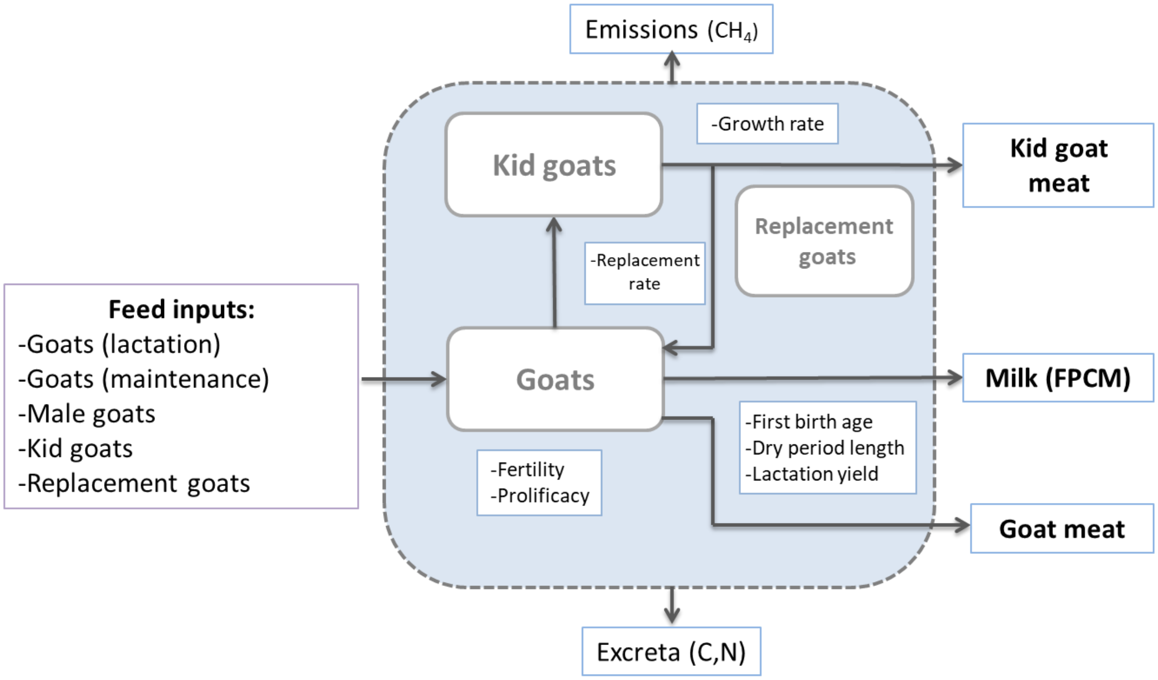

Figure 3 – Scheme of the herd model built to simulate the herd structure, technical parameters and animal management in every case.

