Life cycle assessment and environmental claims in Canadian sheep production

An Ontario sheep case study

Ontario Sheep Farmers (OSF)

OSF PROJECT #R21-1

April, 2023

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FUNDED BY: **Ontario Sheep Farmers (OSF)**
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Summary

Background: Life cycle assessment (LCA) has emerged as an important tool in quantifying and reducing the environmental footprint of human activities, specifically greenhouse gas (GHG) emissions. The potential for governments and organizations in tackling climate change through market intervention and technological innovation is well-recognized, but the role consumers play in mitigating climate change through product consumption (i.e., demand-side approaches) has received less attention. Ontario Sheep Farmers (OSF) – a producer-run organization representing over 3,000 sheep farmers in Ontario – recognized this opportunity and funded the study *#R21-1* with the aim of leveraging LCA to quantify the environmental performance of Ontario sheep production and substantiate environmental claims (e.g., ecolabelling) of Ontario sheep products. The results of the study are presented in this report

Objectives: The main objectives of this study are to i) Review the state-of-the-art on life cycle modelling of sheep farming, ii) Create a 'cradle-to-farmgate' parametric LCA model for sheep production, iii) estimate the range of life cycle impacts through the LCA model using the collected data, and iv) create a framework for making environmental claims on sheep products through LCA. The collected data and LCA model code are also publicly made available for replication and further improvement.

Data collection: Data on Ontario sheep farming practices – specifically on sheep population, product output, feeding/grazing practices, manure management, farm infrastructure, transportation, and other misc. farm inputs – is collected mainly through a 16-page survey form. Survey responses from 23 farms are parameterized and inputted into the LCA model to estimate Ontario-specific environmental impacts of sheep farming.

LCA 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 livestock leave the farm for slaughter (i.e., cradle-to-farmgate system boundary). Allocation of overall impacts to sheep meat is done through protein mass allocation (PMA), and impact scores are normalized using a functional unit of kg live weight (kg LW).

LCA results: Life cycle impacts per kg LW Ontario sheep 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%). Ontario sheep sector's impact scores, particularly for GW, are consistent with values observed in the literature. 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.

Environmental labelling: Using Canadian guides on 'self-declared' environmental labelling (provided by the Canadian Standards Association and Competition Bureau Canada), a checklist of eight requirements for making environmental claims through LCA are created such that claims made using this checklist should be compliant with Canadian legislation relevant to ecolabelling. A combination of sensitivity, uncertainty, and scenario analysis is used to i) identify parameters related to sheep production with a high influence on its environmental performance, ii) create alternate scenarios representing 'ideal' farming practices, and iii) quantify any improvements in the environmental footprint of sheep production, through which benchmarking criteria for environmental claims can be set. The application of this methodology is demonstrated by creating alternate 'ideal' scenarios (through sensitivity analysis) which effectively reduces the environmental footprint of Ontario sheep production by 25% – 31% from current practices, after accounting for any fluctuation (uncertainty) in environmental factors.

Conclusion / Recommendations: This study is one of the first to estimate the life cycle impacts of Ontario sheep production using Ontario-specific primary data. It also aims to bridge the gap between LCA and environmental labelling, specifically in the Canadian context, by presenting a methodology for making environmental claims on products through LCA metrics. The LCA modelling component could be improved, however, by including the effects of carbon sequestration (through changes in land management practices) on overall GW impacts and considering aquatic eutrophication impacts of sheep farming. Furthermore, the framework for making environmental claims could be expanded to include ISO type I & III ecolabelling schemes as well (the current framework uses a type II scheme).

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Abbreviations

BMP	Best management practices
CSA	Canadian Standards Association
COV	Coefficient of variation
DE	Digestible energy
DMI	Dry matter intake
ECCC	Environment and Climate Change Canada
ED	Energy demand
EPD	Environmental Product Declaration
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gases
GLEAM	Global Livestock Emission Assessment Model
GW	Global warming
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCCA	Life cycle cost assessment
LCI	Life cycle inventory(ing)
LCIA	Life cycle impact assessment
LEAP	Livestock Environmental Assessment and Performance Partnership
LW	Live weight
MC	Monte Carlo simulation
OAT	One-at-a-time sensitivity analysis
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
OSF	Ontario Sheep Farmers
PMA	Protein mass allocation
RSV	Relative sensitivity value
WD	Water depletion
PMA	Protein mass allocation
UN	United Nations

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 3,000 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 to reduce the environmental footprint of their production while maintaining or increasing their production to meet market demands.

These concerns and opportunities for improvement were recognized by Ontario Sheep Farmers (OSF),[1] as well. Potential areas for investigation identified by OSF (2019) during a stakeholder meeting included further research towards a more complete estimation of environmental life cycle impacts of local sheep production. Such a study would provide avenues for sheep producers to recognize and improve on farming/processing techniques with the most significant environmental burdens. A quantification of life-cycle impacts associated with sheep products may also be used to substantiate environmental claims and set criteria for an 'eco-labelling' program. This may aid in increasing perception and preferences towards sheep products among more environmentally-aware consumers.

Life cycle assessment (LCA), particularly as defined by ISO (2006b, 2006c) standards 14040/44, 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. Research in the sheep sector, however, is relatively scarce, and the majority of studies related to sheep production have been limited to operations in Europe and Oceania.

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[1] `ontariosheep.org`

1.1. LCA IN ONTARIO'S SHEEP SECTOR

In 2017, OSF had commissioned Groupe AGÉCO[2] to conduct an environmental LCA of Ontario's sheep sector. The Groupe AGÉCO (2017) study quantified GHG emissions, energy use, land use, and water consumption for Ontario sheep, but it was based on a streamlined analysis, relying on generic, readily-available data; no Ontario-specific primary data collection was undertaken. It was also missing some key LCA features which prevented confident decision-making through its results, namely: sensitivity and uncertainty analysis, and effect of multi-functionality / allocation on impacts. Lastly, while the LCA methodology used by Groupe AGÉCO was communicated transparently, the underlying data and the LCA model was not made available to the stakeholders, preventing further analysis of the relationship between sheep farming practices and the environmental impacts of sheep farming (e.g., scenario analysis).

Thus, OSF requested that a more comprehensive, ISO-standard LCA study (i.e., the present study, partly funded by the research grant *OSF PROJECT #R21-1*) be conducted to close the gaps remaining from the previous study, with the expectation that it would,

- Provide avenues for sheep producers to better identify and improve on farming practices with the most significant environmental burdens,
- Reduce the sheep sector's GHG emissions
- Allow sheep producers to make environmental claims on their products, and
- Set the foundation for an 'eco-labelling' program

1.2. PROJECT GOALS

The main objectives and sub-objectives of this study are to:

i. Review the state-of-the-art on life cycle modelling of sheep farming

ii. Create a 'cradle-to-gate' LCA model for sheep production

  a. Develop a parametric (dynamic), attributional LCA model for Ontario's sheep sector
  b. Provide sensitivity and uncertainty analysis metrics

iii. Collect primary data on Ontario-specific sheep farming practices

iv. Estimate the range of life cycle impacts through the LCA model using the collected data

v. Create an interactive LCA application which predicts the life cycle impacts of sheep products based on user-defined inputs

vi. Create a set of benchmarking criteria for making environmental claims

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[2] `groupeageco.ca`

An overview of the approach taken to fulfill the objectives is shown in Fig. 1. Through a review of existing literature, important phases of farming practices in the sheep sector and the parameters relevant to these practices are identified. An LCA model which accepts these parameters as inputs is created to quantify the life cycle impacts of sheep production. Farming and production practices in Ontario's sheep sector is assessed and parameterized through primary data collection. 'Typical' values of parameters representing average Ontario practices are identified through the data acquisition phase and serve as baseline (default) values for local sensitivity analysis. The spread of parameter values in the acquired data is fitted to common statistical distributions, and these distributions serve as a basis for global sensitivity / uncertainty analysis.

The sensitivity analysis and uncertainty analysis modules use the LCA model, which accepts parameter values provided by these two modules as inputs and returns impact assessment in various impact categories as outputs. The results obtained through these processes are used to provide an assessment of the environmental impacts of Ontario's sheep sector and best management practices (BMPs) recommendations to reduce said impacts. The interactive application utilizes the same LCA model, but it allows the user to input their own parameter values and return the impact values based on the inputted parameters.

1.3. CONTENTS OF THIS REPORT

This report is comprised of the following sections:

Sec. 2: **Review of LCA in sheep farming** — Summarizes the existing literature on LCA of sheep farming, revived specifically for this study and published in the *Journal of Cleaner Production* (Bhatt & Abbassi, 2021).[3] The published article identifies the standard practices, system boundaries, functional units, allocation methods, impact categories, and life cycle impact range in the peer-reviewed sheep LCA literature space. This work is used to create the LCA model for this study and compare model outputs to literature.

Sec. 3: **Statistics on Ontario sheep farming** — Presents the methodology for primary data collection & analysis undertaken for this study, and summarizes the collected data in terms of inputs / outputs of material and energy in Ontario sheep farms. Steps taken to transform the data into usable input parameters for the LCA model are also explained here.

