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GREENHOUSE GASES EMISSION BASELINE SCENARIO FOR SHEEP SECTOR AT TERRITORIAL SCALE

A Sardinia case study

Bachelor's thesis

Bachelor of Engineering

Environmental Engineering

2020

South-Eastern Finland
University of Applied Sciences

Author	**Degree title**	**Time**
Pham Minh Anh Nguyen	Bachelor of Environmental Engineering	February 2019

Thesis title

Greenhouse gases emission baseline scenario for sheep sector at territorial scale.
A Sardinian case study

44 pages
06 pages of appendices

Commissioned by

National Research Council of Italy – Institute of Bioeconomy

Supervisor

Enrico Vagnoni
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Abstract

The main objective of this thesis was to estimate a new emission baseline for Sardinia dairy sheep sector using 2017 production data. The baseline scenario was aligned with the main goals of SheepToShip LIFE project to define the most effective action, viable strategies of GHG mitigation at farm and processing plant level and then plan future policy regulation of the regional government to reduce the total emission amounts by 20% in the next 10 years. For the last few decades, agriculture accounted for 10-12% of total anthropogenic GHG emission of which 14.5% was contributed from livestock sector. Small ruminants farming turned out to be an important factor to have emitted 6.5% of the GHG sector's emission and the emission intensity of sheep products usually reaches higher values than cow and goat. Moreover, sheep equals to 60% of the world ruminant population and is expected to increase which causes larger negative impact to the atmosphere. Therefore, within the Mediterranean area, Sardinia region (Italy) with a distribution of 14000 farms, production systems and stocking rates despite small surface was targeted as the best context for demonstrative actions of GHG emission mitigation on dairy sheep sector throughout the project.

Estimated baseline was finalized to calculate a proposed value and 43.2ktons showed as an amount of CO2-eq emissions that must be cut down per year to achieve the project goal of reducing GHG emission by 20% in 10 years. The whole dairy sheep supply chain's cumulative emission in Sardinia was 2159ktons of CO_2 equivalent with attribution to 80% and 20% for milk and meat, respectively. Generally, new baseline scenario was carried out following LCA methodology and covered emissions from "cradle to dairy plant gate" accounting for 3 million sheep heads and 286 million litres of produced milk with an average emission intensity of 4.8kg of CO_2 equivalent per litre of milk. Similar to cattle, small ruminants' milk and meat production emission was calculated from the two main sources namely enteric CH_4, N_2O, feed fertilizers, manure management and other emissions to the farm gate. Processing plant was considered due to its creation for 12% of total LCA emissions. Then, each of emission amount computed from cradle to farm gate and from the farm gate to dairy plant was combined to establish the total value of emission.

Keywords

GHG emission, SheepToShip project, LCA study, eco-innovation

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1 INTRODUCTION

With the urgent of temperature increase between 1.8 and 4ºC as predicted by the International Panel of Climate Change (IPCC) for the next 90 years, the incentives to reduce total amount of greenhouse gas (GHG) emission plays a vital role to avoid any threats from climate change to the planet, its population and economies (Skuce et al., 2013). FAO estimated that the amount of non-CO_2 emission from agricultural was 5.2–5.8 Gt CO_2-eq/year, corresponding to 10-12% of total anthropogenic GHG emissions (Gerber et al., 2013). In particular, livestock sector was responsible for 14.5% of all anthropogenic GHG emissions, with a significant impact of CH_4 and N_2O emissions (44% and 53% of global emissions, respectively). Within the livestock sector, cattle breeding had the most emission. In addition, projections by 2025 made with the CAPRI model illustrated that dairy cattle would be about 30% of the total agriculture GHG emissions in EU-28 (European Commission, 2015). Small ruminants farming is also an important contributor (just under 0.5 Gt CO_2-eq and 1/3 of GHG emissions of bovine milk production), representing around 6.5% of GHG sector's emissions (Gerber et al., 2013; Opio et al., 2013). In specific, emission intensity of sheep products (kg of CO2-eq/kg of sheep milk or meat) usually reached much higher values than cow and goat products both for their lower production levels and higher milk solid content. Despite sheep and goat milk was less than 2% of the global milk production, sheep and goats accounted for about 60% of the total world ruminant population (FAO, 2019) and its milk production was expected to increase by 26% and 53% in the given order by the next 10 years (Pulina et al., 2018).

Moreover, sheep farming plays a large socio-economic and environmental role in some specific economies, providing food besides relevant ecosystem services. Having 29% of global sheep milk made in Europe, with dairy sheep farms mainly in Mediterranean regions confined to Southern and Central Europe (Zygoyannis, 2006), dairy sheep production systems showed a large diversity in terms of farm structure and intensification level. Italy, with more than 7 million sheep heads in 68 thousand farms, turned out to be the third country in EU-28 for sheep population (IZS, 2016). According to (FAOSTAT, 2012), Italian sheep farming was in charge of more than 6% of the total enteric methane emissions by the European agricultural sector. Within the Italian sheep sector, Sardinia is by far the main region with more than 45% of Italian sheep ewes and about 13 thousand farms (ISTAT, 2016) spreading all over the island. 25% of total EU-27 sheep milk production came from Sardinia (Rural Development Programme of Sardinia - RDP, 2014-2020). The whole Sardinian sheep milk production (more than 300,000t/year) is transformed in cheese, produced with a semi-artisanal or industrial process. Sardinian milk sheep cheese production has three Protected Designation of Origin cheeses (PDO), i.e. “Pecorino Romano” (mainly intended for export and represents more than 90% of the total Sardinian PDO cheeses) (Osservatorio Regionale della filiera ovicaprina, 2012), “Fiore Sardo”, “Pecorino Sardo” and several minor products, all closely linked to the territory and local traditions (Piredda et al., 2006). Also, in other Mediterranean regions, Sardinian sheep sector is characterized by a strong farm fragmentation, with a predominance of small family-run farms (herds below 300 heads). Only in the more fertile and irrigated plains that medium/big farms are found. Therefore, contrasting dairy sheep farming systems coexist in Sardinia, with differences in input utilization, land use and intensification level which depend on geographical location of farms, specific economic conditions and other external factors such as public incentive policies and local or global market trends (Sitzia et al., 2015).

Initially, several studies have been dedicated to the environmental assessment of cow systems (Baldini et al., 2017; de Boer, I.J.M, 2003; de Vries et al., 2015; Soteriades et al., 2016) because they have a worldwide economic relevance, play an essential role in human diet as a protein food source and largely contribute to global CH_4 and N_2O emissions. Secondly, all authors suggested environmental performances should be using Life Cycle Assessment (LCA) approach, the widely accepted, complete and standardized computational tool to provide a widespread knowledge on the environmental aspects associated with products, services or activities. The LCA analysis also represents the first step towards sustainability of production systems by identifying environmental impacts and damages of the products (Baldini et al., 2017). Thirdly, despite their significance in the global trends of livestock productions, little research has been focused on the environmental implications of dairy sheep systems from a life cycle perspective (Opio et al., 2013; Weiss and Leip, 2012; Vagnoni et al., 2015; Marino et al., 2016). For such, Carbon Footprint (CF) of sheep milk showed in those studies was double per kg compared to cow milk which outweighed the ratio between sheep and cow milk energy. On the other hand, Mediterranean dairy sheep farming could be an interesting case study of the trade-off between agricultural intensification and benefits of multiple services of livestock systems, a crucial issue on the greening agenda. Considering the above features, Sardinia was targeted as the best context for testing mitigation strategies and to carry out demonstrative actions aimed to reduce GHG emissions from dairy sheep supply chain through SheepToShip LIFE (www.sheeptoship.eu). Specifically, SheepToShip LIFE is a 5-year (from July 2016 to June 2021) project financed by the EU LIFE Programme Climate Action 2014-2020 to improve the environmental sustainability of the dairy supply chain in Sardinia and its overall objective is to reduce GHG emissions from the Sardinian dairy sheep sector by 20% in 10 years. Thereby, its actions promote the inclusion of environmental strategies for the sheep sector into rural development programmes with a focus on i) efficiency of production systems and ii) valorisation of the ecosystem services resulted in pasture-based farms. Furthermore, the immediate goals of the project are to identify innovative solutions for the emission reduction through LCA approach and to demonstrate the environmental and socio-economic benefits derived from eco-innovation in the dairy sheep farming and dairy industry sector. Along with that, the final goal is to transfer the knowledge into an Environmental Action Plan for the sheep sector of Sardinia, which harmonizes the project intervention strategy with regional policies to mitigate climate change.

