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Review on LCA approaches and GHG mitigation actions in sheep supply chain

A.2.1 Scientific and technical state of the art update

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Authors

Dipartimento di Agraria UNISS

Alberto S. Atzori

Agris Sardegna

Giovanni Molle
Mauro Decandia

CNR Ibimet

Enrico Vagnoni
Laura Sanna
Pasquale Arca
Pierpaolo Duce

CNR ISPAAM

Antonello Franca
Claudio Porqueddu

Coordinated by:

Executive summary

The report analyzes the state of the art of the literature on the environmental impact of the sheep supply chain, relatively to global warming. LCA studies on sheep productions (meat, wool, milk and cheese, ecosystem services) and on post-farm emissions were reviewed and discussed focusing their methodological approach and main outcomes. Studies focusing the most important biological and technical option for the reduction of methane emissions, nitrogen excreta and variation of soil carbon stock were also reviewed and discussed. The report allowed to deduce important information for the planning of emission mitigation strategies to be applied in dairy sheep sector at territorial level in the European sheep farming systems.

Summary

Premises

The SheepToShip LIFE project

This review represents a deliverable of SheepToShip LIFE (LIFE15 CCM/IT/00123), a project funded by the European Commission under the LIFE programme - Climate Action - Climate Change Mitigation.

SheepToShip LIFE seeks to contribute in a practical way to EU climate change objectives by helping to reduce emissions of greenhouse gases from the sheep farming sector and dairy supply chain in Sardinia. The main objective of the project is to reduce by 20% in 10 years greenhouse gas (GHG) emissions (nitrous oxide – N_20, methane – CH_4 and carbon dioxide – CO_2) from the Sardinian livestock sector and sheep industry.

The immediate objectives of the project are:

- Encouraging environmental improvements of production systems in the sheep sector and demonstrating the environmental, economic and social benefits deriving from eco-innovation in the dairy supply chain and sheep farming sector;
- Promoting the implementation of environmental policies and rural development, guided by the life-cycle approach, and aimed at enhancing the environmental quality of local sheep's milk and cheese supply chains;
- Increasing the level of knowledge and awareness of stakeholders and the general public regarding the environmental sustainability of products made from sheep's milk and their contribution to the mitigation of climate change.

SheepToShip LIFE is aligned to the Europe 2020 strategy and in line with EU policies and regulations in terms of combating climate change, environmental protection and sustainable development. It demonstrates strategic and methodological approaches to develop knowledge for estimating and monitoring the mitigation measures of climate change, and applying good practices and solutions for the reduction of GHG emissions in the sheep sector in Sardinia.

Livestock and global warming

Livestock contributes to global emissions, and their emissions of the GHG as CO_2, N_2O and CH_4 are of particular concern. GHG emissions and Carbon Footprint (CF) are expressed in units of CO_2 equivalents (CO_2-eq). This is because different GHGs have different impacts on the atmosphere, with 1 kg of CH_4 being equivalent to 25 kg of CO_2 and 1 kg of N_2O equivalent to 298 kg CO_2 over a 100 year time horizon (IPCC 2007). The conversion of N_2O and CH_4 to CO_2-eq is based on their effect on the radiative forcing of the atmosphere relative to the effect of CO_2. This depends, amongst other factors, on their atmospheric lifetime, their current concentration in the atmosphere and their ability to capture infrared radiation. Both CH_4 and N_2O are at much lower concentrations in the atmosphere than CO_2, but because their global warming potentials are 25 and 298 times greater than that of CO_2, respectively, small changes in these gases can have relatively large effects on climate change and its mitigation. For the livestock producer, these emissions are losses of energy, nutrients and soil organic matter and often reflect the non-efficient use of resources. Moreover, these losses often reduce the economic viability of livestock production systems. On the basis of the Global Livestock Environmental Assessment Model (GLEAM) developed by FAO (Hristov et al., 2013), livestock supply chains emitted about 7.1 Gt CO_2-eq per annum of total (GHG) for the 2005 reference period. They consist of 14.5 % of total human-induced emissions (IPCC, 2007). About 44 % of the agriculture sector's emissions are in the form of CH_4. The remaining part is almost equally shared between N_2O (29%) and CO_2 (27%). Cattle are the main contributor to the sector's emissions with about 4.6 gigatonnes CO_2-eq, representing 65% of sector emissions but only the 4.0% on the human-induced emissions scale (Opio et al., 2013).

Small ruminants and global warming

Small ruminants have much lower emission levels than cattle, ranging between 7 and 10 % of livestock emissions, depending on year and source (Gerber et al., 2013). World population of small ruminants exceeds 2 billion of heads and makes 55% of global ruminant domestic population (cattle, buffalo, sheep and goats) (FAO, 2012; www.faostat.fao.org/site/569/default). Small ruminant products, compared with cattle, constitute a relatively small share of globally-produced ruminant meat and milk, being about 17% and 4%, respectively (Opio et al., 2013). Globally sheep produces 40% of the milk and 62% of the meat from small ruminants, the remaining being produced by goat (Opio et al, 2013). Sheep adapt very easily to different production conditions, from arid to humid areas and from poor extensive production systems to intensive ones. Despite their relative contribution to global milk and meat output, sheep and goat farming plays a large socio-economic role in some specific economies, especially in developing countries (subsistence) or in Europe and Oceania (market trade). In particular, in the Mediterranean region the majority of sheep and all goats belong to dairy breeds, for which milk is the main product and meat is a secondary product (Gerber et al., 2013). Due to high specialization of breeds and farming systems, in Western Europe small ruminants reach higher production levels and efficiency and higher economic importance than in other temperate areas or in most developing countries (Opio et al., 2013). Italy in particular plays an important role in the small ruminant production sector, being one of the first world sheep milk producers and the top world sheep cheese exporter (FAO, 2012). At the same time consumers are paying, day by day, more attention to environmental friendly products and the concept of environmental sustainability was included in industrial management, considering low environmental impact as an added value for products.

Studies on small ruminant products also confirmed that CF and GHG estimations may be used to inform supply chain professionals about the relative impacts of different products and activities. The packaging carbon label could act in a similar way to many other product labels, which assume that concerned consumers will preferentially purchase goods with attributes of low CF that they value (Edwards-Jones et al. 2009).

Several studies have been carried out in large and small ruminants to estimate livestock emissions and main causative factors (Zervas and Tsiplakou, 2012). Sheep world production contributes to GHG emissions with around 254 Mt CO_2-eq (Opio et al., 2013). FAO estimated that total emissions of sheep milk system are about 67.1 Mt CO_2-eq (Hristov et al., 2013).

Most of the studies about CF are based on cattle dairy farms, with only few cases on sheep dairy farms (Opio et al., 2013; Weiss and Leip, 2012; Vagnoni et al., 2015; Marino et al., 2016). These studies show that CF of sheep milk is more than the double per kg compared with cow milk, which also outweighs the ratio between sheep and cow milk energy. In this context, grazing systems are important resources in sheep feeding, especially in areas where natural grasslands are part of the landscape. From a global change perspective, managed grasslands contribute to the anthropogenic GHG emissions due to livestock sector (Gerber et al., 2013).

Scope and structure of the Review

This review will put the basis for planning future activities and networking of the SheepToShip LIFE project. The overview was driven by the necessity to organize and classify the studies on Life Cycle Assessment (LCA) that focused sheep farming systems. The review aim to build a clear picture of the published in the last 10 years on the LCA applied to the sheep sector especially for adopted approaches and findings. A more specific focus will be given to the evolution of the opinion of the scientific community regarding the opportunities and limits of LCA of sheep farming systems. The investigation and study of these aspects will allow: i) to adopt the most advanced focus when the

LCA will be carried out in the farms involved in this project; ii) to produce from the project activities high informative outcomes to share with the scientific community; iii) to stimulate the brainstorming of new attitudes for the planning of mitigation strategies at territorial level. A critical approach will be used in this report in order to deduce useful tips for data recording and emission estimations to further support the project accomplishments. In particular, the overview will take in consideration all the studies on sheep systems but focusing possible indications that might be useful for application in the dairy sheep supply chain.

The structure of the report follows two main lines: i) after a brief general introduction section on the LCA approach and principles, the report presents a literature overview on LCA studies carried out on sheep farming systems oriented to meat, milk and wool productions. The main focus of the literature review was to evidence the CF emission intensities reported in each study and discuss the methodological approach adopted by different authors and relatively to functional units, allocation methods, impact categories, data inventories and hotspots. A special section on LCA studies on post-farm emissions has been also included. ii) a deep analysis of the mitigation strategies focus the animal emission hotspots and the land use emissions and sinks. This section covered the actual state of the art of the literature in terms of nutritional and managerial factors that allow to reduce sheep farm emissions (mainly from enteric CH_4 and from nitrogen excretion) and the main agronomical strategies related with forage systems and feed production emissions (mainly from nitrogen and carbon (C) stock changes).
Inspired by the project goals, the review ends with several considerations on the approaches that might be adopted to reduce GHG emissions in the dairy sheep supply chain at territorial level. In particular, a special case study of territorial data analysis to drive the mitigation strategies has been reported showing how the mitigation priorities might change if different ranking techniques of farm performances are adopted. A practical example was also added, data from 12 farms were gathered from Batalla et al. (2015) and a Pareto analysis on of the cumulative emissions was performed to show an example of identification of the most effective mitigation plans.
The report has been written considering that the reader will go through its content firstly familiarizing with the contribution of small ruminants on global warming and acquainting with adopted methodological approaches and CF emission intensities determined with application of LCA. Then the reader will continue training with the most important technical strategies that could be applied for farm mitigation and finally figuring out a possible way to identify target farms hotspots to run an effective mitigation plan on a territorial level. Separate paragraphs will describe specific topics such as functional units, allocation criteria, system boundaries, data inventories and hotspots. Final considerations will be deduced at the end of each paragraph in order to get summarized messages and recaps that might be useful for application in dairy sheep supply chains.

Introduction

Life Cycle Assessment for GHG emission estimation

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 quantification of the 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 CO_2-eq or as CF, i.e. total emissions per unit of product (e.g. kg of CO_2-eq/kg of milk). Their main goal is to identify production systems and technical practices which allow to use 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, with the exception of 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 (GLEAM; Hristov et al., 2013);
- 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 common 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 N_2O	Direct and indirect N_2O emissions from manure deposited on pasture Direct and indirect N_2O emissions from organic and synthetic N applied to crops and pasture
Feed CO_2	
blending and transport	CO_2 arising from the production and transportation of compound feed
fertilizer production	CO_2 from energy use during the manufacture of urea and ammonium nitrate (and small amounts of N_2O)
processing and transport	CO_2 from energy use during crop processing (e.g. oil extraction) and transportation by land and (in some cases) sea
field operations	CO_2 arising from the use of energy for field operations (tillage, fertilizer application). Includes emissions arising during both fuel production and use.
Feed LUC CO_2	CO_2 from LUC associated with soybean cultivation and pasture expansion
Indirect (embedded) energy CO_2	CO_2 arising from energy use during the production of the materials used to construct farm buildings and equipment
Manure N_2O	Direct and indirect N_2O emissions arising during manure storage prior to application to land
Manure CH_4	CH_4 emissions arising during manure storage prior to application to land
Enteric CH_4	CH_4 arising from enteric fermentation
Direct energy CO_2	CO_2 arising from energy use on-farm for heating, ventilation etc.
Post farmgate	Energy use in processing and transport

In the latest FAO report on climate change (Gerber et al., 2013) the percentage incidence on the emissions were presented as average for sheep and goats. It resulted that over 55% of emissions from small ruminant milk and meat production were attributed to enteric fermentations and about 35% to feed production (considering feed CO_2 and crop fertilization with manure and chemical fertilizers), whereas emissions from manure were very low because excreta are deposited on pasture (Figure 1). Average emission for the sheep sector was estimated in 8.4 kg of CO_2-eq per kg of sheep milk and 25.0 kg of CO_2-eq per kg of meat.

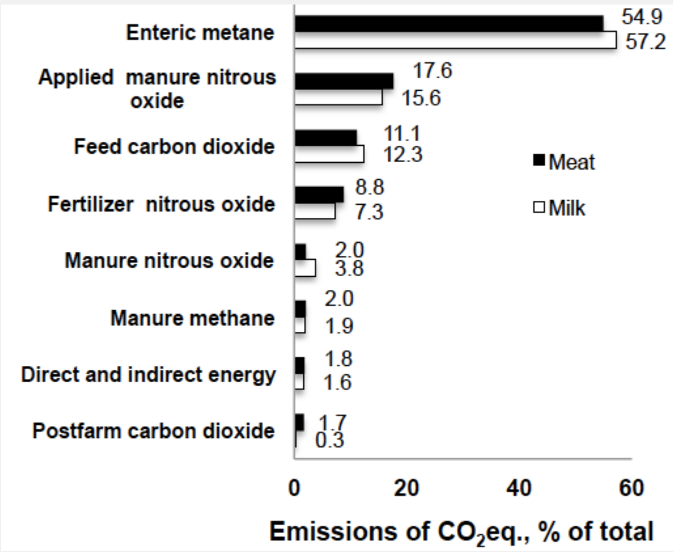

Figure 1. Emission source contribution to small ruminant CO_2-eq for meat and milk production (adapted from Fig. 14 of Gerber et al., 2013).

1. Literature overview on sheep farming systems LCA studies

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 whereas 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 strength and weaknesses of this approach and to execute improved LCA analysis in the future. In order 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 (Table 2), milk (Table 3) and wool (Table 4). 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 tables 2, 3 and 4 generally showed that the most part 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 UK, one from Spain, two from France, one from Sweden) or Oceania (mainly Australia, and one New Zealand farms) (Table 2). 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 approaches and results (Table 2). Sample size also extremely changed; several studies considered only a single case study farm (Peters et a., 2010, Edwards-Jones et al., 2009) others performed surveys including more than 1000 farms (Benoit and Depko, 2012) whereas other designed experimental blocks that considered different farming systems (Edwards-Jones et al., 2009; Jones et al., 2014; Table 2). System boundaries were limited, for the most part of the studies, from production to farm gate, with only 3 studies estimating the emission intensities from production to retail (Wiedemann et al., 2015c; Wallman et al., 2012; Williams et al., 2008), whereas only 1 from production to grave (Table 2). 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 2), 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. The most part 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 the system expansion criteria. It should be noted that the most recently published studies tried to include different allocation approaches in order 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 study and among studies. Within study 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 2), 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 2). 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 the most part 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 considered in that farming system. Heterogeneity of literature values reported in Table 2 does not allow to easily deduce a clear picture of the main factors affecting environmental performance of the lamb meat sector. In this sense each study should be evaluated and analyzed individually in order to exploit the most important factor that affect emission intensities.

Among LCA studies focusing on sheep milk, 4 of them analyzed Mediterranean farms whereas 1 article analyzed an Australian case study (Table 3). 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). 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) 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). CH_4 estimations were obtained using Tier 1, 2 or 3 of IPCC, which made difficult the comparison of values obtained from different studies since enteric 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 were 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; Cottle and Cowie, 2016). 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. In fact, wool production is not totally 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 head 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 4 considering the economic criterion. It is different in dairy farms were 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 + 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 2 and 4).

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, milk and wool 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 are 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 the further sections. Confusing factors are very common when different studies are compared. In addition, findings and outcome of LCA studies only considering CF are difficulty comparable with 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 and relatively to this project, these papers might provide useful qualitative information from a methodological point of view.

Table 2. Carbon footprint values for LCA studies on meat sheep.

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.

Table 3. Carbon footprint values for LCA studies on dairy sheep

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

Note: CW = carcass-weight; LW = Live weight; FPCM = fat and protein corrected milk; ECM = Energy corrected milk; * values not accounting for carbon sequestration, when carbon sequestration is included values might vary from 1.95 to 2.18 per kg CO2-eq/kg of FPCM with the approach of Petersen et al., (2013).

Table 4. Carbon footprint values for LCA studies on wool sheep

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 gate	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.

1.1 Boundaries and contextualization of the impact addressed by LCA

The most part of the studies listed in tables 2, 3 and 4 focuses on biophysical aspects related with global warming potential of sheep farms or farming systems from cradle of production to farm gate. The most part of the studies deeply analyzed few farms representative of a large area or conduction system whereas few of them were based on a large number of farms (Gac et al., 2012, Benoit and Dakpo, 2012, Ledgard et al., 2011). On the other hand, territorial studies and inventories are not often based on LCA.