Sec. 4: **LCA modelling of sheep production** — Describes the LCA model created for this study, including the reference guidelines, impact categories, source(s) of background data, system boundary, functional unit, allocation method, livestock emission model used, and any other assumptions made during the LCA modelling exercise.

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[3] doi: `10.1016/j.jclepro.2021.126192`

Sec. 5: **LCA results** — Summarizes the life cycle impacts (LCA outputs) of Ontario-specific sheep farming in the categories of climate change (global warming), energy demand, and water use. Results are compared to literature values, where applicable. A breakdown of direct emissions from livestock is also provided. This work is published in *The International Journal of Life Cycle Assessment* (Bhatt & Abbassi, 2022a).[4] The published work includes parts of sec. 3 and 4 as well.

Sec. 6: **Environmental claims through LCA** — Provides a framework for making 'self-declared' environmental claims through LCA in the Canadian context. A checklist of eight requirements for making environmental claims are created using Canadian guides on environmental labelling. The sensitivity / uncertainty analysis methods required for this framework are also described. Work on the sensitivity metric created for this study is published in *Integrated Environmental Assessment and Management* (Bhatt & Abbassi, 2022b).[5]

Sec. 7: **Environmental framework – Results** — Applies the framework described in sec. 6 to the present Ontario sheep case study. Influential farming practices are identified (through sensitivity analysis) and changed to create alternate 'environmentally friendly' farming scenarios. Life cycle impacts between the current and the alternate scenarios (gauged through uncertainty analysis) are found to be reduced by 25% – 31% for all three impact categories.

Sec. 8: **Conclusions & Recommendations** — Summarizes the work done for this study and provides recommendations on further improvements to the LCA model. One of the suggestions made is to include the effect of carbon storage / sequestration from changes in on-farm land management practices. This section also provides preliminary results of the impact of this inclusion on the overall average GW score found in this study.

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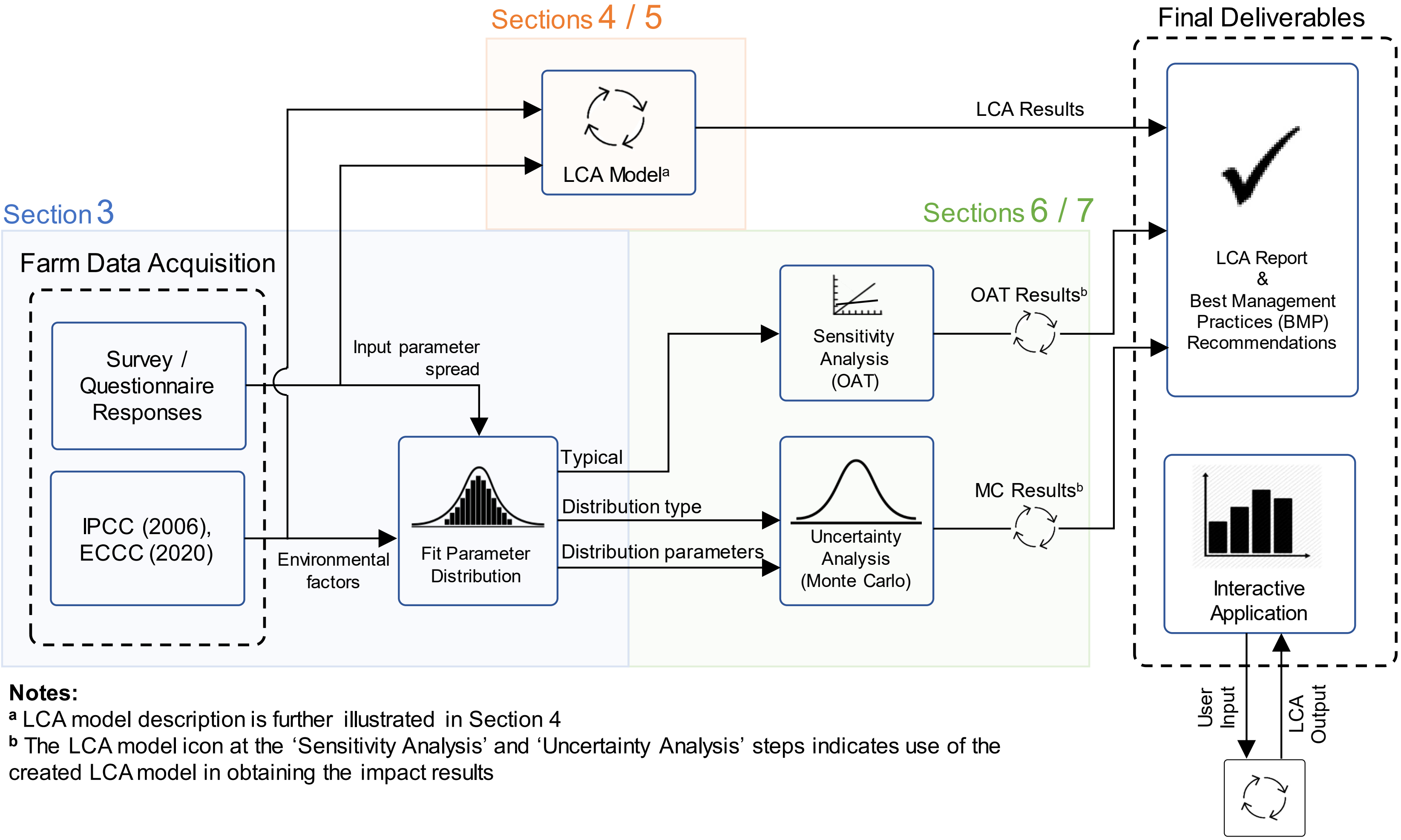
[4] doi: `10.1007/s11367-022-02105-1`

[5] doi: `10.1002/ieam.4701`

Fig. 1 Study approach



Notes:

[a] LCA model description is further illustrated in Section 4

[b] The LCA model icon at the 'Sensitivity Analysis' and 'Uncertainty Analysis' steps indicates use of the created LCA model in obtaining the impact results

1.3.1. *Supplementary data*

The LCA model code, input parameters (primary data), and full LCA results (including Ontario-specific impacts, sensitivity analysis, and uncertainty assessment) from this study are available on GitHub under the General Public License (GPL-3.0).[6]

The executable for the interactive LCA application can be downloaded through Google Drive.[7] It will require the installation of MATLAB Runtime[8] before execution.

The calculations / code for the LCA model local sensitivity metric created for this study is available on Mendeley (Bhatt, 2022) [DOI: 10.17632/B2YWNZVV82.1] under the Creative Commons License (CC BY 4.0).

The pdfs of the majority of articles and reports cited in this document can be accessed through OneDrive.[9]

This data is made available so that others may i) reproduce and verify our work with ease, and ii) continue to improve on our work.

2 | Review of LCA in sheep farming

In preparation for the project, the current state-of-the-art on life cycle assessment in the sheep sector was established and published in the *Journal of Cleaner Production* (Bhatt & Abbassi, 2021). This section summarizes the findings of the published article.

Key LCA studies in the sheep sector within the last fifteen years are reviewed (30 in total, 27 of which are peer-reviewed), and their methodologies and findings are categorized by sheep products, system boundary, impact categories, allocation, enteric emission model, and farm classification. A paucity of LCA studies (compared to LCA studies in other agricultural sectors)[10] is noted in this review paper, and the heterogeneity in methodologies among the studies – particularly in allocation, enteric emission modelling, and farm classification – have resulted in wide-ranging life cycle impact scores for sheep products. In the category of global warming, the life cycle impacts associated with sheep meat, milk, and wool fall in the range of 5 to 25 kg CO_2 eq/kg liveweight, 2 to 5 kg CO_2 eq/kg fat and protein corrected milk (FPCM), and 20 to 60 kg CO_2 eq/kg greasy wool, respectively.

