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Review

Review of environmental performance of sheep farming using life cycle assessment

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A R T I C L E I N F O

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A B S T R A C T

Life cycle assessment (LCA) is increasingly being used as a tool to estimate environmental impacts in the sheep sector. Policymakers have been keener on developing policies and recommending best management practices from a life cycle perspective. This paper reviews the key LCA studies of the sheep sector within the last fifteen years to assess the state of the art of the environmental impacts of the sheep supply chain. Peer-reviewed LCAs as well as global, organizational efforts on the subject have also been reviewed and discussed. Discussions are categorized by products, hotspots, methodologies and system boundaries, and impacts of interest. The vast majority of studies have utilized a "cradle-to-farmgate" system boundary, where impacts associated with production of major farm inputs, management/applications of inputs and direct emissions from livestock are included. The sole focus of the majority of studies in terms of the category of impact has been climate change, quantified through greenhouse gas (GHG) emissions. The impact results are difficult to generalize due to wide discrepancies in farming practices, production efficiencies, product allocation and emission modeling methods. The GHG emissions, however, associated with sheep meat, milk and wool fall in the range of 3.5–25 kg CO_2-eq/kg live weight, 2–5 kg CO_2-eq/kg fat and protein corrected milk (FPCM), and 20–60 kg CO_2-eq/kg greasy wool, respectively. The overwhelming consensus is that the single largest contributor to GHG emissions is direct methanic emission from livestock, generally contributing to 50%–75% of overall GHG emissions. More research needs to be conducted on determining impacts of "post-farm" activities such as processing of sheep products before it reaches the consumers, inclusion of the benefits of carbon sequestration, and consideration of environmental impacts other than climate change.

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1. Introduction

World population of small ruminants (sheep and goats) exceeds 2 billion and makes over 50% of global ruminant (cattle, buffalo, sheep and goats) domestic population. Approximately 15% and 5% of the world's ruminant meat and milk, respectively, comes from small ruminants, of which 60% and 40% comes from sheep, respectively (Hristov et al., 2013; Opio et al., 2013). Sheep, in particular, adapt easily to a variety of production conditions and climates, from extensive production systems to intensive ones and from dry to humid areas. Sheep play a large socio-economic role in developing countries, where they are primarily raised for subsistence. Growth in emerging economies has expanded the ruminant sector over the past decades. Market trade of sheep products such as lamb meat, wool, milk and cheese has also increased over the past decades (Hristov et al., 2013). Due to high specialization of breeds and farming systems, small ruminants in more developed regions reach higher production levels and efficiency and have a higher economic importance than in most developing countries.

There is currently a concern about the relationship between agricultural activities and climate change. Animal husbandry in particular is a significant source of greenhouse gas (GHG) emissions. Approximately 15% of all anthropogenic greenhouse gas emissions (measured in kg CO_2-eq) and 45% of the global agriculture sector's emissions are emitted from livestock (Hristov et al., 2013). Although small ruminants have lower emission levels than cattle, ranging between 7 and 10% of all livestock emissions (Gerber et al., 2013), studies on small ruminant products confirmed that their GHG estimations amount to nearly 600 million ton of CO_2-eq, nearly half of which are from sheep (FAO, 2019).

The largest two sources of GHG emissions from sheep are through enteric fermentation and feed production. GHG emissions from rumen fermentation could be reduced by increasing digestibility of feed. For example, it has been shown that using corn or legume silage over grass can reduce GHG emission intensity due to lower fiber content. Supplementation with small amounts of concentrate feed in intensive practices has shown to increase productivity and decrease GHG emission intensity. There is also indication that improving animal health and reducing mortality increases herd productivity and reduces environmental impacts associated with sheep farming, particularly in the category of climate change (Gerber et al., 2013; Hristov et al., 2013).

Life cycle assessment (LCA), particularly as governed by ISO standards 14040 and 14044 (ISO, 2006a; 2006b), has become a recognized instrument in estimating the environmental impacts associated with all the activities related to agricultural systems. LCA studies of majority of products typically utilize generic and non-spatial life cycle inventory (LCI) databases to estimate impacts in any category. LCA in the agricultural sector is complicated, however, by high variability in life cycle inventorying data due to differences in management practices, climatic variations between regions, and the co-production of multiple products (Notarnicola et al., 2017). Furthermore, emissions from livestock are a significant contributor to greenhouse gas (GHG) emissions, and their emission intensities are too variable to be quantified in generic LCI databases with certainty.

Due to this heterogeneity in methodology and findings related to LCA of the sheep sector, it is difficult to gauge the state-of-the-art on this topic. The lack of a single source of information which summarizes the recent scope and findings on the topic limits researchers' and policy-makers' ability to use the existing literature as a basis for further research or to form sound policies. Similar literature reviews for cattle and poultry industry can be found (de Vries et al., 2015; de Vries and de Boer, 2010), but no peer-reviewed literature review for LCA of the sheep sector currently exists.

In this review article, a literature review of state-of-the-art related to LCA in the sheep industry is presented with the aim of communicating the methods and conclusions common among the current relevant research. Differences in motivations and methodologies and unique objectives that some studies have presented are also highlighted. Where applicable, general results of the LCA studies are compared based on a common LCA metric of GHG emissions. The summaries, objectives and the main findings of the reviewed studies are presented in Table 1 and Table 2.

2. Methods

The following keywords with Boolean operators were entered into Google Scholar, Science Direct, and Compendex to search the available literature: ("life cycle assessment" OR "life cycle analysis" OR "LCA") AND ("sheep" OR "sheep farming" OR "wool" OR "lamb"). This search criteria also resulted in several articles on LCA of mineral wool or rock wool insulating material, which were discarded. The articles are chosen such that they are published within the last fifteen years (2005–2020) for the sake of relevance, to focus the discussion on more recent findings and to provide an understanding of the current state-of-the-art (though there is one exception in the final list of articles).

The majority of published studies in the last decade have focused on meat production systems at a farm level and are based on farms located in Europe, Oceania and the United States (though a few in South America exist). The differences in the type and scale of the farms studied as well as the methodological differences in the goal and scope of the studies have resulted in drastic differences in the results of these studies, but all the articles used a "cradle-to-farmgate" system boundary which included the processes shown in Fig. 1. There were some articles which expanded on the provided system boundary to include processes beyond the farmgate. Those articles are included and discussed in this review as well.

Prevalence of sheep farming in the developing world (particularly in Asia and Africa) is highlighted by the Food and Agriculture Organization (FAO) of the United Nations (Gilbert et al., 2018) and the World Bank (Winrock International, 1983). It was, however, difficult to find LCA studies which have focused on those regions. For that reason, 'grey' literature such as organizational efforts to aggregate LCA studies from around the world have been identified, most notably by FAO (Gerber et al., 2013; Hristov et al., 2013; Opio

Table 1
Summary of studies reviewed.