The most part of mitigation actions suggested by the authors included technical approaches and policies based on biological strategies. On the other hand the cumulative emissions quantified with LCA are often allocated and distributed following economic criteria at farm gate. From this point of view economic criteria are principally based on farm gross revenue obtained from selling each products at processing plants. Jones et al. (2014) highlighted the difference, within the same boundary, between the farmer approach, which does not allocated the input resources in his decision making process, and the LCA approach, which is stressing the boundary splitting among co-products. This aspect should require deeper discussions in order to standardize and build consistence in the LCA point of view. The economic allocation criteria, within a certain spatial and temporary boundary, follow the idea that revenues might be the principal driver of production. Nevertheless, this approach might appear incomplete from a socio-economic outlook.

For that reason, several authors highlighted the needs to consider social and economic aspects in LCA studies and to enlarge the system boundaries to the multifunctionality of the production systems (Flysjö et al, 2012; Ripoll-Bosch et al., 2013; Batalla et al., 2014; Zethermeier et al., 2012). Figure 2 shows the general boundaries of a livestock farm that might be extended to variables that approaches social boundaries (manpower units, relationships with rural areas, tourism and traditional cultural aspects, etc.) and economic boundaries (cost and revenues, taxes and national subventions, local economic advantages of added values, general willingness to pay for environmental goods and ecosystem services). Integrative analysis should also consider social LCA (LCAs) and Life Cycle Costing (LCC) (Notarnicola et al., 2017). A particular aspect of the system contest consisted of multifunctionality. This aspect has important implication on the allocation methods and the sharing of resources, inputs and impact (Ripoll-Bosch et al., 2013).

To perform exhaustive LCA the farm that is 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 in order 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.

Remarks: LCA studies are often not contextualized and do not address the big picture of the system. Environmental impacts should not only focus GHG emissions but should take into account socio-economic aspects and multifunctionality that are important drivers of the emissions.

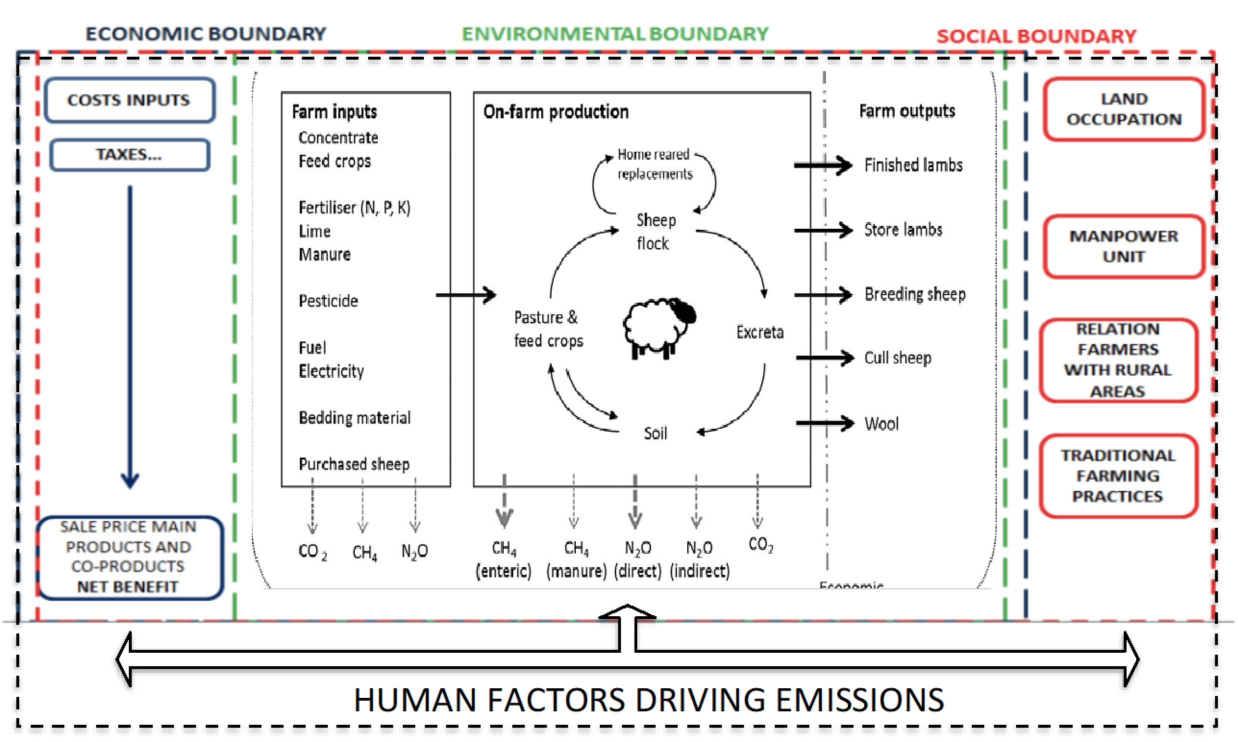

Figure 2. Environmental system boundaries inclusive of economic and social aspects (Adapted from Jones et al., 2014 and Batalla et al., 2014).

1.2 Functional units

To define a production system it is necessary to perform quantified descriptions of its features. Functional unit is the quantified performance of a product system, for use as a reference unit (ISO. 14044: 2006E). The functional unit is a very important issue that affect final results and moreover the impact on the result communication and dissemination. The general goal of LCA is the quantification of the footprint per kg of product. In terms of CF the cumulative amount of gases emitted by a given production process is attributed to a kg of the product destined to the market. It usually refers to what happen in a certain year or short time interval. This approach reveals an anthropogenic perspective, for which this functional unit results an indicator aimed to minimize the input use and the impacts per unit of marketable product. It derives from the human challenging of increasing productivity and production efficiency in order to keep sustainable and resilient the use and exploitation of natural resources. The CF indicator, expressed in terms of kg of CO2-eq/kg of product, is easily understandable and easily usable to communicate environmental performances and for that reason is becoming very popular (Batalla et al, 2014). Even though, it can generate conflict in other categories inside environmental quality indicators depending how results are reported and moreover where high yield farms could have less emissions per unit produced (Batalla et al., 2014). CF indicator cannot be generalized and used for wider environmental impacts from food products (Röös et al., 2013). As emphasized in the previous sections other environmental focus than only global warming should be consider when a LCA is performed.
Literature is also concerning the fact that increases of milk yield per animal is the most promising way to decrease GHGs emission (Zehetmeier et al., 2012). Similar results can be deduced from other studies (Ripoll-Bosch et al., 2013; Batalla et al., 2015; Vagnoni et al., 2015).
The choice of the functional unit also characterized all the studies listed in tables 2, 3 and 4 and important differences among them were highlighted. The most part of the considered studies expressed emission intensities in term of CF per kg of lamb meat, sheep meat, kg of FPCM or kg of

greasy wool (Table 2, 3 and 4). Functional units refer to the final product in different ways, depending on the considered production process, the farming system, the purpose of the study and the sample characteristics either for milk (kg of milk, kg of energy corrected milk, kg of milk solids, etc.) and for meat (kg of LW, CW, retail eat) or for wool (kg of greasy or cleaned dry wool) (Table 2, 3 and 4). Emission can be also expressed per ha of farm land, in order to emphasize the land use and occupation, or per kg of protein fixed in the products to emphasize the system ability to produce human edible protein (Garnett et al., 2014). The protein mass approach has been also largely used for wool production even if wool is not considerable a food source (O'Brien et al., 2016; Wiedermann et al., 2015a; 2015b; 2016; Cottle and Cowie, 2016).
Batalla et al. (2014) particularly examined how different functional units might affect results. The same authors stated that functional unit preferences might affect the results in a relevant manner and change the benchmarking of the experimental units. Emission intensities from the same LCA expressed with different functional units are different, might be highly correlated with the original farm variable used and are specific for defined purposes (Batalla et al., 2014; Table 5).

Table 5. Variability of the CF results depending by the functional unit used. Adapted from Batalla et al. (2014).

Carbon footprint (CF)	Average CF	Linked farm variable	CF regression vs. the linked farm variable	Aspect to study
kg CO_2-eq/ ha	3,190.75	Farm land, Ha	R^2 = -0.65	Productive. Efficiency
kg CO_2-eq/ Net margin	5.13	Farm net margin,	R^2 = -0.62	Land Occupation
kg CO_2-eq/ Manpower Unit	131,309.69	Manpower units	R^2 = +0.41	Human resources
kg CO_2-eq/kg Energy corrected milk	3.35	Liters of milk per ewe	R^2 = +0.89	Economic/profitably

Furthermore functional units might cause misinterpretations of the environmental performances of the products. When foods are ranked for GHG emissions, meat and dairy products showed highest values of emissions if these are expressed per 100 grams of food, but when emissions are expressed per 100 Mcal of energy provided to human diet, then processed fruit and vegetables showed highest emissions than animal products (Drewnowsky et al., 2015). When optimizing diets with regard to sustainability, it is crucial to account for nutritional value (Werner et al., 2014). Intuitively, diets with highest nutritional quality are not those with the lowest diet-related GHG emissions (Vieux et al., 2013) and excluding animal products from the diet does not necessarily mitigate climate change but might have negative nutritional consequences (Werner et al., 2014).

Remarks: functional units need to be defined considering the purpose of the study and the target sector. When a LCA study is carried out might be appropriate to show how results might change if different functional units are used. The standardized use of functional units should allow to evaluate similarities and differences among studies or scenarios. The use of specific functional units to conveniently show possible implications should be avoided. Sensitivity analysis could also consider variability of impact when different functional units are used.

1.3 The allocation methods

Often LCA studies focuses on the emissions of the principal product that drives the managerial choice of the farmers (i.e. milk production in a dairy farm). However, only focusing on the main products, without taking into account changes in the co-product systems, can result in erroneous conclusions because negative changes in the co-product system have the potential to outweigh positive changes in the main product system (Notarnicola et al., 2016; Zehetmeier et al. 2012; Wiedemann et al., 2015a). Several paper focused on allocation of ruminant farm products considering that they are not only oriented to food production but can assumes large multifunctional roles (Ripoll-Bosch et al., 2013; Zehetmeier et al. 2012). A common feature of most sheep farms is the interesting co-production of meat and milk or milk and wool (Mondello et al., 2016), which adds a degree of complexity in the LCA approach (Cottle and Cowie, 2016). In fact, sheep are often raised in farms that include other livestock species such as beef or dairy cattle or goats, or crop systems such as forages and grains. In these cases the co-product handling might be quite easily carried out by dividing the farm in sub-systems (Wiedemann et al., 2015a). On the other hand, the same sheep production systems have to account for co-products that are jointly produced such as milk, meat from lamb, meat from culled animal, and wool, breeding live animals (muttons), etc. (Cottle and Cowie, 2016; Wiedemann et al., 2015a). The relative proportion and quality of meat, milk and wool varies depending on raised breed of sheep, livestock system, market prices and product values, etc. The farming systems are often dual purpose and all products are produced in order to maximize returns, there is not a principal product and by-products but all the systems are oriented to its co-products. In this sense LCA must account for a distribution of the inputs and environmental impacts and the final results will be surely affected by methods and criteria utilized in the impact allocation (Ayer et al., 2007). The options for handling co-products according to ISO 14044 (ISO 2006) have been reported by Cottle and Cowie (2016):

- Clear subdivision of the system (no allocation)
- System expansion (expanding the product system to include the additional functions related to the co-products). It can be considered a method to avoid allocation while handling co-products (Wiedemann et al., 2015a).
- Allocation on the basis of physical or biological relationship (mass, protein or energy for example).
- Allocation on some other basis; most commonly economic (market) value.

All those methods are reasonably applicable to a sheep farming system. On the other hand, strengths and limitations of each used approach can be disclosed. Recently, several papers specifically challenged the allocation problem in the sheep sector (Biswas et al., 2010; Ripoll-Bosch et al., 2013; Coottie and Cowie, 2016; Batalla et al., 2014; Wiedemann et al., 2015; Mondello et al., 2016; Vagnoni et al., 2015; Atzori et al., 2015). Some of them deeply compared and discussed the co-product allocation debate (Ripoll-Bosch et al., 2013; Batalla et al., 2014; Wiedemann et al., 2015b; Cottle and Cowie, 2016; Mondello et al., 2016).

<u>No allocation</u>. The no allocation criteria is based on the assumption that the main product charge for all the impact of the production process. All the authors agreed that without allocation the emphasis of the LCA analysis is only focused on the increasing of production efficiency. Following this, indicator mitigation strategies will be limited to increase production level of animals and crops in order to reduce impact per unit of product. Therefore, following this approach, intensive systems are always better performing than extensive ones (Ripoll-Bosch et al., 2013; Wiedemann et al.,

2015a and 2015b; Batalla et al., 2014). As already stated, sheep farms with a single principal product are very rare and co-products are often produced.

Economic allocation. Economic allocation attributes the environmental impact to the income values of the co-products. It results the most frequently adopted allocation method and is 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). However the economic allocation is highly dependent from prices and values at the moment of the LCA analysis (Jones et al., 2014; Mondello et al., 2016). Possible alternative could be the use of prices that considered large time intervals (Jones et al., 2014) or to perform sensitivity analyses accounting for price fluctuation (Biswas et al., 2010). The economic allocation usually gives values that are very different from biophysical allocations (Cottle and Cowie, 2016).
A particular case of economic allocation is the inclusion of ecosystem services that could be greatly relevant in farms with high degree of multifunctionality. Ripoll-Bosch et al. (2013), studying Spanish lamb meat production, focused on the allocation of emission in farm with different levels of multifunctionality. In particular, ecosystem services carried out by the farms with different degree of intensity are proportional to the payments that EU gives within the program of Common Agricultural policy (maintenance of meadow and pastures, indemnities for low production in less favorable areas, use of autochthonous breeds, maintenance of natural grasslands, etc.). Ripoll-Bosch et al. (2013) found that accounting only for meat production the GHG emissions of the systems were 19.5 and 25.9 kg CO_2-eq per kg of lamb LW, referring to the zero grazing and pasture based system, respectively. When accounting also for ecosystem services lowest values of meat production impact was attributable to pasture-based system (13.9 kg CO_2-eq per kg of lamb LW) and the highest for zero-grazing system (19.5 kg CO_2-eq per kg of lamb LW). This approach assumes that, if farmers do not perform ecosystem services, other governmental stakeholders must cover similar actions.

Biophysical allocation. The biophysical allocation assumes that co-products could be separated for biological criteria such as, produced mass in kg or liters, energy content or protein content or protein mass of the products following ISO (2006) rules. Protein mass allocation is considered superior to simple mass allocation as it relates directly to the digestible protein leaving the stomach in individual animals, which is the major biophysical driver of LW growth and wool (Cronje 2012). Considering biophysical allocation in dairy sheep farms, the most part of the impact attributed to milk production always results much higher than other co-products in percentage terms. Mondello et al. (2016) performed a comparison of allocation methods within the same farm and obtained that impact of milk production was lower with biophysical allocations than with the economic one. The allocation based on protein mass attributed the lowest impact to milk compared to other methods (4.56, 4.27, 4.33, 4.03 and 3.36 kg of CO_2-eq for kg of milk for no allocation, mass balance, economic energetic and protein mass, respectively) whereas attributed the highest to meat (83,82, 4.27, 3.85, 4.58 10.32 kg of CO_2-eq for kg of meat for no allocation, mass balance, economic energetic and protein mass, respectively) and also to wool (279.41, 4.27, 2.40, 18.17 and 40.14 kg of CO_2-eq for kg of wool for no allocation, mass balance, economic energetic and protein mass, respectively). Similar comparisons were performed for meat and wool farms by other authors (Biswas et al., 2010; Wiedemann et al., 2015). As practical example of resources sharing when handling co-products, the values estimated by Cottle end Cowie (2016) were reported (Table 6). Detailed methods of biophysical allocation on meat and wool farms were deeply investigated and tested by Wiedemann et al. (2015). They calculated three alternative allocation scenarios based on these data: (i) allocation to wool and sheep meat based on the fraction of protein required for wool or meat divided by total utilized digestible protein from the whole flock (BA 1); (ii) allocation based on division of the maintenance requirements for the breeding flock between wool and meat according to the wool to sheep meat ratio (as in (i)) together with all maintenance requirements for slaughter lambs directly attributed to meat and all direct requirements for growth attributed to meat (BA 2); and (iii) allocation of all flock maintenance requirements and requirements for LW production to the meat product, and allocation of direct wool protein requirements to the wool product (BA 3). The allocation percentages between meat and wool reported in Table 7 seem to show little differences among methods. Nevertheless, on the basis of the obtained results the authors stated that protein allocation provides higher stability in the long term than the economic allocation (Wiedemann et al., 2105a). Little differences among biophysical allocation and economic allocation were also found by Eady et al. (2012).

Cottle and Cowie (2016) and Wiedemann et al. (2015a) suggested that the protein mass allocation can be considered a simple and easily applied allocation approach for use when attributional LCA is undertaken. In addition, when lambs are the most significant product, the biophysical allocation BA2 was specifically suggested (Wiedemann et al., 2105a). Similar tests should be carried out on dairy sheep farming systems.