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[6] `github.com/akoolbhatt/ON-sheep-LCA`

[7] `drive.google.com/drive/folders/1UebETnueokgE5ZwuZ5wWkb9G1Mw5Z8aU`

[8] Freely available on `mathworks.com/products/compiler/matlab-runtime.html`

[9] `uoguelphca-my.sharepoint.com/:f:/g/personal/akul_uoguelph_ca/ErUSFtwySOhJu5iDSl4YiroBXvMvN-0SmsVATeEOQk-j_Q?e=Qgxbbh`

[10] LCA research in agricultural sectors other than sheep are more prevalent in literature. In fact, several Canadian LCA studies on dairy (Arsenault *et al.*, 2009; McGeough *et al.*, 2012), beef (Beauchemin *et al.*, 2010), poultry and egg (Turner *et al.*, 2022), and pork (Vergé *et al.*, 2016) can be found in the peer-reviewed space. Organizations such as and Dairy Farmers of Canada, Chicken Farmers of Canada, and Canadian Pork Council have also utilized LCA internally to benchmark their environmental performance, but their reports are not always readily available

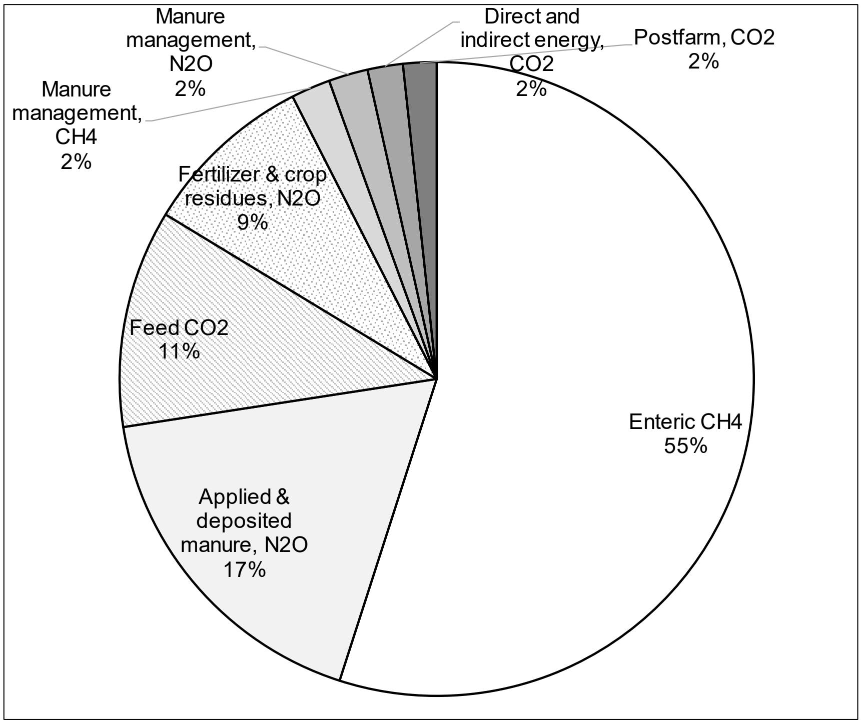

Fig. 2 Breakdown of GHG emissions from small ruminant supply chains

The majority of studies have focused on estimating the life cycle global warming impacts (measured in greenhouse gas (GHG) emissions) using a "cradle-to-farmgate" system boundary, whereby the impacts of all upstream processes up to the point where the sheep product leaves the farmgate are included. Impacts associated with processing of sheep products beyond the farmgate are rarely considered. The primary enterprise for over 70% of the studies in the literature was sheep meat.

2.1. BREAKDOWN OF GHG EMISSIONS

Fig. 2 shows the average literature-observed breakdown of GHG emissions from sheep production. The primary contributor to global warming for the vast majority of studies are GHG emissions from livestock through methanic (CH_4) enteric fermentation, making up between 40% to 75% of overall global warming impacts. For intensive and extensive production systems, GHG emissions associated with feed production and manure management is generally the next largest contributor to global warming, respectively. 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.

2.2. 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. Virtually all studies have utilized emission model created by the Intergovernmental Panel on Climate Change (IPCC), which categorizes enteric emissions' estimation into three tiers (IPCC, 2006). 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. In literature, the majority (57%) of studies have utilized tier 2 (or equivalent) method; the remaining have used tier 1 factors to estimate direct enteric emissions from sheep.

2.3. ALLOCATION

The most popular form of allocation found in literature is *economic*, meaning that impacts are allocated based on the relative income generated by each co-product (allocation methods are further discussed in sec. 4.2.3). It is selected based on the assumption that incomes and revenues are the most important driver of production and management choices. In the literature reviewed, 67% of studies have utilized some form of economic allocation. Economic factor allocations for each reviewed study (where available) vary depending on the primary product of the farm and the surrounding markets. As an example, economic allocation factors where meat is the primary product range from 40% – 100%. For wool (as the primary product), they range from 1% – 70%. 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%.

2.4. 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.

In literature, the majority (60%) of studies which assessed the relationship between intensification and GHG emissions observed that more intensified operations had lower emissions due to better feed management and greater control over animal breeding options. For these studies, the difference in global warming impacts between intensive and extensive varied from mild (4.5% reduction) to strong (30% reduction). However, these studies did not identify the effect of the quality of grazing/feeding, climate, and management choices such as efficiency of fertilizer use and selective breeding on overall GHG emissions.

3 | Statistics on Ontario sheep farming

Due to variation in farming practices and production demand from region to region, the variables which affect LCA results also vary dramatically between regions. This imposes the need for locally-relevant input parameters, requiring the acquisition of primary data. Furthermore, sensitivity / uncertainty analyses, often utilized in 'ecolabelling' programs, also require sample data upon which statistical distributions of LCA input parameters may be created.

This section summarizes the data on Ontario sheep farming collected for this study. Specifically, it describes the methodology used for data collection and analysis, descriptive statistics of the data obtained from surveys, and details on statistical distributions fitted to the data (which serve as inputs for the LCA model). Any statistical relationships between farm productivity and production practices are also determined here. Specifically, an important assumption made by Groupe AGÉCO (2017) in their report to OSF on whether a difference in parameter values between annual and accelerated lambing systems exists is verified by comparing their claims to the observed survey data.

The data acquisition task for this project was originally separated into two phases. Phase I consisted of gathering Ontario-specific, farm-level primary data on:

a. Livestock population, mortality / cull rates, body weight distribution
b. Primary enterprise: annual number / amount of products sold
c. Lambing period: number of lambings, lambing season, birth ratio
d. Livestock activity, as defined by IPCC (2006, vol.4, ch.10)
e. Feeding/grazing practices: feed composition and amounts
f. Manure management: manure production and management systems in place
g. Farming resource use: farm area / type, water usage, fertilizer application rate
h. Animal needs: water intake, bedding straw, etc.
i. Indoor infrastructure: barn / shed area, electricity, heating, and electricity usage
j. Transportation: mass, distance, and type

Phase II data collection was intended to address any gap in data remaining from phase I and to collect farm-level monetary input/output data. Phase I data has been acquired through surveys and is the subject of this study. However, due to various delays in acquiring survey results and inability to visit farms (both caused by COVID-19), phase II acquisition had been cancelled, and the following goals are excluded from the final analysis:

- Eutrophication impacts; due to lack of farm-level data on soil management and more detailed fertilization practices
- Life cycle costing; due to lack of data on monetary inputs/outputs at the farm level (Aggregate data and budgeting tools are already readily available; see OMAFRA (2010a), OSF Budgeting Tool (2022), and OSMA (2012a, 2012b))

Despite these exclusions, the phase I data collected is deemed sufficient to meet the main objectives of the study: i) provide a detailed life cycle environmental assessment of sheep farming in Ontario with sensitivity analysis and uncertainty analysis, and ii) provide a sufficient framework for creating ecolabelling criteria.

3.1. DATA COLLECTION / ANALYSIS METHODS

A 16-page survey form was created with the intent of obtaining primary data on sheep farming practices listed above. An initial draft of the survey form was created with consultation from OSF alongside the development of the LCA mode. Survey questions in the final draft were framed to provide all the necessary foreground data on Ontario sheep farming required by the LCA model. The final draft of the survey form was shared with OSF board members during a presentation, which took place in Aug 2021, and approved by the members before it was distributed (by Jenn MacTavish (General Manager, OSF)) to various sheep producers across Ontario between the months of Nov 2021 – Apr 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 Appendix A.

The results of the filled-out surveys, assumed to be representative of the provincial sheep farming practices, are used as sample data for LCA input parameters (described in Appendix C). Survey results are inputted manually into a spreadsheet program, and any further analyses, including data transformation, descriptive statistics, hypothesis testing, regression analyses, and distribution fitting are done using the MATLAB® programming language.

In the survey, 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 transformed after the raw data was entered into the database.

Feed production is typically the second largest contribution to life cycle global warming impacts (sec. 2), 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) are 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.

Other, non-feed-related estimates of farm infrastructure and inputs such as farm area, electricity usage, fertilization rates, etc., were filled out on an annual or daily basis for the entirety of the operation and transformed after raw data entry. Where applicable, all input parameters are normalized by the scale of operation, represented either through the sheep population on farm or total area of farm, to facilitate comparison of farming practices between (often drastically) different farm sizes.

3.1.1. *Statistical procedures*

Unless otherwise stated, all tests of significance of difference are performed using a 2-tailed Welch's 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% (i.e., $P < 0.05$).

All samples are graphed on normal Q-Q plots and visually inspected for normality. Outliers are also identified using Q-Q plots and, where applicable, rejected using Dixon's Q test. The spread of all samples is graphed onto boxplots for visual inspection before appropriate distributions are fitted onto them (Appendix B). The goodness of fit of distributions is assessed using the Anderson-Darling test at 5% significance level (i.e., $P > 0.05$). Where multiple asymmetric distribution types are applicable, the distribution associated with the largest P is chosen.

3.2. FOREGROUND DATA ON SHEEP FARMING PRACTICES

Survey responses from 23 farms 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). A summary of farm classification is provided in Table 1.