With the aim of targeting future strategies of effective mitigation within the SheepToShip LIFE initiative, this thesis provided an updated estimation of the values of GHG emissions baseline for the Sardinian dairy sheep sector. The baseline scenario refers to the Sardinia sheep milk production for the 2017 reference year and covers GHG emissions launching “from cradle to dairy plant gate” system boundary. The specific goals of the emission baseline estimation aim to i) define the most effective demonstrative action and the most viable strategies of GHG mitigation at farm and processing plant level; and ii) plan the future policy regulation of the regional government to get an important reduction of emissions in the next 10 years.

2 LITERATURE REVIEW ON LCA CONCEPT

LCA is a globally accepted and standard method used to identify and quantify the environmental impacts of a product (Buratti et al., 2017) which is a suitable concept for the thesis. LCA analyses the entire life cycle of a product which means from manufacture to disposal such as resource consumption, polluting emissions, energy usage, etc (Goldstein et al., 2016). Application of LCA to livestock production systems is a relatively new area of research (Cottle and Cowie, 2016). Several studies have been published on dairy and beef cattle while few papers have been published on LCA of the sheep sector. Therefore, a review of these studies for methodological and quantitative issues could be helpful to highlight the strength and weaknesses of this approach and to execute improved LCA analysis in the future. To perform a literature review on the most relevant studies regarding world sheep productions, twenty-five LCA studies were classified considering their focus on the farm main product, in particular distinguishing among meat (Appendix 3.1), milk (Appendix 3.2) and wool (Appendix 3.3). The list of published papers reported in the following tables might be considered exhaustive of the actual literature even if it cannot be excluded that other papers have been published and provide quantifications of the emissions intensities of the sheep supply chain under different livestock systems and conditions.

Literature information and appendix tables 3.1, 3.2 and 3.3 generally showed that the most of the LCA studies published since 2008 to present on sheep farms quantified emissions of meat productions systems at farm level. The studied farms were located in Europe (mainly the UK, one from Spain, two from France, one from Sweden) or Oceania (mainly Australia, and one New Zealand farms) (Table 3.1). This highlights the relevance of the sheep production systems in these two areas. Despite this general aggregation, the studies were very heterogeneous in terms of scope, focus, methodological approach and results

(Table 3.1). Sample size also extremely changed; several studies considered only a single case study farm (Peters et al., 2010, Edwards-Jones et al., 2009) others performed surveys including more than 1000 farms (Benoit and Dakpo, 2012) whereas other designed experimental blocks that considered different farming systems (Edwards-Jones et al., 2009; Jones et al., 2014; Table 3.1). System boundaries were limited, for the major part of the studies, from production to farm gate, with only 3 studies estimating the emission intensities from production to retail (Wiedemann et al., 2015; Wallman et al., 2012; Williams et al., 2008), whereas only 1 from production to grave (Table 3.1). Differences were also found on the methods used to estimate the emission from enteric fermentation. It has to be noticed that the most recently published studies mainly preferred to adopt the Tier 2 or 3 approaches from IPCC guidelines (2006; Table 3.1), which are considered more appropriate to get accurate estimates of the emissions at farm level. Allocation methods used to distribute emissions among farm products were also very different among studies. Most of them adopted the economic allocation criterion, whereas the allocation based on biophysical mass balance was the second most diffused approach. Only one study included system expansion criteria. It should be noted that the most recently published studies tried to include different allocation approaches to provide more information on the impact quantification.

The emission intensity output was expressed in terms of carcass weight (CW) or live weight (LW), and only one single case in terms of meat ready for retail eat. The CF of the meat production largely varied within and among studies. Within the studies, the largest observed variation ranged from 5.4 to 33.3 kg of CO_2-eq/kg of LW lamb meat. Differences were large even within the same meat farming system (Jones et al., 2014; Table 3.1), mainly because animal productivity was indicated as number of lambs per ewe mated and lamb growth rate. Among studies, the CF of the lamb meat varied from 5 to 33.3 kg of CO_2-eq/kg of LW lamb meat. A large number of values resulted within 8 and 20 kg of CO_2-eq/kg of lamb meat (CW or LW; Table 3.1). Functional units always matter but, due to the extreme variability within and among studies, emission intensities expressed per kg of CW were not always higher than those expressed per kg of

LW. Even if it is very difficult to define a typical range of CF, two values of emission intensities resulted very far from the observed range obtained in majority of the studies. The value reported by Benoit and Dakpo (2012) resulted equal to 82 kg of CO_2-eq/kg of CW lamb meat for a France farm, representing the extreme value obtained in a sample of 1180 farms, and the value reported by Edward Jones et al. (2009) resulted equal to 144 kg of CO_2-eq/kg of CW lamb meat for an extensive UK farm, the only consideration in that farming system. Heterogeneity of literature values reported in Table 3.1 does not allow to easily deduce a clear picture of the main factors affecting the environmental performance of the lamb meat sector. In this sense, each study should be evaluated and analysed individually in order to exploit the most important factor that affects emission intensities.

Among LCA studies focusing on sheep milk, 4 of them analysed Mediterranean farms whereas 1 article was about an Australian case study (Table 3.2). Sample size was very limited in all the considered studies: 1 case study farm (Atzori et al., 2015), 3 farms representative of 3 farming systems (Vagnoni et al., 2015); the largest sample included 12 surveyed farms (Batalla et al., 2015); one study focused on 4 simulated farm scenario without performing a specific farm survey (Atzori et al., 2013). System boundaries were limited from production to farm gate in all considered dairy sheep studies (Table 3.2). Emissions were, for the most part, economically allocated to farm products and then expressed per kg of Fat and Protein Corrected Milk (FPCM). Emission intensities from European farms (studies from 1 to 4 in Table 3.2) on average varied from 2.0 (Vagnoni et al., 2015) to 5.35 CO_2-eq/kg of FPCM (Batalla et al., 2014). The most frequent values were included among 2.0 and 3.0 CO_2-eq/kg of FPCM. The Australian farms showed values from 3.64 to 4.10 CO_2-eq/kg of FPCM (Michael, 2011; Table 3.2). Enteric CH_4 estimations were obtained using Tiers in IPCC, which was difficult for the comparison of values obtained from different studies since CH_4 is the most important component of farm emissions.

Relatively to wool production all the considered studies were performed in Australian farms and considered specific farms (Brock et al., 2013; Cottle and

Cowie, 2016) or more general farming systems. System boundaries framed emissions from production to farm gate and the output was commonly expressed per kg of greasy wool. Emissions were allocated using different criteria (mass, economic, protein and system expansions approaches). Observed emission intensities for wool production were quite variable and very large differences were found when system expansion allocation method was applied (Biswas et al., 2010). Emissions intensities were quite similar among studies when the economic allocation was considered, specifically ranging from 20.6 (Cottle and Cowie, 2016) to 29.4 (Brock et al., 2013) kg of CO_2-eq/kg of wool. From a certain point of view, the separation of meat studies from wool studies was an oversimplification of the production systems. Wool production was not separated from meat production and emission intensities for the two products often came from the same studies (Cottle and Cowie, 2016; Biswas et al., 2010). Indeed, the most part of the wool sheep breeds have double aptitude both for meat and wool production and they may be considered as co-products (Cottle and Cowie, 2016; Biswas et al., 2010). The number of sheep heads produced yearly in a wool production system is quantitatively important for the farm balance and flock dynamics, both from a biophysical and economic outlook. The amount of resources and impact allocated to wool in Australian sheep farms varies from 33 to 79% for the studies reported in Table 3.3 considering the economic criterion. It is different in dairy farms where wool production contributed to total production for 0.9, 1.5, 6.5, 14.3% using economic, mass balance, energetic and protein allocation criteria (Mondello et al., 2016). Biswas et al. (2010) in crop, meat and wool farming systems also decided to account for specific allocations to crop productions (wheat) causing that emission intensities of meat and wool were lower than those from other studies on similar sheep production systems (Table 3.1 and 3.3).

The large heterogeneity of the listed results does not allow to summarize general and useful information for the quantification of average value of the CF of the sheep meat and milk production systems. A comparison of estimates might be not informative even within hotspot if similar approaches have not been used to get farm data and to determine the emission coefficients (Curran et al., 2014).