Table 6. Allocation proportion and obtained values of emission intensities for meat and wool sheep using contrasting methods for handling co-production for Australian farms (Cottle and Cowie, 2016).

Products	**Mass balance allocation**	**Protein mass**	**Economic**	**System expansion**	**System expansion**	**System expansion**
Allocation proportion						
Greasy wool	14-15%	35-37%	55-65%	Purpose grown sheep meat	Purpose beef	Purpose mixed meat (beef, pork and chicken meat)
Sheep sales (lamb + mutton –LW) kg	85-86%	63-65%	35-45%			
Emission intensities						
Sheep fine wool (greasy	8.5	20.7	35.8	9.0	-6.6	23.7
Sheep meet (lamb and mutton LW)	8.5	6.3	3.6			-

The total GHG (562,537 kg CO_2-eq) per kg of total product (9,995 kg greasy wool + 56,178 kg LW sold) is 8.5 for the mass balance allocation method.

Table 7. Effects of different allocation methods on relative allocation between wool and meat. Modified from Wiedemann et al. (2015a).

Allocation method CS 1	**Case study**				
	1	**2**	**3**	**4**	**Average**
BA based on the proportion of utilised protein for wool and meat					
Allocation factor for wool, %	22	43	50	45	40.0
Allocation factor for meat, %	78	57	50	55	60.0
BA based on allocation to meat of the maintenance requirements for lamb, LW gain and a proportion of flock maintenance					
Allocation factor for wool, %	15	38	39	34	31.5
Allocation factor for meat, %	85	62	61	66	68.5
BA based on all maintenance requirements to sheep meat and direct protein requirements to wool only					
Allocation factor for wool, %	7	17	22	15	15.3
Allocation factor for meat, %	93	83	78	85	84.8
Allocation based on protein mass					
Allocation factor for wool, %	19	39	40	35	33.3
Allocation factor for meat, %	81	61	60	65	66.8
Economic allocation					
Allocation factor for wool, %	4	19	47	52	30.5
Allocation factor for meat, %	96	81	53	48	69.5

System expansion. System expansion (SE) method is a preferred option in the international standards for LCA (ISO 14044) and its application is justified as a comparison method. It allows to handle co-products without forcing the allocation of the resources. SE quantifies the farming system impact in respect to possible alternative to the production process under study. It considers that a possible system change oriented to mitigate emissions might result in cumulative higher emissions if effects in other sectors are not accounted for. Increase in productivity of dairy cows might result in lower milk CF but also in higher emissions from beef cattle due the increase in beef cattle consistency to cover the reduction of meat production from dairy farm caused by specialization (Zethermeier et al., 2012). Sensitivity to changes in the co-product system has also resulted in substantially different results between allocation and system expansion in the dairy sector (Cederberg and Stadig, 2003; Flysjo et al., 2012; Zehetmeier et al., 2012). As example milk or meat from sheep farming might be substituted with beef cattle or other sheep breeds with different aptitude. Possible alternative might consider other substitutive systems. Two constraints are applied when determining the avoided system: (i) the product must be a suitable replacement in the market; and (ii) the production system must be a suitable replacement taking into account the biophysical (land) resources available to the current sheep system (Weindemann et al., 2015a). On handling co-production, SE showed the greatest contrast between two studied flocks and highlighted the importance of meat from wool production systems (Cottle and Cowie 2016; Table 6). The SE analysis should be used to investigate the implications of a change in production, the implications of choosing alternative products or systems, to evaluate system change strategies, in which case consequential and dynamic modelling is adopted, and should be used as comparison method to analyze sensitivities to input changes (Wiedemann et al., 2015a). The same authors reported that SE provided lower impact than biophysical allocation in Australian sheep meat systems. It might be due to the fact that beef production has proportionally higher production levels and are more efficient in terms of resources uses than sheep systems. SE method usually shows large differences from other allocation methods because is based on biological and market characteristics that are out of the farm considered boundaries.

Remarks: reporting results without any allocation should be avoided in sheep farming systems considering the frequent presence of co-products. The use of biophysical (mass, energy, protein) allocations seems to be the preferred methods for handling co-products. They are in line with the LCA theory and principles and provide useful information for the system management with little dependence from the fluctuation of conditions. On the other hand, a more comprehensive approach including system expansion should be applied, tested and reported in the LCA studies in order to frame the sheep farming production in broad production contest that evaluates environmental and socio-economic consequences of the production alternatives.

1.4 Impact categories and data inventory

Classified papers of LCA analysis that have been included in the list of this report showed different numbers of impact categories and different data inventory within category. The environmental focus is mainly devoted to technical aspects that drive gas emissions at farm level. In terms of analyzed impacts the studies listed in table 2, 3 and 4 limited the focus on the global warming potential of the sheep production process (Lambe et al., 2014; Biswas et al., 2010; Jones et al., 2014; Batalla et al., 2015; Atzori et al., 2015) or examined a larger representation of the environmental impact including eutrophication, acidification, water and land use, and ecosystem services (O'Brien et al., 2016, Batalla et al., 2015, Vagnoni et al., 2015; Ripoll-Bosch et al., 2013) offering a more exhaustive snapshot of the studied system. Few studies perform complete environmental evaluations estimating the environmental impact also in terms of eutrophication, acidification, water consumption and land use (O'Brien et al., 2016; Vagnoni et al., 2015). Considerable variability in inventory data between agricultural systems was unquestionably observed. The selected papers clearly showed different approaches adopted for the data inventories and emission calculations and differences that might be due to farm characteristics and data. Some of those aspects include different management practices, soil types and climates, seasonality, life cycle of perennial crops, and distances (and related transportation modes) between locations of activities. Some sources of variability are related to the timescale adopted for the study, seasonality, transport distances. Those concepts practically reflect the life cycle of production systems (Weidermann et al., 2015a; 2016). Similar aspect can be observed in husbandry systems for raised breeds, reproduction and production performance, health and welfare conditions, farm inputs, managerial practices, facilities and barn conditions. Input differences increase variance of final results and for that reason is very important to distinguish between variability and uncertainty in LCA. Jones et al. (2014) listed two sources of variation in estimates of farm-level CF: i) variation arising from uncertainties in the data and models employed to calculate the impact, and ii) natural variation relating to differences in environmental conditions and management practices between farms. The former originate from imprecise data and uncertainty when modelling the biological processes associated with specific emission sources and hotspots, and the latter from variability between farm characteristics and management practices. Uncertainty may be reduced by additional research but variability describes actual differences among alternative processes and/or products (Steinmann et al., 2014). However, relatively few LCA studies have actually focused on the variability within these categories (Weidermann et al., 2015a). By refining input data (and emission factors) the precision of estimation models can be improved both spatially and temporally and consequently it will reduce in turn the uncertainty of emission intensities (Jones et al., 2014). Simplified LCA have also been adopted as an application of the LCA methodology for a comprehensive screening assessment of impact categories and data inventory. A simplified LCA should cover three steps: i) Screening: identifying those parts of the system (life cycle) that are either important or have data gaps. ii) Simplifying: using the findings of screening in order to focus on further work on the elementary flows. iii) Assessing reliability: checking that simplifying does not significantly reduce the reliability of the overall result. Simplifying methods can reduce the complexity of an LCA and so reduce the cost, time and effort required, by exclusion of certain life cycle stages, system inputs or outputs or impact categories, or use of generic data modules for the system under study (Klöpffer, 2014). Oversimplification in the focus might result in a partial picture of the environmental role of the target process and might affect unintended consequences and side effects of proposed mitigation actions. Adequate approaches should be adopted when multiple environmental impact categories are considered.

1.5 Hotspots

In terms of considered hotspots all the studies prioritize those having higher relevance, in quantitative terms, for GHG emissions. Hotspots that generate positive emission of gases are reported in Table 1 and account for emissions of CH_4, N_2O and CO_2 for the main emission sources. Hotspots that are commonly accounted for in the sheep farming LCA studies included: enteric fermentation, manure fermentation, application of organic and chemical fertilizers (at least N or all agrochemicals), electric power for crop and barn equipment, machinery fuel (gasoil) used for crop cultivation and barn operations. Other positive emissions are often added to the life cycle impact assessment. It might consist of CO_2-eq emissions from CO_2, N and S gaseous compounds due to kerosene use, bedding materials, lime application, ammonia volatilization and re-deposition, pesticides, plastic use, (Obrien et al., 2016; Vagnoni et al., 2015; Jones et al., 2014), N gaseous compounds from drainage of peat soils and CH_4 and N_2O from purchased animals (Jones et al., 2014), farm machinery inputs (Wiedemann et al., 2015), veterinary products (Brock et al., 2013; Weidemann et al., 2015). Recent studies also included calculation of C sequestration showing that it might have important effects on the final values (Batalla et al., 2015; O'Brien et al., 2016; Wiedemann et al., 2015). Only few studies included the effects of C sequestration on the production impact of the whole LCA (Batalla et al., 2015; O'Brien et al., 2016). Both these authors showed as LCA not accounting for C sinks brings to significantly lower emissions in intensive vs extensive systems ($p<0.05$), whereas differences among systems were much smaller and not significant when accounting for C sequestration. Batalla et al. (2015) also showed that C sequestration might be estimated with different approaches (i.e.: accounting for different C fluxes of agricultural soils or different temporal allocations of soil C), which heavily affect final values of CF (from 2.18 to - 3.41 kg of CO_2-eq for kg of sheep FCPM for extensive farms using the Petersen et al. (2013) or the IPCC (2006) approaches, respectively). It seems that there are not accepted methodology to include C sink in LCA studies even though the inclusion of this source plays an important role for the evaluation of systems based on the use of grasslands or with high crop residue and manure inputs in crop management (Batalla et al., 2015; O'Brien et al., 2106; Giglio et al., 2015; LEAPp, 2015). In this sense methodological improvements of C sink calculation are needed, perhaps adopting dynamic estimations of the C stocks (Giglio et al., 2015), in order to limit the attributional features of the LCA and obtain adequate evidences to support sustainable long term policies (Brandao et al., 2014).

All the studies agreed on the most important drivers of emissions. Enteric fermentation results the most important emission source in terms of incidence on total emissions in agreement with all the literature in other ruminant species (Hristov et al., 2013).

However the incidence and the intensity of CH_4 emissions on the final value of CF resulted highly variable among studies and within study. The former was caused by the adopted CH_4 estimation method that followed Tier 1, 2 or 3 of the IPCC (2006) guidelines and was based on different equations (Table 2, 3 and 4). In this sense the most recent studies used equations that account for multiple animal and diet variables and are most recently developed in order to bring accurate estimates when applied both at farm or territorial level (Vermorel et al., 2008) and in LCA studies.

Methodological issues and considered hotspots can cause large differences on final outcomes of different studies even on LCA performed on similar farming systems. In particular misperceptions on the relevance of enteric contribution to total emissions could be caused by the number of considered hotspots. Two papers (O'Brien et al., 2016 and Jones et al., 2014) studying differences among sheep farms producing lamb meat in similar environment of the same country (UK lowland and hills) were considered to highlight this variability. Enteric emissions were equal to 61-68% and 42-48% of total emissions in O'Brien et al. (2016) and Jones et al. (2014), respectively, with CF values (expressed as kg of CO_2-eq/kg of LW) ranging from 10 to 14 in the former and from 11 to 18 kg in the latter. This discrepancy was principally due to differences in inputs, animal productivity and farming systems that caused different sharing of emissions among sources.

Batalla et al. (2015) reported incidences of enteric emissions that were very different within study: 19% of total in farm 1 (Semi intensive farm; 2.61 kg of CO_2-eq/kg of FPCM), 41% of total in farm 6 (Semi intensive farm; 2.87 kg of CO_2-eq/kg of FPCM) to 45% of total in farm 8 (Semi extensive farm; 3.60 kg of CO_2-eq/kg of FPCM). These differences were partially due to production efficiency of the animals and in part to the effect of using different amount of inputs (17%, 0% and 0%, for fertilizers emissions in farm 1, 6 and 8, respectively) that diluted the incidence of enteric emissions on the total impact.

Manure management, feed production and purchasing, and energy were the most important hotspots in terms of emission intensity and incidence in the classified studies (Jones et al., 2014; O'Brien et al., 2016; Batalla et al., 2015; Vagnoni et al., 2015). On the other hand, Biswas et al. (2010), reported enteric emissions varying from 37% to 90% and fertilizer emissions varying from 8.9% to 59% for sheep wool production systems that are based on crop wheat or mixed pasture, respectively. Differences highlighted by these authors were due moreover to the system boundaries that in the case of the wheat systems, considered livestock production of wool and meat farm co-products of cereals grains destined to market.

The effects of the data uncertainties and input variability on the final results and on the environmental performances are often quantified using sensitivity analysis. It consists on varying the amount of inputs used in the production process and to assess the variation in the emissions. The use of this method is often coupled to MonteCarlo analysis where the input variation is assumed within a range of probability distribution. It should reflect the probability to obtain the resulting respective emissions within the same system. Vagnoni et al. (2015) showed that performing an LCA on 3 case studies of different farming systems was possible to simulate the variability of inputs and calculate the probability of significant differences among farming systems in a broad range of production conditions. The use of these techniques is often supported by specific tools of the software used for the LCA assessment (Vgnoni et al., 2015). A check of this analysis might include the fitting of the input variation to local distributions in order to increase the accuracy of the software outcomes.

Remarks: methods and approaches highly influence results, outcomes and take-home messages of the LCA. The literature overview suggests that comparison of studies is difficult and multifaceted. Within homogenous areas and similar farming systems comparisons might be carried out adjusting emission intensities for the same considered emission sources and scaling the impact to the same functional units. Evaluation of observed differences needs to take into account the purpose of the study, methodological issues and the selected final outputs. The observed variability among studies confirms that affordable tips and guidelines for the impact mitigation and efficiency improvements are mainly achievable within study by comparing technical choices of different farms or technical practices. LCA of single farm case studies are capable to bring very limited information and should be discouraged. On the other hand sensitivity analysis based on the knowledge of local input variability might help to extend the LCA results to broad conditions. Specific constraints need to be considered when LCA is performed at farm level to plan strategies that have to be applied at territorial level.

1.6 LCA studies on post-farm emissions

The emissions related to the post-farm sub-system mainly include those that account for the energy used to transport raw milk from the farm to the dairy or directly to the retail distribution, to process the raw milk into primary products (fresh milk, fermented milk, cream and butter, cheese, whey and milk powder), to refrigerate during transport and processing and to produce packaging material. Moreover, animal manure storage and management outside of the farm system, such as in drylot, make a relative small contribution toward the overall CF (Yanez-Ruiz & Martin-Garcia, 2016).

Even though the Global Livestock Environmental Assessment Model (GLEAM) (Opio et al., 2013) contains also an additional module for the calculation of direct and indirect post-farm gate emissions, unfortunately 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 (Head et al. 2011) and limitations in the available data (Jones et al. 2014), by lack of methodology or consensus on the quantification approach (Opio et al. 2013) and of appropriate characterization factors (Kanyarushoki et al. 2008, 2010). 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).

As reported in Table 2, only few papers extend their system boundary to retail or to grave in the LCA analysis of sheep meat production. In the literature there are no specific analyses of the post-farm emissions from the sheep milk dairy, just some studies (Kanyarushoki et al. 2008, 2010) that included the entire chain for goat/sheep milk and goat/sheep meat, from farm gate to retail entrance gate. On the basis of general studies that calculated average European GHG emissions related to processing at the farm gate equal to 0.155 kg of CO_2-eq per kg of milk, it was estimated that packaging accounts for 0.038 kg of CO_2-eq while transport from farm to dairy and from dairy to retail is 0.030 kg of CO_2-eq (Yanez-Ruiz & Martin-Garcia, 2016).

The lack of an accurate quantification of post-farm gate emission in the sheep livestock system highlights the need to improve LCA studies on both sub-systems (on-farm and post farm) as essential approach to identify the weak points of the sheep milk production chain and to take action to reduce the overall impact of this sector.

2. Animal emission hotspots

2.1.1 Factors related to animal diet

Grazing systems are important resources in sheep feeding, especially in areas where natural grasslands are part of the landscape. Nutritional strategies for reducing emissions in ruminants target the reduction of losses dietary nitrogen and CH_4. Ruminants excrete between 75% and 95% of the ingested N (Eckard et al., 2010), with excess dietary N increasingly excreted in the urine, whereas dung N excretion remains relatively constant (Castillo et al., 2000; Eckard et al., 2007; Decandia et al., 2011; Figure 4).