Finished lamb is the primary economic 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). This low economic value of wool in Ontario is consistent with findings from wool production in Eastern (Corscadden *et al.*, 2017) and Western Canada (Dyer *et al.*, 2014). Between 20% – 30% of farms keep other animals, including cattle, pigs, chickens, and goats. The same proportion 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.

3.2.1. *Farm population & productivity*

Table 2 summarizes the sheep population statistics on farm. 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 weighs 72 (± 1.4), 89 (± 1.9), and 39 (± 1.0) kilograms, respectively. The estimates of lambing percentages, mortality rates, and body weights are consistent

Table 1 Farm classification summary, lists the number (and %) of farms

Number of farms surveyed		**23 (100%)**
Farms with ewes	15 – 100	11 (48%)
	101 – 500	8 (35%)
	>500	4 (17%)
Farms with sheep products	Meat	23 (100%)
	Wool	13 (57%)[a]
	Milk	2 (9%)[a]
	Annual lambing systems	15 (65%)
	Accelerated lambing systems	8 (35%)
Farms which purchase feed externally[b]	Grains	6 (26%)
	Roughage	19 (83%)
Farms with other animals	Cattle	7 (30%)
	Chicken	6 (26%)
	Goats	3 (13%)
	Other	4 (17%)
Farms with other product outputs	Beef	7 (30%)
	Grains[c]	5 (22%)
	Hay / straw	4 (17%)
	Chicken / eggs	4 (17%)

[a] Primary enterprise of wool and milk producing farms is still finished lamb (> 95% economic allocation to sheep meat)

[b] Remaining farms predominantly grow their own feed

[c] Corn, soybean, or wheat

with the performance targets suggested by the 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) kilogram of wool was sold annually per adult ewe and ram, respectively. The amount of wool from lambs which was sold was negligible (0.2 kg/head/year).

3.2.2. *Feeding / grazing practices:*

Table 2 also lists the annual average sheep dietary practices employed by the surveyed farms. 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 and concentrates, however; 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. Between 0.3 – 0.5 kilograms of grain are consumed per head daily, consisting of, on average, 55% corn, 20% barley, and 20% oats; the remaining 5% consists of other miscellaneous grains such as wheat, soybeans, etc. The roughage to grain ratio for adult sheep observed from sample data is consistent with the guidelines provided by OMAFRA (2010b), 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 liter per adult sheep and 2.8 liter per lamb. These estimates are slightly below the recommendations provided by OMAFRA (2019).

3.2.2a FARMING PRACTICES & PRODUCTIVITY Identification of farming practices which maximize (or at the very least, increase) productivity is beneficial from an environmental perspective, because a higher ratio of product output to material and energy inputs directly lowers the environmental footprint of the farm per functional unit. For example, the Groupe AGÉCO (2017, sec. 7.2) report presented to the OSF concluded that the life cycle impacts per kilogram live weight from accelerated systems are lower, primarily due to a higher lambing percentage in accelerated systems. Some peer-reviewed sheep LCA studies have also established the significance of relationships between number of lambings (Batalla *et al.*, 2015; Ripoll-Bosch *et al.*, 2013), lambing rate (Jones *et al.*, 2014), feed intake (O'Brien *et al.*, 2016; Toro-Mujica *et al.*, 2017) and farm productivity. Are these relations observed in the Ontario-specific sample data collected for this study? Linear 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'.[11] A total of 36 linear regression analyses between these two metrics (treated as response variables) and the following parameters were 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; and vii) livestock activity percentage – fattening lambs. No significant relationship between any pairwise combination of any of these nine parameters is found. XY plots of some of these covariates are presented in Fig. B1, which clearly show no sign of a relationship between farm productivity parameters and farm practices parameters.

Based on the reported number of lambings per year, farms were separated into annual lambing and accelerated lambing systems, and two parameters – 'lambs per ewe' and 'lamb mortality rate' – between the two groups were tested for significance of difference. Despite claims from the Groupe AGÉCO (2017, pp.9-10) report,[12] there

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[11] These two productivity parameters are chosen because local sensitivity analysis showed them to have the largest effect on life cycle impacts

[12] AGÉCO report uses 1.4 and 2 lambs per ewe for annual and accelerated systems, respectively

does not seem to be a meaningful difference in the number of lambs per ewe or lamb mortality rate between annual and accelerated lambing systems, at least for the 23 farms sampled so far. Daily grain intake by lambs for accelerated systems is observed to be higher ($P = 0.02$), but total (grains + roughages) daily feed intake is not meaningfully different between the two systems.

3.2.3. *Farm infrastructure & 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. 38% (± 7%) of all sheep manure produced is also spread on pastures. The remaining 47% (± 5%) and 14% (± 5%) is 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 greater than 3× larger 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) litres 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 round-trip transportation distance for livestock auction house, slaughterhouse, etc., is 171 (± 34) km approximately, and average distance for purchased grains and fertilizer is 78 (± 25) and 30 (± 9) km, respectively. The total annual mass-distance transported per head is 11,085 (± 2,458) kg·km on average, from which nearly 65% is due to transportation of grains.

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

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 [m²/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/day]	63.3 (± 35.8)	0 - 4.6 - 39.0	(0, 300)
TRANSPORT	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, 14806)
		Grains	7239 (± 1842)	705 - 3825 - 13588	(0, 22237)
		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

3.2.3a OPERATION SIZE & FARM INPUTS Farm inputs such as farm area, electricity use, fertilization rate, diesel use, etc. will logically change based on the sheep population on farm; a larger population will require a greater number of inputs, and vice versa. This correlation (or dependency) violates one of the assumptions of Monte Carlo (MC) simulation: input variables need to be independent from each other.[13] Correlation among input variables can exaggerate farm input demand and severely overestimate or underestimate the results (USEPA, 1997). Any correlation among input variables must first be identified, and if detected, the data must be transformed or normalized such that the correlation is removed, and variables could be safely assumed to be independent from each other.

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 dependence 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 Fig. B2, also show no sign of a relationship between the operation scale and farm inputs. The normalized parameters can be safely treated to be random independent variables for Monte Carlo uncertainty assessment. Hence, normalized farm infrastructure and input data (Table 3) is used in the LCA model. Note that although no relationship between annual plastic use and operation size was found, plastic usage is normalized by total population on farm as well for consistency's sake.

3.3. STATISTICAL DISTRIBUTIONS OF SAMPLE DATA

Quantifying uncertainty in LCA impacts of sheep farming in Ontario requires a statistical distribution of provincial farming practices and environmental factors (i.e., input parameters for the LCA model). The data collected from the surveys is used to fit a theoretical distribution, from which farming practices representative of the provinces can be simulated through random repeated sampling. Each set of random inputs can be passed through the LCA model to obtain a set of LCA output results. This process, illustrated in Fig. 3, forms the basis for Monte Carlo (MC) simulation. The centre (mean, median, etc.) of the distribution of output LCA impacts (MC results) could be characterized to be the average or most-likely environmental impacts of sheep farming in Ontario, and the uncertainty in the average impacts could be estimated through the dispersion (e.g., standard deviation) of the distribution of output impacts.

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[13] Methods for simulating correlated random variables exist but require a sufficiently large sample size

Based on a one-at-a-time (OAT) or global sensitivity analysis of input parameters, a set of influential (sensitive) input parameters could be chosen for setting ecolabelling criteria. A new distribution for the sensitive input parameters representing 'ideal' practices may be created, and the same process described above could be used to obtain a set of LCA results for the more environmentally-friendly, 'ideal' farming practices. The difference (and significance of difference) in environmental impacts between the current baseline practices and 'ideal' practices could be determined via statistical inference (hypothesis testing).

3.3.1. *Distribution fitting*

Sample data for each variable is plotted on normal Q-Q plots (Fig. B3) and boxplots (Fig. B4) to visually inspect if the data follows a normal distribution. A Q-Q plot is a plot of the quantiles of a data set against a quantile of a known theoretical distribution (in this case, normal distribution), while a boxplot is used to graphically demonstrate the locality, spread and skewness groups of data through their quartiles. Underlying data is approximately normal if datapoints on a Q-Q plot appear to be a straight line. Possible skewness or kurtosis in non-normal data is noted using these plots, and outlier are also identified.

Q-Q plots suggest that the majority of important farm variables appear to be approximately normally distributed along the centre. Any skewness on the upper end is due to outlier presence, and skewness on the lower end is due to lower-limit constraints imposed on the data (i.e., data values for parameters such as lambs per ewe, grain intake, farm area, transport distance, etc. clearly cannot be less than zero (0)). Some parameters, such as 'wheat%', 'liquid MS', 'Activity% - hilly grazing', etc., appear to be horizontal lines. This is due to their relatively low importance in farming practices (i.e., very few farms use wheat as a feed type or manage liquid manure).

The boxplots do a better job of presenting the symmetricity of the data and serve as a useful aide in selecting an appropriate distribution type for the data. For example, the median of 'lambs per ewe' is (more-or-less) equidistant from both the lower and upper quartiles. Therefore, a normal distribution is a good fit for this parameter. The median of 'adult ewes' is much closer to the lower quartile, however, and appears to be skewed to the right. Therefore, an asymmetric distribution such as log-normal distribution would make a better fit for this parameter.

