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LCA FOR AGRICULTURE

Life cycle impacts of sheep sector in Ontario, Canada

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Abstract

Purpose Sheep sector in Canada is growing, and producers have ranked their desire to estimate the environmental performance of sheep farming (for benchmarking and marketability) high. Life cycle assessment (LCA) studies on the Canadian sheep sector are underrepresented, however, and record on feeding options and pasture management on sheep farms is difficult to find. This study aims to address this knowledge gap by conducting a cradle-to-gate LCA on sheep production using Ontario-specific primary data.

Methods Life cycle implications of Ontario's sheep meat production in the categories of global warming (GW), non-renewable energy demand (ED), and water depletion (WD) are estimated by considering the impacts of livestock emissions, feed production, manure management, and farming infrastructure/operations up to the point where the animal leaves the farm for slaughter (i.e., cradle-to-farmgate system boundary). Data on sheep farming practices from 23 farms in Ontario is gathered (primarily through surveys), parametrized, and inputted into the LCA model to estimate Ontario-specific impacts. Allocation of impacts to sheep meat is done through protein mass allocation (PMA), and impact scores are normalized using a functional unit of kilogram liveweight (kg LW). The LCA model code is made available under General Public License (GPL) for further application and improvement.

Results and discussion Life cycle impacts per kg LW meat for over 90% of the sampled farms are in the range of 8.4–18.6 kg CO_2 eq for GW, 18.6–92.4 MJ for ED, and 0.06–0.27 m^3 for WD. PMA factors for meat are in the range of 68–80%. On average, enteric emissions from livestock are responsible for 39% of greenhouse gas (GHG) emissions, followed by feed production (29%), farm operations (23%), and manure management (10%). ED and WD impacts are each roughly split evenly between feed production and farm operations. Regression analysis between farm practices and impacts shows that farming intensity does not have a significant effect on impact scores.

Conclusions and recommendations Ontario sheep sector's impact scores, particularly for GW, are consistent with values observed in the literature. This study may represent an important first step in understanding the life cycle environmental implications of Canadian sheep farming, but room for improvement remains. It is recommended that a sensitivity analysis be carried to gauge the effect of farming practices on impact scores, and aquatic eutrophication impacts should be included in the model, considering the presence of algal growth in Ontario.

Keywords Sheep · Lamb · Global warming · GHG · LCA · Carbon footprint · Energy demand · Water depletion

1 Introduction

There are over 800,000 sheep in Canada, 32% of which are found in the province of Ontario (Statistics Canada 2021). The slaughter rates for sheep in Ontario have been steady over the past decade, and more than 3000 sheep farms in Ontario serve the province's demand for sheep products. Environmental impacts of livestock production, particularly in climate change (global warming), energy use, and water demand, are increasingly being recognized for their contribution to the global declaration of the natural environmental. In the case of global warming potential, approximately 12% of all global greenhouse gases (GHG) emissions are released through agricultural activities, and livestock emissions constitute 45% of these emissions (IPCC 2014; Smith et al. 2014). Consequently, livestock producers face the pressure

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to reduce the environmental footprint of their production while maintaining or increasing their production to meet market demands.

Life cycle assessment (LCA), particularly as described by ISO standards 14,040 and 14,044 (ISO 2006a, b), is a set of procedures used to identify sources of environmental impacts from any production system and quantify its environmental footprint. Through an LCA, a causal link between farming practices and their impacts on the environment can be established. Furthermore, LCA techniques can allow decision-makers to make "apples-to-apples" comparisons of impacts either between competing production scenarios for the same product or competing products based on their function.

LCA has been used extensively to benchmark the environmental performance of livestock production (de Vries et al. 2015; McAuliffe et al. 2016; Costantini et al. 2021), but research in the sheep sector is relatively scarce (Bhatt and Abbassi 2021). The majority of peer-reviewed LCA studies related to sheep production have been limited to operations in Europe and Oceania. LCA of sheep farming in the developing world (parts of Asia and Africa) have also been reported by the Food and Agriculture Organization (FAO) of the United Nations (UN) as part of an effort to estimate global emissions of livestock using the Global Livestock Environmental Assessment Model or GLEAM (Gerber et al. 2013; Hristov et al. 2013; Opio et al. 2013).

Currently, Canada-specific organizational or peer-reviewed LCA studies on the impacts of Canadian sheep farming practices are underrepresented in the literature. The closest (non life cycle) estimates of global warming impacts from Canada's sheep sector are the total Canadian GHG emissions by sector reported in the National Inventory Report by Environment and Climate Change Canada (ECCC 2020). On a similar note, although aggregate statistics on sheep supply chains are available (OMAFRA 2021; Statistics Canada 2021; Agriculture and Agri-Food Canada 2021a), more detailed primary data on farming practices in the Canadian sheep sector is difficult to find.

Ontario sheep farmers recognized an opportunity for improvement in the sheep sector's environmental performance and marketability (OSF 2019) and commissioned Groupe AGÉCO (www.groupeageco.ca) to determine life cycle impacts of sheep farming in Ontario through secondary, aggregate input data (Groupe AGÉCO 2017). However, regional variation in farming practices, geography, and climatic conditions between Canada and other regions can make it difficult to extrapolate the life cycle impacts of sheep production from other countries to Canada's. Hence, the need for a regionally relevant LCA study on sheep farming based on locally sourced primary data is established.

1.1 Objectives

The main objectives of this study are to estimate the cradle-to-gate life cycle impacts of sheep production in the province of Ontario, Canada using primary data representative of Ontario's sheep farming practices. A parametric attributional LCA model (described in Sect. 2) is created to quantify the impacts of livestock emissions (i.e., enteric fermentation and manure management), feed intake, farm inputs, and farm infrastructure in the impact categories of climate change, non-renewable energy demand, and water depletion. Primary data on Ontario's sheep farming practices is collected through surveys from 23 farms and parameterized. The parameter values representing farming practices (presented in Sect. 3) serve as inputs for the LCA model. In Sect. 4, the resulting LCA impacts are shown and discussed in the context of the greater literature (on LCA of the sheep sectors around the world).

To aid transparency and replicability, the LCA model code and farm statistics are provided on GitHub (see Supplementary Information (SI)).

2 Methods

The efforts for this study can generally be divided into two parts: (i) LCA model building (Sect. 2.2) and (ii) data collection (Sect. 2.3).

Figure 1 conceptualizes the LCA modeling exercise. Parameterization is used to output life cycle impacts (I) of sheep farming as a function (f) of farming practices (X). The process of parameterization involves representing farming practices through integers, float-type variables, or logical values, which can then serve as inputs to the LCA model. A total of 142 parameters are separated into two types and five categories:

Parameter types:	Parameter groups shaded in orange in Fig. 1 are farm-related, and their values were obtained through surveys/questionnaires. The unshaded parameter groups are environmental factors and obtained from various guidelines (and other external literature)
Parameter categories:	Parameters are separated into five categories: (i) population/products; (ii) dietary inputs; (iii) gross energy/enteric fermentation; (iv) manure management; and (v) farm operations

Data on Ontario's sheep farming practices was collected via surveys mailed to the province's sheep producers. Responses from 23 filled-out surveys are used to create sample datapoints for each input parameter (Sect. 3). The