Study	Country	Number of farms	Products (functional unit)	Allocation	Emission model	Carbon sequestration	GHG emissions
Batalla et al. (2015, 2014)	ES	12	Milk (1 kg ECM[a] and FPCM[b])	Economic (90% milk, remaining 10% to meat and milk)	IPCC Tier 2	No	2.11–5.35 kg CO_2-eq/kg ECM
Bell et al. (2012)	AU	4 (simulated)	Meat (1 kg LW[c])	None (100%)	IPCC Tier 1	No	10.1–21.7 kg CO_2-eq/kg LW
Biswas et al. (2010)	AU	1 (three pasture types)	Meat (1 kg meat), wool (1 kg GWool[d])	Economic (70% meat, 30% wool)	IPCC Tier 1	No	5.5 kg CO_2-eq/kg meat, and 16 lg CO_2-eq/kg GWool regardless of pasture type (slight differences observed)
Brock et al. (2013)	AU	n/a (simulated)	Wool (1 kg GWool)	Economic (30%–60% to wool, remaining to meat)	FarmGAS	No	24.9 kg CO_2-eq/kg GWool
Cardoso (2013)	AU, NZ	3	Wool (1 kg finished wool)	Economic (30%–80% wool; 13%–70% meat)	IPCC Tier 1	No	26.7–62.6 kg CO_2-eq/kg finished wool
Colley et al. (2020)	AU	10 (3 regions)	Wool (1 kg GWool)	None (100%)	n/a	No	n/a
Cottle et al. (2016)	AU	28 (simulated)	Meat (1 kg LW), wool (1 kg GWool)	Protein content (73% meat, 27% wool)	GrazPlan	No	19–35 kg CO_2-eq/kg GWool 3.9–7.3 kg CO_2-eq/kg LW
Cottle and Cowie (2016)	AU	2	Meat (1 kg LW), wool (1 kg GWool)	Mass (85% meat, 15% wool), protein content (65% meat, 35% wool), economic (40% meat, 60% wool)	GrazPlan	No	8.5–20.7 kg CO_2-eq/kg GWool 3.6–8.5 kg CO_2-eq/kg LW
Dougherty (2018)	US	5	Meat (1 kg LW), wool (1 kg GWool)	Economic, protein content	IPCC Tier 1 (equivalent)	No	10.4–18.1 and 6.59–10.1 kg CO_2-eq/kg LW for economic and protein allocation, respectively; 10.4–17.8 kg CO_2-eq/kg GWool
Eady et al. (2012)	AU	1	Meat (1 ram/ewe), Wool (1 kg GWool)	Economic (54% wool, remaining to other sheep products), biophysical (resource use) (68% wool remaining to other sheep products)	FarmGAS	No	Economic allocation: 26.6, 141 and 667 kg CO_2-eq per kg GWool, ewe and ram, respectively
Edwards-Jones et al. (2009)	UK	2	Meat (1 kg LW)	Economic (55% meat; 2% wool; 9% to cull; 35% to beef)	IPCC Tier 1	No	2.8–12.9 kg CO_2-eq/kg LW
Furesi et al. (2015)	IT	1	Milk (1 L FPCM)	Economic (82% milk, 18% meat)	IPPC Tier 2	No	2.27 kg CO_2-eq/L FPCM
Jones et al. (2014)	UK	64	Meat (1 kg LW)	Economic (73% lamb; 2% wool; remaining to live, bred and culled sheep)	IPCC Tier 1	No	10.85–17.86 kg CO_2-eq/kg LW
Mohan et al. (2018)	NZ	1	Milk (1 ha)	n/a	IPCC Tier 1	No	128 kg CO_2-eq/ha
Mondello et al. (2018)	IT	1	Cheese (1 kg “Pecorino” cheese)	Economic (83% milk, 17% meat)	IPCC Tier 1	No	22.1 kg CO_2-eq/kg cheese
O’Brien et al. (2016)	IE	167 (modeled)	Meat (1 kg LW)	Economic	IPCC Tier 2	Yes	9.7–14.2 kg CO_2-eq/kg LW
Payen and Ledgard (2017)	NZ	2	Meat (1 ha)	n/a	n/a	No	n/a
Peters et al. (2011)	AU	3	Meat (1 kg HSCW[e])	Economic	n/a	No	n/a
Ripoll-Bosch et al. (2013)	ES	3	Meat (1 kg LW)	Economic	GLEAM (IPCC Tier 2)	No	19.5–25.9 kg CO_2-eq/kg LW
Sabia et al. (2020)	IT	4	Milk (1 kg FPCM)	Economic (91% milk, 7% meat, 2% wool)	IPCC Tier 2	No	3.78 kg CO_2-eq/kg FPCM
Schönbach et al. (2012)	CN	4	Meat (1 kg LW), wool (1 kg GWool)	Economic (69% meat, 31% wool)	IPCC Tier 1	Yes	Too variable
Sim and Prabhu (2018)	US	n/a	Wool carpet (0.09 m^2 carpet)	n/a	n/a	No	38 kg CO2-eq/m^2 carpet
Toro-Mujica et al. (2017)	CL	3	Meat (1 kg LW)	Economic	IPCC Tier 2	Yes	7.4–13.3 kg CO_2-eq/kg LW
Uusitalo et al. (2019)	FL	1	1× sheep farm producing 1000 kg meat, 114 kg wool and 400 kg biomass per year)	n/a	IPCC Tier 1	No	30,000–102,000 kg CO_2-eq per functional unit
Vagnoni et al. (2015)	IT	3	Milk (1 kg FPCM)	Economic (90% milk, 9% meat, 1% wool)	IPCC Tier 1	No	2–2.3 kg CO_2-eq/kg FPCM
Wiedemann et al. (2015a)	AU, NZ, GB	4	Meat (1 kg LW), wool (1 kg GWool)	Biophysical, protein content, economic	IPCC Tier 1	No	Too variable
Wiedemann et al. (2015b)	AU	200	Meat (1 kg retail-ready lamb)	Economic	IPCC Tier 2 (equivalent)	Yes	15.5 kg CO_2-eq/kg retail cut

(continued on next page)

Table 1 (*continued*)

Study	Country	Number of farms	Products (functional unit)	Allocation	Emission model	Carbon sequestration	GHG emissions
Wiedemann et al. (2016)	AU	10 (3 regions)	Wool (1 kg GWool)	Biophysical (35%–40% attributed to wool; rest attributed to lamb meat)	IPCC Tier 2	No	20.1–21.3 kg CO_2-eq/kg GWool
Zonderland-Thomassen et al. (2014)	NZ	7 classes of farms (simulated)	Meat (1 kg meat)	Economic	n/a	n/a	n/a (0.26 L H_2O-eq/kg meat)

[a] ECM – Energy corrected milk.
[b] FPCM – Fat and protein corrected milk.
[c] LW – Live weight.
[d] GWool – Greasy wool.
[e] HSCW – Hot standard carcass weight.

et al., 2013). Another notable organizational study focusing on wool production was done by Henry (2012) on behalf of the Australian Wool Innovation & International Wool Textile Organization, in which nine wool LCA studies were reviewed is also included in this assessment. A master's thesis authored by Cardoso (2013) focusing on LCA of wool production (along with cotton) and a PhD thesis authored by Dougherty (2018) focusing on LCA of sheep meat production (along with beef production) in the US is also briefly reviewed in the relevant sections. Lastly, findings of Mohan et al. (2018), who presented an assessment of sheep dairy farming in New Zealand, is also summarized due to the low number of peer-reviewed papers on sheep dairy farming.

This selection process generated a list of 30 original articles (not counting the FAO reports), 27 of which are peer-reviewed (all summarized in Table 1). The discussion on the reviewed studies is categorized by the products assessed in the LCA studies, allocation used, classification of farming/management, impacts of interest, hotspot analysis, and regional variation. Unique motivations and methodological approaches of the reviewed papers are also highlighted.

2.1. Limitations

While the original focus of this review was on a global scale, it draws mainly on studies conducted in Europe, United States (US), Oceania and Chile due to the economic relevance of sheep products in those regions. It was difficult to find rigorous, peer-reviewed LCA of sheep products in Africa and Asia (with the exception of one study in China), and the studies reviewed in this manuscript have not presented the impacts of unique farming practices, climactic and economic conditions on the overall life cycle impacts in these regions. To substitute for this lack of discussion, summary of fundamental differences in farming practices and differences that exist in these continents as identified by various FAO reports (Gerber et al., 2013; Hristov et al., 2013; Opio et al., 2013) is presented in section 3.8.

An inherent difficulty in reviewing LCA studies lies in the fact that methodological choices and assumptions such as system boundary delineation, functional units, and allocation techniques are partly subjective and have a significant effect on the results. Additionally, the categories of impact(s) of interest can also vary between studies. This makes it difficult for reviewers to present "apples-to-apples" comparison of results.

3. Findings

In peer-reviewed efforts, the scope of the reviewed studies largely falls into two categories: small-scale, farm-level assessments, which have collected primary data from 1 to 4 farms for their assessment; and large-scale assessments, which have either used data from national surveys or modeled the inputs using various available methods to represent impacts of an entire region of over 50 farms. Small-scale studies, as expected, have generally used more robust methodologies, particularly in modeling livestock emissions (further discussed in section 3.5). Their results also have a higher level of certainty due to usage of primary data. Large-scale studies have proven useful in identifying the heterogeneity in the land characteristics and management practices that exist in a single region and how environmental impacts are shaped by said heterogeneity. These large-scale studies have proven useful for policy formation in best management practices (Brock et al., 2013). The sample size of each study (in terms of the number of farms) is listed in Table 1.

The studies reviewed were diverse not only in their scale, but in their specific objectives as well (which also informed their methodologies). For example, Batalla et al. (2014) attempted to include social and economic impacts of sheep production, which required them to modify their methodology to include employment indicators and net profit margin. Brock et al. (2013) estimated the direct emissions from livestock using five emission models (further discussed in section 3.5) to compare their results. Cottle and Cowie (2016) and Wiedemann et al. (2015a) investigated the role that the allocation method played in final impact scores. They considered allocation by protein content and various biophysical allocations and attempted to use system expansion as a substitute for allocation. Jones et al. (2014) and O'Brien et al. (2016) attempted to determine relationships between various farm variables (related to land use and intensification) and GHG emissions using large datasets. Toro-Mujica et al. (2017) used probabilistic modeling in determining GHG emissions and attempted to include the impacts of "ecosystem services" (further discussed in section 3.9). Zonderland-Thomassen et al. (2014) focused on impacts related to water scarcity and resulting eutrophication potential instead of GHG emissions, as sheep farming is an inherently water-demanding process, and many researchers have neglected to consider this impact in their assessment. A summary of primary objectives of all the peer-reviewed articles reviewed and the main conclusions drawn by them is presented in Table 2.