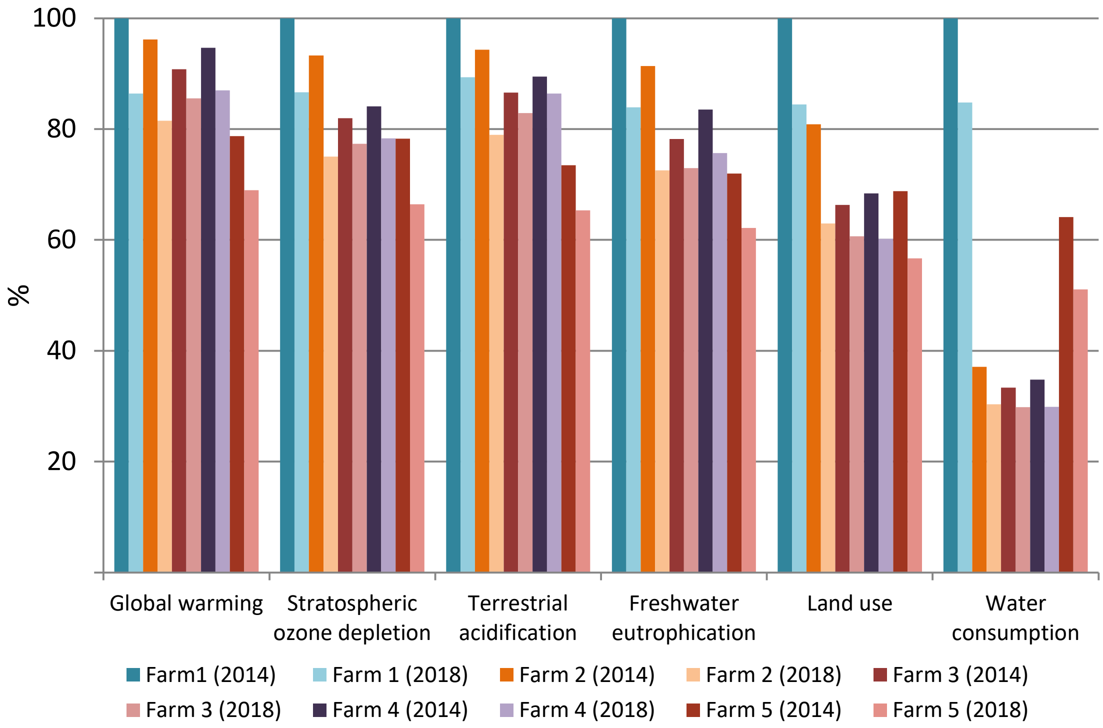

Figure 4 – Relative changes to different environmental impact categories after PLF platform implementation

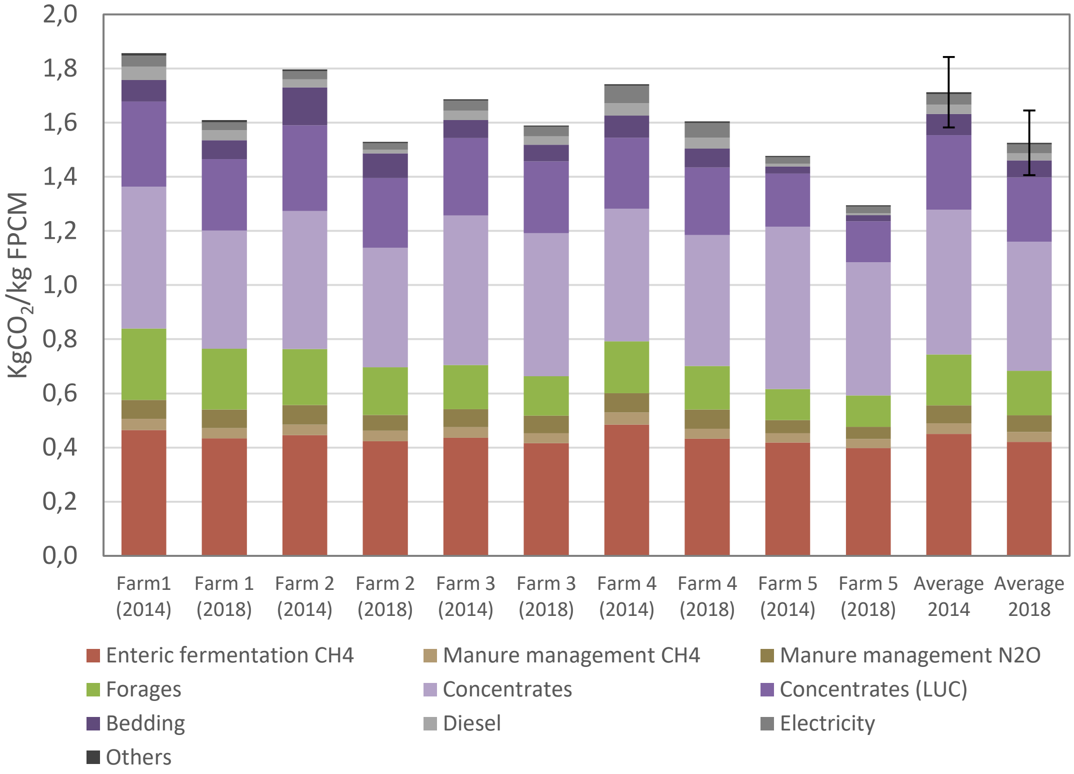

Figure 5 – Carbon footprint of 1kg of Fat and Protein Corrected milk (FPCM) for different dairy goat farms in the analysed period. Last two columns show average of all farms in the selected year. Bars show standard deviation.

Figure 6 – Scatter plot for carbon footprint of goat milk against a selection of physiological and productivity variables: a) annual milk yield, b) milk yield per lactation, c) prolificacy, d) first birth age, e) dry period length, f) forage/concentrate