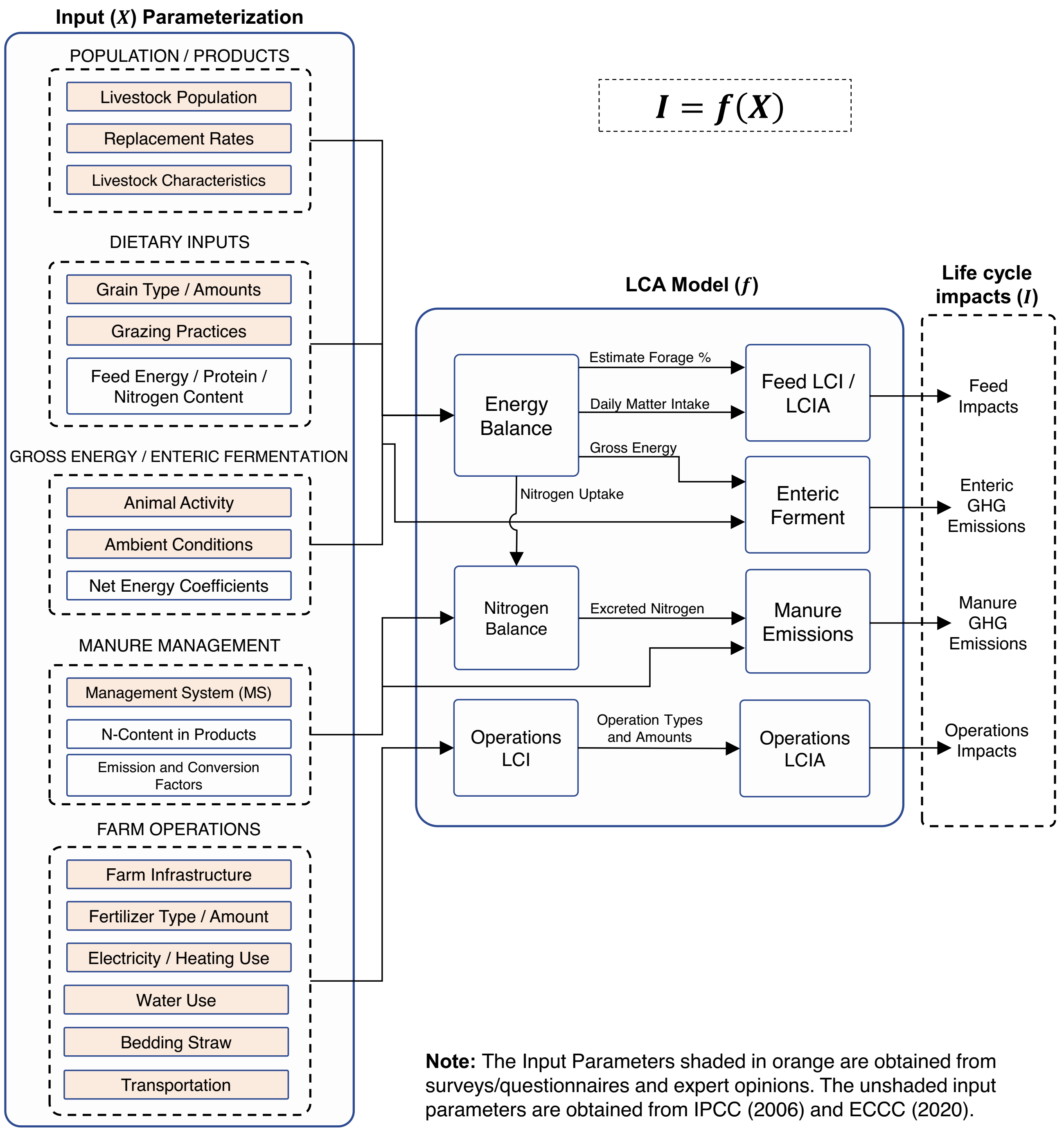

Fig. 1 Conceptual overview of input parameterization and LCA model

LCA model is ran 23 times, once for each set of farm inputs, and the statistics of the resulting LCA outputs are summarized (in Sect. 4) from the full model outputs, presented in Supplementary Information (SI).

The input parameterization, LCA modeling, and output (tables and graphs) generation are done using the MATLAB® programming language. The LCA model code may be used to determine life cycle impact scores for any set of input parameters.

Unless otherwise stated, all tests of significance of difference are performed using a two-tailed Welch's *t*-test or one-sample *t* -test, and significance of correlation is determined using linear regression analysis. Statistical differences or relationships are deemed significant at *p*-value less than 5% ($P < 0.05$).

2.1 LCA model — reference guidelines

The LCA approach defined by ISO (2006a, b) provides only a general framework for LCA applicable to any sector. Two additional international guidelines on life cycle assessment and greenhouse gas estimation specific to small ruminant supply chains are utilized in creating the LCA model:

i. The Food and Agriculture Organization of the United Nations (FAO)'s *GHG emissions and fossil energy demand from small ruminant supply chains* (FAO 2016), and
ii. The Intergovernmental Panel on Climate Change (IPCC)'s *Guidelines for National Greenhouse Gas Inventories: Agriculture, forestry and other land use* (IPCC 2006)

The FAO (2016) guidelines are created through the Livestock Environmental Assessment and Performance (LEAP) Partnership, whose goal is to "improve the environmental sustainability of the livestock sector through better metrics and data." FAO (2016) provides a methodology for preparing the LCA model and presents information regarding key components of a livestock LCA model, including system boundary alternatives, population modeling methods, decision trees for choosing allocation methods, approaches for addressing data gaps, and characterizing uncertainty.

The IPCC (2006) guidelines provide methodologies for estimating inventories of anthropogenic greenhouse gas emissions for various sectors. The guidelines are comprised of five volumes. Chapters 10 and 11 in volume no. 4 detail the methodologies for estimating enteric emissions from livestock, manure management, and soil management. These chapters are referenced in estimating emissions from enteric fermentation and manure management (Sect. 2.2.4).

2.2 LCA methodology

Virtually, all life cycle assessment studies follow the ISO standards 14,040 and 14,044 (ISO 2006a, b), which define the framework and provide guidelines for conducting an LCA. LCA studies are comprised of four stages, namely (i) goal and scope definition, (ii) life cycle inventorying (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation of results.

The goal of the study is addressed in Sect. 1.1 of this paper. The scope of the study (system boundary, functional unit, and allocation method) is discussed in the following subsections. Impact categories chosen are listed in Table 1; a brief description of impact categories and the impact factors used in the model are available in Supplementary Information (SI). Climate change and water conservation in the agricultural sector is deemed important by Agriculture and Agri-Food Canada (2021b). Thus, impact categories chosen are global warming, non-renewable (fossil, nuclear, and non-renewable biomass) energy demand, and water depletion.

The inventorying (LCI) of livestock's energy needs (for feed intake), enteric emissions, and emissions related to manure management are quantified using methods prescribed in IPCC (2006) and ECCC (2020). The LCI for feed production, fertilizer production, and miscellaneous operations (i.e., electricity, heating, water treatment, bedding straw, farm machinery usage, and transportation) is obtained from the *ecoinvent 3* LCI database (Kägi and Nemecek 2007; Wernet et al. 2016). Note that global (i.e., globally averaged) *ecoinvent* process is used for quantifying feed production-related inventory, as Canada-specific data was not readily available. The indoor infrastructure on farms consists of (often ventilated) barns and sheds, which include feed and straw storage areas, enclosure for sheep, and housing for miscellaneous farm equipment. The inventory associated with 1 $m^2 \cdot$ year (product of floorspace and lifespan) of indoor area is estimated using the "agricultural building" (in Switzerland) process, as described in Kägi and Nemecek (2007); a shed lifespan of 50 years is assumed for this study. All other *ecoinvent* processes used in this study source their data from Canadian operations (either Ontario or Quebec-based).

2.2.1 System boundary

System boundaries of ruminant livestock LCA studies are typically "cradle-to-farmgate," whereby impacts of upstream farm inputs, animal feed production, manure management, and livestock emissions, up to the point where animals leave the farmgate (for further processing), are included. Feed production and livestock methanic (CH_4) emissions (i.e., enteric fermentation) are especially important as these two categories contribute to over 70% of overall GHG emissions from ruminant supply chains (Gerber et al. 2013).

Table 1 Impact categories reported in this study and their associated methods

Impact category	Unit	LCIA method
Global warming (GW)	kg CO_2 eq	IPCC (2013) 100y
Energy demand, non-renewable (ED)	Megajoule (MJ)	Cumulative energy demand, CED (Hischier et al. 2010)
Water depletion (WD)	m^3 water	ReCiPe (H) 2008 (Goedkoop et al. 2008)

The cradle-to-farmgate system boundary used for the present study is shown in Fig. 2. It includes the impacts of feed production, enteric emissions from sheep, manure management, and farm operations. The feed inputs are categorized into rough pasture grazing, improved pasture grazing, roughages, and grains. The impacts of structures (barns and sheds), electricity and fuel consumption, water consumption, fertilizer production and application, and transportation activities are included in farm operations.