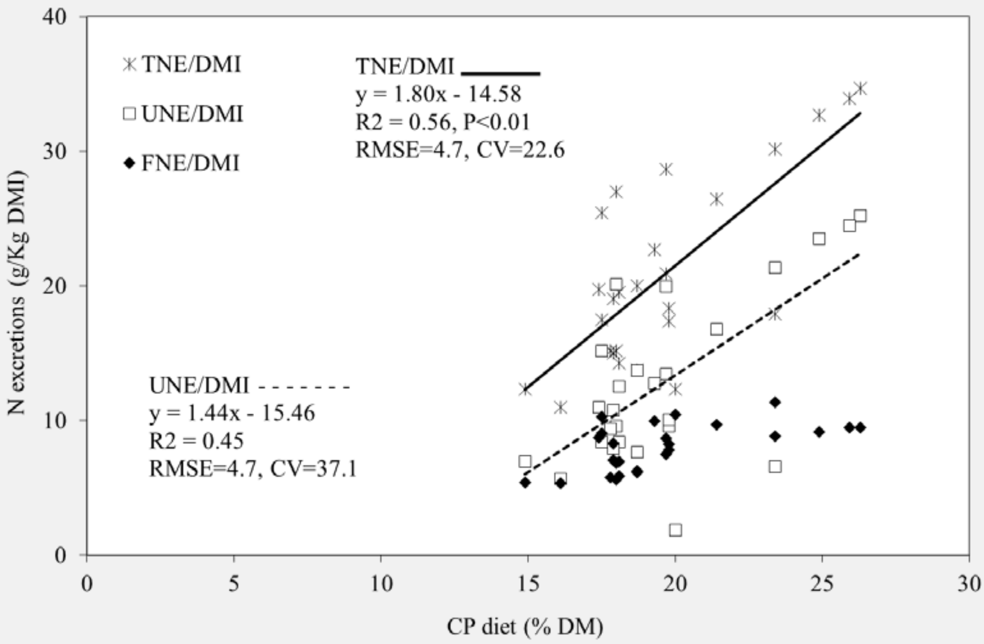

Figure 4. Relationships between faecal (FNE), urinary (UNE), total (TNE) N excretion (g/kg dry matter intake (DMI)), and crude protein (CP, % DM) in the diet of lactating sheep (modified from Decandia et al., 2011).

Gross feed energy intake lost as CH_4 in ruminant ranges from 2 to 15% (Eckard et al., 2010).
In the following sessions, the main animal and dietary factors impinging on the amount and type of emissions (CH_4 and N as a potential source of N_2O) will be reviewed, with particular reference to studies on meat and dairy sheep.

2.1.2 Rumen population modifiers

CH_4 and CO_2 are natural by-products of microbial fermentation of carbohydrates and amino acids in the rumen and the hindgut of farm animals. CH_4 is produced in anaerobic condition by a methanogen microbes mainly belonging to the Archea group. Methanogenesis is essential for an optimal performance of the rumen because, as an electron receptor process, removes hydrogen gas (H_2) from the rumen.
In fact as described by Cottle et al., (2011), anaerobic microbial fermentation of dietary organic matter components (starch and plant cell wall polysaccharides, and proteins and other materials) releases different end-products such as volatile fatty acids (VFA), CO_2, H_2 and CH_4. Fermentations oxidise dietary carbohydrates using the coenzyme NAD+ and forming NADH/H+ (Figure 5).

Afterwards the reduction of protons associated with the NADH/H+ generates H_2. The H_2 diffuses out of microorganisms and can be either used by other microorganisms, or accumulated in the rumen gas space. In the final stages of fermentation, H_2 is used as a reducing agent and NAD+ is regenerated.
In particular, methanogens oxidise the H_2 to reduce CO_2 to CH_4, thereby gaining energy for their growth (Figure 5). This H_2 removal is extremely important because, if H_2 accumulates, reoxidation of NADH to NAD+ is restricted, and this inhibits carbohydrate degradation, ATP production and microbial growth. Therefore forage digestion and the resultant production of VFA are restricted.
The microbial fermentation of substrates produces different products that are not equivalent in terms of H_2 output. Acetate and butyrate production results in a net release of H_2 favoring CH_4 production, while propionate formation is a competitive pathway for H_2 use in the rumen and usually results in a lower CH_4 production (Cottle et al., 2011).

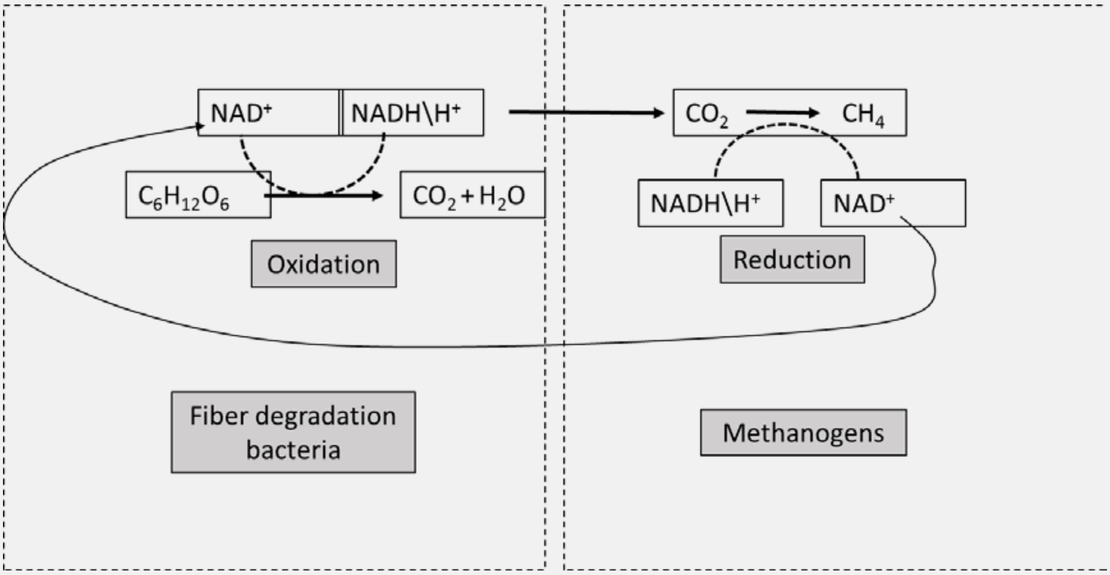

Figure 5. A sketch of the basic process underlying CH_4 emission at rumen level.

The metabolic pathways involved in H_2 production and utilization, as well as the methanogenic community are important factors that should be considered when developing strategies to control CH_4 emissions by ruminants.
A number of rumen modifiers have been proposed and tested in the past decades.
Some bacteriocins are known to reduce CH_4 production *in vitro* (Callaway et al., 1997; Lee et al., 2002). Ionophores antibiotics such as monensin have a clear effect on rumen metabolism (decreased acetate-to-propionate ratio and decreased CH_4 production) but are banned in EU. Few *in vivo* results reported a significant decrease of CH_4 emissions in sheep with the oral administration of nisin, a polycyclic antibacterial peptide produced by the bacterium *Lactococcus lactis* (Santoso et al., 2004).
Unfortunately, the inhibition of methanogenesis due to bacteriocins seems not to persist over time and the use of antibiotics as feed additives, being a public health concern, has been banned in the EU since 2006 (Marino et al., 2016).
Because of the growing concern over the use of chemicals and antibiotics in animals used for human consumption, Wright et al. (2004) developed a novel immunization approach based on the stimulation of the animal's immune system to elicit an immune response and produce antibodies against the methanogens. In Australian sheep, a vaccine against selected methanogens decreased CH_4 production by nearly 8% (Wright et al., 2004). However, vaccines prepared with a different set of methanogen species or tested in other geographical regions did not elicit a positive response

(Wright et al., 2004). The highly diverse methanogenic community present in animals reared under different conditions (Wright et al., 2007) and the replacement of the ecological niche left by the targeted species by other methanogens (Williams et al., 2009) might account for these vaccination failures. Up to now, immunisation has not delivered a clear, positive answer in reducing CH_4 emissions by ruminants, highlighting the difficulties of this approach.

Considering that H_2 is the key element for reducing CH_4 production and protozoa are large producers of this metabolic end-product, their elimination is another option to reduce CH_4 production in the rumen. The methanogens found both attached and inside ciliate protozoal cells have been estimated to contribute between 9% and 37% of rumen methanogenesis (Finlay et al., 1994; Newbold et al., 1995). Some lipids, saponins, tannins and ionophores are toxic to protozoa (see next paragraphs for details). The defaunation (removal of protozoa from the rumen) has been shown to reduce CH_4 production by 26% in terms of kg of CO_2-eq per kg of dry matter intake in protozoa-free lambs. This was explained by a decrease in the proportion of methanogens in the total bacterial population of the whole ruminal content (reviewed by McAllister and Newbold, 2008). Morgavi et al. (2008) found that lower CH_4 emissions in defaunated animals were maintained for more than 2 years. The elimination of the rumen protozoal population appears interesting, but this option should be carefully evaluated in terms of livestock performances. The absence of protozoa from the rumen can have different effects on animals either negative or positive depending on the diet and the type of production targeted.

It is also important to highlight that animals on forage-based diets usually have lower protozoal numbers (10^4–10^5/mL) than grain-fed animals (>10^6/mL) (Jouany, 1991 cited by Buddle et al., 2011) and protozoal control measures may be less effective overall on ruminants fed forage based diets such as grazing ruminants (Hegarty, 1999). This hypothesis is backed by a recent long term experiment on the effects of defaunation wherein no change in CH_4 emissions was found at either 10 weeks or 25 weeks post-defaunation between defaunated and control ewes fed only lucerne (Bird et al., 2008).

Due the inconsistency of these results, up to now, practical defaunation techniques are unavailable.

Another approach to decrease CH_4 emissions is the use of probiotics or the stimulation of rumen microbial populations. There is insufficient evidence of the direct enteric CH_4 mitigating effect of yeast and other direct-fed microbes. However, yeasts appear to stabilize pH and promote rumen function, especially in dairy cattle, resulting in small but relatively consistent responses in animal productivity and feed efficiency, which might moderately decrease CH_4 emission intensity (Hristov et al., 2013). For instance, Mwenya et al., (2004) found a reduction of 10% in CH_4 emission (L per day) coupled with an increased energy retention in fistulated wethers receiving yeast culture and ß1–4 galacto-oligosaccharides.

Remarks: Overall the use of rumen population modifiers such as antibiotics, rumen defaunation techniques and vaccination have shown limited or variable mitigation effects so far. Moreover the use of antibiotics, even in Countries where their use is legal, it raises issues related to the outbreak of antibiotic resistance.

2.1.3 Intake and diet digestibility

In the light of the literature on ruminant nutrition, increasing the intake of DM (DMI) usually results in an increase of the CH_4 emissions in both cattle (Charmley et al., 2016) and sheep (Williams and Wright, 2005 quoted by Cottle et al., 2011). In a review based on a wide database, FAO experts proposed a general equations to estimate CH_4 emissions which predicts an increase of CH_4 emissions of 19.14 g/d for each kg increase of DM intake (Hristov et al., 2013) whereas Charmley et al. (2016) more recently found a slightly higher coefficient (20.7 g/d). This coefficient is also close to the one estimated by Cottle et al. (2011) with reference to sheep: 18.7 g/d.

In contrast, the increase of the level of intake may have a lowering impact on methane emissions, as found by Yan et al. (2000) in cattle fed grass-silages. These authors estimated a decrease on CH_4 emissions expressed as energy (MJ/day) of 2.45 or 2.30 MJ per each extra level of intake above maintenance depending on the expression of the second driver of the emission (the ratio between silage and total intake expressed as ADF or DM). In general, the higher the proportion of silage in the ingested diet the higher was CH_4 emission.
However, in lambs fed at 0.8, 1.2, 1.6 and 2.0 level of maintenance, CH_4 emissions increased along with the level of intake (Table 8, Knight et al., 2008).

Table 8. Mean (±SED) ryegrass based pasture dry matter intake (DMI, kg DM/day) in growing lambs and CH4 emissions per day (g/day) and per kg DMI (g/kg DMI) for the treatment groups 0.8M, 1.2M, 1.6M and 2M fed at the indicated levels of maintenance (M) modified from Knight et al., 2008.

Treatments	DMI (kg DM/day)	DMI (proportion of intake at M)	CH4 (g/day)	CH4 (g/kg DMI)
0.8M	0.355	0.75	8.95	25.25
1.2M	0.554	1.13	13.20	23.82
1.6M	0.702	1.47	16.22	23.10
2.0M	0.871	1.80	18.05	20.77
SED	0.21	0.45	-	0.768
Probability	< 0.001	< 0.001	-	< 0.001

The reduction of methane production along with the increase of the level of intake cannot be taken for granted because diet digestibility can be lowered at high levels of intake (Hristov et al., 2013). The resultant can be either beneficial, if the digestibility counter-effect is limited, as may happen in moderate to high digestible feedstuffs or detrimental if the opposite is true, for instance with poorly digestible feedstuffs. In fact, the transit time is usually reduced at high levels of intake, which may decrease abruptly the rumen effective degradability and digestibility of poor quality feedstuffs.
Hegarty et al. (2010) investigated the effect of forage digestibility in grazing lambs, showing that the higher is the digestibility the lower is the CH_4 emission per kg of DM intake (DMI).
In general, increasing diet digestibility brings about a reduction of CH_4 emission per animal and per kg DMI. In fact, the digestibility coefficient of DM or energy (dE) are the main explanatory variable of CH_4 yield as % of gross energy intake (Vermorel et al., 2008).
The product of DMI and diet DM or OM digestibility (i.e. intake of digestible DM (DDMI g) or digestible OM (DOMI g)) can be seen as the main determinant of ruminant performance.
According to Hristov et al. (2013) an appropriate unit to scale CH_4 emission of a feed should be DDMI or DOMI instead of DMI because DMI does not reflect diet feeding value, i.e. the net energy of the nutrients the animal can retrieve from its consumption *ad libitum*.

Remarks: The increase of diet digestibility is regarded as a key to mitigate CH_4 emissions. The mitigation effect of increasing the level of intake is limited and inconsistent.

2.1.4 Forages and forage-based diets

Theoretically, the most obvious way to increase the digestibility of a ruminant diet is the accretion of the digestibility of the basal diet (i.e. the forage). In practice, increasing the digestibility of forage is far to be a trivial matter. Forage digestibility varies in fresh forages among forage species, parts of the plant, herbage mass, growth stage, cultivation techniques such as fertilization level and grazing or cutting management.

With reference to the forage utilization, sward height and herbage mass at the beginning of grazing or at cutting, and residual sward height and herbage mass are known to impact on herbage digestibility and voluntary intake of ruminants (Hodgson, 1990).

Grazing management aimed at maximizing forage digestibility of the grazed herbage can reduce the emissions of GHG, as shown in a modelling study on the cow-calf stage of North America beef system by Beauchemin et al. (2011). However, experiments did not always confirm this estimate since in some studies the raise of digestibility was mirrored by a raise of intake, reducing feed efficiency and increasing the emissions on a per head basis (Hart, et al., 2009). The techniques of forage conservation exert also an impact on the above variables, impinging on the diet potential emission of GHG. Cutting forages for silage production at an early than mature stage can offer an opportunity to mitigate CH_4 emissions through an increase of diet digestibility (Keady et al., 2012).

In the following sections, the literature on the effect of forage quality will be overviewed with reference to the methane emissions in sheep. To the best of our knowledge, only few of the many factors affecting forage quality and hence voluntary intake and digestibility of ruminants have been addressed by the literature focused on sheep nutrition and production systems.

For instance the N fertilization level has been addressed in two studies. In one UK study, the fertilization level of a pasture failed to display any effect on CH_4 emission per head and per kg DMI in dry ewes (Murray et al., 2001). In contrast, on a tropical pasture based on pearl millet grazed by lambs in Brazil, there was a trend to a reduction of CH_4 emissions per head along with the increase of N fertilization level from 50 to 400 kg/ha, with no change of CH_4 emissions per kg DMI (Amaral et al., 2016). However, in this experiment the stocking rate was increased to adjust it to the increased biomass on offer and hence the emissions per unit of land area were markedly pushed up by the fertilization. No reference to N release to the environment or N_2O losses was given.

Forage species may or may not impact on the GHG emissions of sheep. For instance, chicory did not differ from perennial ryegrass for their CH_4 emissions when fed to wethers at 1.3 maintenance requirement (Sun et al., 2011). Usually legumes are more digestible and show higher DDMI than grasses at equal growth stage (Rochon et al., 2004). For this reason, it is not surprising that wethers fed fresh white clover and other legumes showed lower CH_4 emissions than counterparts fed fresh ryegrass (Waghorn et al., 2002).