The information gathered from literature is in general not comparable and difficult to discuss. Similarities can be highlighted among methods and findings reported in the classified studies but the published emission intensities might be considered affordable only within study. On the other hand, characteristics of input information and initial assumption adopted for each study need to be deeply considered when emission intensities of a single study are discussed in order to avoid misperceptions. Considering that a large number of variables and factors affected the final values, the comparison among studies should be cautious even considering the percentage incidence of emission sources on the total impact. Detailed examples will be presented in further sections. Confusing factors are very common when different studies are compared. In addition, the findings and outcome of LCA studies only considering CF are comparable with difficulty to other studies that include different degrees of environmental impacts. Nevertheless, cautious comparisons between studies are useful to validate results (O’Brien et al., 2016). A meta-analysis approach might be used to get more information from these papers in a quantitative term. On the other hand, relatively to this project, these papers might provide useful qualitative information from a methodological point of view.

3 LCA METHODOLOGY FOR ECOLOGICAL EFFECTS AND GHG EMISSIONS

LCA, as governed by the ISO standards 14040 and 14044, has become a recognized instrument to assess the ecological burdens and human health impacts connected with the complete life cycle (creation, use, end-of-life) of products, processes and activities, enabling the practitioner to model the entire system from which products are derived or in which processes and activities operate (Curran, 2014). Outcomes of the LCA studies result in the quantification of environmental impact of each sector, including agriculture, and livestock farm models have been also suggested or adopted to get estimated emissions from surveyed and simulated scenarios both alone or integrating LCA approaches (Eckard et al., 2010; O’Brien et al., 2016). Traditionally, LCA methods have mostly relied on generic, nonspatial, and steady-state multimedia environmental models (Notarnicola et al., 2017). Most LCA studies represent the impacts as mere flows of resource used and emissions, not assessing the potential environmental damage arising from these uses. However, in the agricultural sector, site-dependent and closely related environmental aspects, such as natural resources (i.e., water and land) and ecosystems quality, acquire special relevance (Notarnicola et al., 2017). Although LCA methods are well defined, the studies vary considerably in their level of detail, their definition of system boundaries, the emission factors they use, and other technical aspects such as the allocation techniques and functional units they employ (Vellinga et al., 2013). LCA protocols have been applied to entire production processes, "from cradle to grave", to quantify GHG total emission of milk and meat production per unit of time of CO2-eq or as CF, i.e. total emissions per unit of product (e.g. kg of CO2-eq/kg of milk). Their main goal is to identify production systems and technical practices which allow using less natural resources per unit of product, reducing the food production environmental impact.

Regarding the sheep sector, the most inclusive studies on GHG emissions using life cycle approaches have been published by FAO (Opio et al., 2013). From a geographical point of view, estimates from FAO reported that, except for Western Europe (for sheep milk and meat) and Oceania (for sheep meat), small ruminant productions are generally more important in developing world regions. Emission intensity for small ruminant milk is however highest in developing regions such as North Africa and Asia due to poorer production conditions in which animals are for the most part reared for subsistence purposes (Opio et al., 2013). In contrast, in industrialized countries where small ruminant milk production is important, emission intensity is on average lower than developing areas due to the specialization of production. Considering the methodological approach FAO estimates were performed after developing the Global Livestock Environmental Accounting model (Hristov et al., 2013) and following ISO, 2006. Environmental management – Life Cycle Assessment- Requirements and guidelines - BS EN ISO 14044 and British Standards Institute PAS 2050; 2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (BSI, 2008). FAO estimates are in line with the guidelines of the Livestock environmental animal performance partnership (LEAPp, 2014). In particular, the considered emission sources of FAO LCA for the small ruminant sector at global level included all the variables listed in Table 1. These emission sources are the most commonly considered in the LCA studies but emissions from other sources might be added to the production processes, as further discussed.

Table 1. Emission categories considered in the FAO estimates (Opio et al., 2013).

Category	Description
Feed N2O	Direct and indirect N2O emissions from manure deposited on pasture Direct and indirect N2O emissions from organic and synthetic N applied to crops and pasture
Feed CO2	
blending and transport	CO2 arising from the production and transportation of compound feed
fertilizer production	CO2 from energy use during the manufacture of urea and ammonium nitrate (and small amounts of N2O)
processing and transport	CO2 from energy use during crop processing (e.g. oil extraction) and transportation by land and (in some cases) sea
field operations	CO2 arising from the use of energy for field operations (tillage, fertilizer application). Includes emissions arising during both fuel production and use.
Feed LUC CO2	CO2 from LUC associated with soybean cultivation and pasture expansion
Indirect (embedded) energy CO2	CO2 arising from energy use during the production of the materials used to construct farm buildings and equipment
Manure N2O	Direct and indirect N2O emissions arising during manure storage prior to application to land
Manure CH4	CH4 emissions arising during manure storage prior to application to land
Enteric CH4	CH4 arising from enteric fermentation
Direct energy CO2	CO2 arising from energy use on-farm for heating, ventilation etc.
Post farmgate	Energy use in processing and transport

4 LCA STUDY ON SHEEP FARMING SYSTEMS

The study of a new GHG emission baseline estimation was conducted for Sardinia dairy sheep sector based on literature reviews and site-specific LCA studies of the same subject. As GHG emission, especially from dairy sheep production, achieves a higher level of kg of CO2-eq emission per litre of milk than cattle and has a greater potential of global warming due to its rising population, a thorough and defined understanding of the environmental assessment of sheep systems is essential. This research provided a general review on developing an emission baseline referring to Atzori et al. (2017) report as the main structure. The documentation of LCA data collection of 2017 dairy sheep production in Sardinia is still in the elaboration within SheepToShip LIFE project and not yet published. Methodological standards and results provided in the handbook were confidential whereas acceptably given a part of it in the research for computing the baseline and the rate of emission amounts from dairy sheep supply chain released to the environment because an annual cut-down emission value was proposed with estimated baseline at the end of this thesis will act as a promotion of eco-effective strategies at territorial and dairy farm/plant level referred to the project. This chapter will demonstrate a better definition of the LCA methodology used for baseline development.

There are a variety of processes to produce sheep milk whereas little research has been undertaken with a life cycle perspective to analyse GHG emission of dairy sheep system. Therefore, the project aimed to search for more specific data by assessing both production phases namely agriculture and industry of Sardinia dairy sheep with LCA method (ISO, 2006a). Several main works previously published were found as useful references to design future mitigation strategies or even build an environmental action plan for sheep milk production in a Mediterranean context such as (Atzori et al., 2015; Vagnoni et al., 2015 and Marino et al., 2016). During 2017, 18 dairy sheep farms were investigated through questionnaires to farmers during the field visits. All farms are located in the Sardinia region and distributed as in Figure 3. As we all know, Sardinia is a Mediterranean island of about 24000 km2 and according to (Molle et al., 2017), it is traditionally devoted to livestock production and dairy sheep raising because of poor land conditions for agriculture. Around 14000 sheep farms, a large diversity of production systems and stocking rates were distributed despite small surface. The Sardinia climate has 2 sharp transition seasons with mild rainy winters and hot dry summers making the annual average temperature go from 16 to 22ºC during summer and drop from 14 to 7ºC during winter. As a consequent, all the participating farms have pasture areas and different production systems for sheep milk. The type of sheep farming operated in the studied area (Figure 2) varies from semi-intensive to extensive with a large scale of natural pastures. As all the farms are COPRADO members, which is an association to buy feeding stuff, sell milk and other farm products, provided more details for the surveys.