For farms with more than one type of livestock (e.g., cattle or poultry), feed, water, and bedding straw intake by other livestock type is separated from intake by sheep; only the intake by sheep is reported (in Sect. 3) and included in the model. Infrastructure-related inputs (farm area, barns and sheds, electricity use, etc.), however, are not separated by animal type, and the total on-farm estimates are used for obtaining the inventory for farm infrastructure. The products produced by other animals are also not represented by the functional unit.

2.2.2 Functional unit

The primary sheep product of the vast majority of sheep farms in Ontario is lamb meat (Sect. 3). Among peer-reviewed literature, the primary enterprise of the majority of studies also appears to be sheep meat from lamb; though LCA studies exclusively for wool (Brock et al. 2013; Wiedemann et al. 2016; Sim and Prabhu 2018; Colley et al. 2020) and milk (Vagnoni et al. 2015; Furesi et al. 2015; Batalla et al. 2015; Sabia et al. 2020) do exist. The most common functional unit appears to be kilogram live weight (kg LW) of sheep meat. Hence, to facilitate a more direct comparison of impacts between this study and others, the functional unit chosen for this study is made to be kg LW as well.

The FAO reports (Gerber et al. 2013; Hristov et al. 2013; Opio et al. 2013) use kilogram carcass weight (kg CW) for functional unit. A kg LW to kg CW conversion factor (i.e., dressing percent) of 45% as suggested by Agriculture and Agri-Food Canada (2013) is used to compare the global warming impacts of this study to the impacts reported by FAO.

2.2.3 Allocation

Where possible, ISO (2006b) recommends that allocation be avoided by dividing the main process into sub-processes. It is not possible to separate the inventory associated with each co-product (meat, wool, and milk) in the case of livestock production, so allocation cannot be avoided. In such cases, allocation based on physical or causal relationships is recommended.

In literature, many sheep LCA studies have allocated impacts based on economic value of each co-product (Edwards-Jones et al. 2009; Biswas et al. 2010; Eady et al. 2012; Brock et al. 2013; Ripoll-Bosch et al. 2013; Jones et al. 2014; Furesi et al. 2015; Batalla et al. 2015; O'Brien et al. 2016; Toro-Mujica et al. 2017; Mondello et al. 2018). However, Cottle and Cowie (2016) and Wiedemann et al. (2015) investigated the effect of multiple allocation methods on sheep LCA results and found that, as expected, the choice of allocation method had a drastic effect on the impact score. In the end, both these studies listed protein mass allocation

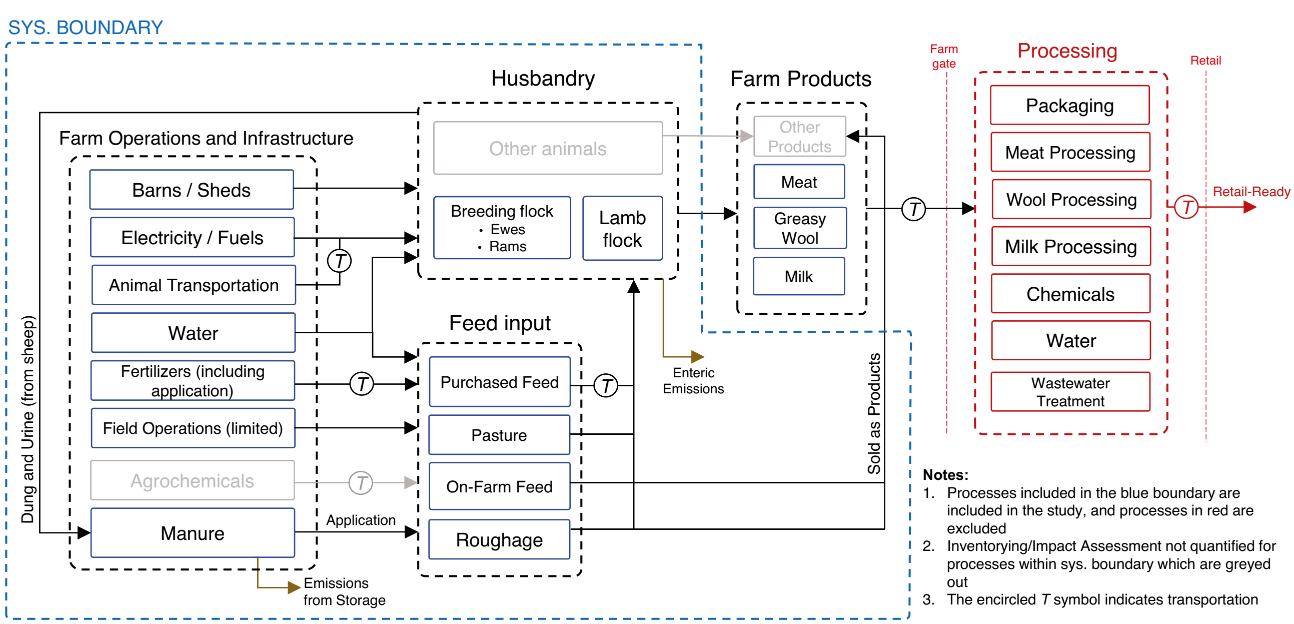

Fig. 2 System boundary diagram of LCA model

(PMA) as one of the recommended allocation methods. FAO (2016) also recommends allocation based on protein requirement if livestock co-products are meat and fiber (wool), as fiber production is primarily determined through protein requirements. Furthermore, the GLEAM-based estimates of life cycle global warming impacts of sheep meat (reported by FAO) also allocate impacts between sheep meat and milk using protein content of the two respective products (impacts of wool were not considered).

Thus, for this study, PMA is used to attribute impacts to meat (kg LW), assuming protein content of 18% for live weight and 65% for wool (protein content estimates obtained from Wiedemann et al. (2015) and FAO (2016)).

2.2.4 Enteric fermentation and manure management emissions

Ruminant animals CH_4 emissions through the process of enteric fermentation, and both CH_4 and nitrous oxide (N_2O), are released through their manure. Enteric CH_4 emissions in particular are a dominant source of climate change impacts in the sheep sector (Hristov et al. 2013). It is crucial, therefore, to obtain accurate estimates of enteric fermentation.

IPCC (2006) does provide default enteric emission value of 8 kg CH_4/head/year (tier 1 emission factor) for sheep. However, a tier 2 characterization methodology which provides an estimate of emissions based on animal productivity, diet quality and management practices is recommended for sheep as it provides more accurate estimates of emissions. It also allows the practitioner(s) to gauge the impacts of diet quality and management practices on the overall emissions and provide recommendations for impact reduction. This study utilizes the tier 2 methodology.

IPCC (2006) recommends using country-specific data for conversion and emission factors when possible. Environment and Climate Change Canada has published a National Inventory Report for greenhouse gases, in which they have compiled the typical values and range for the majority of the relevant factors (ECCC 2020). The LCA model used for this study utilizes factor values and statistical distributions listed in part 2 of ECCC (2020). Values used for estimating livestock emissions are presented in Supplementary Information (Table S1).

2.2.5 Energy balance and nitrogen balance

Estimates of daily dry matter intake (DMI) of grains and roughages are obtained through primary data collection (Sect. 3). It is, however, difficult to measure (in terms of mass) the intake of forages through grazing. Thus, an energy balance method as described in FAO (2016) is used to estimate the daily dry matter intake of forages to be:

$$DMI_{forage} = \frac{E_{req} - \left(\sum_{i=1}^{n} DMI_{grain,i}E_{grain,i} + \sum_{i=1}^{m} DMI_{roughage,i}E_{roughage,i}\right)(1-W)}{E_{forage}} \tag{1}$$

where DMI_{forage} [kg/head/day] is the daily matter intake through foraging/grazing; E_{req} [MJ/head/day] is the total energy requirements of the livestock (determined through tier-2 IPCC (2006) method); DMI_{grain} and $DMI_{roughage}$ are the inputted daily matter intake through grains and roughages, respectively; E_{grain} and $E_{roughage}$ [MJ/kg] are the energy content of grains and roughages, respectively; W is the percent of feed wasted (5%, as per FAO (2016)); and E_{forage} is the average energy content of the forages. E for all feed types is obtained from AHDB (2018). Although Eq. (1) is explicitly defined for DMI_{forage}, the total energy requirement (E_{req}) is a function of the digestible energy of the feed (among other parameters), which in turn is a function of DMI_{forage}. Therefore, DMI_{forage} is estimated iteratively up to three decimal places in the LCA model.