The Anderson-Darling (AD) test (at $P > 0.05$) is used to first confirm that the sample data for variables suspected to be normal are actually drawn from normal distribution. For non-normal data, various asymmetric statistical distributions are fitted, and the AD test is again used to confirm that a good fit is achieved. Values of 0 (zero) for all asymmetric data were turned into 0.0001 so that asymmetric statistical distributions (e.g., lognormal, Weibull, etc.) may be applied to the data.

The histogram and the statistical distribution chosen for each variable (LCA input parameter) are presented in Fig. B5. The bin width of histograms is determined using the Freedman–Diaconis rule. The details of the fitted distribution for each variable along with its AD test p-value is listed in Table B1. All distributions appear to be a good representation of the underlying data ($P > 0.05$). Note that while the histogram for each

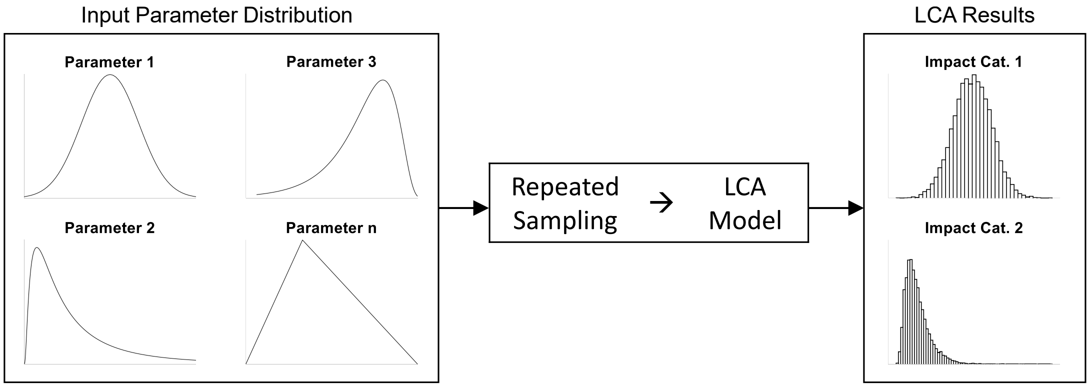

Fig. 3 Conceptualization of uncertainty propagation using Monte Carlo (MC) analysis

sample contains all the data-points, including any potential outliers, the distributions overlayed on the histograms does not consider the outliers.

Although some producers have reported wool production rates in their survey responses (Table 2), their estimates are suspected to be under-reported. This is likely due to the negligible economic value of wool from these farms; producers are reporting the wool amount that they've sold, not the wool amount produced. However, an accurate estimate of wool *production* is needed to determine the net energy requirements of the livestock. Thus, wool production rates from Brock *et al.* (2013), Eady *et al.* (2012), and Jones *et al.* (2014) are used for fitting the statistical distribution for the wool production-related parameters (instead of using the survey sample data).

There are several environmental coefficients and conversion factors not controllable at the point of production whose statistical distributions are also required for the final environmental impact assessment. The data for these distribution are obtained from ECCC (2020) and IPCC (2006, 2014); see sec. 4 for more details.

4 | LCA modelling of sheep production

Livestock LCAs are typically model-based, whereby farming choices and operational practices of the producer serve as inputs in an LCA model, which then outputs the environmental impacts associated with said set of choices (represented through input parameters). The section details the creation of the LCA model, made specifically for this study.

Fig. 4 conceptualizes the LCA modelling 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 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, collected via surveys mailed to the province's sheep producers (summarized in sec. 3), is used to create sample datapoints for each input parameter. The LCA model is run 23 times, once for each set of farm inputs, and the statistics of the resulting LCA outputs are summarized and discussed (in sec. 5) from the full model outputs. Instructions for accessing the model outputs can be found in Appendix C.

The input parameterization, LCA modelling, and output (tables and graphs) generation is done using the MATLAB programming language.[14] The LCA model code utilizes a 'process matrix' framework 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% ($P < 0.05$).

4.1. REFERENCE GUIDELINES

The LCA approach defined by ISO (2006b, 2006c), described below, provide 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:

1. 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
2. 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, allocation decision tree, 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 com-

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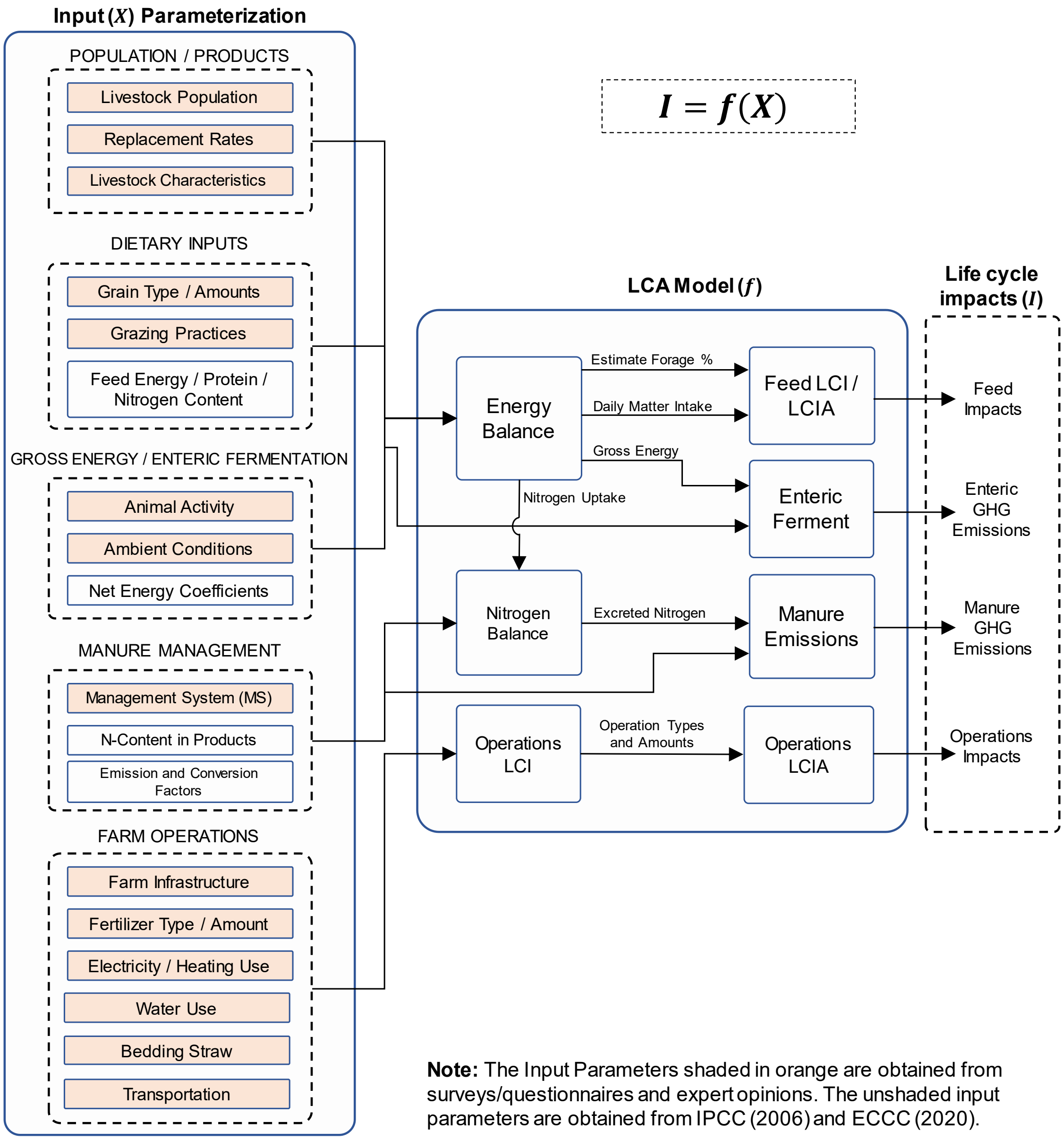
[14] `matlab.com`

Fig. 4 Conceptual overview of input parameterization and LCA model



Note: The Input Parameters shaded in orange are obtained from surveys/questionnaires and expert opinions. The unshaded input parameters are obtained from IPCC (2006) and ECCC (2020).

prised 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 (sec. 4.2.4).

4.2. LCA APPROACH

Virtually all life cycle assessment studies follow the ISO standards 14040 and 14044 (2006b, 2006c), which define the framework and provide guidelines for conducting an LCA. LCA studies are comprised of four stages (Fig. 5), namely:

i. Goal and scope definition,
ii. Life cycle inventorying (LCI),
iii. Life cycle impact assessment (LCIA),
iv. Interpretation of results.

The goal of the study is addressed in sec. 1.2. The scope of the study (system boundary, functional unit, and allocation method) is discussed in the following subsections.