Within legumes and forb classes, plant species may differ significantly for their impact on CH_4 and N release due to differences in the content of bioactive compounds such as tannins and saponins. For instance, Sulla (*Hedysarum coronarium* L.), a Mediterranean perennial legume rich of condensed tannins can lower both methane and N release to the environment when fresh fed or grazed (Waghorn et al., 2002). The effects of plant secondary metabolites will be extensively covered below (see “Plant bioactive compounds”).

Another strategy to mitigate methanogenesis and N emissions is the use of grasses and legumes with high content of water-soluble carbohydrate (WSC). These forages have the potential to reduce the NH_3 escaped from rumen and increase intake and performance as found in lambs by Lee et al. (2001). Moreover, diluting the fiber content with high WSC forages contributes to the reduction of CH_4 emissions. For instance, Jones et al., (2014) reported that lambs reared on a mix of three high WSC grasses produced 25% less CH_4/kg live weight gain compared with the control diet based on a conventional (“normal WSC”) grass. Digestibility is higher in leaves than stems and decreases with plant maturity due to enhanced concentration of cell wall constituents, namely NDF, ADF and ADL.

Offering to the grazing herbivore a sward kept as long as possible in a leafy stage brings about a putative mitigation of CH_4 emissions but consolidated data on sheep is lacking. For instance, adopting a rapid rotation of pasture has been suggested as a way to limit the digestibility decay related to herbage mass accumulation. Moreover, part-time grazing (i.e. the allocation to pasture restricted to some hours a day (less than 8 h/d)) using a balanced supplementation can mitigate GHG emissions as found in cattle by Clark et al., (2010). Finally, the part-time allocation of pasture in

the afternoon rather than morning hours is a further technique able to decrease the release of urine N, thanks to the raise of WSC content in the grazed herbage during the day. The “sweeter” herbage grazed during afternoon hours enables rumen microbes to better incorporate herbage N, reducing N losses and possibly enhancing ruminant intake and performance (Gregorini, 2012). Preliminary data confirm these responses in dairy sheep (Molle et al., 2016).
Even the conservation and processing techniques of forages can affect methane emissions. Feeding pelleted grass to sheep of different genotypes has been shown to be conducive to lower CH_4 emissions than feeding fresh or ensiled grass of the same forage, with fresh grass resulting in lower emissions than the silage (Zhao et al., 2016). Pelleting could be then regarded as an interesting technique for forage processing with the aim of mitigating CH_4 emissions and possibly reduce carbon footprint related to transport (lower volume to be transported) but its economic viability should be carefully evaluated.

Remarks: Increasing the forage quality by the choice of high quality forages such as legumes, and their management under cutting and grazing regimens aimed at keeping quality high as long as possible can contribute to limit emissions. Conservation techniques can also play a role but probably to a lower extent.

2.1.5 Plant bioactive compounds

The effect of forage on methane emission is often a consequence of minor plant components (plant secondary metabolites) which can however exert a relevant impact on rumen fermentation pattern. These metabolites are hereunder named as plant bioactive compounds. There is growing interest in the use of plant bioactive compounds (condensed tannins, saponins, plant extracts) as a GHG mitigation strategy (reviewed by Jouany and Morgavi, 2007). Plant compounds are considered as a natural alternative to chemical additives that have been banned or that may be negatively perceived by consumers. Most experiments with plant extracts have been done *in vitro* and the activity of these molecules on methanogenesis is highly variable (Martin et al., 2010).
For tannin containing plants, the anti-methanogenic activity has been studied mainly for condensed tannin (CT) rich plants or extracts because of their lower risk of toxicity than hydrolysable tannins (HT) (McSweeney et al., 2001; Beauchemin et al., 2008), even if HT are more effective than CT in decreasing methane emissions *in vitro* (Goel and Makkar, 2012). The action of tannins on methanogenesis is probably due to either a direct effect on ruminal methanogens or an indirect effect on hydrogen production by lowering feed degradation (Tavendale et al., 2005). A reduction of CH_4 emissions by up to 30% was recorded in sheep in different experiments with plants or extracts of condensed tannin-containing plants (Woodward et al.; 2001; Carulla et al., 2005; Abdalla et al., 2007; Tiemann et al., 2008; Patra et al., 2011, Table 9).

Table 9. Effects of condensed tannin (CT) rich plants or extracts on ruminal methanogenesis in vivo modified from Goel and Makkar 2012.

Tannin source, composition	Animal and feeding levels of diet	Control diet offered to the animal	Tannin-containing diet	Methane reduction	Decrease in digestibility	Reference
LP (CT 5.3% by butanol–HCl Method)	Sheep (800–900 g DM/day)	Ryegrass-based pasture Lucerne	LP	28.5% as g/kg DDMI compared to ryegrass 23.6% as g/kg DDMI compared to lucerne	Not reported	Woodward et al. (2001)
AM extract (61.5% CT by butanol–HCl Method)	Sheep (75 g of forage DM per kg metabolic BW	Rye grass Rye grass + red clover (1:1) Rye grass + alfalfa (1:1)	41 g of crude extract /kg dietary DM 41 g of crude extract /kg dietary DM 41 g of crude extract /kg dietary DM	15% as kJ/MJ of GE intake 13% as kJ/MJ of GE intake 11% as kJ/MJ of GE intake	Decrease in DE intake[a]; decrease in apparent digestibility of all nutrients except hemicellulose[a]	Carulla et al. (2005)
MC (CT 7.2% by butanol–HCl method)	Sheep (1.3 kg DMI/day)	Forage–concentrate diet (66:34)	12.7% MC (CT 0.91% in diet)	28% as L/day	Decrease[a]	Abdalla et al. (2007)
CC (CT 17.5%) and FM (CT 11.5%) by butanol–HCl method)	Lamb 6 treatments (combinations of grass, grass + legume, grass + legume + Tannin-rich diet); fed at 60 g DM/ kg metabolic BW	BB (100) BB/V (55:45)	BB:V:CC (55:30:15) CT 2.23% BB:V:CC (55:15:30) CT 3.28% BB:V:FM (55:30:15) CT 1.42% BB:V:FM (55:15:30) CT 2.88	7.8% as L/day compared to BB:V 21% as L/day compared to BB 7.8% as L/day compared to BB:V 21.5% as L/day compared to BB	8.3% in OMD compared to BB:V 8.3% in OMD compared to BB 9.1% in OMD compared to BB:V 8.3% in OMD compared to BB	Tiemann et al. (2008)
TC seed pulp (CT 0.11% DM)	Sheep (47.2 g DM/kg BW)	Forage/concentrate (50:50)	10 g TC seed pulp/kg DMI	24% as L/kg digested DM intake	Increase[a]	Patra et al. (2011

LP, Lotus pedunculatus; CS, Castanea sativa; AM, A. mearnsii; MC, Mimosa caesalpineaefolia; CC, Calliandra calothyrsus; FM, Flemingia macrophylla; TC, Terminalia chebula; BB, Brachiaria brizantha; V, Vigna unguiculata; DMI, dry matter intake; DDMI, digestible dry matter intake; BW, body weight; DE, digestible energy. [a]Value not provided

Castrated male lambs fed with haylages prepared from pure swards of different species (ryegrass, red clover and alfalfa) showed a clear depression in CH_4 when supplemented with 41 g/kg of dietary DM of a crude tannin (stated content of condensed tannins of 0.725 g/g DM) extracted from the bark of *Acacia mearnsii* (Carulla et al., 2005). In this study, CT influenced daily CH_4 release in a similar way as it affected NDF digestibility, suggesting that the inhibition of methanogenesis by tannins was primarily the result of a suppressed fibre degradation. However, a direct effect of condensed tannins on ruminal methanogens cannot be excluded (Field et al. 1989; Tavendale et al., 2005).
Some studies on CH_4 emissions by dietary addition of hydrolysable tannins (HT) have been realized using chestnut tannin. Sheep fed 30 g/kg DMI of chestnut tannin had an average emissions of CH_4 (45.85 g/animal per day or 23.58 g/kg of DMI) significantly lower than those fed 10 or 0 g/kg DMI of the same tannin (61.18 g/animal per day or 31.07 g/kg of DMI and 57.10 g/animal per day or 29.19 g/kg of DMI, respectively) (Liu et al., 2011). The reduction of CH_4 emitted was higher when sheep were also supplemented with coconut oil (Liu et al., 2011). The inclusion of a tannin-rich tropical shrub legume (*Calliandra calothyrsus* Meisn. and *Flemingia macrophylla* Willd.) in the diet of castrated male lambs reduced methane emission per day and per unit of feed and energy intake by up to 24% (Tiemann et al., 2008). However, in this study, CH_4 produced per unit of digested NDF was not affected by supplementation with the CT-rich legume, as also found by Carulla et al. (2005). Condensed tannins from Lotus have been reported to reduce methane production (g/kg of dry matter intake) by about 15% in sheep (Waghorn and Woodward, 2006) and 16% in lambs (Waghorn et al., 2002).
Also Ramirez-Restrepo et al., (2010) found a reduction of CH_4 breath emissions in hogget sheep grazing willow (*Salix spp.*) fodder blocks (a combination of small trees (i.e., ~1.0 m of height a.g.l.) and herbage) in comparison to a control pasture (perennial ryegrass/white clover). This effect, probably due to the CT contained in the willow leaves, was however associated with lower BW gain, carcass weight and carcass fatness of the sheep.
In fact, according to Goel and Makkar (2012), the reduction in methane emission due to the inclusion of tannin in the diet, would be difficult to achieve without decreasing the feed digestibility and animal productivity. Since the effects of tannins depend on their nature, there is a need to find 'ideal' tannins that are specific in decreasing methanogenesis but do not adversely affect animal nutrition and production.
On this topic, interesting results were presented by Patra et al. (2011) using seed pulp of Harad (*Terminalia chebula* Retz.) and bulb of garlic (*Allium sativum* L.) as feed additive in sheep diet. These plants, with a level of total phenolics and condensed tannins of 4.89% and 0.11% in T. chebula and 2.36% and 0.37% of DM in A. sativum, showed anti-methanogenic activity and improved nutrient digestibility. The latter plant is also a rich source of essential oils containing sulphur compounds. However, its use in lactating animals could be risky for the high probability of off-flavour in milk and cheese.
Carulla et al., (2005) in growing, castrated male lambs found an increment of faecal N loss caused by the tannin supplementation with the extract of *Acacia mearnsii*, compensated by a reduction in urinary N. This was associated with lower water consumption and as a consequence with a decreased urine volume. The shift in N excretory pattern from urine to faeces as a result of the presence of tannins is of practical relevance because urinary N is prone to ammonia emission during manure storage (Sliwínski et al. 2002). Tannins, in this respect, could reduce the amount of easily volatile urine N and continue their protein-binding activity during manure storage.
The implication of the use of tannins on N partitioning between urine and faeces in favour of the latter is highly relevant to pasture conditions because urine N released to pasture can be easily leached after nitrification or released to the atmosphere as N_2O or NOx after denitrification. To this end, in a pluriannual study lactating dairy ewes grazing sulla-based pasture *(Hedysarum coronarium*) showed a reduction of the proportion of N in urine and an increase of that in faeces as compared

with counterparts grazing legumes-based pastures free of tannins (*Medicago polymorpha* and *Trifolium subterraneum*, Molle et al., 2009).
The typical effect of condensed tannins on the partitioning of N losses with an increase in faecal N excretion and a decrease in urinary N excretion was also demonstrated in an experiment with fistulated wethers fed sainfoin-made silages (Theodoridou et al., 2012). Similar results were obtained feeding sainfoin as fresh forage (Theodoridou et al., 2010).
Similarly to what found in studies on sheep fed forages containing condensed tannins (Waghorn et al., 1987, 1994; Waghorn and Shelton, 1995; Min et al. 2003), small amounts of CT (quebracho) in the drinking water of grazing sheep can reduce their urine urea excretion onto pastures, in particular if they are consuming forage with high levels of CP (Kronberg and Liebig, 2011). Further research is needed to determine if this reduction in urea excretion can lead to reduced amounts of ammonia and nitrous oxide emitted to the atmosphere. Furthermore, it has to be clarified if other types of CT can be added to the water to reduce N excretion in the urine.
As for extracts based on tannins, a limited number of *in vivo* studies have been conducted feeding extracts rich of saponins (Table 10, Goel and Makkar, 2012). Saponins are glycosides found in many plants that can decrease protein degradation and improve at the same time microbial protein synthesis (Makkar and Becker, 1996), two processes that determine a reduction of hydrogen for CH_4 production (Dijkstra et al., 2007).
Similar to tannins, the source of saponins is important. Using Yucca extracts as source of saponins, Santoso et al. (2004) observed a decrease of 6.7% and Wang et al., (2009) of about 20% of CH_4 emissions whereas Sliwínski et al. (2002) did not find any methane reduction. A decrease in methane production, was also recorded by Hess et al. (2004), using dried fruits of *Sapindus saponaria* L., a medium-sized south American deciduous tree, in lambs fed both tropical grass-based and grass-legume-based diets. Also tea saponins reduced methanogenesis in lambs by 28%, decreasing protozoa populations even if population of methanogens was not inhibited (Mao et al., 2010). Similar results have been reported by Zhou et al., (2011). The antiprotozoal effect of saponins seems to be transient (Koenig et al., 2007) and it is not always accompanied by a decrease in CH_4 production (Pen et al., 2007; Goel et al., 2008) indicating that other modes of actions are also important. The addition of *Yucca schidigera*, a plant species rich in saponins, to the diet of sheep significantly reduced rumen ammonia concentration and urinary N excretion, with a probable reduction effect on N_2O emission, while it increased microbial N supply and efficiency (Santoso et al., 2004; 2006). Among other plant rich of bioactive compounds, the effect of rosemary (*Rosmarinus officinalis* L.) leaves and essential oils on the composition of rumen microbial population was evaluated in ruminally cannulated sheep (Cobellis et al., 2016). The rosemary leaves only lowered the abundance of rumen protozoa, potentially decreasing protozoa associated methanogens and their contribution to methane production.
Also by-products have been used to extract bioactive compounds. Several studies aimed at verifying the effect of cottonseed byproducts in CH_4 emission reduction in sheep (Arieli, 1992; de Mello Tavares Lima et al., 2014). Although some results were encouraging, there is a great limiting factor for using cottonseed byproducts in animal production systems due to the presence of gossypol, a toxic compound found throughout the whole cotton plant. If gossypol is ingested it may cause several harmful effects to animal health (McCaughey et al., 2005; Zhang et al., 2007).

Remarks: Overall, dietary plant secondary compounds can be regarded as a potent tool to curb CH_4 emissions in sheep farms. Tannins have the greatest potential but also some saponins can play a role. Forages containing these compounds may contribute substantially to mitigation when digestibility is not impaired markedly. This depends upon the concentration and type of compounds in the forage and the forage intake. Although extracts of byproducts (tannins, saponins, etc.) are commercially available, their cost is currently prohibitive for routinary use in ruminant production systems. In contrast, the use of locally plants that contain these compounds already used in grazing condition could be probably more cost-effective.

Table 10. Effects of saponin-rich plants or extracts on ruminal methanogenesis in vivo in sheep, modified from Goel and Makkar, 2012

Saponin-rich source and content	Animal and feeding level	Treatments	Methane reduction	Decrease in digestibility	Reference
YS extract (saponin content: 30%)	Lamb (1.16 kg/day)	Hay/concentrate (1:1) +2 mg saponin /kg DM Hay/concentrate (1:1) +30 mg saponin /kg DM	No effect	No effect	Sliwinski et al. (2002)
YS extract (saponin content: not given)	Sheep (fed at 55 g DM per kg metabolic BW)	Grass silage/concentrate (70:30) +120 mg YS extract/kg DM	6.7% as L/kg BW	No effect	Santoso et al. (2004)
SP dried fruits (saponin 12%)	Lamb (fed at 60 g DM per kg metabolic BW)	Grass hay+0.6 g/kg metabolic weight of crude saponin from fruits of SP Grass/CA (1:2)+0.6 g/kg metabolic weight of crude saponin from fruits of SP Grass/CA (2:1)+0.6 g/kg metabolic weight of crude saponin from fruits of SP	10.5% as L/day 5.7% as L/day No effect	5.3% in OMD 3.7% in OMD 3.6% in OMD	Hess et al. (2004)
TS (triterpenoid saponins >60%)	Sheep	(1 kg DM) Hay/concentrate (3:2)+5 g/kg TS	8.7% as L/kg DMI	Not reported	Yuan et al. (2007)
QS extract (saponin 5–7%) or YS extract (saponin 8–10%)	Sheep (fed at 55 g DM per kg metabolic BW)	Concentrate and Italian ryegrass hay (2:3) +0.8–1.13 g QS extract/day or 1.31–1.64 g of Yucca saponins/day	No effect	No effect	Pen et al. (2007)
YS extract	Sheep (1.72 kg DM)	Hay/concentrate (3:1) + extract (170 mg/day)	15.5% as g/day	No effect	Wang et al. (2009)
TS (triterpenoid saponins >60%,)	Lamb (at maintenance requirement for digestible energy)	60:40 Wild rye/concentrate + TS 3 g/day	27.2%	Not reported	Mao et al. (2010)
TS (600 g triterpenoid saponins/kg DM)	Sheep (at maintenance requirement for digestible energy)	60:40 Wild rye/concentrate + TS 3 g/day	10.6%	Not reported	Zhou et al. (2011)

YS, Yucca schidigera; SP, Sapindus saponari; CA, Cratylia argentea; TS, Tea saponins; QS, Q. saponaria; DM, dry matter; DMI, dry matter intake; OMD, organic matter digested

2.1.6 Level of concentrate supplementation and concentrate to forage ratio

Providing concentrates as supplement is common in sheep dairy systems but focus-feeding based on concentrates is also a must in many extensive sheep systems for meat and wool production. The inclusion of concentrates usually provides a mean to increase intake, when the forage availability at pasture is limited and to increase diet digestibility, if forage quality is limited. Substitution and associative effects modulates the performance response of the ruminant to concentrate supplementation and hence the impact on methane emissions.