3.1. Summary of products

Aside from Mondello et al. (2018), who assessed the impacts of producing cheese from sheep milk, and Sim and Prabhu (2018), who quantified the life cycle impacts of wool carpets, all studies reviewed have focused on the three primary products of sheep: meat, wool and milk. Although a typical range of GHG emissions associated with each product is defined below, heterogeneity of emission values in the literature, reported in Table 1, does not allow one to easily define a narrow range of environmental impacts associated with each product. The extent to which operational factors contribute to emissions also differs drastically between studies. Each study must be reviewed individually to determine the

Table 2
Main objectives and conclusions drawn by the reviewed studies.

Study	Main Objectives	Main conclusions
Batalla et al. (2015, 2014)	Quantify GHG emissions with functional units that also encompass social and economic impacts. In addition to using productive functional units, GHG emissions are quantified on a basis of "net margin" (economic consideration) and "manpower" (social consideration). Consider the effects of soil carbon sequestration on the overall emissions.	GHG emission intensity is inversely proportional to farming intensity ($R^2 = 0.65$). More intensive farms with higher amount of milk production per sheep have lower carbon footprint values than more traditional farms with less efficiency. When soil carbon sequestration is included in the assessment, the carbon footprint values decrease much more in the lower productive farms due to highest C sequestration from grazing practices. Carbon footprint values per kg FECM are still higher, but there is no longer a statistically significant difference between groups
Bell et al. (2012)	Predict the effect of future climatic conditions on productivity and GHG emissions associated with pasture-based lamb products at four sites in Australia. GHG emissions were estimated based on $t-CO_2-eq/ha$ and $t-CO_2-eq/kg$ LW	Positive correlation between rate at which rainfall declined and GHG emission was observed. The predicted N_2O emissions through denitrification increased in all cases due to climate change. The inclusion of a pasture species that is more tolerant of hotter and drier conditions was recommended.
Biswas et al. (2010)	Compare the life cycle climate change impacts of meat and wool in grazed subterranean clover pasture and mixed pasture. Both pre-farm and on-farm stages are considered	Between 82% and 90% of all GHG emissions can be attributed to enteric emissions. The GHG emissions from sub-clover pasture is slightly higher due to higher nitrogen content of the soil (and thus higher N_2O emissions). GHG emissions attributed to wool are significantly higher than that of wheat and sheep meat. For wheat, N_2O emissions from the soil were the most significant contributor to GHG emissions.
Brock et al. (2013)	Quantify GHG emissions related to producing 19-μm wool. Determine the relative GHG emissions associated with each farm activities. Compare enteric emission output from five recognized methods	Direct emission of methane (enterically) contributed to 86% of all GHG emissions. Only 2% of total GHG emissions were from farm inputs, including fertilizer use. The GHG emissions varied by 27% based on which emission method was used.
Cardoso (2013)	Master's thesis: A comparative LCA between cotton and wool textile is undertaken using data from various suppliers from multiple countries.	During the sheep farming phase, enteric emissions are the greatest contributor to impacts in the categories of climate change, human toxicity, acidification, and marine eutrophication. Between 85% and 95% of the total impacts of woolen yarn production in these categories can be attributed to the farming phase
Colley et al. (2020)	An LCA study which quantifies the differences in impacts of conventional sheep farming systems (results of Wiedemann et al. (2016)) to "regenerative" farming systems, where regenerative farming systems are classified as agricultural practices which are extensive, reduce or eliminate pesticide/herbicide and fertilizer use, and use high-intensity, short-duration grazing with long rest periods.	In regenerative agriculture, the most significant impacts in all the categories was from reducing the use of phosphorus-based fertilizer. Reduction in the impacts of fossil-fuel depletion and water footprint were significant, but difference climate change impacts were small between the industrial and regenerative agriculture scenarios. If soil sequestration is considered, however, a significant amount of carbon is offset.
Cottle et al. (2016)	Calculate GHG emissions using multiple modelling packages and capture the diversity of Australian sheep farming through data from 28 farms. Determine if emission intensity can be reduced by management changes such as animal breeding options and pasture management	Operations with crossbred ewes had the lowest GHG emissions in all scenarios. Operations with a high stocking rate (higher intensity) and an emphasis on meat production had lower emissions compared to operations which focused on wool production.
Cottle and Cowie (2016)	Examine the effects of allocation on impacts attributed to meat and wool. Impacts were allocated based on mass, protein and economic. System expansion using beef and purpose-grown sheep meat as a substitute for sheep meat was also utilized	Economic allocation generally yields a higher allocation of impacts towards wool in farms primarily focused on producing wool. Differences in emissions between the two farms due to differences in climatic and production systems were also observed
Dougherty (2018)	PhD Thesis: Data from five sheep farms in California was used to estimate the carbon footprint and water use associated with lamb meat and wool. The animal models were based on the U.S. National Research Council's (NRC) guideline (NRC, 2007)	Higher carbon footprints were observed for sheep grazed on irrigated pastures. Enteric methane was the largest source of emissions (72.3% of all GHG emissions on average).
Eady et al. (2012)	Estimate the total impacts from a mixed farming system (wool, meat, grain) using system expansion to separate the effects of grain, and allocation to separate the effects of wool/meat.	A higher percentage of impacts were attributed to wool using biophysical allocation compared to economic allocation. Among live animals, stud rams had the highest estimated carbon footprint.
Edwards-Jones et al. (2009)	Estimate and compare the GHG emissions from two mixed-cattle (beef and lamb) in Wales. Determine the relative contribution of farm inputs to GHG emissions.	Contribution of enteric fermentation to GHG emissions was 45%; lower compared to other studies. The overall GHG emissions were generally comparable to other studies, however
Furesi et al. (2015)	Assess the economic and environmental sustainability of extensive dairy sheep farming, with a focus on the profitability and economic viability of small ruminant dairy farming in Sardinia.	Based on a single-farm case study, it was found that a dairy farm is not profitable without support of public financial aids. The authors suggest that policy schemes aimed to encourage environmental-friendly practices through economic incentives could adequately ensure long-term financial security for dairy farms.
Jones et al. (2014)	Assess the relationship between farm variables and carbon footprint at a multi-farm level using a large dataset. The farm variables were system type (lowland, upland and hilly) and management variables (number of lambs, lamb growth rate and breed replacement rate, among others).	Enteric emissions were responsible for 65% of total GHG emissions. Number of lambs reared per ewe and lamb growth rate were inversely proportional to carbon footprint.
Mohan et al. (2018)	[Non-peer-reviewed] Based on a thesis (Mohan, 2018): life cycle impacts in multiple categories are quantified for a single sheep dairy farm in New Zealand. The environmental hotpots are identified with the intent to formulate performance indicators in the development of an environmental certification system.	Enteric emissions of livestock and the production and use of fertilizers/pesticides were found to be the biggest contributors in all the impact categories. Barley feed was responsible for over 90% of the freshwater eutrophication and human toxicity impacts.
Mondello et al. (2018)	Assess the environmental performance of producing "Pecorino" cheese from sheep milk (sheep raised intensively), packaged at the dairy farm gate.	25% of climate change impacts are attributed to enteric emissions. Feed production resulted in 40% of GHG emissions. Environmental hotspots in most impact categories are connected to enteric emissions and feed production.
O'Brien et al. (2016)	Assess the effect of intensification on several measures of environmental impact and resource use for grass-based sheep farms. Data from a National	Food-related environmental impacts and resource use of the average lowland sheep farm could be improved by intensifying grass and animal production. Increasing animal production by feeding more concentrate

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Table 2 (*continued*)