The greenhouse gas emission from manure management is a function of the nitrogen (N) excreted through manure and various environmental factors (emission and conversion factors). The emission and conversion factors related to manure management practices are obtained from ECCC (2020). The nitrogen excreted from livestock through manure, using the nitrogen balance method described in FAO (2016), is equal to the difference between nitrogen ingested through feed and nitrogen present in the products, i.e.:

$$N_{excreted} = \sum_{i=1}^{n} DMI_{feed,i}N_{feed,i} - \sum_{i=1}^{3} A_{product,i}N_{product,i} \tag{2}$$

where $N_{excreted}$ is the estimated nitrogen amount in manure; DMI_{feed} is the daily matter intake of feed; $A_{products}$ is the amount of sheep products produced; and N_{feed} and $N_{product}$ are the nitrogen content in the feed and the products, respectively. $A_{products}$ of the two sheep products relevant to Ontario (meat and wool) are obtained through primary data collection (Sect. 3). Output of milk from sheep is typically not measured by Ontario sheep farmers, so a value of approximately 100 kg/ewe of annual milk production is back-calculated based on Eq. (10.10) in IPCC (2006) (i.e., annual per-head milk production is approximately $5 \times (BW_{weaning} - BW_{birth})$, where BW_{birth} and $BW_{weaning}$ are body weight of sheep in kilograms at birth and at time of weaning, respectively).

Values of N_{feed} and $N_{product}$ are obtained from FAO (2018) and FAO (2016), respectively. The relevant values obtained from ECCC (2020) and FAO (2016, 2018) are presented in Supplementary Information (Table S1). In the LCA model, the energy balance is performed before the nitrogen balance to obtain DMI_{forage}. Therefore, DMI of all feed types can be concatenated into DMI_{feed}, and Eq. (2) can then be used to find $N_{excreted}$ explicitly.

2.3 Data collection and analysis

Primary data on farming practices was collected through a survey form (questionnaire) created to gather farm-level data on:

- Livestock population, mortality/cull rates, body weight distribution
- Primary enterprise: annual number/amount of products sold
- Lambing period: number of lambings, lambing season, birth ratio
- Livestock activity
- Feeding/grazing practices: feed composition and amounts
- Manure management: manure production and management systems in place
- Farming resource use: farm area/type, fertilizer/pesticide application rate
- Animal needs: bedding straw, vaccination, etc.
- Water consumption: drinking water for sheep, water application on farm
- Indoor infrastructure: barn/shed area, electricity, heating, and electricity usage
- Transportation: mass, distance, and transport type

Sheep producers in the region were contacted through Ontario Sheep Farmers (OSF, ontariosheep.org) between the months of November 2021–April 2022. A total of 23 sheep farms participated in this data collection process, for which they were monetarily compensated by the OSF. An example of a completed survey form is provided in Supplementary Information (SI).

Survey results are inputted manually into a spreadsheet program, and any further analyses, including data transformation, normalization, descriptive statistics, hypothesis testing, and regression analyses are done using MATLAB.

Producers had the option to fill out the statistics on farm population, mortality/cull rates either as absolute values (e.g., total number of lambs) or relative values (e.g., lambing percentage). Product outputs of farm were filled out on an annual rate basis (e.g., ton live weight sold per year) and are transformed and normalized after raw data entry.

Feed production is typically the second largest contribution to life cycle global warming impacts (Gerber et al. 2013), so a greater emphasis was placed on obtaining more accurate feed-related input data. Survey questions were framed to obtain feed composition and amounts fed to adult ewes, adult rams, and lambs for both grains/concentrates and roughage (hay, straw, silage, and grazed roughage). The summary of per-farm feed composition results (Table 2) is obtained by finding the dot product of feed composition by sheep population type (adult ewes, adult rams, and lambs) and their relative population on farm.

Farm inputs such as farm area, electricity use, fertilization rate, diesel use, etc. will logically change based on the scale of operation (i.e., sheep population on farm); a larger population will require a greater number of inputs, and vice versa. This effect of operation scale is neutralized by normalizing the inputs by the scale. Normalization not only facilitates a better comparison of farming practices between (often drastically) different farm sizes but also removes correlation among input parameters, which may exaggerate farm input demand and severely overestimate or underestimate LCA results in a Monte Carlo uncertainty analysis (USEPA 1997).

For the collected sample data, linear regression analyses show moderate to strong relationships (correlation) between sheep population on farm and its indoor (shed/barn) area (P = 0.002), total outdoor area (P = 0.04), and electricity usage (P = 0.07). Thus, to remove the effect of population on these parameters, they are all normalized by total sheep population on farm. Similarly, total outdoor area has a strong effect on annual fertilizer application rate (P = 0.005) and diesel consumption (P = 3E-4). These two parameters are, therefore, normalized by total outdoor farm area to remove the interaction between outdoor farm area and fertilizer and diesel usage. Another round of regression analyses on the normalized parameters show that the effect of operation size (represented through sheep population or outdoor area of farm) is effectively removed (P > 0.3). The XY plots of the normalized parameters, shown in Supplementary Information (Fig. S3), also show no sign of a relationship between the operation scale and farm inputs. Although no relationship between annual plastic use and operation size was found, plastic usage is normalized by sheep population on farm for consistency's sake.

3 Foreground data on sheep farming practices

Twenty-three (23) survey responses have been collected: 11 from small farms (15–100 ewes), 8 from mid-sized farms (101–500 ewes), and 4 from larger scale operations (> 500 ewes). Approximately 65% of the farms lamb annually (March–May being the most common lambing season), and the remaining 35% lamb more than once per year (1.5–6 lambings per year). Finished lamb is the primary economic

Table 2 Descriptive statistics on Ontario sheep farms' productivity and feeding practices

			Average (± SE[a])	25th – 50th – 75th percentile	(Min, Max)
POPULATION & PRODUCTIVITY	Population	Adult ewes	206 (±48)	52 – 108 – 259	(3, 818)
		Ewes per ram	34.2 (±4.8)	17.2 – 29.1 – 50.0	(7.3, 90.9)
		Lambs per ewe	1.81 (±0.08)	1.6 – 1.8 – 2.0	(1.10, 2.85)
	Mortality Rate	Ewes	3.4% (±0.4%)	1.4% – 3.3% – 4.6%	(0.8%, 7.7%)
		Lambs	7.5% (±0.9%)	5.1% – 7.0% – 10.0%	(2.0%, 21.6%)
	Cull rate	Ewes	12.4% (±1.6%)	10% – 10.8% – 14.8%	(2.0%, 32.3%)
		Rams	10.1% (±1.8%)	0.0% – 8.2% – 17.5%	(0%, 33.0%)
		Lambs	87.3% (±2.2%)	78% – 81.3% – 92.7%	(72%, 96.3%)
	Number of lambings [/year]		2.0 (±0.3)	1.0—1.0—2.0	(1.0, 6.0)
	Body weight [kg]	Adult ewes	72.4 (±1.4)	69.5 – 72.5 – 73.8	(57.5, 92.7)
		Adult rams	89.2 (±1.9)	85.6 – 87.5 – 90.8	(70.0, 115.3)
		Lambs	38.7 (±1.0)	35.0 – 39.0 – 41.1	(30.0, 47.3)
		Lambs – weaning	24.6 (±1.4)	20.5 – 26.8 – 29.0	(12.0, 36.0)
		Lambs – at birth	3.8 (±0.2)	3.2 – 4.0 – 4.5	(2.2, 5.0)
	Wool produced [kg/head/year]	Adult ewe	2.5 (±0.2)	2.2 – 2.6 – 2.8	(1.4, 3.6)
		Adult ram	3.9 (±0.5)	2.7 – 3.4 – 4.7	(2.0, 6.7)
		Lamb	0.2 (±0.1)	0.1 – 0.2 – 0.3	(0.0, 0.4)
FEEDING & ANIMAL ACTIVITY	Grain intake [kg/head/day]	Adult ewes	0.49 (±0.09)	0.20 – 0.40 – 0.60	(0.0, 1.5)
		Adult rams	0.33 (±0.08)	0.03 – 0.20 – 0.50	(0.0, 1.4)
		Lambs	0.51 (±0.12)	0.12 – 0.25 – 0.79	(0.0, 1.9)
	Grain composition[b] [%]	Corn	56.1% (±9.2%)	33.0% – 65% – 82.5%	(0%, 100.0%)
		Barley	20.4% (±7.5%)	0.0% – 4.0% – 34.8%	(0%, 100.0%)
		Oat	19.1% (±5.3%)	0.0% – 8.5% – 36.3%	(0.0%, 60.0%)
		Wheat	2.7% (±2.1%)	0.0% – 0.0% – 0.0%	(0.0%, 33.0%)
		Soybean	1.8% (±0.8%)	0.0% – 0.0% – 1.3%	(0.0%, 10.0%)
	Roughage / grazing composition[b] [%]	Silage	16.9% (±6.3%)	0.0% – 0.0% – 22.5%	(0%, 100.0%)
		Hay and straw	58.3% (±6.2%)	37.5% – 55% – 75.0%	(0%, 100.0%)
		Tilled pasture	16.1% (±4.3%)	0.0% – 1.0% – 30.0%	(0.0%, 65.0%)
		Rough pasture	9.5% (±3.3%)	0.0% – 0.0% – 20.0%	(0.0%, 50.0%)
	Water intake [L/head/day]	Adult sheep	4.75 (±0.62)	2.75 – 5.00 – 5.75	(0.8, 10.0)
		Lambs	2.84 (±0.40)	1.70 – 2.25 – 4.00	(0.4, 6.0)
	Animal Activity – time spent [%]	Housed ewes	36.1% (±5.5%)	17.0% – 25% – 52.5%	(0.0%, 90.0%)
		Flat grazing	39.3% (±7.2%)	7.5% – 29.0% – 70.0%	(0%, 100.0%)
		Hilly grazing	5.0% (±3.3%)	0.0% – 0.0% – 0.0%	(0.0%, 70.0%)
		Lamb fattening	19.6% (±4.1%)	5.0% – 10.0% – 30.0%	(0.0%, 71.0%)