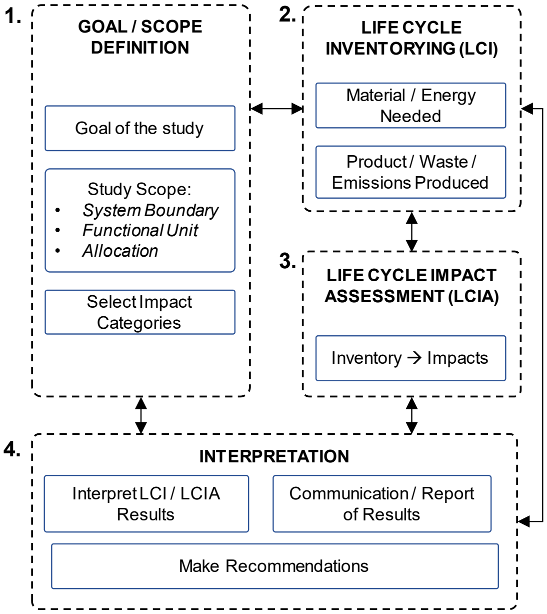


Fig. 5 ISO-defined LCA framework

Impact categories chosen for LCIA are listed in Table 4; a brief description of impact categories and the impact factors used in the model can be found in the full LCA model files (Appendix C). Climate change and water conservation in the agricultural sector is deemed important by Agriculture and Agri-Food Canada (2022). Thus, impact categories chosen are global warming (GW), non-renewable (fossil, nuclear and non-renewable biomass) energy demand (ED), and water depletion (WD).

GW impacts are estimated using 100-year GHG characterization factors provided by IPCC (2013). Non-renewable ED impacts are determined using characterization factors from the CED method (Hischier *et al.*, 2010) and making factor values associated with renewable energy sources to be 0 (zero). WD impacts are determined using the ReCiPe 2008 midpoint method (Goedkoop *et al.*, 2008). This method uses a WD characterization factor of 1 m^3/m^3 for all water sources (lake, river, well, etc.), meaning water extracted from any source is assumed to have an equal impact on WD. Thus, WD impacts, as defined here, can be interpreted to be simple 'water use' impacts.

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) using Canada-specific environmental factors, obtained from 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 & Nemecek, 2007; Wernet *et al.*, 2016). Note that global (i.e., globally averaged) ecoinvent process

Table 4 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 (Hischier *et al.*, 2010)
Water Depletion (WD)	m^3 water	ReCiPe (H) 2008 (Goedkoop *et al.*, 2008)

are 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·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). Foreground data on these processes is summarized in Tables 2 and 3.

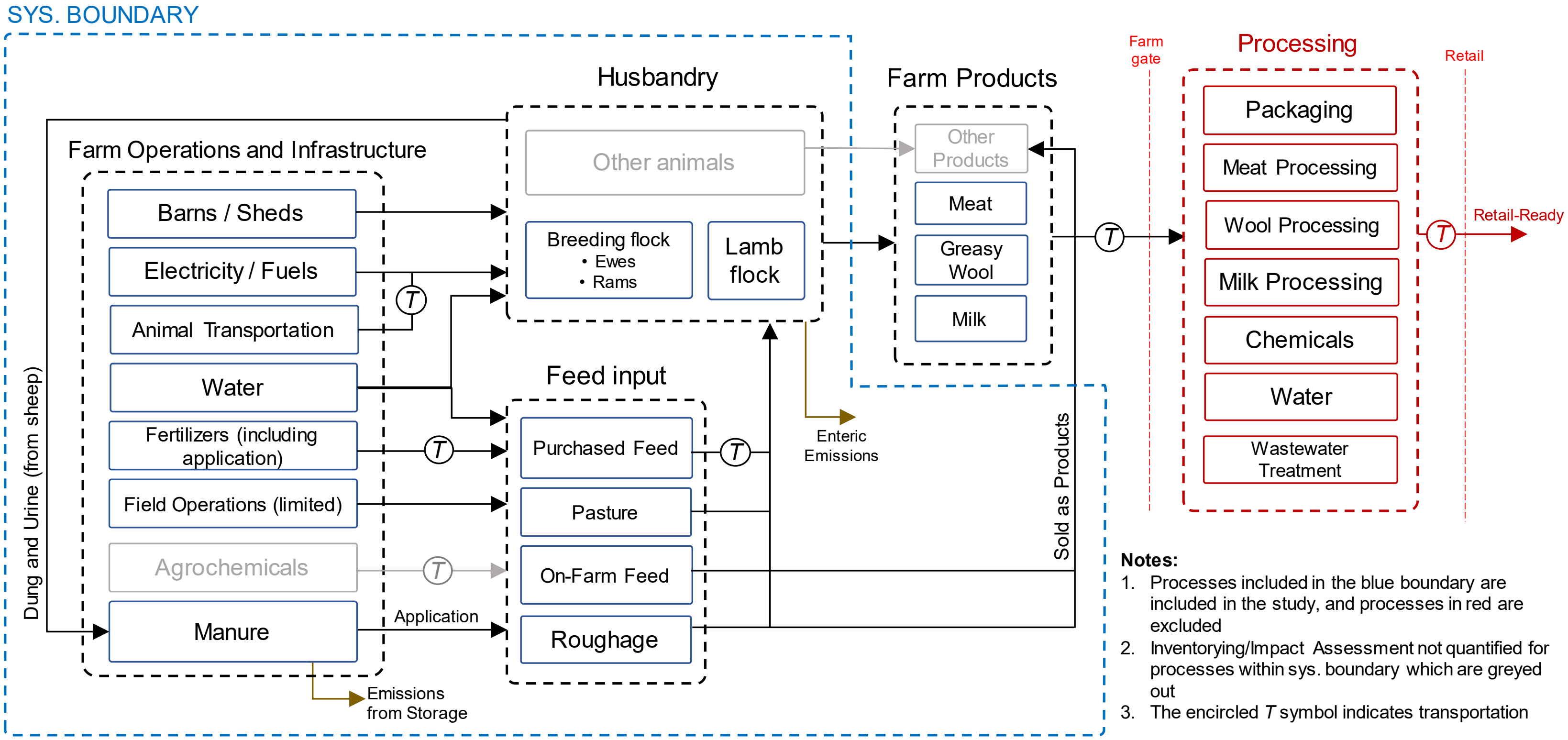
4.2.1. *System boundary*

An LCA system boundary defines the processes whose impacts are considered in the assessment. It typically follows the supply chain logic relevant to the sector, starting from raw material extraction to the point at which the reference flows (i.e., products defined by the functional unit) are produced. Majority of LCA studies in the livestock sector are "cradle-to-gate", whereby life cycle phases from the extraction of raw materials to the point at which the product leaves the farm gate are considered in the study. 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 (sec. 2). Processes beyond the farm-gate such as finishing lamb, wool scouring, milk processing (and the associated use of consumables, packaging, energy, refrigeration, etc.) and end-of-life scenarios are generally not included in assessments; though exceptions do exist (Bhatt & Abbassi, 2021).

The cradle-to-farmgate system boundary used for the present study is shown in Fig. 6. 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 sec. 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.

Fig. 6 System boundary diagram of LCA model



Notes:

1. Processes included in the blue boundary are included in the study, and processes in red are excluded
2. Inventorying/Impact Assessment not quantified for processes within sys. boundary which are greyed out
3. The encircled *T* symbol indicates transportation

4.2.2. *Functional unit*

LCA is a relative approach, and results of the LCA of an operation need to be normalized with respect to the function the operation provides. Hence, all LCA studies present their impact results relative to a functional unit, which is a quantified performance of the function of the operation(s). Comparison of impacts based on functional units allows for a direct comparison of impacts between operations producing similar products with drastically different scales and practices, and it lets decision-makers or consumers make "apples-to-apples" comparison of different products with similar functions (e.g., wool vs. acrylic fibers).

The primary sheep product of the vast majority of sheep farms in Ontario is lamb meat (sec. 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; Colley *et al.*, 2020; Sim & Prabhu, 2018; Wiedemann *et al.*, 2016) and milk (Batalla *et al.*, 2015; Furesi *et al.*, 2015; Sabia *et al.*, 2020; Vagnoni *et al.*, 2015) 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 (Frischknecht *et al.*, 2007; Gerber *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.

4.2.3. *Allocation*

For operations with multiple product outputs (e.g., meat, wool and milk), the estimated impact values of the entire supply chain (as defined by the system boundary) need to be allocated to each product to determine the impacts associated with individual products. For any category of impact, the impact value per functional unit, I_p, associated with any sheep product p is:

$$I_p = \frac{I_T}{A_p} \times Alloc_p \tag{1}$$

where I_T is the total annual impact of the supply chain in consideration, A_p is the annual amount of product p produced in the units defined by the functional unit (kg LW, in this case), and $Alloc_p$ is the allocation factor attributed to that product. The sum of the allocation factors of all the products in the supply chain should add up to 1 or 100%.

There are several methods through which allocation factors can be determined. The choice of allocation method for handling co-production can significantly alter the final impact values associated with each of the co-products, especially when the impact score is being used for benchmarking or comparison to other products.