Study	Main Objectives	Main conclusions
	Farm Survey is used to determine inputs from a large number of modeled farms to reflect the variety of conditions present in Ireland.	was less efficient and increased environmental impacts compared to increasing grass production, because concentrate required significantly more resources than pasture to produce and generated more emissions
Payen and Ledgard (2017)	Compare different impact methods' estimations of eutrophication impacts in New Zealand's largest lake from two nearby farms. The implications of using both generic and site-specific emission factors is presented.	A wide variation in eutrophication impacts were observed between different methods. The nutrient flow inventory at the farm level and the fate factors must be site-specific, as using default emission factors resulted in overestimation of eutrophication impacts.
Peters et al. (2011)	A nutrient balance for three Australian farms producing red meat (sheep and cattle) is presented and the soil acidification potential of on-farm activities is estimated.	All three nutrients studied (nitrogen, phosphorus and potassium) were accumulated on the farm properties as a result of on-farm activities. The authors suggest reducing the leaching of soil N to balance the N budget without causing acidification.
Ripoll-Bosch et al. (2013)	Compare emissions of three contrasting meat-sheep systems, which differed in their degree of intensification. Specifically, reproduction rate, land use and grazing management differed between the farms assessed	Zero-grazing (highly intensive) management had the lowest GHG emissions. Pasture-based management had the highest GHG emissions. In pasture-based system, however, consideration of ecosystem services (soil health and landscape conservation) significantly reduced GHG emissions of pasture-based system.
Sabia et al. (2020)	Investigate the carbon footprint and the related damages generated by dairy sheep farming by using a simplified LCA approach.	In line with previous studies, the enteric emission from sheep, particularly methane, was the most impactful category in terms of GHG emissions, followed by the production of meadow hay
Schönbach et al. (2012)	Determine how grazing intensity results to life cycle GHG emissions at a controlled farm in Inner Mongolia steppe. Determine the extent to which carbon sequestration is affected by grazing intensity.	Moderate to heavy sheep grazing can change the steppe from a carbon sink to a source due to depletion in soil organic carbon. Grazing exclusion has a potential to restore soil carbon stocks and increase the potential to further sequester CO_2.
Sim and Prabhu (2018)	Compare the cradle-to-grave life cycle impacts of wool and nylon carpets in the categories of climate change and energy requirements. Impacts of wool production are obtained from Wiedemann et al. (2016). The impacts of uncertainty of market share are also investigated.	Climate change impacts of wool and nylon carpets per functional unit are 6.35 and 4.80 kg CO_2-eq, respectively. Energy requirements of wool and nylon carpets per functional unit are 20.42 and 25.42 MJ, respectively. Majority (54%) of climate change impacts for wool carpets are from greasy wool production.
Toro-Mujica et al. (2017)	An existing empirical, probabilistic simulation model of grazing sheep production was modified to allow for a cradle-to-farm-gate quantification of GHG under a number of scenarios. The model considered pasture availability and utilization, supplementation of sheep, milk and lamb production, and carbon sequestration by forages and soils among others.	Farms that used higher inputs had higher forage production and lower GHG emissions, which decreased further if soil carbon sequestration is accounted for. Large farms that had lower stocking rates than the rest, and that used Merino sheep with high reproductive rates, had lower emissions than the smaller farms that make a more intense land use.
Uusitalo et al. (2019)	Positive impacts of sheep farming in Finland are assessed using "planetary boundary perspective" alongside conventional LCA metrics of climate change, water use and land use.	Negative impacts associated with sheep farming in the categories of climate change, water demand and land use were observed. Positive impacts of sheep farming were also observed, however, in the categories of biotope biodiversity protection (genetic diversity) and biogeochemical flows.
Vagnoni et al. (2015)	Compare the impacts of sheep milk production in Italy and identify the hotspots in terms of climate change impacts and endpoint impacts determined using ReCiPe (Goedkoop et al., 2009)	Enteric emissions contributed between 34% and 45% of overall GHG emissions, followed by field operations (tillage and sowing) at 8%–27%. For other impact categories (as determined by ReCiPe), greater differences in impact scores were observed between the three farms due to differences in land use.
Wiedemann et al. (2015a)	Investigate the effect of five allocation methods (three biophysical, one protein, and one economic) and two system expansions on the relative GHG contributions of wool and meat from four farms	Relatively small differences in allocation methodology changed results drastically enough to reorder impacts between case studies It is concluded that whenever allocation methods are applied, results of all the co-products must be presented to avoid shifting of burden.
Wiedemann et al. (2015b)	Quantify the cradle-to-gate impacts of Australian lamb with an expanded boundary that considered the impacts of transportation and warehousing in the US. Alongside GHG emissions, energy demand, water use and land use were also quantified.	Freshwater consumption, fossil energy, and crop land occupation per 1 kg of retail-ready lamb was 450 L, 28 MJ, and 275 m^2, respectively. Transportation from AU to US contributed to less than 5% of overall GHG emissions. 14%–23% of total energy demand, however, was attributed to said transportation.
Wiedemann et al. (2016)	Compare the life cycle impacts of regions producing three different types of wool in Australia: super-fine Merino, fine Merino, and medium Merino wool. Climate change impacts, energy demand, water use, and land use were quantified.	No significant differences in GHG emission were observed between the three wool types. Different methods of handling co-production significantly changed the estimated GHG emissions by up to threefold.
Zonderland-Thomassen et al. (2014)	Assess the impacts of sheep farming (an inherently water-demanding system) on freshwater availability and eutrophication potential	Blue water losses associated with evapotranspiration from irrigated pasture comprised the greatest proportion of the total water scarcity footprint, despite the small areas of farmland irrigated. Gaseous emissions of nitrogen compounds contributed 33%–40% of the total, and their contribution to water pollution is uncertain.

regional and methodological factors that contribute to the emission intensities.

3.1.1. Meat

Of al the studies which included the impacts of sheep meat, ten were based in Oceania, six in Europe, one in the US, one in China, and one in Chile. The functional unit for meat used by the majority of studies (eleven in total) was 1 kg live weight (LW). Among studies, the GHG emissions associated with meat varied from 3.6 to 25.9 kg CO_2-eq/kg LW lamb meat. Cottle and Cowie (2016) had the lowest GHG emissions at 3.6–8.5 kg CO_2-eq/kg LW due to differences in methodology regarding feed composition and digestibility, and Ripoll-Bosch et al. (2013) had the highest GHG emissions at 19.5–25.9 kg CO_2-eq/kg LW due to their economic allocation being attributed almost entirely to meat. Emissions estimated by Biswas et al. (2010), who used a functional unit of 1 kg lamb meat, were also within the range after converting kg meat to kg LW (15.7 kg CO_2-eq/kg LW).

Opio et al. (2013), an FAO effort, estimated the environmental performance of small ruminant meat (goats and sheep) using the Global Livestock Environmental Assessment Model (GLEAM) (see section 3.5). They estimated average GHG emissions from small

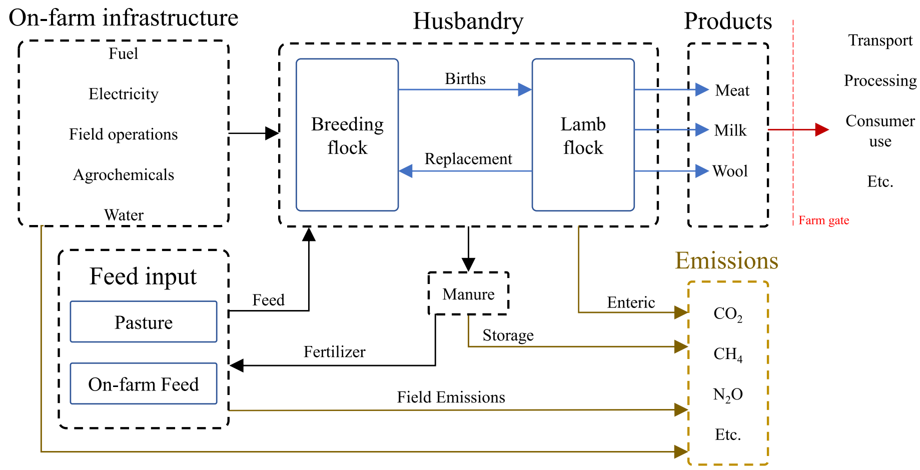

Fig. 1. System boundary utilized by the cradle-to-farmgate LCAs in the sheep sector.

ruminants per carcass weight (CW) to be 23.8 kg CO_2-eq/kg CW. The small ruminants' GHG emissions reported by Opio et al. (2013) are within the range of GHG emissions found by studies reviewed in this paper (after conversion of CW to LW). Opio et al. (2013) also assessed the environmental performance of beef and buffalo meat and reported their GHG emissions to be 46.2 and 53 kg CO_2-eq/kg CW, respectively. These emissions, on average, are twice as high as those of sheep meat.

3.1.2. Milk

Two of the six studies that looked at milk used kg of fat and protein corrected milk (FPCM) as a functional unit for milk. FPCM is determined using equation (1) by Pulina et al. (2005):

$$FPCM = R(0.25 + 0.085F + 0.035P) \quad (1)$$

where R, F, and P indicate raw milk amount [kg], fat content [%] and protein content [%] of the raw milk, respectively. One study, Batalla et al. (2014), used kg of energy corrected milk (ECM), however, determined using equation (2):

$$ECM = 0.071F + 0.043P + 0.2224 \quad (2)$$

All six studies minus one (Mohan et al. (2018) was based in New Zealand) were located in Europe. Emission intensities varied from 2 to 5 kg CO_2-eq/kg FPCM. Enteric estimations, the most significant GHG contributors, were obtained using different methods, which made it difficult to compare the values obtained from different studies. The difference in results was also attributed to the differences in breed and the farming system. The Sardinian sheep considered by Vagnoni et al. (2015) is predominantly farmed and is more productive than the Merinos derived breeds considered by Sabia et al. (2020). The farming systems described in Sabia et al. (2020) were also semi-extensive, with low energy inputs and no concentrates and silages. A higher production would tighten the range of reported GHG emissions.