[a]Standard error

[b]Feed composition for entire sheep population on farm, obtained by finding the dot product of reported feed composition by sheep population type (adult ewes, adult rams, and lambs) and their relative population on farm

driver of all the farms, though some farms also sell replacement/breeding stocks. Roughly half of the farms sell wool as well, but the economic outcome of wool is low (< 5% of overall income). Between 20 and 30% of farms keep other animals, including cattle, pigs, chickens, and goats. The same proportions of farms also produce and sell other animal products (beef, chickens, eggs, etc.), grains, or hay/straw bales. Although the vast majority (> 80%) of farms produce their own roughage for feed, only 25% of farms produce their own grains; the remaining 75% purchase their grains externally.

The following subsections describe the inputs on farms, including feed, infrastructure, and energy consumption, as well as sheep production on farms. Boxplots of sample data for these parameters are shown in Supporting Information (Fig. S1).

3.1 Farm productivity and feeding practices

Table 2 summarizes the sheep population, productivity statistics, and dietary practices employed by the surveyed farms. The average (± standard error) farm has 206 (± 48) ewes, 6 (± 2) rams, and 370 (± 16) lambs. Farms have, on average, 34 (± 5) ewes per ram and 1.8 (± 0.1) lambs per ewe. The mortality rates for adult ewes and lambs are 3.4% (± 0.4%) and 7.5% (± 0.9%), respectively. An average adult ewe, ram, and lamb weigh 72 (± 1.4), 89 (± 1.9), and 39 (± 1.0) kg, respectively. The estimates of lambing percentages, mortality rates, and body weights are consistent with the performance targets suggested by Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA 2011).

Approximately 12% of adults and 87% of lambs are culled for processing (for meat). Farms which tracked their wool production reported that, on average, 2.5 (± 0.2) and 4 (± 0.5) kg of wool were sold annually per adult ewe and ram, respectively. The amount of wool from lambs which was sold was negligible (0.2 kg/head/year).

Adult sheep intake 0.33–0.49 kg grains per head daily (0.4–0.7% of body weight), and lambs intake 0.51 kg grains per head daily (1.3% of body weight). Only 15–25% of feed intake is from grains/concentrates; the bulk of the diet is from roughage. Sheep typically spend 6 months (range is 3–9 months) grazing outside, and they obtain approximately 15% of their roughage intake through grazing from tillable pasture and 10% from rough pasture. Hay constitutes a major source of roughage intake (60% approximately), and the remaining 15% of roughage intake is from silage. The roughage to grain ratio for adult sheep observed from sample data is also consistent with the guidelines provided by OMAFRA (2010), but unlike those guidelines, which recommend that greater than 60% of lamb diet consist of grains, only 30% of diet fed to lambs consist of grains in the observed data. The average reported daily water consumption is 4.8 l per adult sheep and 2.8 l per lamb. These estimates are slightly below the recommendations provided by OMAFRA (2019).

3.1.1 Relationship between farming practices and productivity

Some sheep LCA studies have established the significance of relationships between number of lambings (Ripoll-Bosch et al. 2013; Batalla et al. 2015), lambing rate (Jones et al. 2014), feed intake (O'Brien et al. 2016; Toro-Mujica et al. 2017), and farm productivity. Are these relationships observed in the Ontario-specific sample data collected for this study? Regression analysis is used to determine relationships between certain farm practice-related parameters and farm productivity.

Since the primary enterprise of all the farms is finished lamb, the metrics for gauging farm productivity are chosen to be "number of lambs per ewe" and "average lamb body weight." Linear regression analyses between these two metrics (treated as response variables) and the following farming practices-related parameters are performed: (i) lambings per year; (ii) daily grain intake by adult ewes and (iii) lambs; (iv) daily roughage intake by adult ewes and (v) lambs; (vi) livestock activity percentage — housed ewes; (vii) livestock activity percentage — fattening lambs; and (viii) number of lambings per year. No significant relationship between any pairwise combination of any of these parameters is found. XY plots of some of these covariates are presented in Supplementary Information (Fig. S2), which show no sign of a relationship between farm productivity parameters and farm practices parameters.

3.2 Farm infrastructure and miscellaneous inputs

Table 3 describes the farm infrastructure and farm input statistics of the sampled data. Per head, average (± standard error) outdoor area on farm occupied by rough pastures, improved pastures, and arable cropland is 184 (± 48), 115 (± 42), and 700 (± 125) m^2, respectively. This average includes 8 farms which had no rough pastures, 10 farms which had no improved pastures, and 3 farms which had no arable cropland. Approximately 3 (± 0.6) m^2 of indoor area (barns and sheds) per head is also utilized on average.

Annual fertilizer application rate for farms which do apply fertilizers is 193 (± 47) kilogram per hectare of outdoor area, 45% of which is nitrogen-based (NH_4NO_3), 28% phosphorus-based (P_2O_5), and 24% potassium-based (K_2O). This estimate only includes the 65% of farms which do apply external fertilizer; 35% of farms do not use any fertilizers. A total of 38% (± 7%) of all sheep manure produced is also spread on pastures. The remaining 47% (± 5%) and 14% (± 5%) are kept unconfined in solid storage or dry lots, respectively.

Per-head annual electricity consumption on farm is 11 (± 3) kWh. This estimate does not include two of the farms, which reported electricity consumption three times greater than the overall group's electricity usage. One of these outlier farms included electricity use from a commercial kitchen and the other was predominantly a poultry farm (> 800 chicken). Electricity usage for these farms could not be attributed exclusively to sheep production, and thus their electricity values were discarded from the group. Annual diesel consumption, predominantly used for operating farm machinery, is 68 (± 18) l per hectare of total outdoor area on farm. Daily bedding straw requirement is 0.6 (± 0.1) kg for an adult sheep and 0.4 (± 0.1) kg for a lamb.