For a new baseline, the literature used LCA method to estimate GHG emissions from “cradle to dairy plant gate” of Sardinia sheep production systems and their contributions to CF. The farm under LCA analysis has an important role in the system understanding. For that reason, it should be involved in the decision of the system boundaries and context definition to: i) gather high-quality data, ii) include all the relevant steps of the production process in the boundaries (Bicalho et al., 2017) and, iii) consider the implications of the impact in the socio-economic boundaries. Within the LCA methodology, the functional unit (FU) is an important concept to compare a mixture of food products among diverse means to achieve the same targets (Owsianiak et al., 2014). For this study, the FU will be used as the reference unit of all the related emissions and the reference depends on the main type of production in each system. Generally, in dairy sheep systems, FU is a kg of milk and expressed in kg of FPCM. Milk was corrected by the work of Pulina et al. (2005) and the use of FPCM helped to ensure a relevant comparison between a variety of analysed farms and with other research papers. It also took the recommendation by IDF (2015) for international decision-making on milk issues. Since the general goal of LCA is the quantification of the footprint per kg of product, FU results an indicator aimed to minimize the input use and the impacts per unit of marketable product which is called CF. The CF indicators were calculated by following the guidelines for national GHG inventory (IPCC, 2006) and expressed in kg of CO_2-eq because certain GHG has potential impacts on global warming relevant to CO_2 such as methane (CH_4), nitrous oxide (N_2O)

and each gas has a specific value: 1 for CO_2, 25 and 298 for the rest. These emission factors are taken from IPCC for most of the farming processes, for example, manure management, enteric fermentation for easier conversion among the gases produced by the system. The main sources of GHG emissions are manufacture and transportation of sheep feeding including processing, producing, packaging, and delivering from the factory to the sheep farms. As can be seen from Figure 1, LCA studies are often not contextualized and do not address the big picture of the system. Environmental impacts should not only focus on GHG emissions but should take into account socio-economic boundaries and multifunctionality that are important drivers of the emissions by using allocation methods. Apparently, economic allocation attributes the environmental impact to the income values of the co-products. Emissions were, for the most part, economically allocated to farm products and then expressed per kg of FPCM. It based on the assumption that profit and incomes are the most important driver of farm production and managerial choices (Nguyen et al., 2012; Cottle and Cowie, 2016). In this sense economic allocation might easily account for co-products and give satisfying results and outcomes especially in dairy sheep farms (Vagnoni et al., 2015).

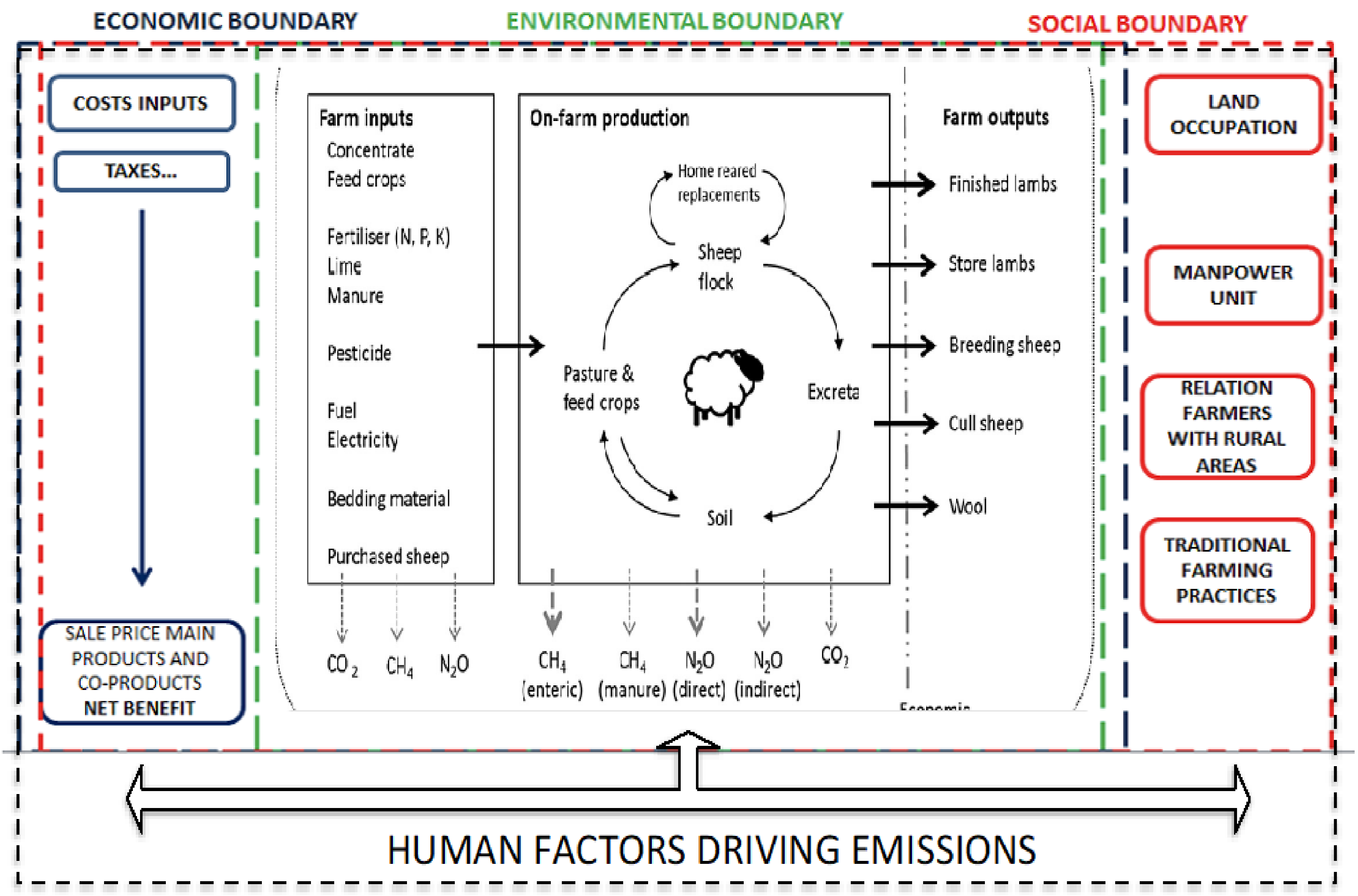

Figure 1. Environmental boundary of dairy sheep sector inclusive of social and economic aspects (Jones et al., 2014)

Furthermore, emission intensity for small ruminant productions is important for LCA studies too. Emission intensities expressed per kg of CW were not always higher than those expressed per kg of LW. Each study should be evaluated and analysed individually in order to exploit the most important factor that affects emission intensities to be delivered in this thesis. The literature overview suggests that enteric fermentation is the most important emission source in terms of total emissions' incidence. CH_4 estimation method followed Tier 1, 2 or 3 of the IPCC (2006) guidelines and was based on differential equations.

Last but not least, LCA studies on post-farm emissions. The emissions related to the post-farm sub-system mainly include the energy used to transport raw milk from the farm gate to the dairy plant because most of the LCA studies on the sheep supply chain computed GHG emissions from cradle to farm gate. The reasons for the exclusions are motivated by the negligibility of the impacts of post farm emissions, as well as by the high degree of uncertainty, limitations in the available data (Jones et al. 2014), by lack of methodology or consensus on the quantification approach (Opio et al. 2013) and appropriate characterization factors. Furthermore, post-farm gate processes have not computed when different farm systems are compared as they are assumed to be equal for each system (Ripoll-Bosch et al., 2013). The lack of accurate quantification of post-farm gate emission in the sheep system highlights the need to improve LCA studies on both sub-systems (on-farm and post farm) as an essential approach to identify the weak points of the sheep milk production chain and to take action to reduce the overall impact.

5 MATERIAL AND METHODS

The new GHG emissions baseline scenario for the Sardinia dairy sheep sector was carried out following the same methodological approach used by Atzori et al. (2017) in the previous estimation for the 2015 production data.

The baseline calculation was adjusted to consider the Sardinia sheep milk production for the 2017 reference year. In this study, the emission intensity for dairy sheep was one of the important factors to carry out the estimates of GHG emission on industrial production levels. The intensity value was carried out at the regional scale and preferred to a meta-analysis of different literature studies. The reason of doing this was because of the availability of documented data with a focus on specific production and environmental condition but they were based on different methodological approaches which resulted in the difficulty for result’s comparison and estimation of weighted average values within Sardinian conditions. The population profile of the Sardinia sheep flock was elaborated from National databases as shown in Table 2 (ISTAT and Anagrafe Nazionale Zootecnica).

Table 2. Population profile of Sardinia sheep flock (our elaboration from National database).