All the aforementioned studies were based in Europe, making it difficult to extrapolate their findings to other regions. Mohan et al. (2018), however, summarized the work presented in a thesis (Mohan, 2018), which estimated the GHG emissions of a 63 ha farm in New Zealand producing sheep milk. Greenhouse gas emissions in this study were estimated to be 128 kg CO_2-eq/ha.

Global comparison of GHG emissions from milk from various livestock types was done by the FAO. Per mass basis, carbon footprint of sheep milk is more than double compared to cow milk (Marino et al., 2016; Opio et al., 2013; Vagnoni et al., 2015). However, this is due to a higher prevalence of small ruminants in the developing world where specialization in production of milk does not exist (Opio et al., 2013).

3.1.3. Wool

Almost all the studies reviewed here that have looked at LCA of wool (eleven in total) utilized primary data from farms in Oceania. The most common functional unit used was 1 kg greasy wool. Cardoso (2013) did use 1 kg finished (clean) woolen yarn, however. The system boundaries for the remainder of the studies only included the production of greasy wool (impacts of processing the greasy wool were not included). The range of GHG emissions estimated from wool production was 20–60 kg CO_2-eq/kg greasy wool. Observed emission intensities for wool production were quite variable, and large differences were found when biophysical allocation or system expansion allocation method was applied due to a larger number of assumptions required for these methods (Biswas et al., 2010; Cottle and Cowie, 2016). Emissions intensities were similar, however, among studies which utilized economic allocation (20.6 (Cottle and Cowie, 2016), 26.6 (Eady et al., 2012) and 29.4 (Brock et al., 2013) kg CO_2-eq/kg greasy wool). Cardoso (2013) and Dougherty (2018) reported higher emissions at 50–60 kg CO_2-eq from some of the farms. This was due to a combination of pasture-based farming and higher economic allocation towards wool at those farms.

Wiedemann et al. (2016) compared the impacts of three different Merino wool types (super-fine, fine and medium) in three different regions in Australia and found no significant differences in GHG emissions between the wool types. Henry (2012) conducted a review of nine wool LCA studies and observed a range of emission similar to what is found here (for the same allocation). Publications which did not take into consideration enteric emissions or emissions from manure were also reviewed by Henry (2012), and up to 10× reduction in GHG emissions was found due to exclusion of those direct emissions.

With the exception of Dougherty (2018), all the wool studies were based in Oceania, and the validity of their results in other regions cannot be easily verified. Sim and Prabhu (2018) did compare the impacts of manufacturing a wool carpet in the US, but their impacts of wool production were based on estimates from Wiedemann et al. (2016), an Australian study.

3.2. System boundary

All studies included in this review performed a “cradle-to-farmgate” LCA, with boundaries similar to what is shown in Fig. 1. This includes all the upstream processes in livestock production up to the point where the animal product leaves the farmgate. Impacts associated with production of farm inputs (e.g. feed, fertilizer, fuel, electricity, manure, etc.), management of inputs (e.g. emissions from storing manure) and direct emissions from livestock are included in cradle-to-farmgate system boundaries. As is typical in LCA studies, the studies did not include the production of machinery and building in their analysis.

There were exceptions, however. Some studies included miscellaneous input such as vaccination (Brock et al., 2013; Eady et al., 2012), and others included packaging within farm (Batalla et al., 2014; Edwards-Jones et al., 2009). Mondello et al. (2018) paid consideration to industrially-produced feed (as that was a dominant source of feed at that particular farm). Cottle et al. (2016) did not consider most of the farm infrastructure shown in Fig. 1. In O’Brien et al. (2016)’s case, it was unclear whether farm inputs beyond fuel and agrochemicals were considered.

Some studies expanded the boundary beyond the farmgate. Mondello et al. (2018) in the LCA of cheese production expanded the system boundary beyond the farmgate to include the impacts of producing cheese from milk. Impacts of transportation beyond the gate as well as the water, electricity, fuel, machinery and chemicals necessary for processing the milk into cheese were considered. Cardoso (2013) expanded the system boundary in LCA of wool to include the processes of scouring, spinning and dyeing the wool as well. Wiedemann et al. (2015b) expanded the system boundary to include transportation of Australian lamb to the USA and warehousing in the USA. The processing of meat past the farmgate was also included. Sim and Prabhu (2018), in order to determine the life cycle impacts of wool carpets, expanded the system boundary to include the processes of wool scouring, dying, carding, spinning, tufting, drying and finishing.

3.3. Impacts categories

The most common impact category quantified by every study, with the exception of Zonderland-Thomassen et al. (2014), is climate change, estimated through GHG emissions. The most significant contributor to climate change (often called the “hotspot”, further discussed in section 3.4) is direct methanic (CH_4) enteric emissions from the livestock, followed by GHG emissions from feed management. These include production of feed as well as fertilizer production and field operations (e.g. fertilizer use, tractor use). In studies which assessed pasture-based systems, all studies also included CH_4 and nitrous oxide (N_2O) emissions from manure storage prior to application. Impacts of transportation of goods (up to farmgate) are also considered in all the studies, though their overall impacts are insignificant.

Cardoso (2013) has assessed life cycle impacts of manufacturing woolen yarn in multiple impact categories as recommended by the ILCD life cycle impact assessment (LCIA) method (EC-JRC, 2010). The impact distribution in the categories of human toxicity (carcinogenic), acidification, marine eutrophication and freshwater ecotoxicity was similar to that in the category of climate change; that is field and livestock emissions were the dominant emitters (>80%) of pollutants relevant to those categories. The production and application of fertilizers contributed most significantly (>70%) in the categories of ozone depletion and freshwater eutrophication, however.

Mondello et al. (2018), in estimating cradle-to-gate impacts of producing cheese from sheep milk in Italy, utilized the ReCiPe midpoint LCIA method (Goedkoop et al., 2009) to quantify impacts in all the available categories (in that particular method). In twelve out of eighteen midpoint categories, industrially-produced feed was the most significant contributor, followed by direct emissions and farm-produced feed.

Mohan et al. (2018) quantified the impacts of a New Zealand sheep dairy farm in multiple impact categories using the ReCiPe midpoint method. They were not able to identify a single hotspot for all the categories. Enteric emissions contributed to 71% of overall GHG emissions; pesticide use contributed to 78% of freshwater ecotoxicity and 86% of terrestrial ecotoxicity; and barley feed contributed to nearly all the freshwater eutrophication impacts. Payen and Ledgard (2017) focused on comparison of eutrophication impacts from sheep farms in New Zealand among various LCIA methods. They observed drastic differences between the methods. Upon further inspection, they determined that the different methods address different process of nutrient fate and place a different burden on nitrogen and phosphorus to overall eutrophication impacts.

O’Brien et al. (2016) quantified impacts of acidification, eutrophication, fossil fuel energy de-mand and land occupation along with climate change impacts. Release of ammonia from fertilizer and manure was the largest contributor to acidification. Nitrate and phosphorus loss due to application of artificial fertilizer was the main source of eutrophication. The majority of fossil fuel was consumed pre-farm in fertilizer and feed concentrate production.

Sabia et al. (2020) and Vagnoni et al. (2015) in their assessment of dairy sheep used the ReCiPe endpoint method to estimate impacts in multiple categories. Sabia et al. (2020) quantified the three common endpoint indicators, damage to human health, ecosystem diversity, and resource availability, for five dairy sheep farms. Vagnoni et al. (2015), on the other hand, used a single-score impact to aggregate impacts into multiple categories into a single value. Furesi et al. (2015), in their assessment of a dairy farm in Sardinia, also assessed the long-term economic viability of sheep dairy farming along with an environmental LCA. A budget analysis using the farm’s balance sheet is presented, and they have determined that dairy farms’ financial stability needs to be partially secured through governmental grants to remain economically viable (currently, over 20% of the farm’s gross revenue was through financial grants).

Wiedemann et al. (2016, 2015b) determined energy demand, water use and land use alongside GHG emissions in estimating the impacts of meat and wool production using a large dataset. Meat processing and international transport contributed significantly (>50%) to overall energy demand.

Zonderland-Thomassen et al. (2014) assessed water scarcity footprint and eutrophication. The method for water scarcity footprint is based on freshwater withdrawal to availability ratio, taking into consideration not only the freshwater demand but hydrological conditions as well. The eutrophication impacts were estimated using impact factors from the CML2001 method (Guinée et al., 2002). Dougherty (2018) simply used freshwater consumption as an impact category.