Increasing the proportion of conventional (grain-based) concentrate in the diet usually shifts rumen fermentation pattern towards an increase of the molar proportion of propionic acid and a corresponding reduction of that of acetic acid. Propionic is a better sink than acetic acid for the H_2 produced during carbohydrates fermentation, resulting in a lower synthesis of CH_4 by methanogenic bacteria.

The impact of supplementation level and forage to concentrate ratio (F/C) or concentrate proportion in the diet (CoP) has been extensively investigated in cattle but less information is available on sheep. Literature is relatively inconsistent on the effect of CoP. Benchaar et al. (2001) found that an increment of the proportion of concentrates in the diet would reduce CH_4 production in ruminants. To better investigate the topic, a meta-analysis of 87 studies inclusive of cattle, sheep and goats was run. The results showed that the CH_4 yield as % of gross energy intake (GEI) is quadratically related with CoP and level of intake (LI) and is linearly related to the interaction between LI x CoP in the diet (Sauvant and Giger-Reverdin, 2007). However, when the equation computed by the above authors was challenged by data from other experiments, the estimated values were rather different from the actual ones (Hristov et al., 2013). Nevertheless, according to these authors the equations by Sauvant and Giger-Reverdin (2007) is helpful to highlight that only at high levels of intake, the proportion of concentrate can markedly change CH_4 yield actually reducing it (from 6 to 3% GEI at LI = 3.0 % BW with a change in CoP from c.a. 0.20 to 0.85). However, when the LI equals 2% BW, CH_4 yield changes just a little between low and high CoP (from 6 to 7 % of GEI). This is in line with data by Moss et al. (1995) who found no effect of CoP varying between 0 and 75% at maintenance level (LI= 1) but a quadratic decrease of on CH_4 emission at higher LI.

In general, there seems to be little scope to mitigate CH_4 emissions through an increase of the concentrate inclusion in the ruminant diet but this may not be true if CH_4 is scaled to the unit of output.

Furthermore, if the basal diet is rich in high-CP forages, such in sheep grazing immature pastures, increasing dietary energy through a higher inclusion of cereal-based concentrates may help to mitigate N release in the *excreta,* and hence the putative emission of the most powerful GHG source: NOx (Molle et al., 2008). The viability of this approach and the detailed level of supplementation must be evaluated on a case by case basis. On the other hand, trade offs between reducing N_2O and CH_4 emissions have been studied by Dijkstra et al. (2014) reducing N supply in order to reduce N excretion might reduce digestibility and increase CH_4 emissions.

Total mixed ration (TMR) is frequently used in dairy cattle feeding but is not rare even in dairy sheep systems. Under these circumstances, the selection of the most palatable and ingestible dietary items is constrained. Intake depends upon many factors but, according to Mertens (1994), the forage content of NDF is a key determinant. Within an optimal range depending on ruminant species, physiological stage and level of production decreasing NDF content usually results in higher intake and often also higher diet digestibility. Low NDF and high digestibility are synergic to mitigate CH_4 emissions. At equal NDF, concentration other components can play a role. For instance, dairy cattle fed iso-nitrogenous and iso-fibrous (NDF) TMR based on lucerne silage showed higher intake, digestibility and milk yield than herd-mates fed a TMR based on ryegrass silage (Broderick et al., 2002). This was explained by the lower ADF concentration of the legume. However, emissions were not measured.

Data on dairy sheep fed TMR are scanty. Interestingly, in a Japanese study, the CH_4 emissions were reduced feeding sheep fermented rather than fresh TMR (Cao et al., 2010). This is probably a result of the degradation of dietary carbohydrates in the silo that prevented the enteric emission post-feeding. Microbes in the silo tend to use sugars and starch to produce acetate rather than methane and this effect is environmentally advisable.

Free choice of complementary feed ingredients could be regarded as a welfare-friendly alternative to TMR, if the risks associated to a biased diet are limited. According to Yurtseven et al., (2009), providing to dairy ewes a mixed diet as free choice tends to reduce CH_4 emissions as compared with a TMR based on the same ingredients.

Under conditions of poor quality forages or low yield cereal crops devoted to grazing, it is probably better to use urea-molasses feeding blocks to mitigate CH_4 emissions. This supplement can enhance diet digestibility (Ben Salem and Nefzaoui, 2003). Alternatively, the forage or the cereal at heading phase could be cut, chopped and stored in airtight silos after spraying it with urea solution (0.5 – 3% of biomass, e.g. Roy and Rangnekar, 2006). Similar systems implement NH_3, NaOH or, more recently, $Ca(OH)_2$ with or without urea. These treatments are expected to enhance forage digestibility and its CP content, because part of urea is converted by urease into NH_3 which tends to bind to forage fiber. However, no information is available on the effect of these forage conservation techniques on CH_4 emissions by sheep.

Remarks: Increasing the proportion of concentrate in ruminant diet although theoretically effective may be not a viable strategy. Adjusting the proportion of concentrate to the basal diet in order to limit N losses has some scope, provided that CH_4 emissions do not raise markedly.

2.1.7 Concentrate source: lipid-based and starchy concentrates

Dietary fat seems a promising nutritional alternative to depress ruminal methanogenesis. In a recent review (Eckard et al., 2010) five possible mechanisms by which lipid supplementation can reduce CH_4 are presented: by reducing fibre digestion (mainly long-chain fatty acids); by lowering DMI (if total dietary fat exceeds 6%– 7%); the suppression of methanogens (mainly medium-chain fatty acids); the suppression of rumen protozoa; and to a limited extent, through rumen biohydrogenation.

These effects are dependent on the source of fatty acids and results are variable. The direct infusion into the rumen of young wethers, fed fresh ryegrass, of linseed and sunflower oils up to 5% (DMI) did not affect methane production, DMI, energy digestibility or rumen VFA concentrations or proportions (Cosgrove et al., 2008). These authors also found an increment of faecal energy concentration in sheep as the quantities of oil increased, suggesting a low level of absorption.

Machmüller et al., (2000) studied the effects of coconut oil, crushed whole oilseeds (rapeseed, sunflower seed and linseed) and rumen-protected crystalline fat on methane release, digestion and energy balance in growing lambs. The daily methane amount per kg live weight as well as the energy lost via methane was reduced, particularly by coconut oil and sunflower seed.

In different studies, coconut oil showed a reduction of CH_4 emissions in male sheep (Machmüller and Kreuzer 1999; Machmüller et al., 2001; Machmüller et al., 2003) but the effect was basal-diet dependent, with particular reference to its NDF content. Medium-chain FA (MCFA), provided by coconut oil, seems to be the more effective in mitigation (7.3% decrease per percentage unit of added lipids) than linoleic acid (soybean and sunflower, 4.1%), linolenic acid (linseed, 4.8%) and monounsaturated fatty acids such as oleic acid (rapeseed, 2.5%) (Martin et al., 2010). According to Dohme et al. (2001), lauric acid (C12:0) and myristic acid (C16:0) taken alone have similar effects, but a combination between these two acids has a synergistic effect leading to a sharp decrease in CH_4 emissions (Soliva et al., 2004).

Overall, there is a large body of evidence that enhancing lipids in the diet can dramatically limit CH_4 production in the rumen. Grainger and Beauchemin (2011) summarizing data from several studies indicated that, with a fat level in diet under 8%, a 10 g/kg DMI increase in dietary fat would decrease

CH_4 emissions by 2.6 g/kg DMI in sheep. The same authors, in contrast to Martin et al. (2010) found that fatty acid type had no effect on CH_4 yield, nor did the form of fat added (oil v. oilseed) or fat source (e.g. coconut v. sunflower). Using a dataset restricted to practical dietary fat levels, these authors also highlighted a significant difference in the relationship between dietary fat and CH_4 yield among beef cattle, dairy cattle and sheep, finding that more data are needed to give an accurate assessment of the effect of fat supplementation in sheep. Results of a recent study in Wales, reported by Jones et al. (2014), presented that lambs fed diets supplemented with linseed oil or a novel high fat naked oat, showed a reduction in CH_4 emission by 22% and 33% respectively in the two supplements, compared with a control diet.

Dietary fat inclusion is a factor that should be carefully considered due to its putative negative impact on animal production resulting from a reduction of DMI and milk fat and/or protein contents in dairy ruminants. Therefore, at least part of the mitigation effect of dietary lipids reported in literature is a result of decreased intake of dietary carbohydrates, which is a consequence of decreased DMI as a result of lipids replacing carbohydrate in the diet (Hristov et al., 2013).

In contrast with fat-enriched supplements, starchy concentrate are commonly used on farm and are safe for the animal, at least at the moderate level of supplementation usually implemented. As anticipated before, there is a clear relationship between starch intake and the pattern of ruminal fermentation; more H_2, and consequently CH_4, will be produced on fermentation of fibre- as compared with starch-based concentrates. Feeding high starch concentrates, such as grains, not only usually increases diet digestibility and feed intake but also favours propionate production in the rumen providing an alternative pathway to methanogenesis for hydrogen use (Eckard et al. 2010; Martin et al., 2010). However, Dragostis et al. (2008) highlighted that the reduction of CH_4 emission was low (1%) in sheep fed high vs low starch diets.

Also the source of starch may impact on the emissions. An interesting result on this topic was presented by Yurtseven and Ozturk (2009) in a study with lactating Awassi sheep fed free choice isoenergetic and isoproteic diets including either corn or barley. The CO_2 emissions per animal were not significantly different, but the emission of CH_4 values per kg DMI and per digestible energy intake decreased significantly in the animals fed with corn-based diet, probably due to the different degradability rate of the starch-sources in the rumen.

Remarks: Feeding fat-enriched concentrates is a potent strategy to limit ruminant CH_4 emissions. The applicability of this practice will depend on its costs. For instance, high-oil by-product feeds, such as distiller's grains, may offer an economically feasible alternative to oilseeds as a mitigation tool, although their higher fibre content may have an opposite effect on enteric CH_4 production, depending on basal-diet composition. Also feeding starch-based concentrate can be effective to mitigate CH_4 emission although at a lower extent than fat. Viability of feeding these concentrates must be taken into account as well as ethical issues, since cereals are a fundamental source of food.

2.1.8 Dietary additives to reduce denitrification and leaching of N in excreta

The inclusion of sodium chloride (NaCl) in the diet increases water intake in ruminants, both reducing their urinary N concentration and inducing more frequent urination events, thus spreading urinary N more evenly across grazed pasture (Eckard et al., 2010). Some authors (van Groenigen et al., 2005) in a laboratory study, showed that a reduction of N concentration in urine was effective to lower N_2O emissions from incubated soil cores by 5%–10%.

In a recent study, Liu and Zhou (2014) found a reduction in ammonia (NH_3) and nitrous oxide (N_2O) emissions in a pasture treated with urine of grazing sheep fed with high NaCl diet. Salt supplementation did not affect total urine N excretion, but increased total urine volume, and decreased the concentration of N in urine. There was, however, no increase in the frequency of urine events, so the distribution of the N load on pasture would not be affected. Moreover the sheep supplemented with 6 g/kg DM of NaCl showed no adverse effects on growth performance and N balance.

Remarks: This research area deserves further studies to consolidate the animal response to NaCl supplementation in order to evaluate the medium to long term effect of this strategy.

2.1.9 Dietary additives acting as electron receptors

These additives are fumarate, nitrates, sulphates and derivatives such as nitro-ethane. These compounds share the ability to scavenge electrons from the rumen, which can limit or even negate the reduction of CO_2 to CH_4 by methanogenic bacteria. Nitrates are the compounds by far more studied in both cattle and sheep. When nitrates are added to diets, they may decrease CH_4 emissions by 50% (Hristov et al., 2013). However, nitrates can be converted to nitrites (NO_2) which are toxic and can increase the prevalence of methemoglobinemia. For this reason, dosing or feeding nitrates warrants a relatively long adaptation period during which doses are gradually increased up to desired level (usually 2-4% of the diet in sheep). Moreover, if the diet is already rich in proteins, the administration of nitrates can increase the emissions of NH_3 in the rumen as well as the urinary release of N, which can be putatively converted to NO_x in the soil or leached after oxidation to nitrates.

Literature on nitrates dosed to sheep is relatively rich. Wethers were fed two iso-nitrogenous diets based on oaten chaff, one group received 4% of KNO_3, the other had urea as non-protein additive (Nolan et al., 2010). The effect of nitrate addition was marked, with a reduction of CH_4 yield by 23% as compared to the control diet. Using again wethers, a Japanese research team (Sar et al., 2004) confirmed the reduction of CH_4 emissions with nitrate, with no further reduction when it was dosed combined with 1-4 galacto-oligosaccharides or nisin.

Li et al. (2013) tested in groups of wethers different levels of nitrate alone or with S compared to an urea-fed control group. They found that coupling nitrates at 1.88% with S at 0.18% of the diet was the most effective mitigation treatment. The same research team showed that replacing 1.5% of urea with 3% calcium nitrate lowers CH_4 emissions in ewe lambs, without affecting sheep performance (Li et al., 2012).

In another study, male lambs received either no additive, nitrate, sulphate or a mixture of nitrate and sulphate. In this case the reduction of enteric CH_4 emissions was found in both nitrate and nitrate and sulphate dosed lambs (Van Zijderveld et al 2010). Lambs receiving both electron receptors showed a higher reduction of the emissions, being their effect approximately additive.

Only one recent study on sheep has explicitly investigated the effect of nitrate dosing on methemoglobinemia hazard (de Raphaelis-Soissan et al., 2014). These authors evaluated the putative effect of dosing a probiotic with the nitrate to control the outbreak of nitrous oxide toxicity. Nitrate supplementation has been proven beneficial in terms of wool production and confirmed its mitigation effect but displayed some risk of methemoglobinemia in the wethers fed oaten chaff at a restricted level. The probiotic did not help to limit the probability of outbreaks and had no effect on CH_4 emissions.

Fumaric acid has also been evaluated as electron receptor in ruminants, although rarely. In a study, lambs were dosed with partially hydrogenated vegetable oil (PHVO), fumaric acid (FA) and fumaric acid encapsulated in the partially hydrogenated vegetable oil (EFA). FA and EFA decreased CH_4 emissions by 62 and 76%, respectively, suggesting that fumaric acid can be very effective as alternative to nitrate but it may be better to encapsulate it in an oil matrix (Wood et al., 2009). Surprisingly, encapsulation process has not been evaluated so far with reference to nitrate additives.

Remarks: The dietary administration of additives containing compounds acting as H sink is the most potent mitigation strategy (Veneman et al., (2016). However, its application must be approached

<u>with extreme caution since they are putatively toxic and may also impact negatively to the environment such as the nitrates when diets are rich of protein</u>.

2.1.10 Generalization of dietary mitigation strategies

A generalization of mitigation strategies has been attempted by Veneman et al. (2016 – MitiGAte). With a meta-analytical approach based on more than 400 published papers. This analysis identified clear differences in terms of their effectiveness in decreasing emissions (Table 11). In particular mitigation potentials varied between 6% and 25% with high heterogeneity that need to be better understood to obtain CH_4 mitigation outcomes and applicability of strategies within specific production systems (Venemon et al., 2016). The same authors clearly identifies chemical inhibitors as the most effective mitigation strategy, (methane reduction of 25% on average; $p < 0.001$), dietary supplements such as hydrogen sinks, tannins or lipids (CH_4 reduction of 10% on average) (Table 8). Vaccination appeared to have no impact on methane emissions (P = 0.1), whereas grazing intensity, probiotics and defaunation were not considered significantly effective in that meta-analysis (P = 0.02). The authors also advise that even if several mitigation strategies were identified as technically very effective, there are economic implications for implementation of these strategies.
Evaluation of cost-effectiveness should be done at local level, at least at national scale.