Population profile	Flock (%)
Ewes	76.5
Rams	3.5
Young lambs	20.8
Lambs exceeding the replacement	
Breastfeeding lambs	6.8
Fattening lambs	-
Reproduction	
Fertility of adult ewes	0.88
Prolificacy of lambed ewes	1.2
Milk yield (kg/year/ewe)	145

As can be seen from Figure 2, FAO estimated that the incidence of each emission source on the LCA approach “cradle to cradle” was adequate for this study. The coefficients were reliable because FAO LCA was applied to a wide range of conditions at a territorial scale and considered mixed and pasture farming systems. Other emissions to farm gate caused by produced and purchased feeds, energy and secondary emissions reached 26.9% of total emissions regarding FAO estimates in Figure 2. Whereas for processing and post farm, the emissions were equal to 10% following site-specific studies and unpublished data. The net emissions from the whole dairy sheep were attributed to 80% for milk and 20% for meat and depending upon that we can estimate the 2017 baseline scenario.

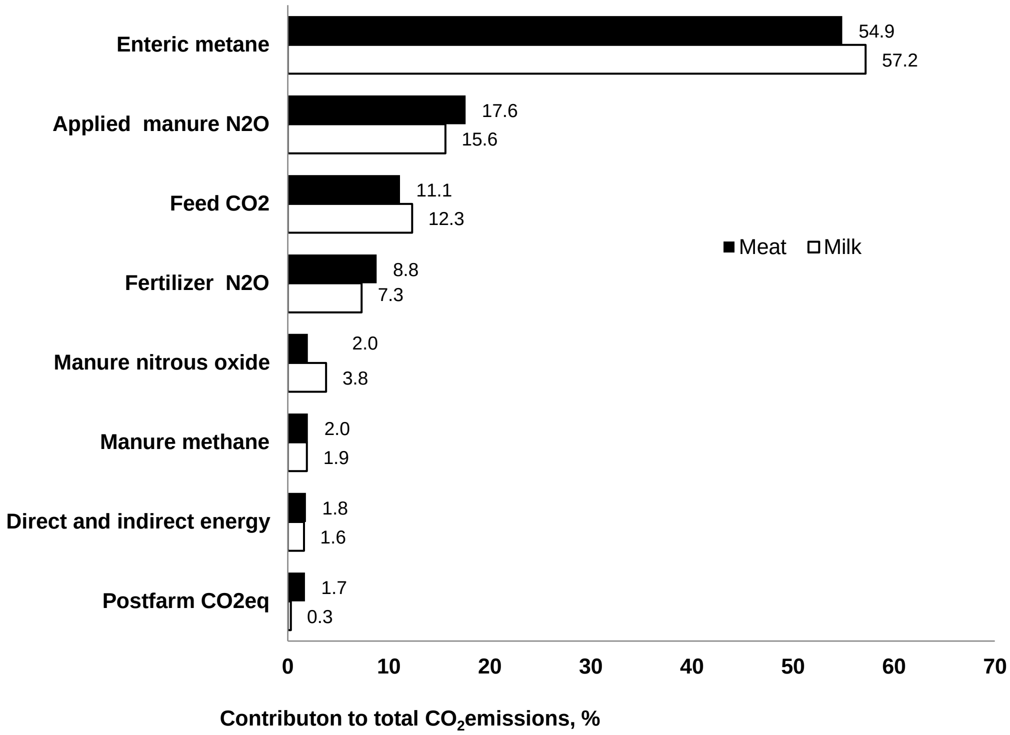

Figure 2. Contribution from each emission source to total CO2 emissions of small ruminant milk and meat production (Gerber et al., 2013)

The GHG emission intensity of sheep milk derived from the site-specific LCA studies conducted within the SheepToShip LIFE project during 2018. These studies were implemented in 18 farms located in contrasting pedo-climatic zones as can be seen in Figure 3. Following ISO standards 14040-14044 (2006a, b), the system boundary was from “cradle to farm gate”. In particular, it covered i) the fodder crops and pastures amount consumed by flocks, crosschecked with forage production and nutritional needs of each animal category by gender, age, physiological and production level; ii) energy and water consumption; iii) tractor and machinery production; iv) agrochemicals and consumable materials; v) distance and transportation modes. While LCA of products and services considers many environmental impacts, for instance, acidification and eutrophication potential and more, it is common for LCA of sheep milk and meat products to only target their global warming impacts.

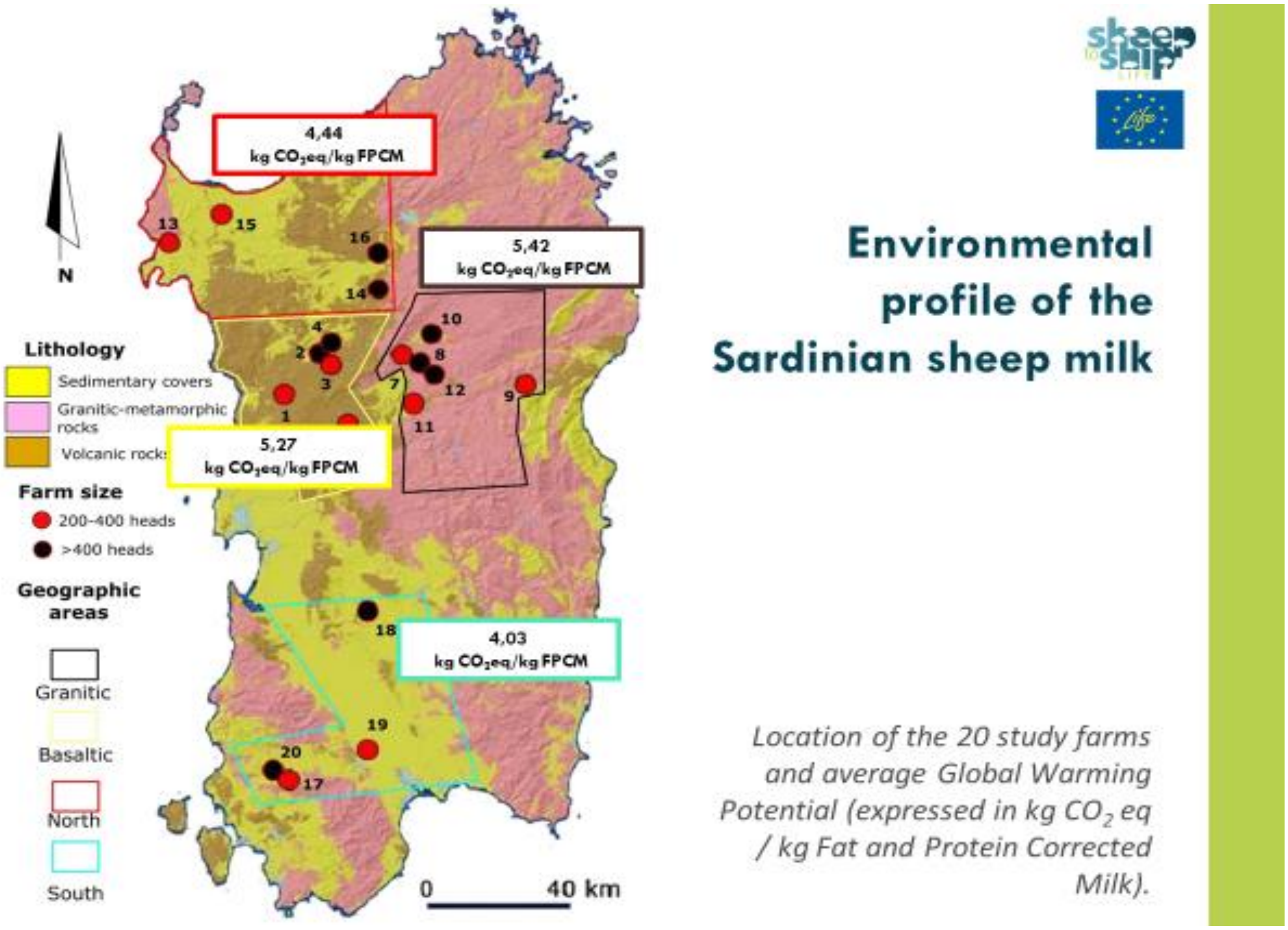

Figure 3. GWP of Sardinia sheep milk distributed by geographic areas (SheepToShip LCA studies in 2017)

With the support of farmers, an annual life cycle LCI of cradle-to-gate production processes including flock information, animal diets, feed purchases, crops, farm stocks and an energy use audit was compiled and completed. In this case, the analysis used 1kg of FPCM as FU and calculated FPCM by Pulina and Nudda (2002) equation:

$$FPCM = raw\ milk\ x\ (0.25 + 0.085\ fat\% + 0.035\ protein\%) \qquad (1)$$

where	FPCM	Fat Protein Corrected Milk	[kg]
	raw milk	raw milk produced	[kg]

Here, the impacts of products under study are evaluated in terms of impact categories. Even though there is a variety of them, and they can be combined in weights to give an overall assessment, it is not considered further in this thesis which concentrates solely on climate change impacts. To be specific, the global warming impact is assessed by cumulating the emissions of all GHGs which are individually expressed as CO2-eq and calculated from their relative global warming potential (GWP).