Uusitalo et al. (2019) attempted to quantify the positive impacts of sheep farming in Finland using a “planetary boundary perspective.” In Finland, the primary goal of sheep grazing is to protect and save endangered biotopes. Based on various assumptions, Uusitalo et al. (2019) have estimated the positive impacts sheep grazing has on maintaining biosphere integrity (genetic diversity). They have also recognized the challenges associated with harmonizing the quantified impacts on biodiversity with more conventional LCA metrics for easy comparison.

3.4. Hotspot analysis (for GHG emissions)

The majority of studies that have provided a detailed breakdown of GHG emissions are in agreement regarding the relative contribution of each farming activity on GHG emissions. The highest GHG emission are from enteric fermentation. Generally, between 50%–75% of all GHG emissions related to sheep farming were attributed to enteric methanic emissions; they were found to be as low as 40% in some studies and as high as 87% in some studies, however. Manure deposition is typically the next largest contributor to GHG emissions (18%–25%; particularly in the form of N_2O). Emissions from fertilizer and crop residues as well as emissions from feed production are typically responsible for 10%–15% of GHG emissions each. The remaining activities, including machinery use, crop cultivation, heating and lighting have a combined impact of less than 10%. Organizational efforts, particularly by FAO, have yielded estimates of GHG contributions of farm activities in the global sheep sector. The results from one such study, published by Gerber et al. (2013) and shown in Fig. 2, agrees for the most part with the summarized results from the peer-reviewed papers.

A source of discrepancy in the studies is due to the choice of emission model used. Differences in farming systems, animal productivity and spatial disparity, which are used to estimate the emissions in multi-equation models are another driver of differences in emission values. In one of the farms assessed by Edwards-Jones et al. (2009), the direct N_2O emissions from the soil contributed to 74% of the total GHG emissions. The farm in question had adopted much of the environmental advice given to farmers in the region. These results were attributed partly to higher available nitrogen in the soil. On that particular farm, the stocking rate (as advised by the local governing body) also resulted in high GHG emissions per functional unit. The emissions in multi-equation models are another driver of differences in emission values. Batalla et al. (2015) also observed enteric emission values which varied between the farms: 19% (in semi-intensive farm; 2.6 kg of CO_2-eq/kg of FPCM), 41% (in semi-intensive farm; 2.9 kg of CO_2-eq/kg of FPCM) and 45% (in semi-extensive farm; 3.6 kg of CO_2-eq/kg of FPCM) of overall GHG emissions were attributed to enteric emissions. They noted that these differences were partly due to higher breeding rate in semi-intensive practices and in part due to the reduction of enteric emissions (relative to overall GHG emissions) from increased fertilizer use. Biswas et al. (2010) reported enteric emissions which varied from 35% to 90% and fertilizer emissions which varied from 9% to 60% attributed to sheep wool from crop wheat-based or mixed pasture-based farms, respectively. The drastic differences presented here were due to the inclusion of wheat systems in the system boundaries.

3.5. Enteric fermentation emission models

As direct enteric emissions are the most significant source of GHG emissions in the sheep sector, careful consideration needs to be placed on accurately estimating their impacts. The majority of studies have utilized emission model created by the Intergovernmental Panel on Climate Change (IPCC), which categorizes enteric emissions' estimation into three tiers (IPCC, 2019). Tier 1 method involves using pre-defined emissions factors listed (in units of kg CH_4/head/y) based on livestock species, region and productivity system. Tier 1 estimates are simple but have a high degree of uncertainty. Tier 2 method involves using country-specific climatic data and animal feed intake amounts to determine more accurate, regional emission factors. Tier 2 method uses equation (3) to predict the emission factor, *EF*, to be:

$$EF = GE \times (Y / 100) \times 365 \times 55.65 \quad (3)$$

where *GE* and *Y* are the gross energy intake (MJ/head/y) and the methane conversion factor (%), respectively. Both these factors depend on multiple operational parameters, and the methodology used to estimate them is defined in detail in IPCC (2019). Tier 3 is

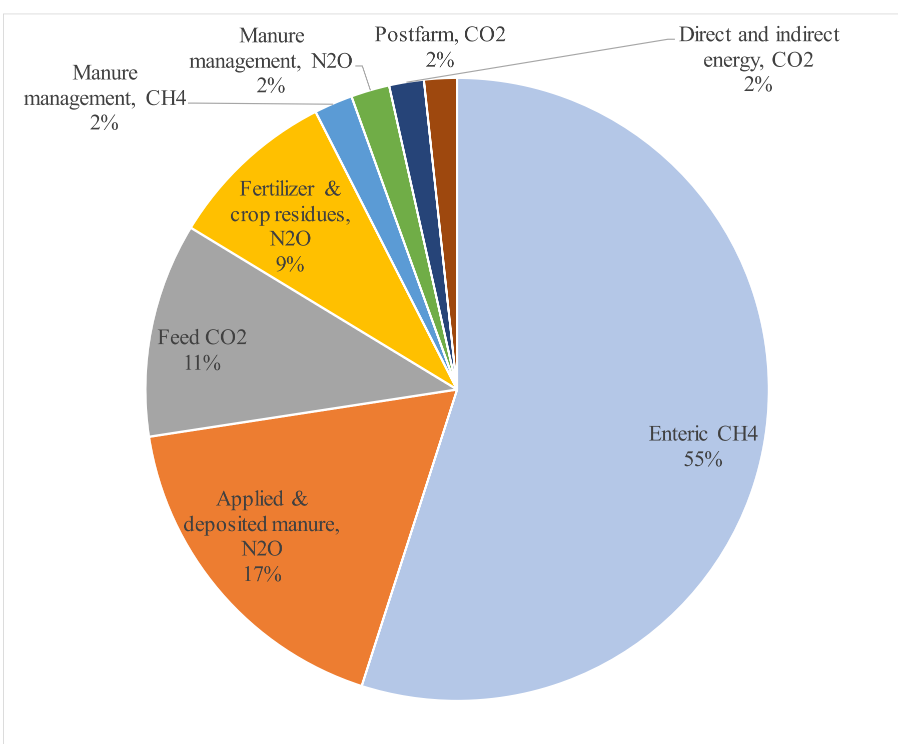

Fig. 2. Global GHG emissions from small ruminant supply chains; adapted from Gerber et al. (2013).

the most complicated method and utilizes diet composition, seasonal variations and direct experimental measurements to improve the accuracy of the tier 2 method. The majority of studies reviewed here have used tier 1 or 2 approaches from the IPCC guidelines.

Other studies reviewed here have estimated the enteric emissions from sheep using empirical models. For example, Bell et al. (2012) have estimated the effect of future climate change on GHG emissions from sheep grazing systems using a relationship (equation (4)) developed by Blaxter and Clapperton (1965):

$$E = (1.3 + 0.112D + F)(2.37 - 0.05D)G \tag{4}$$

where E is daily emission rate of CH_4 [MJ d^{-1}], D is the digestibility of gross energy consumed [%], F is the feed intake relative to that required for maintenance [%], and G is the gross energy intake of the animal. The digestibility of the feed depends on the fraction of protein, sugars and cell wall material of the feed and were estimated based on a publication by Johnson et al. (2003).

Dougherty (2018) utilized a statistical model (equation (5)) developed by Patra et al. (2016) in estimating enteric emissions from sheep. Patra et al. (2016) constructed a database from 80 publications to predict enteric methanic emission rate from sheep based on dietary nutrient composition, energy intake and digestibility of organic matter with good accuracy ($R^2 = 90\%$):

$$\begin{aligned} E &= 5.70\ (\pm 1.94) - [5.70\ (\pm 1.94) - 0.133(\pm 0.047)] \\ &\cdot \exp[-0.021\ (\pm 0.0071)\ M] \end{aligned} \tag{5}$$

where M is the intake of metabolizable energy [MJ d^{-1}].

A more recent approach in estimating GHG emissions from livestock is the Global Livestock Environmental Assessment Model (GLEAM) created by FAO (FAO, 2019). It consists of five distinct modules: herd module, manure module, feed module, system module, and allocation module. These modules estimate the GHG emission intensities along the pre-farm (from the manufacturing of inputs), on-farm (from feed and animal production), and post-farm (from the processing/transportation of products) supply chains which can extend the system boundary beyond the farmgate (though most studies have not used this module). It also includes the impact of soil quality, climate and land use on the emissions (Gerber et al., 2013). These factors are dependent of the geography and can have a significant impact on the enteric emissions of livestock. (IPCC, 2019; MacLeod et al., 2018).

FarmGAS is a GHG emissions estimator tool created by the Australian Farm Institute (AFI, 2009). It uses a range of Australian-specific emission and production factors couple with industry data to estimate on-farm GHG emissions for various livestock (including sheep) and management scenarios. Brock et al. (2013) and (Eady et al. (2012) have both utilized *FarmGAS* in their direct emissions' estimations of Australian farms.