Table 3 also presents the statistics for transportation-related farm inputs. Annual roundtrip transportation distance for livestock auction house, slaughterhouse, etc. is 171 (± 34) km approximately, and average distance for purchased

Table 3 Descriptive statistics on Ontario sheep farms' (non feed-related) inputs

			Average (±SE)[a]	25th – 50th – 75th percentile	(Min, Max)
FARM SIZE	**Farm area [m^2/head]**	Rough pasture	184.0 (±47.9)	0 – 159.3 – 241.0	(0, 708.8)
		Improved pasture	114.7 (±42.0)	0 – 26.6 – 156.5	(0, 753.0)
		Arable cropland	699.9 (±125.3)	253 – 583.8 – 997.6	(0, 1911.2)
		Total outdoor	1110 (±172.8)	594 – 915.4 – 1368.4	(267, 3294.9)
		Barns and sheds	3.0 (±0.6)	1 – 2.4 – 4.1	(0, 13.9)
MANURE & FERTILIZERS	**Manure management [%]**	PRP[b]	38.3% (±6.6%)	7.5% – 40.0% – 66.0%	(0%, 100%)
		Solid storage	46.9% (±5.2%)	29.5% – 50% – 60.0%	(0%, 95.0%)
		Drylot	13.5% (±4.5%)	0.0% – 0.0% – 20.0%	(0%, 80.0%)
		Liquid system	1.3% (±1.3%)	0.0% – 0.0% – 0.0%	(0%, 30.0%)
	Fertilizer application	Application rate[c] [kg/ha/year]	193 (±47)	51 – 168 – 288	(3, 527)
		Nitrogen %	44.7% (±6.7%)	30.0% – 40% – 58.0%	(6.5%, 100%)
		Phosphorus %	28.0% (±3.7%)	22.0% – 30% – 33.0%	(0%, 50.0%)
		Potassium %	23.5% (±3.1%)	17.0% – 20% – 33.0%	(0%, 40.0%)
FARM INPUTS	Electricity [kWh/head/year]		11.3 (±3.2)	3 – 7.6 – 18.9	(1, 35.2)
	Diesel [L/ha/year]		68.2 (±17.5)	23 – 49.4 – 71.6	(12, 240)
	Plastic, LDPE [kg/head/year]		1.31 (±0.57)	0.54 – 0.69 – 1.22	(0, 7.2)
	Bedding straw — adults [kg/adult/day]		0.63 (±0.13)	0.24 – 0.50 – 0.72	(0.09, 2.50)
	Bedding straw — lambs [kg/lamb/day]		0.43 (±0.08)	0.23 – 0.40 – 0.50	(0.04, 1.50)
	Misc. water use [L/year]		63.3 (±35.8)	0 – 4.6 – 39.0	(0, 300)
TRANSPORTATION	**Transportation distance [km/year]**	Livestock	171.2 (±34.3)	47.8 – 127.5 – 212.5	(23.0, 600.0)
		Grain	77.5 (±25.2)	18.5 – 50.0 – 100.0	(10.0, 500.0)
		Fertilizer	29.5 (±9.1)	10.0 – 20.0 – 25.0	(0.0, 100)
	Percent grains transported		67.1% (±9.6%)	15% – 100% – 100%	(5%, 100%)
	Percent fertilizer transported		92.3% (±7.7%)	100% – 100% – 100%	(0%, 100%)
	Transport mass-distance [kg•km/(head•year)]	Livestock[d]	4344 (±842)	1429 – 3463 – 6380	(7, 14,806)
		Grains	7239 (±1842)	705 – 3825 – 13,588	(0, 22,237)
		Fertilizer	557 (±238)	0 – 100 – 576	(0, 2711)

[a]Standard error

[b]Pasture/range/paddock

[c]35% of sampled farms do not apply external fertilizer (other than manure). These statistics are only for the remaining farms which do apply fertilize

[d]Includes distance to auction, slaughterhouse, etc., and transport of replacement stock

grains and fertilizer is 78 (±25) and 30 (±9) km, respectively. The total annual mass-distance transported per head is 12,140 (±2,458) kg · km on average, from which nearly 60% is due to transport of grains, and 40% is due to transportation of livestock.

4 LCA results

Breakdown of life cycle impacts per functional unit is listed in Table 4 (full model results may be found in Supplementary Information (SI)). Average (±standard deviation) global warming (GW) impacts of sheep production are 13.2 (±3.7) kg CO_2 eq/kg LW, of which 39% and 29% are due to enteric CH_4 emissions and feed production alone, respectively. Average non-renewable energy demand (ED) is 66.9 (±34.2) MJ/kg LW, and water depletion (WD) impacts are 0.15 (±0.08) m^3/kg LW. Feed production and farm infrastructure/operations each contribute roughly 50% to the overall impacts in both these categories. Boxplots of overall impacts (Fig. 3) show that > 90% of the farms have per-functional unit (kg LW^{-1}) GW, ED, and WD impacts in the ranges of 8.4–16.4 kg CO_2 eq, 18.6–92.4 MJ, and 0.06–0.27 m^3, respectively. Two outlier farms exhibit impacts greater than the range in the categories of GW and ED: one due to a large proportion of feed intake by lambs being from grains/concentrates (> 95% by weight), and the other due to excessive fertilization (2.7 × the average rate).

Average Ontario GW impacts (13.2 kg CO_2 eq/kg LW) are consistent with literature-observed values of 3.6–25.9 kg CO_2 eq/kg LW (Bell et al. 2012; Ripoll-Bosch et al. 2013; Jones et al. 2014; Wiedemann et al. 2015; Cottle et al. 2016;

Table 4 Average (± standard deviation) life cycle impacts per functional unit, including average percent contributions of processes to impacts in phase

Phase	Global warming (GW) [kg CO_2 eq/kg LW]	Energy demand (ED) [MJ/kg LW]	Water depletion (WD) [m^3/kg LW]
ENTERIC CH_4 EMISSIONS	**5.1 (± 0.5) [39%]**	**n/a**	**n/a**
FEED PRODUCTION	**3.8 (± 2.6) [29%]**	**31.8 (± 19.5) [48%]**	**0.08 (± 0.08) [52%]**
Silage	3% (± 6%)	3% (± 5%)	11% (± 23%)
Hay	31% (± 30%)	38% (± 31%)	12% (± 29%)
Corn	41% (± 31%)	38% (± 31%)	60% (± 36%)
Barley	9% (± 12%)	9% (± 11%)	1% (± 2%)
Oat	10% (± 12%)	8% (± 10%)	5% (± 10%)
Wheat	3% (± 8%)	3% (± 9%)	7% (± 20%)
Soybean	4% (± 6%)	2% (± 4%)	4% (± 8%)
MANURE	**1.3 (± 0.4) [10%]**	**n/a**	**n/a**
Manure CH_4	25% (± 13%)	–	–
Direct N_2O	60% (± 12%)	–	–
Indirect N_2O	15% (± 3%)	–	–
OPERATIONS	**3.0 (± 2.5) [23%]**	**35.1 (± 25.2) [52%]**	**0.07 (± 0.03) [48%]**
Barn / shed	12% (± 14%)	7% (± 8%)	1% (± 1%)
Water intake	0% (± 0%)	0% (± 0%)	46% (± 18%)
Electricity	6% (± 5%)	13% (± 10%)	10% (± 9%)
Natural gas	0% (± 0%)	1% (± 1%)	0% (± 0%)
Diesel	16% (± 15%)	19% (± 16%)	1% (± 1%)
Tilling, rolling	2% (± 2%)	2% (± 1%)	0% (± 0%)
Bedding straw	13% (± 11%)	9% (± 7%)	25% (± 15%)
Plastic, LDPE	5% (± 5%)	12% (± 11%)	1% (± 1%)
Transportation	3% (± 4%)	4% (± 4%)	0% (± 0%)
Fertilization	42% (± 28%)	32% (± 23%)	15% (± 15%)
TOTAL	**13.2 (± 3.7) [100%]**	**66.9 (± 34.2) [100%]**	**0.15 (± 0.08) [100%]**

O'Brien et al. 2016; Toro-Mujica et al. 2017; Dougherty 2018). GW impact breakdown by phase is similarly consistent with literature. Contribution of enteric CH_4 emissions to overall GW impacts in the present study (39%) is within the range of 25–65% observed in the literature (Ripoll-Bosch et al. 2013; Jones et al. 2014; Vagnoni et al. 2015; O'Brien et al. 2016; Mondello et al. 2018); although some studies (Biswas et al. 2010; Brock et al. 2013; Dougherty 2018; Mohan et al. 2018; Sabia et al. 2020) have reported the relative contribution of enteric emissions to GW to be much higher (70–90%). The GW impact scores and impact breakdown from this study also agree with the GLEAM results