Table 11. Summary table of meta-analysis by Veneman et al., (2016) on the odd-ratio mean effect and estimated heterogeneity parameters for mitigation strategies where original results were reported on a per feed intake basis and included some measure of variance.

Mitigation strategy	Mean effect size (95% CI)	*n*	*P*	Heterogeneity	
				I^2	*P*
Animal management					
Level of feed intake	0.90 (0.85–0.94)	44	<0.001	95.2	<0.001
Grazing intensity	0.95 (0.91–0.99)	15	0.022	26.9	0.160
Diet manipulation					
Feed quality					
Forage quality	0.95 (0.93–0.98)	105	<0.001	91.2	<0.001
Concentrate quality	0.88 (0.81–0.96)	26	0.003	94.0	<0.001
Increasing concentrate	0.93 (0.90–0.95)	124	<0.001	77.9	<0.001
Inclusion of legumes	0.94 (0.90–0.98)	63	0.004	79.8	<0.001
Dietary supplements					
Dietary oils	0.86 (0.83–0.89)	179	<0.001	93.5	<0.001
Pre- and probiotics	0.96 (0.94–0.99)	22	0.020	0	0.801
H sinks	0.85 (0.81–0.90)	54	<0.001	87.1	<0.001
Plant secondary compounds					
Tannins	0.82 (0.78–0.87)	40	<0.001	88.8	<0.001
Saponins	0.94 (0.91–0.97)	24	<0.001	35.7	0.043
Essential oils	0.92 (0.89–0.94)	40	<0.001	0	0.769
Rumen manipulation					
Antibiotics	0.91 (0.88–0.95)	40	<0.001	98.7	<0.001
Vaccination	1.12 (0.98–1.29)	7	0.100	0	0.993
Chemical inhibitors	0.75 (0.70–0.79)	52	<0.001	52.2	<0.001
Defaunation	0.83 (0.71–0.96)	11	0.015	60.6	0.005

3. Non- nutritional factors

3.1 Animal genetics

The heritability of methane emissions (measured in 1 h/d) adjusted for live weight has been estimated equal to 0.13 by Pinares Patiño et al. (2003) and 0.10 by Robinson et al., (2010). Taking these estimates into account, the mitigation option of breeding for low CH_4 has been explored in several studies as reviewed by Cottle et al., (2011). According to Eckard et al. (2010) the potential reduction achievable by selection for low methane emissions sires can be 10-20%, but a more convenient strategy would be to select for animals with higher feed conversion rate or, in other words, for improved feed efficiency. The limited scope for directly implementing CH_4 emissions as selection criteria relies on i) the competition between this trait and more economically relevant traits (such as milk or meat production); ii) the cost of its measurement in vivo; and iii) the important role of rumen and gut microbioma as modulator of the emissions. Indicators of feed efficiency such as the residual feed intake (RFI) have a higher heritability than methane emissions and are usually correlated with this trait.

However, according to recent reviews on this topic (Waghorn and Hegarty, 2011, Hristov et al., 2013) selecting animals with low RFI (i.e. more efficient) does not necessarily result in a reduction of methane emissions per kg DMI but may eventually decrease the emissions per unit of output.

This is probably explained by the role of microbioma. Marked changes in the diet such from stall-feeding to grazing has a major impact on the enteric microbioma. Efficient animals tend to be efficient under different feeding conditions but may respond differently in terms of emissions under different feeding regimens (Cottle et al., 2011).

Although the interaction genotype-environment has an overriding role for the expression of methane emissions, in meat sheep breeding in Australia, the selection for low RFI has been suggested as the main mitigation strategy, particularly under extensive conditions, where nutritional mitigation options are unfeasible or unviable (Hegarty et al., 2010).

Nevertheless, SNP chips containing tens and hundreds of thousands markers are currently available and affordable for many livestock species. This opens promising perspectives for implementing selection programs based on marker assisted selection (Dekkers, 2004) or genomic selection (Meuwissen, et al. 2001) for those traits that are difficult and costly to measure, such as methane emissions.

A specific study was conducted by Lambe et al., (2014) to assess effects of genetic improvement on profitability and global warming. The authors found that when selection tried to increase meat sheep productivity by increasing the body size of the ewes, the increase in productivity was associated to increased methane emissions. Therefore selection index should aim to increase lamb production efficiency rather than its productivity.

3.2 Animal reproduction management and animal health

Effective reproduction management is a key to reduce the CH_4 emissions as highlighted by several studies and reviews. In cattle, Garnsworthy (2004) showed that enhancing herd fertility to the optimal level from the current level (hence reducing the number of replacement cattle) would decrease CH_4 and NH_3 emissions up to 24 and 17%, respectively.

While the mitigation effect of fertility is equally fundamental in sheep, in this species prolificacy can also play a role. In fact the higher the prolificacy and hence the fecundity the lower the number of replacement sheep can be. This is true only if multiple rearing sheep are fed adequately to sustain the higher putative growth rate of their litter (Hristov et al., 2013). Harrison et al., (2014) showed that fecundity rates are more important than animal stocking rate for flock intensification and emission mitigation. In particular these authors demonstrated how carbon footprint of lamb

production can be reduced by more than 20% improving fecundity rates from 0.94 to 1.54 lambs per ewe.
Two other aspects are relevant to mitigate methane emissions through reproduction management in sheep as well in other species: the reduction of the time between birth and first mating or lambing and the time between birth and culling.
As far as the first point, with reference to meat sheep, Hegarty et al. (2010) suggested to anticipate ewe-lamb mating from 19 (hoggets) to ~7 months of age, which is close to the management of ewe-lambs in dairy sheep flocks (7-9 months of age at mating).
Culling time is related to animal longevity in economic terms and hence also to animal health. Despite the putative advantage of a fast turn-over of animals thanks to the more efficient genotypes of replacement vs. adult animals, Hegarty et al. (2010) found a 6% mitigation effect by lengthening the career of ewes from 5 to 6 years, with a proportional decrease of flock replacement rate.
To this end, the control of the main pathologies in the flock is fundamental. Animal welfare is also expected to favour these mitigation approaches. A strategy based on the above points (improved fertility and fecundity, early mating of ewe-lambs and late culling) could bring about a 13% mitigation effect on methane emissions according to the above authors.

3.3 Generalization of non-nutrition mitigation strategies

Overall there is scope for considering these strategies as the most promising at medium and long term scale. However, strategies based on the implementation of selection and reproductive strategies may entail investments that go far beyond farm financial capabilities.

4. Mitigation potentials of managed grasslands

On managed grasslands, significant portions of world milk and beef production occur (Sere et al. 1995). Dairy sheep farming systems are grassland-based farming systems that produce the roughage, part of the animal's feeds and straw eventually used for bedding. Most of inputs, such as fertilizers and supplementary feed, are purchased and direct energy derived from fossil fuels is used (Soussana et al., 2010). In recent years, the potential of soil C sequestration in grasslands has emerged as research hotspot (Fornara et al., 2011, 2013; Lal, 2011; Smith, 2014; Soussana et al., 2010; Rodríguez-Ortega et al., 2014).

Bernues et al. (2017) highlighted that because soil C sequestration is dynamic and soil C content tends to equilibrium or saturation, grasslands cannot sequester C indefinitely in time, and hence, the potential of soil C sequestration in grasslands is considered as limited and will dependent on their type, maturity and management. The management of the grasslands can influence the soil C sequestration potentials, but it is essential to maintain the C sequestered into the soil (stock). However, an inadequate soil and grassland management cannot achieve an actual removal of C from the atmosphere, and even less for a long period of time.

In the same study, Bernues et al. (2017) have ranked the farming practices according to policy objectives with the focus on soil C sequestration. The ranking of farming practices was as follows: utilizing manure correctly; reduce ploughing/tilling; maintain semi-natural vegetation (trees and bushes); adapting stocking rate to the carrying capacity of agroecosystem; and maintaining grasslands. Being manure utilization a minor farming practice in Mediterranean semi-extensive dairy sheep systems, the reduction of mechanical soil tillage, the grazing management and the maintenance of semi-natural silvopastoral systems and grasslands seemed to be the agronomic practices that affected the potential of soil C sequestration in these agroecosystems.

According to the HILDA land-cover data set, the area of grasslands remained fairly stable during the period 1991–2010 in Northern and Western Europe, but increased in Portugal, Spain, Italy, and Eastern Europe countries (Fuchs et al., 2013). As reported by Chang et al. (2015), the long-term C balance of European grasslands is estimated as a net sink with 15 g C m^{-2} $year^{-1}$, while at farm scale they observed halved values. Also, adding CH_4 and N_2O emissions to net ecosystems exchange, same authors estimated the GHG balance of grasslands at ecosystem and farm scale, obtaining values of 19 and -50 g CO_2-eq m^{-2} $year^{-1}$, respectively. Applied models simulated an increase of soil C stock in European grassland during the last five decades. This result could be explained by the combination of a positive trend of net primary production, due to CO_2, climate and nitrogen fertilization, and the decreasing requirement for grass forage, due to the Europe-wide reduction in livestock numbers (Chang et al., 2015).

Recently, Gocht et al. (2016) calculated that a premium to European farmers on average of 238 EUR /ha for converting 2.9 Mha into grassland could lead to a GHG emission's reduction of 4.3 Mt CO_2-eq. The net abatement of 1 t CO_2-eq should account on average to EUR 97. Soil C sequestration linked to the land-use change towards grassland would be most effective in regions as France, Italy, Spain, Netherlands and Germany. Larger farms and farm-types specialized in 'cereals and protein crops', 'mixed field cropping' and 'mixed crop-livestock' have the highest climate change mitigation potential at relatively low costs.

Nowadays, the greening process of agriculture and livestock supply chain supported by EU climate change policies and driven by the increasing demand of environmental-friendly agri-food products, give an additional importance to the environmental implications of production systems into marketing and production farming strategies. In this scenario, the Mediterranean livestock supply chain can help to better exploring the relationship between sheep farming and climate change (Marino et al., 2016; Wiedemann et al., 2015a).

At farm scale, for mixed crop-livestock farming systems, the net emissions of GHGs (CH_4, N_2O and CO_2) are affected by C and N flows and environmental conditions (Soussana et al., 2010). The effect

of the intensification/extensification level of livestock farming systems on the GHG emissions is still unclear.
Regarding the sheep sector in the Mediterranean regions, there are contrasting farming systems, characterized by different land use, input utilization and intensification level. Several factors determine these differences and they are represented by grazing management, geographical location of farms, contingent market conditions and others external factors such as public incentives policies and local or global markets trends (Biala et al., 2007). However, at farm scale, there is not clear scientific evidence showing that extensive systems are really preferable than those more intensive, in terms of environmental impact. Despite several studies on lamb meat production systems (Biswas et al., 2010; Ripoll-Bosch et al., 2013; Jones et al., 2014; Wiedemann et al., 2015a and b; Zonderland-Thomassen et al., 2014), only few LCA studies regarding dairy sheep sector have explored the environmental impacts of dairy sheep farms from a crop-livestock point of view. Batalla et al. (2015) estimated the average values for CF of sheep milk production systems in Northern Spain ranging from 2.0 to 5.2 kg CO_2-eq/kg of FPCM, without taking into account soil C sequestration. The main outcome of this paper showed that more intensive farms with higher amount of milk production per sheep have lower CF values than more traditional farms with less efficiency per animal. When soil C sequestration is included in the assessment, the CF values decrease much more in less productive farms, due to highest soil C sequestration favored by grazing practices on grasslands (O'Brien et al., 2016). However, extensive sheep farms show lower N and feed efficiency. Consequently, in farming systems where grasslands are a substantial resource for animal feeding, the inclusion of soil C sequestration in LCA analysis is suggested. The development of innovative strategies for a correct management of grasslands and crop residues may affect the increase of soil C sequestration, especially in extensive sheep farms, where grasslands play an important role as C sink.
Grasslands are generally regarded as potential C sink, although some agronomical practices related to the grassland management might alter the soil C sequestration, as the frequency of ploughing and reseeding events, direct emissions from farm machinery and indirect emissions from fertilizer manufacturing (Hopkins and Del Prado, 2007). The increase of soil C stock after a shift from arable crops to grassland is partly explained by a greater supply of C from crop residues left in the soil under grassland, represented by root biomass and shoot litter, and partly by the increased residence time of C, due to the absence of soil tillage (Soussana et al., 2004). The strategies of soil C sequestration include actions aimed at improve the use of crop residues and species with deeper rooting, reducing the soil disturbance (Hopkins, 2012). Conant et al. (2001) highlighted that to obtain sustainable productions in grassland ecosystems is essential to conserve the soil organic matter (SOM), which can be strongly influenced by agronomic management. Despite some cropping practices as the fertilization, the grazing management and the use of improved grassland species for forage production can potentially lead to an increase of SOM, the conversion from cultivation to permanent grassland resulted in the largest increase of soil C stock (Janssens et al. 2005, Soussana et al, 2010). As a consequence, an effective C-oriented farmland management may be identified by adopting revised management schemes that enhance soil C inputs and reduce soil disturbance (Hopkins, 2012). Some studies showed lower environmental impact of the extensive farming systems compared with those intensive, focusing on complex processes that affect yield, resource consumption and C-CO_2 emissions (Bailey et al., 2003; Casey and Holden, 2006; Haas et al., 2001; Nemecek et al., 2011, Vagnoni et al., 2015). Extensive agriculture may contribute to mitigate some negative environmental impacts caused by intensive livestock systems, such as consumption of fossil fuels, demand for macroelements, global warming potential, loss of biodiversity, degradation of soil quality (Biala et al., 2007).
Conversely, the introduction of various low input farming techniques, i.e. manure fertilization, mechanical weeding, minimum tillage and no-till, in some cases was demonstrated to have the

opposite effect (Basset-Mens and Van Der Werf, 2005; Brentrup et al., 2004; Michael, 2011; Batalla et al., 2015; Ledgard et al, 2010).

Recently, Vagnoni and Franca (pers. comm.) have studied with a LCA approach the conversion to grassland of a semi-intensive dairy sheep farm in Sardinia (Italy), with a larger use of natural and artificial pastures, valorizing the role of native legumes-grasses mixtures and adopting low-input farming practices (minimum tillage, reduced use of fertilizers, etc.). The LCA approach demonstrated that the substitution of crops such as irrigated maize and wheat with grasslands, such as oat/ryegrass forage crops and legume-based artificial pastures, improved the overall environmental performances of the farm, but only at minor extent, because of the predominant effect of enteric fermentation compared to the others factors analyzed, also confirmed by Gerber et al. (2013). These results are consistent with Soteriades (2016), who reported that the average eco-efficiency of dairy farms enhance when they reduce the percentage of maize for silage in the total forage area. According to Basset-Mens et al. (2009) and Rotz et al. (2010), the low input techniques in grassland requiring lower amount of fertilizer and field operations than arable land, by determining lower environmental impacts from eutrophication, acidification, GHG emissions and non-renewable energy use on grass-based farms.

Henderson et al. (2015) reported that grazing management can affect the C and N cycling at ecosystem level and its alteration may influence the soil C stock in grazing lands. In grazing lands, soil C losses due to the excessive removal of biomass in prolonged periods of overgrazing, can be partially recovered by reducing grazing pressure (Conant and Paustian, 2002). Conversely, it is also possible to improve grass productivity and soil C sequestration by increasing grazing pressure in slightly grazed lands (Holland et al., 1992). Vigan et al. (2017) tested the impacts of three different French Mediterranean sheep and crop farming systems with different degrees of flock mobility (sedentary, single transhumance and double transhumance) in terms of soil C sequestration/emission and biomass carbon fluxes, using a model approach. The preliminary results showed that sedentary and double transhumance flock mobility caused low C emissions.

In additions, to mitigate the nitrous oxide emissions from farm land, it is important to identify the best options of N fertilization, land drainage and grazing pressure management (Montany et al 2006). On grassland, the N fertilization conducted in spring using urea rather than ammonium nitrate can reduce N_2O emissions from these agroecosystems (Dobbie and Smith, 2003). Indeed, Smith et al. (1997) showed that the application of ammonium nitrate and ammonium sulphate fertilizer with slow release significantly reduced N_2O emissions compared to uncoated N fertilizer. In New Zealand, nitrification inhibitors are used on grazing land in order to reduce the N_2O emissions from urine deposition (Di and Cameron, 2003).