GrazPlan, a commercial software suite created by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), is able to simulate farm inputs such as pasture growth, animal production and livestock management (Donnelly et al., 1997). Both Cottle et al. (2016) and Cottle and Cowie (2016) used *GrazPlan* in simulating the farms used in their assessment as well as the direct emissions from the livestock, which are based on data from Australian National Greenhouse Gas Inventory models.

Brock et al. (2013) compared the differences in direct emissions as a result of using five enteric emission methods. The results were found to vary by 27%. As direct emissions are the most significant contributor to overall GHG emissions (discussed in section 3.4), this variation can have a difference in estimated climate change impacts large enough to affect decision making.

3.6. Allocation

Sheep farms with a single production are rare. The overwhelming majority of farms produce two or three co-products (combination of meat, wool and milk). As such, all the articles reviewed have used some form of allocation factor to distribute the overall impacts between the co-products. Allocations in agricultural LCAs are typically done on an economic or a biophysical basis. Both are common, but they can result in drastically different allocation factors.

The most popular form of allocation is economic, meaning that impacts are allocated based on the relative income generated by each co-product. It is selected based on the assumption that incomes and revenues are the most important driver of production and management choices (Cottle and Cowie, 2016). Economic factor allocations for each reviewed study (where available) are listed in Table 1 and vary widely between farms. As an example, economic allocation factors for wool range from 1% to 70% depending on the primary product of the farm and the surrounding markets. Similar discrepancies are found for meat and milk. Studies which have looked at dairy farms have determined that 90% of income generated is from sheep milk; i.e. the economic allocation factor for milk is 90% (Batalla et al., 2015; Mondello et al., 2018; Sabia et al., 2020; Vagnoni et al., 2015). It is also speculated that using economic allocation will cause results to vary over time in response to market fluctuations, subsidies or price interventions, which might complicate benchmarking of impacts (Wiedemann et al., 2015a).

Biophysical allocation assumes that coproducts could be separated for biological criteria such as product mass, energy content or protein content or protein mass of the products (Cottle and Cowie, 2016). As all the co-products of sheep are proteinaceous, and their quality are partly measured by their protein amount, biophysical allocation is a logical choice for attributing impacts to co-products.

Detailed methods of biophysical allocation on meat and wool farms were deeply investigated and tested by Cottle and Cowie (2016) and Wiedemann et al. (2015a). They allocated the emissions using three alternative biophysical allocation scenarios (along with protein and economic means). They reported a high sensitivity of carbon footprint based on the method used to allocate emissions between total live weight sales and wool. The studies also found that protein mass allocation increased the carbon footprint of wool and decreased that of total live weight sales, while economic allocation led to a more even split between wool and live weight. The allocation percentages between meat and wool did not differ significantly among the scenarios. Both the studies also examined the effect of system expansion (using impacts of beef production or sheep farms where meat was the primary product) and found that using system expansion resulted in the lowest, and often, negative GHG emissions. On the basis of the obtained results, the authors stated that protein allocation provides higher stability in the long term than economic allocation. In the end, both the studies recommended biophysical allocation over other allocation methods and system expansions.

Eady et al. (2012) found smaller differences between economic allocation and their biophysical allocation method applied. This was largely because the biophysical allocation approach taken by Eady et al. (2012) assumed that the nutrients (and therefore emissions) necessary for breeding animals should be attributed to the wool product, as it was the main output of the system. This sensitive decision is based on the view that wool is the primary product, which drives production, so it should bear the full burden.

Generally speaking, economic allocation's impacts on the relative contribution of each sheep product towards GHG emission is dependent on the major system goal of the farm. Operations with meat production as their major goal, such as those assessed by

Dougherty (2018), had higher relative contribution attributed to meat using economic allocation (compared to protein allocation). On the other hand, farms whose primary production goal was wool had a higher relative contribution attributed to wool.

Sim and Prabhu (2018), who estimated the life cycle impacts of wool carpets, determined that climate change impacts of yarn production from greasy wool were negligible (less than 1%) compared to the impacts of producing the greasy wool. The energy requirements of yarn production were 16%, however, of the energy requirements of greasy wool production.

3.7. Farm classification

Farm management can largely be categorized into extensive or intensive systems. Extensive feeding systems rely on grazing in an open field or pasture during the entire year. The feeding cost is low in this system. Intensive systems rely on providing specialized feeds to the livestock in a confined area. Land requirement in an intensive system is lower, and by having a greater control over the feed, livestock could be bred more efficiently and release lower emissions. Semi-intensive rearing methods (a combination of intensive and extensive) are also popular, especially in regions with a high seasonal variation in climate.

With the exception of Cottle et al. (2016), all studies which assessed the relationship between intensification and GHG emissions observed that more intensified operations had lower emissions per functional unit due to better feed management and greater control over animal breeding options. Ripoll-Bosch et al. (2013) assessed three farms in Spain: a pasture-based system in alpine mountains with traditional, low-intensive farming (one lambing per ewe per year); a mid-intensive mixed sheep-cereal system (three lambings per ewe per 2 years); and a zero-grazing, highly-intensive (five lambings per ewe per 3 years). They reported emissions of 19.5, 24.0 and 25.9 kg CO_2-eq/kg LW in high intensity zero-grazing, mid altitude and extensive pasture systems, respectively. Similar differences were observed by Batalla et al. (2015), Jones et al. (2014) and Toro-Mujica et al. (2017). O'Brien et al. (2016) also noted reductions in emissions from extensive (14.2 kg CO_2-eq/kg LW) to intensive (9.7–10.7 kg CO_2-eq/kg LW) after accounting for other factors. Schönbach et al. (2012) assessed the role of sheep grazing intensity on the Inner Mongolian steppe's ability to sequester carbon, and they determined that grazing intensity has a direct correlation with the steppe's ability to carbon sequestration. The steppe acts as carbon sink only when the land remains ungrazed. Lightly-grazed lands were determined to be carbon neutral, however (with some uncertainty).

Differences in the quality of grazing, climate, and management choices such as efficiency of fertilizer use and selective breeding for productivity can also contribute to the variability in GHG emissions. Lowland sheep farms, for example, have lower GHG emissions than hilltop farms (Cottle et al., 2016; Jones et al., 2014; O'Brien et al., 2016). These differences are likely due to the impact of harsher climates and poorer quality grazing on the productivity of hill flock.

For milk, a clear relationship between intensification and GHG emissions was observed by Batalla et al. (2014). Vagnoni et al. (2015), however, found virtually no indication of intensification's effect on GHG emissions. This was speculated to be due to the use of a simpler, IPCC tier 1 emission model by Vagnoni et al. (2015), which utilized a fixed emission intensity factor of 8 kg CH_4/ewe/y. Differences in other endpoint indicators using the ReCiPe method (Goedkoop et al., 2009) between farm types were observed, however. The low-intensity farm had significantly lower endpoint impacts compared to the mid and high intensity. This was due to a lower impact in the category 'agricultural land occupation', which contributed 50% to the overall endpoint impact score.

3.8. Regional variation

With the exception of sheep milk production in Western Europe and lamb production Oceania and Western Europe, meat and milk from sheep is generally more important in the developing world regions (Hristov et al., 2013). Emission intensity for sheep products also tend to be higher in developing regions such as East & Southeast Asia, and Northwest Africa. In contrast, in industrialized countries where sheep production is important, emission intensity is low due to the specialization of production. Opio et al. (2013) estimates that while average emission intensities attributed to milk production are 4.7 kg CO_2-eq/kg FPCM for Europe, they are 8.9 kg CO_2-eq/kg FPCM in East and Southeast Asia. GHG emission intensity for meat (per kg live weight) are also higher in Sub-Saharan Africa (30.5 kg CO_2-eq), North Africa (27.5 kg CO_2-eq), Latin America (25.2 kg CO_2-eq) and South Asia (29.5 kg CO_2-eq) compared to Western Europe (17.6 kg CO_2-eq) and Oceania (15 kg CO_2-eq) (Gerber et al., 2013). Methanic emissions from manure are also slightly higher in Asia and Africa due to higher average temperatures. This difference in emission intensity of meat and milk is due to variations in reproductive efficiency (resulting in a smaller "breeding overhead"), feed quality, and management practices that are generally poorer in developing regions. The differences in enteric emissions attributed to meat and milk production, as demonstrated by the global FAO study using GLEAM, are larger than 100% in some instances (Gerber et al., 2013). Emissions attributed to meat can be as low as 15 kg CO_2 and as high as 31 kg CO_2 per kg carcass weight in Oceania and sub-Saharan Africa, respectively (Opio et al., 2013).