In literature (reviewed in sec. 2), most studies allocate impacts based on economic value of each co-product (e.g., if 95% of income is generated from sheep meat sales and the remaining 5% is generated from wool sales, the allocation factor for sheep meat and wool using economic allocation would be 95% and 5%, respectively). Use of economic allocation is typically justified based on the assumption that revenue generation potential is usually the most important driver of production, and management choices at a farm level are primarily influenced through economic benefits. Benchmarking of LCA impacts using economic allocation also incentivizes the marketing and selling of all co-products, thereby discouraging product waste.[15] Use of economic allocation is generally discouraged by ISO (2006c), however, unless used as a last resort, as there is also no direct, causal relationship between the relative monetary value of co-products and their relative environmental impacts. Economic allocation can also make direct comparisons between farms with vastly different enterprises challenging, and it can vary the impact scores over time due to market fluctuations or price interventions.

ISO (2006c) recommends that where allocation is required,[16] it should be based on physical or causal relationships. Only two peer-reviewed studies on sheep LCA have considered physical allocation: 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 (PMA) as one of the recommended allocation methods. FAO (2016) also recommends allocation based on protein requirement if livestock co-products are meat and fibre (wool), as fibre 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 FAO (2016) and Wiedemann *et al.* (2015)). The PMA factors calculated for the 23 sampled Ontario farms are plotted in Fig. 7(a).

4.2.4. *Enteric fermentation & manure management*

Ruminant animals emit CH_4 through the process of enteric fermentation, and both CH_4 and nitrous oxide (N_2O) 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

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[15] Impact scores of any primary product using economic allocation will always be lowest when the income generated through secondary co-products is maximized

[16] ISO (2006c) recommends that allocation be avoided altogether by dividing the main process into subprocesses. It is not possible to separate the inventory associated with each co-product (e.g., 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

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 (ECCC) 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). Environmental factors used for estimating livestock emissions are presented in Appendix C.

4.2.5. *Energy balance*

Estimates of daily dry matter intake (DMI) of grains and roughages are obtained through primary data collection (Table 2). 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:

$$DMI_{forage} = \frac{E_{req} - \left(\sum_{i=1}^{n} DMI_{grain,i} E_{grain,i} + \sum_{i=1}^{m} DMI_{roughage,i} E_{roughage,i}\right)(1-W)}{E_{forage}} \tag{2}$$

where DMI_{forage} [kg/head/day] is the daily 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 eqn. 2 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.

4.2.6. *Nitrogen balance*

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.:

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

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 $N_{product}$ is the nitrogen content in the feed and the products, respectively. $A_{product}$ of the two sheep products relevant to Ontario (meat and wool) are obtained through primary data collection (Table 2). 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 eqn. 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 sec. C2. 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 eqn. 3 can then be used to find $N_{excreted}$ explicitly.

5 | LCA results

This section summarizes the LCA results for sheep production, obtained by passing the primary data on Ontario sheep farming practice (sec. 3) through the LCA model (sec. 4).

Breakdown of life cycle impacts per functional unit (kg LW) is listed in Table 5 (see Appendix C for instructions on viewing full model results). Average (± standard deviation) global warming (GW) impacts of Ontario 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. 7) 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 global literature-observed values of 3.6 – 25.9 kg CO_2 eq/kg LW (Bhatt & Abbassi, 2021). 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

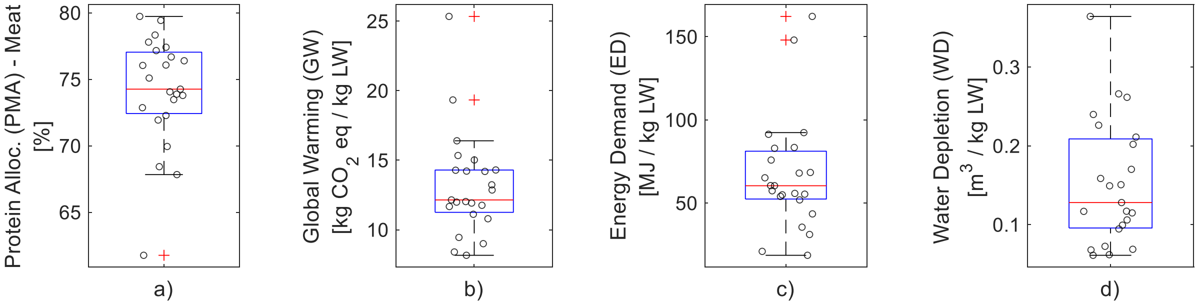

Fig. 7 Boxplot (and datapoint scatter) of a) protein mass allocation (PMA) factors towards meat; and total impacts in b) global warming (GW), c) energy demand (ED), and d) water depletion (WD)

range of 25% – 65% observed in the literature; although some studies have reported the relative contribution of enteric emissions to GW to be much higher (70% – 90%) (Biswas *et al.*, 2010; Brock *et al.*, 2013; Dougherty, 2018; Mohan *et al.*, 2018; Sabia *et al.*, 2020). The GW impact scores and impact breakdown from this study also agree with the GLEAM results (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; O'Brien *et al.*, 2016; Wiedemann *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 (Dougherty, 2018; Uusitalo *et al.*, 2019; Wiedemann *et al.*, 2016) 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 5 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% – 79.7% (Fig. 7). 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.

5.1. 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 (AHDB, 2018; Brock *et al.*, 2013; Cottle

Table 5 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**[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[b]	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%]**

[a] Not applicable
[b] Includes water consumption by sheep

et al., 2016; Kilcine, 2018; O'Brien *et al.*, 2016; Ripoll-Bosch *et al.*, 2013; Schönbach *et al.*, 2012; Wallman *et al.*, 2011), but very few report their estimates.[17] Considering the importance of NE in IPCC-based estimation of livestock (enteric and manure) emissions, which altogether contribute to half of overall GHG emissions (Table 5), NE values are reported here in Table 6. Average (± standard deviation) per-head daily NE requirements for adult sheep and lambs is 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 6) and sheep population on farms) is shown in Fig. 8. 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).

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

Using energy balance (sec. 4.2.5), 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 AHDB (2019), FAO (2016), and IPCC (2006). On average, 81% and 63% of DMI by adult sheep and lambs, respectively, is 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 (sec. 4.2.6) 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.[18] 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 no other input parameter, including grain intake, livestock body weights, animal activity, or birthing ratio had a significant effect on enteric emissions.

5.2. 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

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[18] 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 sec. C2), but they of course cannot be altered to reduce enteric emissions. Hence, they were not considered here

Table 6 Per-head average (± standard deviation) estimations of net energy (NE), gross energy (GE), daily dry 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 EMISSIONS	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

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 5) 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.

5.3. FARM INFRASTRUCTURE & MISC. INPUTS

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).

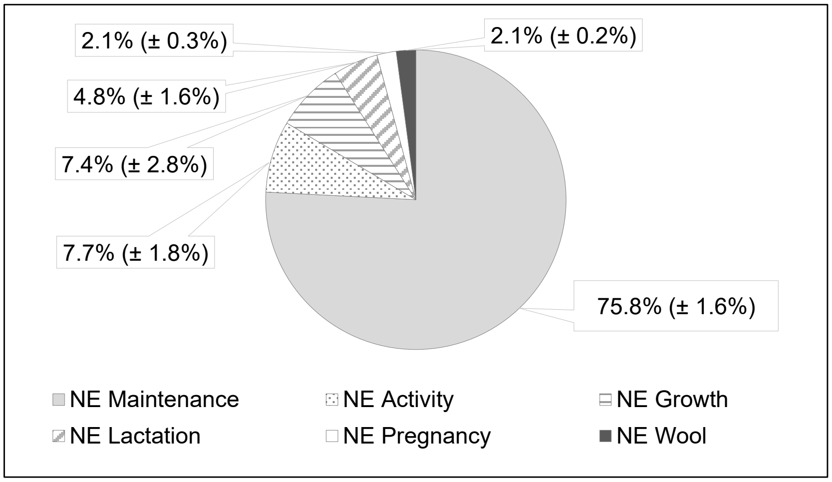

Fig. 8 Average (± standard deviation) contribution of each IPCC (2006) component to livestock net energy (NE) requirements

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.

5.4. FARM CLASSIFICATION VS. INPUTS

Studies which have attempted to form relationship between farming practices and productivity (sec. 3.2.1) have observed moderate differences in GW impacts between intensive (frequent lambing, higher concentrate, zero grazing) and extensive (traditional, annual lambing, pasture-based) sheep farming operations. In the majority of cases, the carbon footprint of more intensive operations was lower compared to extensive operations (Batalla *et al.*, 2015; Jones *et al.*, 2014; O'Brien *et al.*, 2016; Ripoll-Bosch *et al.*, 2013). 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 ($P > 0.1$).