Other agronomic practices as fire management, sowing of legumes and more productive grass species could be used to improve soil C stock in grazing land (Lal, 2004; Smith et al., 2007; Follett and Reed, 2010; Eagle et al., 2012). These measures can increase forage production, crop residues left into the soil and dung (where more animals are introduced to make use of additional forage) on the soil, determining an increase of soil C stock (Piniero et al., 2010). The augmentation of soil C stocks can also provide several agronomic and environmental co-benefits by raising soil fertility, improving soil water holding capacity and soil aggregation and reducing soil erosion (Conant and Paustian, 2002). The improvements to soil water holding capacity, in particular, can increase the resilience of forage production in this agroecosystems to climate change.

Incorporation of crop residues may be a sustainable and cost-effective management practice to maintain the ecosystem services provided by soils, such as the Soil Organic Carbon (SOC) levels and soil fertility in European agricultural soils (Perucci et al., 1997; Powlson et al., 2008). These benefits could be more evident in Mediterranean soils with low SOC concentrations (Aguilera et al., 2013) and in areas where stockless croplands predominate (Kismanyoky & Toth, 2010; Spiegel et al., 2010). Lethinen et al. (2014) observed that crop residues incorporation is an important management practice to maintain SOC concentrations and to sustain soil functioning, but that its influence on

GHG emissions should be considered. On the other hand, Allan et al. (2016) showed that the N accumulation in soils after sheep summer grazing of crop residues in Mediterranean environments is inconsistent.

Remarks: In the Mediterranean regions, there are contrasting dairy sheep farming systems characterized by different intensification level. Extensive systems may contribute to reduce the GHG emissions thanks to potentials of soil C sequestration of managed grasslands. Correct agronomic practices of managed grasslands may affect the increase of soil C sequestration, especially in extensive sheep farms, where grasslands play an important role as C sink. Permanent grasslands improve soil C stock respect to arable crops, partly explained by a greater supply of C from crop residues left in the soil and partly by the increased residence time of C, due to the absence of soil tillage. The management of grazing can improve soil C sequestration on grasslands, decreasing or increasing the grazing pressure on overgrazed and slightly grazed lands, respectively. The management of N fertilization can affect N_2O emission and soil C input from biomass residues.

5. Tailoring mitigation strategies with LCA approaches at territorial level

LCA studies often present their results pursuing the determination of the system performances without target emission sources for future mitigation (Edward-Jones et al., 2009). LCA studies often investigate the mitigation strategies without including them in a farm contest and very few studies focused on the quantification of the application of possible mitigation strategies (Cottle and Cowie, 2014). On the other hand, mitigation strategies are often discussed in literature targeting the emission sources with high emission intensities or considering the most promising technical practices that would allow significant emission reductions within hotspot (Eckard et al., 2010). Nevertheless, all the most promising strategies cannot be applied with similar effectiveness to all the farms (Hristov et al., 2013). In this sense, the expression of the environmental indicators per functional unit, or considering their incidence as percentage of total emission, allows fair comparisons of farm performances but could also cause information losses, misleading with respect to 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: the single farm hotspots that show high emission intensities per functional unit (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.

A possible approach for mitigation strategies at territorial level has been developed elaborating the information provided by Batalla et al. (2015) as case study. This paper investigated the environmental performances of 12 farms (3 from semi-intensive systems with Assaf sheep breed, SIF; 3 from semi-intensive systems with Latxa breed, SIL; 6 from semi-extensive systems with Latxa breeds, SEL), whose characteristics are reported in Table 8. These farms have been studied with a deep LCA analysis in order to quantify the emission intensities of different aggregated hotpots. It were aggregated in 8 emission categories (enteric fermentation, manure management for CH_4, manure management N_2O, direct and indirect N_2O, feed purchased, mineral fertilizers, energy and other inputs).

In this review, the information from the paper of Batalla et al. (2015) was elaborated considering the 12 farm as a case study and assuming that they consist of the total number of dairy sheep farms insisting in a target area. Starting from information reported in this paper, the carbon footprint of each farm (kg of CO_2-eq. per kg of FPCM) have been multiplied per the amount of milk delivered in order to calculate the cumulative emissions of each farm and of the 12 farms (Table 8). As reported in Table 8 the farm ranking is different when calculated for emission intensities and for total cumulative emissions. Farms 7, 8 and 11 and 12 would be selected if only the farms with emission intensities higher than the mean CFP will be target for mitigations. Farms 1, 2 and 3 account for about 60% of the sample total emissions and would be targeted for emission mitigation if a cumulative criteria for mitigation is applied.

With a more detailed approach the same cumulative contribution can be calculated per each single farm hotspot (i.e. kg of CO_2-eq/kg of FPCM from enteric methane in farm 1 times the amount of milk delivered by farm 1). Decision making strategies for emission mitigation in those 12 farms might be provided by applications of the principles of Pareto analysis. The Pareto analysis is a formal method useful to identify the most important problem to solve where many possible courses of action are competing for attention (Poonia, 2010). Using Pareto analysis, the problem-solver estimates the benefit of each action that might deliver a total benefit reasonably close to the maximal possible one (Poonia, 2010). The Pareto rule 20:80 focuses the most important 20% of inputs that is capable to manage the 80% of outputs.

In this particular case, we would like to focus on the 20% of hotspots that emits the 80% of GHG. Figures 3 and 4 show the emission intensities and the percentage contribution to cumulative emissions of each farm hotspots. Hotspots were ranked in the X axis from the highest to lowest contributors. Figure 3 showed that not only the hotspot with the highest emission intensity contributed appreciably to the total impact. The figure 4 focuses only on the 22% of farm hotspots that are related to the 80% of cumulative emissions. From the Figure 4 we can deduce the most relevant farms and hotspots to be targeted to effectively reduce the emissions. As shown in Figure 4 not all the farms should be prioritized for emission reduction, on the other hand the most important hotspots to be targeted involved enteric fermentation and feed purchasing in some farms and energy and fertilizers management in few others.

A more deep analysis could be carried out emphasizing the same approach with further steps:

- to calculate the mitigation coefficient reasonably obtainable in each farm for each hotspot
- to estimate the potential reduction of emissions
- to apply the principle of Pareto Analysis ranking the mitigation potentials to express priorities based on the mitigation potential;
- to identify at territorial level the most relevant action that allows to reduce the emissions
- to calculate the marginal cost of emission reduction in order to establish cost-benefits of mitigation actions and to define the priorities for feasible mitigation plans.

Table 8. Farm characteristics and performance from Batalla et al., (2015).

Farm*	Carbon footprint	Production	Ewes	Land	Milk	Cumulative CO_2-eq.	Farm ranking**	
	kg CO_2-eq./kg FPCM	kg of milk/ewe	n	ha	Lt/year	kg CO_2-eq.	CFP	CFP
SIF1	2.61	386	835	17.7	322522	841782	3	12
SIF2	2.22	339	504	90.2	170765	379098	2	11
SIF3	2.03	318	546	85.9	173367	351935	1	10
SIL4	3.01	166	253	32.0	41881	126062	7	5
SIL5	3.19	206	268	120.4	55260	176281	8	9
SIL6	2.87	149	265	75.6	39506	113383	5	4
SEL7	4.03	138	288	85.9	39868	160669	10	8
SEL8	3.61	106	213	214.3	22475	81136	9	2
SEL9	2.96	128	365	17.7	46641	138057	6	6
SEL10	2.76	156	108	29.1	16833	46458	4	1
SEL11	4.05	144	190	85.9	27406	110993	11	3
SEL12	5.03	111	278	32.0	30949	155672	12	7
Mean	3.20	196	343	73.9	82289	223460		
Total			4113	886.6	987472	2681524		

*semi intensive systems with Assaf sheep breed, SIF; SIL: semi intensive systems with Latxa breed; SEL: semi extensive systems with Latxa breeds. ** Farms are ranked from the lowest to highest emission intensity of carbon footprint (CF) and cumulative CO_2-eq emissions (total GHG).

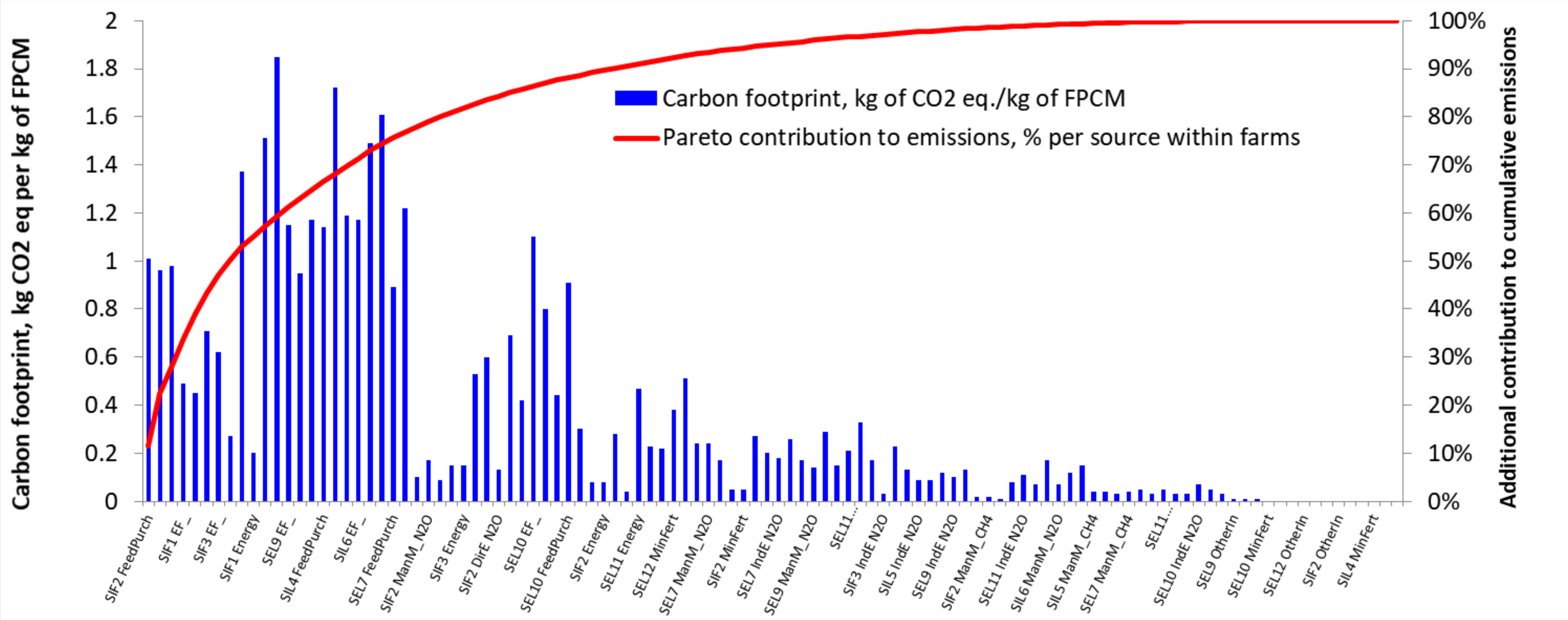

Figure 3. Global warming potential of 12 dairy sheep farms. Bars indicate emission intensities per each farm hotspot as reported in Table 6 of Batalla et al. (2015). The line indicates the percentage cumulative contribution of each single farm hotspot to total emissions of the 12 farm. Cumulative emissions of the 12 farms were calculated using the information reported in the same paper of Batalla et al. (2015). The 100% of emissions of the 12 farms was equal to 2770015 kg of CO_2 eq. (Table 8).

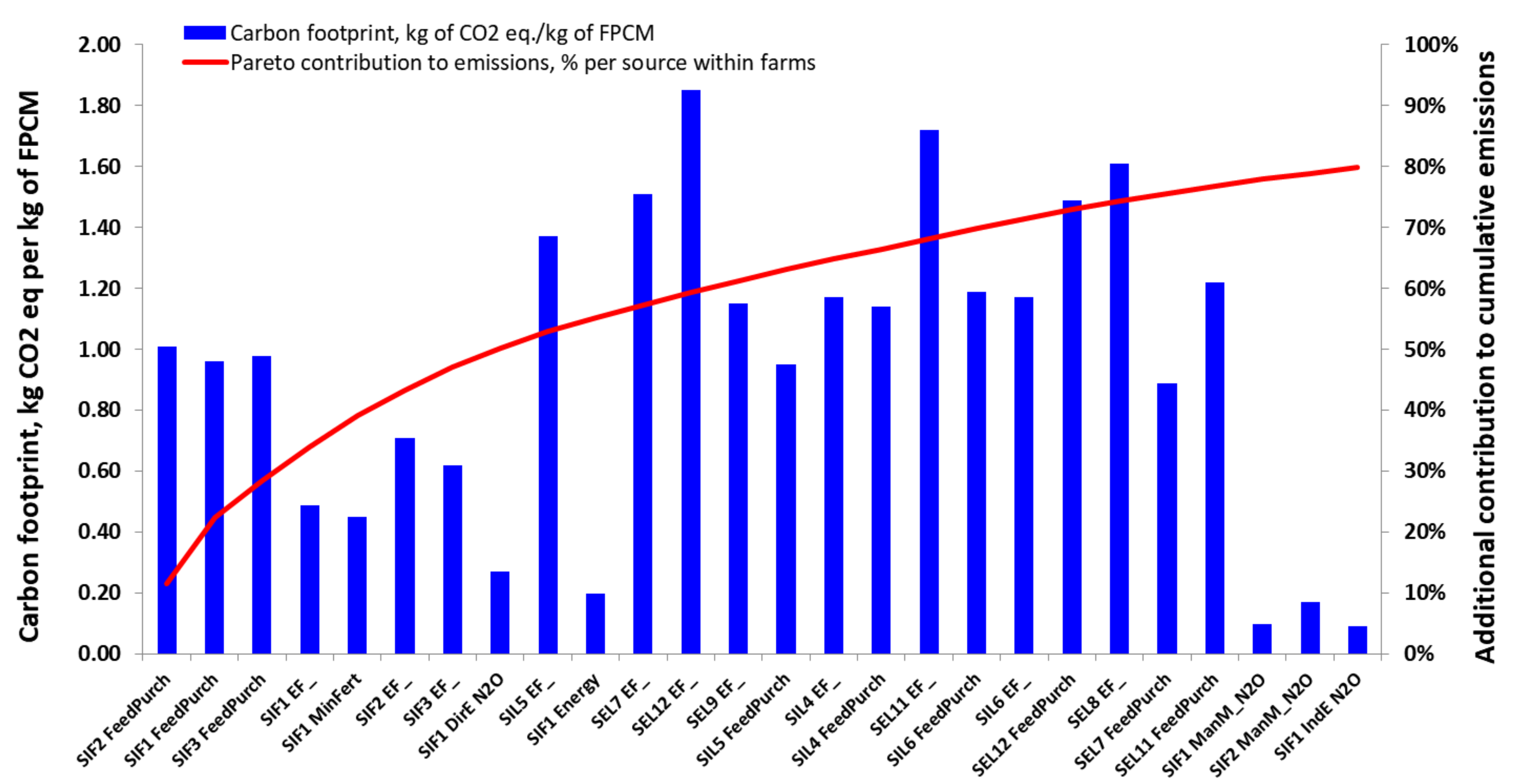

Figure 4. Pareto analysis of the global warming potential of 12 dairy sheep farms. Data are the same from Figure 3 but this chart shows only the first 22% of hotspots that contributes to 79% of the emissions from the 12 selected farms. Bars indicates emission intensities per each farm hotspot as reported in Table 6 of Batalla et al. (2015). The line indicates the cumulative contribution of each single hotspot to total emissions of the 12 studied farm. Cumulative emissions of the 12 farms were calculated using the information in the same paper of Batalla et al. (2015). The 100% of emissions of the 12 farms was equal to 2770015 kg of CO_2 eq. (Table 8).

6. Conclusions

Approaches on LCA studies for the sheep sectors are continuously developing even if the number of studies focusing 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. Otherwise, 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 efficiency of the systems linking production processes with natural resources (air and climate, land, water, energy, etc) and to get social, economical and technical benefits of the studied systems and biological boundaries. Moreover for sheep meat and wool production several studies have been published to quantify the mitigation effectiveness of technical choices. Few studies focused the same approach for dairy sheep farms, both at farm and territorial level. To accomplish the purpose for which LCA is applied, the LCA inventory need to be accurately designed, with defined system boundaries, with non ambiguous functional units. Particular care need to be deserved for allocation methods that have to be clear, transparent and consistent in order 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. LCA studies need to be carried out with the aim to support the planning of effective mitigation actions. Particular care need to be deserved to 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. At territorial level, when organizing broad mitigation plans, actions should consider to target inefficient farm hotspots more than inefficient farms. Costs and benefits of mitigation actions need to be quantified also from an economic point of view.

7. References

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