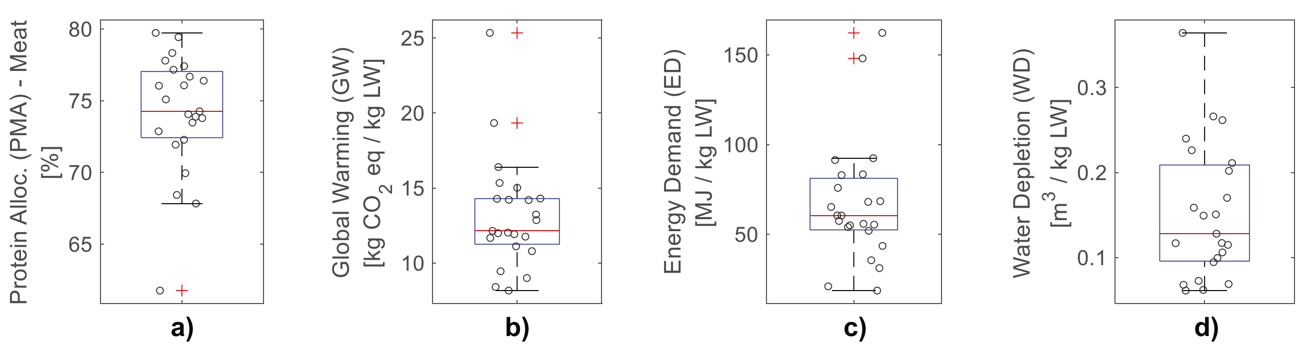

Fig. 3 Boxplot (and datapoint scatter) of **a** protein mass allocation (PMA) factors towards meat; and total impacts in the categories of **b** global warming (GW), **c** energy demand (ED), and **d** water depletion (WD)

(Gerber et al. 2013; Opio et al. 2013), which estimate global average GHG emissions from sheep meat to be 10.7 kg CO_2 eq/kg LW (after conversion from CW to LW), 55% of which is contributed by enteric CH_4, and 37% by feed production.

Impacts in ED are rarely reported in sheep LCA-related literature, and those that have (Ledgard et al. 2011; Wiedemann et al. 2016; O'Brien et al. 2016) only determine fossil fuel energy demand, making it difficult to compare the total non-renewable (fossil fuel and nuclear) energy requirements of sheep production from this study to literature values. Nonetheless, after back-allocating impacts to meat from other sheep products (where applicable), the range of fossil-fuel energy demand in literature is 11.7–41.8 MJ/kg LW; lower compared to this study's ED impacts (67 MJ/kg LW), as expected. Like ED impacts, WD impacts are difficult to find in literature, and methodological differences make it difficult to compare their impacts among studies. Range of water use-related estimates in studies which have assessed such impacts (Wiedemann et al. 2016; Dougherty 2018; Uusitalo et al. 2019) is 0.06–6.33 m^3/kg LW, comparable to this study's WD impacts (0.15 m^3/kg LW).

Results presented in Table 4 are based on average protein mass allocation (PMA), calculated to be 74.1% (±4.2%) for meat. The range of PMA factors for > 90% of the sampled farms is between 68.4 and 79.7% (Fig. 3). The average PMA is slightly higher than the PMA factors of 65% and 71% reported by Cottle and Cowie (2016) and Wiedemann et al. (2015), respectively, due to lower per-head wool production rates in Ontario sheep compared to Australian Merino sheep.

4.1 Energy balance and livestock emissions

The IPCC (2006) tier 2 method for determining livestock emissions (enteric and manure) uses gross energy balance, which is based on the summed net energy (NE) requirements of livestock and energy availability of feed. Several studies cite the importance of net energy calculations on enteric emissions (Wallman et al. 2011; Schönbach et al. 2012; Brock et al. 2013; Ripoll-Bosch et al. 2013; Cottle et al. 2016; O'Brien et al. 2016; AHDB 2018; Kilcine 2018), but very few report their estimates.[1] Considering the importance of NE in IPCC-based estimation of livestock emissions, which altogether contribute to half of overall GHG emissions (Table 4), NE values are reported here in Table 5. Average (± standard deviation) per-head daily NE requirements for adult sheep and lambs are 8.8 (±0.7) and 5.1 (±0.5) MJ, respectively. The relative contribution of each component to total NE requirements on farm (dot product of per-head estimate (Table 5) and sheep population on farms) is shown in Fig. 4. Over 75% of NE is required for maintenance alone, and it does not fluctuate among the sampled farms (coefficient of variation (COV) is 0.02). Animal activity (listed in Table 2) is the next largest (8%) requirer of NE, and NE requirements for pregnancy and wool production are the lowest (2% each).

Using energy balance (Sect. 2.2.5), total per-head daily matter intake (DMI) by adult sheep and lambs is estimated to be 2.2 (±0.2) and 1.3 (±0.2) kg, respectively, or approximately 3.0% and 3.4% of their respective body weights. These estimates are consistent with feed requirements of 1.5–3.5% of body weight recommended by IPCC (2006), FAO (2016), and AHDB (2019). On average, 81% and 63% of DMI by adult sheep and lambs, respectively, are found to be from roughages (silage, hay, and grazing from pastures); though this estimate varies greatly for lambs ($COV = 0.6$).

Resulting per-head annual enteric CH_4 emissions are estimated to be 11.2 (±0.9) kg CH_4 for adult sheep and 4.6 (±0.6) kg CH_4 for lambs. By comparison, IPCC (2006) recommends that 8 kg CH_4/head/year be used for enteric emissions by adult sheep if energy balance is not performed (i.e., a simpler, tier 1 method is used), and Webb et al. (2013) used 3.2 kg CH_4/head/day for lambs. Per-head annual manure CH_4 emissions from adult sheep and lambs are estimated to be 0.6 (±0.5) and 0.4 (±0.3) kg CH_4, respectively. IPCC (2006) recommends manure CH_4 emissions of 0.15–0.37 kg CH_4/head/year in absence of energy balance. Similarly, if nitrogen balance is not done, IPCC (2006) recommends daily nitrogen excretion rate for sheep in North America to be 0.42 (±50%) kg N per 1000 kg animal mass. In comparison, the daily nitrogen excretion rate estimated using nitrogen balance (Sect. 2.2.5) is 0.41 (±0.16) for adult sheep and 0.28 (±0.08) for lambs. The resulting direct N_2O emissions contribute to the bulk (60%) of manure-related GHG emissions, and indirect N_2O emissions are less consequential. These findings are consistent with manure emissions reported by Batalla et al. (2015), Brock et al. (2013), and Jones (2014).

The IPCC (2006) equations for estimating enteric emissions suggest that livestock methanic emissions are inversely related to lambing rate (lambs per ewe), body weight of lambs, and digestible energy of feed (determined through grain intake), and they are positively related with body weight of adult ewes.[2] This relationship is based on an unrealistic assumption of independence among these parameters, but nonetheless, they can be used to predict and reduce enteric emissions. Linear correlation analysis found a moderately strong ($R^2 = 0.53$, $P < 0.0001$) inverse effect of lambing rate on enteric emissions (per functional unit), but

[1] AHDB (2018) and Wallman et al. (2011) report metabolizable energy, but not net energy.

[2] These input parameters are just a small number of parameters which influence enteric emissions. Environmental factors outweigh producer-controlled parameters in estimation of enteric emissions (shown in Supplementary Information (Table S2)), but they of course cannot be altered to reduce enteric emissions. Hence, they were not considered here.