Similar to cattle, data requirements to calculate the amount of GHG derived from the two main emission sources for small ruminant production (milk and meat) namely enteric fermentation and feed fertilization. At the same time, estimation methods were based on them to develop 2017 emission baseline. Therefore, the key sections below were used to indicate computation methods of those emission sources in details.

5.1 Enteric emission

Emission estimation for CH_4 from enteric fermentation was computed using the emission factor (Ym = -0.15 x Digestible energy of the diet % + 21.89
). The energy of emitted gas based on the function of metabolizable energy intake (MEI) requirements by Vermorel et al. (2008):

$$\frac{kg\ of\ CH_4\ emitted}{{}^{day}/_{head}} = MEI\ x\ \frac{Ym}{55.65} \qquad (2)$$

where			
	Ym	emission factor	[MJ]
	MEI	metabolizable energy intake	[MJ/day]

With a strong relation to support the formula above, Small Ruminant Nutrition System (Tedeschi et al., 2010) was applied to estimate dry matter intake (DMI), diet digestible energy (DE), nitrogen excretion (NE) from lactating, dry, pregnant sheep, rams, replacement and fattening lambs. That calculation required as well as the emission from manure management, CH_4 and N_2O per sheep farming system. Cattle coefficients like NE and air temperature were considered which vary with manure management systems from IPCC (2006). In this case, empirical equations were computed to estimate the daily N excreted in animal categories as stated by (Decandia et al., 2011).

5.2 Emission from feed fertilizers, manure management and others to farm gate

Emissions related to pesticide and fertilizer applications were assessed according to the following approaches: equations reported in Ecoinvent report No.15 (Nemecek and Kägi, 2007) for i) emissions of NO_x to air, ii) emissions of heavy metals, PO_3-, P and NO_3- to water and iii) emissions of heavy metals to soil; Tier 1 IPCC method (IPCC, 2006) for both N_2O direct and indirect and CO_2 emissions to air; Tier 2 IPCC method (IPCC, 2006), using national emission factor proposed by ISPRA (2011), for NH_3 emissions to air.

The impacts related to manure management included only the N_2O emitted through animal excreta, with the rationale that in both farming systems, sheep were not confined in small or covered spaces. Its estimation was based on the IPCC (2006) approach to using familiar emission factor for sheep and other categories. Daily N excretion of lactating, dry, pregnant sheep, rams, replacement and fattening lambs was calculated with empirical equations introduced by Decandia et al. (2011). Primary data was taken through farm's register examination, several field visits and farmer interviews. Secondary one was collected from Ecoinvent Centre v3.4 database (Moreno Ruiz et al., 2017) except the sunflower feeding dataset from Agri-footprint 4.0 in 2017.

In line with several LCA investigations on dairy sector from (Baldini et al., 2017; Pirlo et al., 2014), the economic allocation was performed to separate all inputs and outputs of the production system that first of all, milk is the main product with higher economic value than meat, live rams and wool and second, in similar cases, LCA results were not affected by the allocation according to (Salou et al., 2017). Most importantly, SimaPro software (PRé Consultants, 2018) was an effective tool to model the life cycle and impact analysis known with a focus on global warming potential (GWP) indicator over 100-year horizon and expressed as kg of CO_2-eq. In addition to that, Environmental Footprint Method 2.0 approach since 2010 was used with the latest values of CH_4 characterization factor: 34 and 36.75 kg CO_2-eq/kg biogenic and fossil CH_4, respectively.

6 RESULTS AND DISCUSSION

All the necessary data for the baseline estimation and the estimated results were collected in Table 4 below. With the support of the calculation methods introduced above, we then replaced with the new data from 2017 year of production and were able to demonstrate a new baseline estimation. Generally, the records on sheep heads were generated by ISTAT (2017) while there was no specific data about sheep milk production in Sardinia. The value was based on the Italian sheep milk collected in quintals and CLAL (2017) statement that Sardinia produced 67% of the whole country. With several conversion, we were able to come up with the final value. The emission intensity for dairy sheep was calculated on an average of 4.85kg CO_2-eq/kg FPCM (6.5% fat) by the given LCA studied results of 18 farms which are still in the elaboration and not published yet. But, a part of animal emission intensity was summarized in Table 3. As can be seen, manure management, feed production and purchasing were the most important hotspots in terms of emission intensity and incidence. The values of CH_4 enteric emissions confirmed in the inventory per lactating dairy sheep were 13.3 versus 14.4 kg per year. The reason for a lower enteric emission value than in 2015 production year was due to an eco-innovation in dietary change for dairy sheep feeding since then. Therefore, manure became to have a higher incidence of emission in 2017 for comparison. The project is still looking for solutions to recover and recycle the nutrients emitted from manure and more efficient manure management plan on dairy sheep sector.

Table 2. Emission intensity of Sardinia sheep sector (SheepToShip LCA studies in 2017)

	CH_4			N_2O	CO_2-eq		
	Enteric	Manure	Sum	Manure	Enteric	Manure	Sum
kg/head	1.2	0.8	10.8	0.02	253	31	284
kg/adult sheep	13.3	1.1	14.4	0.04	338	41	379
Incidence					88%	12%	100%

According to Figure 2 (Gerber et al., 2013), the animal and manure emission accounted for 73.1% of the total LCA emission and will not be changed for this study. The amount of animal and manure emission was 1389ktons of kg CO_2 equivalents and generated by multiplying the emission intensity with total sheep milk production of Sardinia in 2017. Then, 1389 divided by 73.1% will be the result of CO_2-eq emissions to the farm gate, 1900kton of kg CO_2. Since the system boundary covered emission amount from cradle to dairy plant gate, not only the emission to the farm gate was in need but also from the farm gate to the processing plant. Generally, when the emission from dairy plant was proposed to be 12% of the total LCA emission from several site-specific studies, by having $\frac{19000}{(1-12\%)}\ x\ 12\%$, we were able to finalize the result of 259ktons of kg CO_2 emission from the farm gate to the processing plant. After having the emission amount from cradle to the farm gate and from the farm gate to the dairy plant, the total emission from cradle to dairy plant gate was assumed by combining the two emission amounts to estimate the GHG baseline. To illustrate:

Baseline = “cradle to farm gate” + “farm gate to processing plant” emission
= 1900 kton of kg CO_2 + 259 kton of kg CO_2
= 2159 kton of kg CO_2

Finally, for 2017 reference year, the whole dairy sheep supply chain’s cumulative emission in Sardinia, specifically, from “cradle to dairy plant gate”, was 2159ktons of CO_2-eq with attribution to 80% and 20% for milk and meat.

Table 3. Summary calculation to estimate emission baseline from Sardinia dairy sheep sector

Parameters	Value	UM	Reference
Milk production	286,378,770	litres	ISTAT, 2017
Sheep heads	3,055,605	heads	ISTAT, 2017
Emission intensity	4.85	kg of CO_2 eq/kg FPCM (6,5% fat)	LCA results for 2017 production (confidential data)
LCA emission			
Enteric and manure emission	73.1	% of total	Gerber et al., 2013
From processing plant	12	% of total	site-specific LCA studies
CO_2-eq emission			
Enteric and manure emission	1389	kton of kg CO_2	estimated
Cradle to farm gate	1900	kton of kg CO_2	estimated
Farm gate to processing plant	259	kton of kg CO_2	estimated
Total emission from cradle to dairy plant gate (baseline)	2159	kton of kg CO_2	estimated

The development tasks were adequate for the thesis to generate a new baseline emission using 2017 production data. Updated data is always in need to promote effective mitigation strategies and to optimize the environmental performances of dairy sheep systems. This thesis not only fills in the data gaps for Sardinia dairy sheep sector but also the estimated baseline can be used as one of the mitigating tools for the regional government to regulate future policy on achieving GHG reduction goal.