Regional differences in economic allocation factors have also resulted in dramatic differences in impact amounts produced by different studies of similar system boundaries. Ripoll-Bosch et al. (2013) and Ledgard et al. (2011), for example, had similar system boundaries for farms located in Spain and New Zealand, respectively. The GHG emissions per kg live weight from the latter study were approximately half of that of the former study's. This was due to a greater wool production from the farm in New Zealand and a higher economic allocation towards wool in New Zealand compared to Spain. Discrepancies in economic importance of each sheep product between different regions makes it difficult to compare the impacts of different studies, even with similar system boundaries.

The more complex emission models (such as GLEAM; discussed in section 3.5) have recognized the role that climatic zones of different regions can play in parameters such as manure methane conversion factor and feed digestibility which can drastically change the overall GHG emissions (MacLeod et al., 2018). Opio et al. (2013) have assessed variations in emission intensities within regions and between regions as a function of the agro-ecological zone (categorized into three zones: arid, temperate, and humid). In regions such as Australia, where climatic conditions are more homogenous, only small differences in emission intensities were observed between the zones. In Western Europe and Near East and North Africa (NENA), differences of 70%–100% were observed between the zones.

3.9. Gaps in knowledge base/avenues of further research

GHG emissions are the sole focus of the majority of studies. Only a few studies (discussed in section 3.3) have assessed the water demand, energy demand and other impact categories. They have shown that while enteric emissions are the most significant contributor to climate change, they are not unanimously so in all the possible impact categories. As an example, Vagnoni et al. (2015), in a multi-category endpoint assessment of dairy sheep, observed that more than half of the overall impact score was due to agricultural land use. O'Brien et al. (2016) observed that the belief that more intensive operations are more environmentally "friendly" did not hold for impacts in the categories of eutrophication More in-depth research into impacts of the sheep sector in categories other than climate change, such as water and energy consumption, is rarely presented and discussed; only seven of the reviewed studies have done so here (Colley et al., 2020; Dougherty, 2018; Uusitalo et al., 2019; Wiedemann et al, 2015b, 2016; Zonderland-Thomassen et al., 2014). Doing so may present opportunities for further recommendations in improvement of management practices (from an environmental perspective).

Impacts of processes beyond the farmgate are rarely considered, most likely due to the negligibility of the impacts of post farm emissions as well as by the high degree of uncertainty (due to lack of available data). There is some indication, however, that in impacts other than climate change, post-farmgate processes may have a significant contribution. For example, Wiedemann et al. (2015b), in their estimate of meat processing and transportation impacts (from Australia to the United States), found that meat processing and transportation contributed to 32% and 22% to overall energy demand, respectively. Furthermore, meat processing contributed to nearly 25% of overall freshwater demand. Cardoso (2013) in quantifying impacts of woolen yarn production discovered that in the categories of ozone depletion and water consumption, the post-farmgate processes of scouring, spinning and dyeing the wool contributed more than the combined effects associated with sheep farming. While a "cradle-to-grave" consideration of impacts might not be possible, impacts of processing of the sheep products beyond the farmgate before it reaches the consumers should be considered by future studies.

Economic and social assessment is not considered in the vast majority of studies. Studies which have looked at economic or socioeconomic impacts of the sheep sector (e.g. Shivakumara (2019)) have not done so from a life cycle perspective. Several authors have highlighted a need for expansion of the boundary to include economic and social impacts (Batalla et al., 2014; Ripoll-Bosch et al., 2013). The studies which have looked at the economic impacts (e.g. Batalla et al. (2014) and Furesi et al. (2015)) have not done so with a detailed methodology and follow-up discussion.

Only six of the studies reviewed (Batalla et al., 2015; Colley et al., 2020; O'Brien et al., 2016; Schönbach et al., 2012; Toro-Mujica et al., 2017; Wiedemann et al., 2015b) have included the effects of carbon sequestration. Their results show that inclusion of carbon sequestration has the potential to change climate change impacts of pasture-based systems to the extent that it can affect decision making (though currently, there is no consensus on this assertion). On an institutional level, the FAO models and reports have estimated that up to 50% of the livestock sector's GHG emissions in an extensive grazing system could be mitigated through soil carbon sequestration (Opio et al., 2013). Difficulty in quantifying carbon sequestration as well as a need for better understanding of institutional needs and economic viability of pasture-based systems is acknowledged by the FAO as well (Gerber et al., 2013). Which is not to say that effects of carbon sequestration are not being studied; they are simply difficult to find in the context of LCA studies.

An extension of quantification of positive impacts of carbon sequestration was explored by Ripoll-Bosch et al. (2013), who included "ecosystem services" (ES) provided by pasture-based systems, which consist of benefits provided by increased soil health, landscape conservation, biodiversity enhancement and wildfire prevention in reducing climate change potential. Inclusion of ES brought down the impacts of pasture-based systems from the highest GHG emitters to the lowest. Consideration of these benefits of less intensive, pasture-based systems is lacking in the majority of the reviewed systems. Due to the absence of these consideration, the studies have definitely concluded that intensive systems are more environmentally efficient due to lower GHG emission intensity. Inclusion of ES and/or carbon sequestration may change that conclusion, however. There is a clear avenue of research on more accurate quantification of ES.

4. Conclusion

Out of all the reviewed articles, only eleven and six have focused on wool and sheep milk, respectively. The majority have focused on LCA of sheep meat. All but one sheep dairy farm studies were based in Europe due to the prevalence of sheep milk in that region. Similarly, all but one studies focusing on wool were from Oceania. All but four studies quantified the GHG emission as the primary metric of life cycle impacts. Most common functional units for sheep meat, wool and milk were unit mass of live weight, greasy wool, and fat and protein corrected milk (FPCM), respectively. The range of GHG emissions per functional unit for sheep meat, wool and milk were 3.6–25.9, 2–5, and 20–60 kg CO_2-eq, respectively.

Majority of studies that have assessed the life cycle impacts in the sheep industry have concluded that the variation of flows and impacts between farms is too high to conclusively report generalized life cycle impact figures applicable to the entire industry. A need for more comprehensive life cycle studies of sheep products is recognized across the board. Data from an adequate number of sheep farms of similar scales within a region needs to be collected and analyzed to make conclusive estimations of the sheep industry's environmental impacts in that region.

The majority of GHG emissions in all the reviewed LCA studies are CO_2, CH_4 and N_2O. CH_4 is primarily emitted through enteric fermentation. Emissions of CH_4 decreases as digestibility of the feed increases. Intensive operations, which typically use highly-digestible feed concentrates, have lower CH_4 emissions compared to pasture-grazed operations. CO_2 is primarily emitted through combustion of fossil fuels and increases with increasing intensification due to higher cultivation and transportation amounts. N_2O is primarily emitted through manure deposition and increases with decreasing intensification. GHGs per functional unit tend to be lower in intensified systems due to more productive operations and lower enteric emissions. Pasture-based operations, however, provide additional benefits not considered in most studies, namely carbon sequestration and other difficult-to-quantify benefits such as soil health.

Scopes of the studies for each sheep product were similar in respect to their system boundaries and choice of impact categories and functional units. Where the studies differed (sometimes drastically) were in the classification of their farms (intensive v. extensive; lowland v. hilly) and emission modeling. Farm classification and emission models both have a significant contribution to the differences in overall impacts between the reviewed studies. Even within similar boundaries, variability in emissions between farms can be attributed to differences in local conditions such as quality of grazing and climate, and management choices such as efficiency of fertilizer use and selective breeding for productivity.

The choice of method used to deal with co-production can have a significant impact on LCA results. The complexity of system expansion in LCA of livestock and the wide discrepancies in emissions observed between different operations and livestock types are the reasons why most researchers have opted not to use it. Most researchers have used economic and/or protein allocation to determine relative contributions of each product to the overall impacts. Wiedemann et al. (2015a) and Cottle and Cowie (2016) used biophysical allocation and system expansion to separate the impacts of meat and wool co-products and both the studies recommend biophysical allocation over economic allocation or system expansion due to economic allocation's long-term instability and system expansion's need for added assumptions. Economic allocation is open to vagaries of market fluctuations, but it is at least consistent in application. It is not surprising then that the recommendation in existing FAO guidelines for carbon footprint assessment of co-products where processes cannot be separated is to use the economic value of the co-products. This is what the majority of studies reviewed here have done. It does, however, shift the environmental burden to the higher value co-products and away from the high resource use products.

Methanic emissions (generally contributing between 70%–90% of all GHG emissions) do vary with quality/digestibility of feed, location, and livestock breeds. There is no technology that allows LCA practitioners to readily measure direct emissions based on characteristics of individual animals. Accurate reporting of emission, thus, requires the use of more complex and time-consuming models, which require an assortment of input parameters. The wide range of possible values for these parameters as well as the high sensitivity of these parameters on the overall emission estimates necessitates the collection and usage of primary data; generic LCI databases should be avoided where possible. Higher tier IPCC models (IPCC, 2019) or the GLEAM model (FAO, 2019) should be used when adequate data is available.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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