Table 5 Per-head average (± standard deviation) estimations of net energy (NE), gross energy (GE), daily matter intake (DMI), and livestock emissions

		Unit	Adult ewe [/head]	Lambs [/head]
NET ENERGY	NE maintenance	MJ/day	5.98 (±0.40)	4.02 (±0.35)
	NE activity	MJ/day	0.72 (±0.17)	0.38 (±0.08)
	NE growth	MJ/day	n/a	0.62 (±0.25)
	NE lactation[a]	MJ/day	1.31 (±0.36)	n/a
	NE pregnancy	MJ/day	0.57 (±0.07)	n/a
	NE wool	MJ/day	0.32 (±0.00)	0.07 (±0.00)
ENERGY BALANCE	GE Req'd	MJ/day	26.23 (±2.20)	15.47 (±1.92)
	Total DMI	kg/day	2.15 (±0.20)	1.33 (±0.23)
	Total DMI per BW[b]	%	3.0% (±0.2%)	3.4% (±0.4%)
	% DMI – roughage	%	81.3% (±19.8%)	62.9% (±37.8%)
	Feed average DE[c]	%	67.1% (±1.9%)	68.3% (±3.3%)
SHEEP EMISSION	Enteric CH_4	kg CH_4/year	11.18 (±0.94)	4.57 (±0.57)
	Manure CH_4	kg CH_4/year	0.60 (±0.54)	0.36 (±0.30)
	Nitrogen excretion	kg N/1000 kg BW/day[d]	0.41 (±0.16)	0.28 (±0.08)
	Direct manure N_2O	kg N_2O/year	0.15 (±0.06)	0.05 (±0.02)
	Indirect manure N_2O[e]	kg N_2O/year	0.04 (±0.01)	0.01 (±0.004)

[a]Applies to female adult sheep only

[b]*BW* body weight [kg]

[c]*DE* digestible energy

[d]kg nitrogen per 1000 kg animal mass per day, units chosen to match IPCC (2006)'s unit preference for nitrogen excretion rate

[e]indirect N_2O includes emissions through volatilization and leaching

no other input parameter, including grain intake, livestock body weights, animal activity, or birthing ratio had a significant effect on enteric emissions.

4.2 Feed production

Feed-related GW and ED impacts make up 29% (±14%) and 48% (±20%), respectively, of overall impacts. GW and ED impact factors for all grain types is similar (GW: 0.42–0.63 kg CO_2 eq/kg grain, and ED: 2.85–4.99 MJ/kg grain) with the exception of soybean, whose GW and ED impact factors are significantly larger ($P<0.01$). Thus, for GW and ED, impact score breakdown based on grain type (Table 4) is largely a function of the breakdown of grain intake (Table 2); a larger percent of feed intake consisting of corn results in a larger percent of impacts from corn production. Soybean intake is low enough (<2%) such that its relatively higher impact factors do not significantly increase the overall impact scores. Although GW and ED impact factors for hay are low relative to those of grains (GW: 0.085 kg CO_2 eq/kg hay, and ED: 1.06 MJ/kg hay), it forms the largest part of the overall diet and is consequently the second largest contributor to feed-related impacts (after corn). Feed-related WD impacts make up 52% (±28%), of which 60% are exclusively due to corn production.

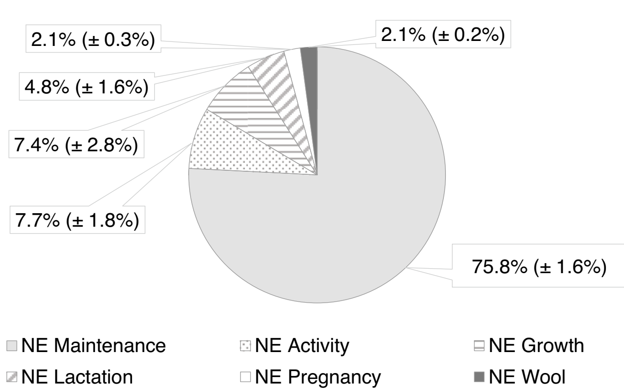

Fig. 4 Average (±standard deviation) contribution of each IPCC (2006) component to livestock net energy (NE) requirements

4.3 Farm infrastructure and misc. operations

Farm infrastructure and operations contribute to 23% (±12%) of overall GW impacts, and fertilization is responsible for over 40% of those impacts. The contribution of nitrogen fertilizer in particular is the largest contributor to fertilization-related life cycle impacts (83%, 67%, and 64% towards GW, ED, and WD, respectively), and the contribution of potassium fertilizer is the lowest (1–3% across all impact categories). These findings are consistent with observations by Edwards-Jones et al. (2009) and Wallman et al. (2011). Fertilization is also the largest contributor to

ED operations impacts, and diesel consumption is the second largest contributor to both GW and ED impacts. WD impacts from farm infrastructure/operations are responsible for 48% (±27%) of overall WD impacts, of which nearly half is due to water intake by sheep. It is also important to note that 20–30% of farms also house livestock other than sheep, and for these farms, inputs related to farm area (indoor and outdoor) and electricity use required by sheep could not separated from the total on-farm inputs (i.e., required by all livestock on farm). Thus, impact scores associated with these inputs may be overestimated.

4.4 Farm classification vs. impacts

Studies which have attempted to form relationship between farming practices and productivity (Sect. 3.1.1) have observed significant differences in GW impacts between intensive (frequent lambing, higher concentrate, zero grazing) and extensive (traditional, annual lambing, pasture-based) sheep farming operations. In all cases, the carbon footprint of more intensive operations was lower compared to extensive operations (Ripoll-Bosch et al. 2013; Jones et al. 2014; Batalla et al. 2015; O'Brien et al. 2016). For the farm samples in this study, however, no significant differences ($P > 0.3$) between life cycle impacts between annual lambing systems and frequent (accelerated) lambing systems are found in all three impact categories. Regression analysis shows a moderate ($P < 0.04$) relationship between DMI of ewes and life cycle impacts across all three categories, but no relationship between life cycle impacts and DMI of lambs is found. Lambing rate also does not influence impact scores in any categories ($P > 0.1$).

5 Conclusions and recommendations

Research on life cycle impacts in the Canadian sector sheep sector is limited. This study has provided statistics on sheep farming practices in Ontario and an LCA model using Canada-specific factors upon which further work on sheep LCA-related research can be done. Current results suggest that both the carbon footprint values and relative contribution (to overall carbon footprint) of each phase of sheep meat production in Ontario are consistent with the range of literature-observed values, but differences in system boundaries, allocation, and emission models make it difficult to compare the results found here to any one particular study.

Although this study is an important steppingstone in creating dialog on life cycle implications for Ontario's sheep sector, there is room for improvement. For example, preliminary analysis suggests that dispersion in overall GW impacts can be mostly attributed to discrepancies in feeding practices and farm infrastructure/operations (Table 4: COV of livestock enteric and manure emissions is 0.1–0.3, while COV of feed and operations-related GW impacts is 0.7–0.8). Since livestock emissions make no contribution to ED and WD, variance in impact scores for these two categories can be entirely attributed to feed and farm operations. This suggests that not all the environmental impacts of are "baked in," and producers have some influence in reducing their environmental footprint by improving their practices. Global sensitivity analysis can be incorporated to isolate variables which have the greatest effect on impact scores and recommend improvements (from an environmental perspective) in production practices. This may also form a basis for setting criteria for a potential ecolabel. Uncertainty in environmental factors (as specified in ECCC (2020)) also needs to be taken in to account.

In Ontario, freshwater aquatic eutrophication impacts are important due to the frequent occurrence of cyanobacteria (blue-green algae) in the Great Lakes, particularly in Lake Erie (Dove and Chapra 2015; ECCC and USEPA 2017). Several sheep LCA studies have incorporated eutrophication impacts into their assessment (Wallman et al. 2011; Zonderland-Thomassen et al. 2014; O'Brien et al. 2016; Payen and Ledgard 2017). Nutrient balance may be incorporated into the LCA model to determine the inventory of nitrate, ammonia, and phosphorus associated with livestock excretion and field losses. The existing model already contains impact factors for eutrophication of feed production and farm operations.

Lastly, while this study focuses on sheep meat production, the model may also be used to determine life cycle impacts for Canada's growing sheep dairy or wool industry. Values of 1, 2, or 3 may be assigned to the variable "enterprise" in the model to output life cycle results using a functional unit of either kg LW, kg wool, or kg milk, respectively (enterprise = 1 is used for the current study).

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Data availability All data generated or analyzed during this study are included in this published article's supplementary information file. Furthermore, the LCA model files created and used to generate the results for this study is freely available under the General Public License on GitHub (https://github.com/akoolbhatt/ON-sheep-LCA).

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