The new emission baseline was used to generate the proposed value which is a must to update the amount of CO_2 emission needs to be cut down in a year along the project. We first multiplied the baseline emission, 2159ktons of kg CO_2 with 20%, then divided by 10 and the result was 43.2ktons of kg CO_2 per year. With this value, human efforts and viable strategies can be made for GHG mitigation at farm and processing plant level. Also, there is a direct relationship between GHG emission intensities and the efficient use of natural resources from producers. Depend upon that, technologies and practices can improve the rate of pollution with better quality and balancing feed to reduce enteric and manure emissions at animal level. Improved animal breeding and health are believed to create a more efficient production system. Furthermore, farm operations should have good practices and management on the maintenance of nutrients loss from manure and energy recovery along the supply chain as a contribution to mitigation.

The literature data used in evaluating the GHG emissions on Sardinia dairy sheep supply chain was reliable but limited due to little published research and the good sign is that studies trying to address LCA approach are continuously developing. When using the literature values, we must accept the large ranges of GHG emissions and emissions per FU from those LCA studies on dairy sheep systems. There are multiple reasons for the differences such as the technologies, contracting operation systems, system boundary and even allocation methods. Apparently, there is also an inconsistency between the actual system and reference one for their different service provisions and some emission sources were not involved in this study. Therefore, the dairy sheep and reference systems were illustrated, and assumptions were made transparently since small changes in methodology and input parameters can have huge impacts on the estimated baseline.

Briefly, the expression of the environmental indicators per FU, or considering their incidence as percentage of total emission (Table 3), allows fair comparisons of farm performances but could also result in information loss, misleading the objectives of the mitigation strategies. From a theoretical point of view, to get rapid reduction of emissions at territorial level, mitigation strategies have to target single farm hotspots that show high emission intensities per FU (low performances) but also high cumulative impact in the considered system. Practically, an efficient mitigation strategy would reduce effectively the general impact of a given product if applied to a large process, actually showing low performances.

7 FURTHER RESEARCH ON ECO-INNOVATION FOR SARDINIA DAIRY SHEEP SECTOR

As stated by Poore et al. (2018), environmental impacts of food are generated by millions of producers and many mitigation opportunities are generated due to impacts' variety among producers of the same product. There are many methods to accomplish low effects and interact with suppliers for producers because mitigation is intricated by trade-offs. This is same with Sardinia dairy sheep supply chain where producers have chances to mitigate their GHG emission, hence, there are limits on how far they can reduce their impacts. Following the Europe 2020 strategy, eco-innovation is a key factor to improve the competitiveness of sheep farming and to valorize typical Mediterranean sheep milk products. An eco-sustainable sheep supply chain not only brings environmental and socio-economic benefits for the producers like enhancing their business' quality by implementing environmental policies and rural development but also increases their knowledge on the sustainability of products. When connecting products with environmental quality, it will add value to make them more competitive and attractive to green international markets nowadays. In fact, there is a struggle between eco-agri-food systems with planetary level challenges such as population growth, productivity, environmental adversity simultaneously and it requires knowledge and interactions with not only suppliers but as well agriculturists, environmentalists, socio-economists and health care workers at all levels.

In that sense, eco-innovation from SheepToShip LIFE project has been urging to determine the environmental hotspots of sheep's milk business in Sardinia based on the estimated baseline and identify each type of production system to optimize management strategies. Besides, sheep farming and dairy businesses should have been distributed with good practices for mitigation of the sector's environmental impact. For instance, feed crops became one of the main contributors to the CF levels of sheep farms according to (Escribano et al., 2020) and dietary change in sheep raising turns out to be one of the suitable mitigation solutions for Sardinia dairy sheep scenario. An improvement plan to dairy sheep farms and businesses introducing low-input techniques while maintaining a product's quality is also necessary. Moreover, good engagement with target groups and stakeholders enables the project to drive eco-innovation in sheep farming techniques and milk production through media, press releases, project website, etc. Since the project is aligned to the Europe 2020 strategy, EU policies and regulations in terms of tackling climate change from dairy sheep sector in Sardinia and sustainable development for dairy sheep products, promotion at international events is an expected result from the project that could help open new collaboration and agreements with national and international organizations. After a long-term framework of environmental action plan, SheepToShip plan and intervention model transfer, the project is anticipated to achieve the reduction target in its 10th year.

8 CONCLUSION

Approaches on LCA studies for the sheep sectors are continuously developing even if the number of studies focusing on sheep farming systems is very limited in comparison to cattle systems. The first published studies adopted more simplified approaches mainly aimed to quantify the environmental performances of the systems in terms of global warming potential. While, more recent studies are trying to address LCA approaches and calculation to determine the emission intensities and other environmental indicators, deduce tips and guidelines for impact mitigation, improve the efficiency of the systems linking production processes with natural resources (air and climate, land, water, energy, etc.) and to get socio-economic and technical benefits of the studied systems and biological boundaries. However, for sheep meat, several studies have been published to quantify the mitigation effectiveness of technical choices and few studies concentrated on the same approach for dairy sheep farms, both at the farm and territorial level. To accomplish the purpose for which LCA is implemented, LCA inventory needs to be accurately designed, with defined system boundaries, with non-ambiguous functional units. Particularly, allocation methods have to be clear, transparent and consistent to favor the comparison with other studies, the evaluations of results and to stimulate the performance improvement of the studied system. More than one allocation method should be applied to the quantified impact. In brief, the new GHG emission baseline will be devoted to improve and revise existing LCA methods implementing on dairy sheep sector and fill in the data gaps at territorial scale. Future LCA studies can be carried out based on this study with the aim to support the planning of effective mitigation actions for Sardinia dairy sheep sector. Special attention also needs to be on accurate estimates of animal emissions, crop emissions, purchased feed emissions, energy consumption and soil carbon sinks, which have been considered the most important hotspot that quantitatively affect the environmental performance of the farms. Environmental indicators provided from LCA inventories and studies should be evaluated and ranked relatively to mitigation effectiveness in order to test its viability at farm and territorial scale. For that reason, at territorial level, when organizing broad mitigation plans, actions should consider targeting inefficient farm’s hotspots more than inefficient farms because the most important hotspot brings out the most accurate estimates. Costs and benefits of mitigation actions need to be quantified also from an economic point of view.

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Appendix 1

EQUATIONS

The Fat Protein Corrected Milk (FPCM) of dairy sheep was calculated through Equation 1.

$$FPCM = raw\ milk\ x\ (0.25 + 0.085\ fat\% + 0.035\ protein\%) \qquad (1)$$

where	FPCM	Fat Protein Corrected Milk	[kg]
	raw milk	raw milk produced	[kg]

The metabolizable energy intake (MEI) for estimating enteric emission was defined through Equation 2.

$$\frac{kg\ of\ CH_4\ emitted}{{}^{day}/_{head}} = MEI\ x\ \frac{Ym}{55.65} \qquad (2)$$

where	Ym	emission factor	[MJ]
	MEI	metabolizable energy intake	[MJ/day]

Appendix 2

LISTS OF FIGURES

Figure 1. Environmental boundary of dairy sheep sector inclusive of social and economic aspects. Data was cited from Jones et al. (2014).

Figure 2. Contribution from each emission source to total CO2 emissions of small ruminant milk and meat production. Data was cited from Gerber et al. (2013).

Figure 3. GWP of Sardinia sheep milk distributed by geographic areas. Data was cited from SheepToShip LCA studies in 2017 (not published yet).

Appendix 3

LISTS OF TABLES

Table 1. Emission categories considered in the FAO estimates (Opio et al., 2013).

Table 2. Population profile of Sardinia sheep flock (our elaboration from National database).

Table 3. Emission intensity of Sardinia sheep sector (SheepToShip LCA studies in 2017).

Table 4. Summary calculation to estimate emission baseline from Sardinia dairy sheep sector.

APPENDIX 3. 1 Carbon footprint values for LCA studies on meat sheep (SheepToShip database).

n	Reference	Country	Production	Data source	System boundary	functional unit (FU)	Enteric methane	Allocation method	Carbon footprint kg CO_2-eq/FU average (range)
1	Peters et al., 2010	Australia	Lamb	1 case farm	Farm gate	1 kg CW	Tier 2	Mass, No Allocation	(10.2-10.8)
2	Eady et al., 2012	Australia	Lamb	1 case farm	Farm gate	1 kg CW	Tier 2	Syst. exp., bioph., econ.	12.6
3	Eblex, 2012	England	Lamb	57 case farm	Farm gate	1 kg LW	Tier 2	Economic	(6-20)
4	Gac et al., 2012	France	Lamb	Survey 104 farms	Farm gate	1 kg LW	Tier 1	Mass	12.9
5	Benoit and Dakpo, 2012	France	Lamb	Survey 1180 farms	Farm gate	1 kg CW	Tier 1-2	Mass	11.9 (15-82)
6	Ledgard et al., 2011	New Zealand	Lamb	Survey 437 farms	Farm gate	1 kg CW	Tier 2	Biophysical, economic	19
7	Ripoll-Bosch et al. 2013	Spain	Lamb	Pasture based	Farm gate	1 kg LW	Tier 2	No alloc./Economic	25.9/13.9
				Mixed	Farm gate	1 kg LW	Tier 2	No alloc./Economic	24.0/17.7

				Zero-grazing	Farm gate	1 kg LW	Tier 2	No alloc./Economic	19.5/19.5
8	Jones et al., 2014a	UK	Lamb	lowland - 27 farms	farm gate	1 kg LW	Tier 1	Economic	10.8 (5.4-21.5)
				upland - 12 farms	farm gate	1 kg LW	Tier 1	Economic	12.8 (8.3-18.3)
				hill - 21 farms	farm gate	1 kg LW	Tier 1	Economic	17.9 (8.8-33.3)
9	Biswas et al., 2010	Australia	Meat sheep	Sub-clover system	Farm gate	1 kg LW	Tier 2	Economic	5.09
				Wheat system	Farm gate	1 kg LW	Tier 2	Economic	-
				Mixed System	Farm gate	1 kg LW	Tier 2	Economic	5.56
10	Harrison et al., 2014	Australia (modelled scenario)	Lamb wool	Low fec.-High density	Farm gate	1 kg fleece+LW	Tier 3	No allocation	9.3
				High fec.-High density	Farm gate	1 kg fleece+LW	Tier 3	No allocation	7.3
				High fec.- Low density	Farm gate	1 kg fleece+LW	Tier 3	No allocation	7.2
11	Bell et al., 2012	Australia (modelled scenario)	Lamb	From 2000 to 2070	Farm gate	1 kg LW	Tier 2	Biophysical	(11 to 10)
				From 2000 to 2070	Farm gate	1 kg LW	Tier 2	Biophysical	(12-21.7)
				From 2000 to 2070	Farm gate	1 kg LW	Tier 2	Biophysical	(12 to 15)
				From 2000 to 2070	Farm gate	1 kg LW	Tier 2	Biophysical	(13 to 17)
12	O’Brien et al., 2016	Ireland	Lamb	Lowland	Farm gate	1 kg LW	Tier 3	Economic	10.4
				Hills	Farm gate	1 kg LW	Tier 3	Economic	14.2
				Intensive mid season	Farm gate	1 kg LW	Tier 3	Economic	9.7
				Intensive early season	Farm gate	1 kg LW	Tier 3	Economic	10.7

13	Wiedemann et al., 2015c	Australia	Lamb	Country level	To retail	1 kg retail eat	Tier 2	Economic	16.074
14	Wallman et al., 2012	Sweden	Lamb	10 case farm	To retail	1 kg CW	Tier 2	Mass/economic	16
15	Williams et al., 2008	UK	Lamb	Country level model	To retail	1 kg CW	Tier 2	Economic	14.1
16	Edwards-Jones et al., 2009	Wales	Lamb	1 intensive farm	To grave	1 kg LW	Tier 1	Economic	12.9 (8.1-31.7)
			Lamb	1 extensive farm	To grave	1 kg LW	Tier 1	Economic	51.6 (20.3-143.5)
17	Cottle and Cowie, 2016	Australia	Meat sheep	1 farm North	Farm gate	1 kg LW	Tier 2	Mass, prot., econ., syst. exp	8.5 for mass all.
			Meat sheep	1 farm West	Farm gate	1 kg LW	Tier 2	Mass, prot., econ., syst. exp	8.7 for mass all.

APPENDIX 3. 2 Carbon footprint values for LCA studies on dairy sheep (SheepToShip database).

n	Reference	Country	Production	System boundary	functional unit (FU)	Enteric methane	Allocation method	Carbon footprint kg CO_2-eq/FU average (range)
1	Vagnoni et al. 2015	Italy	Low input system	Farm gate	1 kg FPCM	Tier 1	Economic	2.30
		Italy	Medium input system	Farm gate	1 kg FPCM	Tier 1	Economic	2.15
		Italy	High input system	Farm gate	1 kg FPCM	Tier 1	Economic	2.00
2	Atzori et al., 2015	Italy	1 case farm	Farm gate	1 kg FPCM	Tier 2	No Allocation	2.77
		Italy	1 case farm	Farm gate	1 kg FPCM	Tier 2	Economic	2.27
3	Atzori et al., 2013b	Italy	Simulated: zero-grazing; 100% self sufficient	Farm gate	1 kg FPCM	Tier 3	No allocation	2.45
		Italy	Simulated: zero-grazing conc. purchase	Farm gate	1 kg FPCM	Tier 3	No allocation	3.05
		Italy	Simulated: grazing, purch. conc.	Farm gate	1 kg FPCM	Tier 3	No allocation	3.05
		Italy	Simulated: grazing only	Farm gate	1 kg FPCM	Tier 3	No allocation	3.16
4	Batalla et al., 2014	Spain	3 farms semi intensive+Assaf	Farm gate	1 kg of ECM	Tier 3	Economic	2.29 (2.03-2.61)*
		Spain	3 farms semi intensive+Latxa	Farm gate	1 kg of ECM	Tier 3	Economic	3.02 (2.87-3.19)*

		Spain	6 farms semi extensive+Latxa	Farm gate	1 kg of ECM	Tier 3	Economic	3.74 (2.76-5.17)*
5	Michael, 2011	Australia	1 case study	Farm gate	1 kg of FPCM	Tier 2	No allocation,	4.10
		Australia	1 case study	Farm gate	1 kg of FPCM	Tier 2	Economic	3.57
		Australia	1 case study	Farm gate	1 kg of FPCM	Tier 2	Mass balance	3.64

APPENDIX 3. 3 Carbon footprint values for LCA studies on wool sheep (SheepToShip database).

n	Reference	Country	Breed	Production	System boundary	functional unit (FU)	Enteric methane	Allocation method	Carbon footprint kg CO_2-eq/FU average (range
1	Biswas et al., 2010	Australia	Meat sheep	Sub-clover system	Farm ate	1 kg wool	Tier 2	Economic	16.69
				Wheat system	Farm gate	1 kg wool	Tier 2	Economic	6.58
				Mixed System	Farm gate	1 kg wool	Tier 2	Economic	15.26
2	Wiedemann et al., 2015a	Australia	Meat wool	7 alloc. methods	Farm gate	1 kg wool	Tier 2	Sist. exp., bioph., economic	(10 - 38) for bioph. alloc.
3	Wiedemann et al., 2016	Australia	Meat wool	Southern pastoral	Farm gate	1 kg wool	Tier 2	Sist. exp., bioph., economic	20.1 for bioph. alloc.
				East High rainfall	Farm gate	1 kg wool	Tier 2	Sist. exp., bioph., economic	21.3 for bioph. alloc.
				New west Wales	Farm gate	1 kg wool	Tier 2	Sist. exp., bioph., economic	20.1 for bioph. alloc.
4	Brock et al., 2013	Australia	Meat sheep	1 case study	Farm gate	1 kg wool	Tier 2/3	Economic	24.9
5	Cottle and Cowie, 2016	Australia	Meat sheep	1 farm North	Farm gate	1 kg wool	Tier 2	Mass, prot., econ., syst. exp	8.5 for mass all.
		Australia	Meat sheep	1 farm West	Farm gate	1 kg wool	Tier 2	Mass, prot., econ., syst. exp	8.7 for mass all.
		Australia	Meat sheep	1 farm West	Farm gate	1 kg wool	Tier 2	Mass, prot., econ., syst. exp	35.8 for econ all.