6 | Environmental claims through LCA

As more and more consumers incorporate the environmental characteristics (e.g., carbon footprint) of products into their purchasing decisions, companies have devised various environmental product information schemes to communicate the environmental impacts of their products and/or services. Ecolabels, for example, have been used to demonstrate the superiority of one product's carbon footprint or water footprint over competing products. However, the value of these claims rests on the assurances that the information provided to consumers is credible and objective. Due to inconsistent criteria and methodologies set by each practitioner, it could become difficult to verify and compare self-declared environmental claims. System boundaries, data sources, or impact assessment methods could also be easily altered to manipulate the overall impact score of a product to its benefit (Bauman & Tillman, 2004; CSA, 2008; Lee & Uehara, 2003; Rubik & Frankl, 2017). The need for international standards related to environmental labelling was recognized by the ISO, and in response, they created standards within the ISO 14020 (2000) family which provided a framework for environmental labelling and declarations. There are numerous ISO standards within this family for evaluation and communication of environmental performance, but the three standards specifically used for green marketing are:

- Type I – ecolabelling programs – ISO 14024 (2018)
- Type II – self-declared environmental claims – ISO 14021 (2016)
- Type III – environmental product declaration (EPD) – ISO 14025 (2006a)

These standards and their applicability are further discussed in Appendix D, but to summarize: type I and III claims must be certified using third party governing bodies, and type II claims (as the name suggests) can be self-declared by the organization making the claim. All three types of claims must still rest on data that is accurate and verifiable. Type I and II claims are communicated to consumers through text or symbols, while type III claims, meant for industries, must present more detailed statistics on their environmental claims. Type III claims are not well-suited for retail consumers due to their technical and rigid nature, and governing bodies which certify type I claims do not facilitate all sectors of the economy. Manufacturers and retailers – particularly in Europe (Rubik & Frankl, 2017, pp.75–77, 164) and Asia (Lee & Uehara, 2003, pp.96–123) – have thus gravitated towards type II claims due to their self-declared nature and more consumer-friendly communication requirements. Due to a higher barrier for implementation of type I and III claims, **type II claims are recommended** for OSF.

6.1. TYPE II CLAIMS IN CANADA

The Canadian Standards Associations (CSA) and Competition Bureau Canada have created a set of guidelines for businesses wishing to implement type II environmental claims: *Environmental claims: a guide for industry and advertisers* (CSA, 2008). The document was created to i) decrease the risk of communicating misleading environmental claims, ii) provide an incentive for producer to improve environmental performance, and iii) increase opportunities for consumers to purchase products with a lower environmental footprint. More specifically, it is intended to be a "best practice guide" for the application of ISO 14021 in the Canadian marketplace and to assist industries and advertisers making type II self-declared environmental claims in complying with the Canadian Competition Act,[19] the Consumer Packaging and Labelling Act,[20] and the Textile Labelling Act.[21] See sec. D2 for more details on CSA (2008).

Despite its length, the guide does not provide explicit steps for the process of making environmental claims, making it difficult for Canadian businesses to employ type II claims simply through the guide. This difficulty is further compounded by an absence of case studies which showcase a proper implementation of type II environmental claims and their enforcement by authorities, especially in a Canadian context. Thus a framework for making type II environmental claims through LCA is created and described in the following sections.

6.2. FRAMEWORK FOR ENVIRONMENTAL CLAIMS THROUGH LCA

A checklist of requirements for environmental claims as well as steps that should be taken to meet the requirements, presented in Table 7, is created with the expectation that any claims made using the methods described here fall within the framework of the laws administered by the Competition Bureau. These requirements reinforce the principles of "preferred" type II claims provided in ISO 14021 (2016) and CSA (2008). A sequence of sensitivity, uncertainty, and scenario analyses (described below) in conjunction with an ISO-standard LCA modelling can be used to ensure that the claim requirements pertaining to scientific rigour, specificity, and transparency (requirement nos. 1 – 6) are adequately met. Requirements related to accuracy and verification of claims (requirement nos. 7 – 8) must be met, respectively, by i) using locally relevant foreground data (on production practices) and background data (environmental factors, LCI / LCIA impact factors, etc.) in LCA modelling, and ii) ensuring (e.g., through auditing) that the foreground data used in the claim are being reflected in the actual production practices.

For the present Ontario sheep case study, the LCA model created for this study (sec. 4) is used to provide and substantiate claims on the *environmental performance* (as defined by Minkov, Lehmann, and Finkbeiner (2020, Table 2)) of Ontario's sheep sector. The metrics used to measure the environmental performance of Ontario sheep production are the total life cycle impact scores outputted by the LCA model using local foreground data (presented in sec. 3). Any reduction of the environmental footprint through changes in production practices is gauged through scenario analysis, whereby

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[19] Competition Act: R.S., 1985, c. C-34, s. 1R.S., 1985, c. 19 (2nd Supp.), s. 19 (current to Nov. 2022)
[20] Consumer Packaging and Labelling Act: 1970-71-72, c. 41, s. 1 (current to Nov. 2022)
[21] Textile Labelling Act: R.S. 1985, c. 46 (1st. Supp.), s. 1 (current to Nov. 2022)

the dispersion (distribution) of impact scores from the current practices is compared to impact score distributions from alternate scenarios representing more environmentally "friendly" practices. The parameters modified in the alternate scenarios are chosen based on the magnitude of their weighted influence on the LCA model. See sec. 6.2.1 for methodological steps.

The methodology shown here aims to balance the three core criteria for ideal environmental claims as stated by ISO and CSA during their conceptualization: claims should be i) accurate (specific), ii) reliable (verifiable and reproducible), and iii) easy to understand by the consumer(s). However, the scenarios described are not to be taken as a final set of benchmarking criteria for making environmental claims but rather as examples to illustrate the application of the methodology. Producers must always be consulted before alternate scenarios for making environmental claims are finalized (this is further discussed in sec. 7.2).

The objective of this framework is to provide a scientifically-sound methodology for making suitable recommendations on changes in practices for any production and for gauging (and presenting) the effect of said changes on the overall life cycle environmental performance of the production. This framework does not provide a guide for *enforcing* these changes in actual practice, for which industry-specific mechanisms at an organizational level must be created, ideally by the same organizations making the environmental claims.

6.2.1. *Sensitivity, uncertainty, and scenario analysis*

The influence of various parameters – representing farming practices or choices – on life cycle impacts is assessed using sensitivity analysis. This forms the basis for parameter screening: values for parameters deemed influential (sensitive) are adjusted in two alternate scenarios representing ideal / improved farming practices (i.e., scenario analysis), and non-influential parameters are left unperturbed from their baseline values. The life cycle impacts of the alternate scenarios are found by passing the adjusted parameter space into the LCA model. The uncertainty in impacts for the baseline and alternate scenarios is assessed through Monte Carlo (repeated sampling) method. The statistical distributions of input samples for the LCA foreground data, needed for Monte Carlo analysis, is obtained iteratively through the Anderson-Darling (AD) test; see sec. 3.3.1 for details.

Parameter influence is ranked through the sensitivity metric *Relative Sensitivity Value (RSV)* on the total life cycle impact score in the impact categories of global warming (GW), energy demand (ED), and water depletion (WD), using the LCIA methods described in Table 4. Bhatt and Abbassi (2022b) describes the methodology behind RSV discusses possible interpretations and applications of RSV. To summarize, the magnitude of a parameter's RSV indicates its local influence in an impact category relative to other parameters. The sign of a parameter's RSV indicates whether increasing the parameter value will raise or lower the impact score: increasing the value of a parameter with a negative / positive RSV will lower / raise the impact score, and the opposite outcome on the impact score is expected if the parameter's value is decreased.

Table 7 Requirements for setting environmental claims and steps taken to meet them; 'claim requirements' partly adapted from Crognale (2009) and CSA (2008)

№	**Requirements for environmental claims**	**Steps taken to meet claim requirement**
1.	Methods used to make claims must be scientifically sound	Use ISO-defined LCA framework
2.	Claims must detail *specific* environmental benefits (e.g., terms such as "green" are too vague)	Use LCI/LCIA to quantify impact reduction in well-defined impact categories
3.	Claims should be accurate: any supportive data needed to verify or challenge the accuracy of the claims must be provided	Provide modelling details and calculations needed to reproduce the metrics used to make the claim(s)
4.	Claims should apply to the entire product life cycle and not just the final product	Use cradle-to-gate life cycle approach
5.	Claims are made on *improvements* to a product (i.e., superiority of one product relative to another product)	Normalize claims by functional unit; use scenario analysis to compare product footprint
6.	Accuracy of claims should not rely on omission of pertinent facts (i.e., misleading claims)	Include all the upstream supply chain processes relevant to the product. Explicitly state any process which are *not* included
7.	Claims should be relevant to the area where the environmental impact occurs	Use locally-relevant foreground and background data in quantifying environmental impacts
8.	Production choices on which the claims are based must be followed in practice	Regular communication and auditing of participating producers

In the parameter screening exercise, 59 (out of total 142) parameters representing environmental factors can be discarded altogether, as producers have no control over them. For the purpose of this exercise, 10 parameters among the remaining 83 producer-controlled parameters deemed influential (through their RSV) are chosen and controlled in two alternate scenarios representing improved practices, described in sec. 7.1. To account for parameter influence in multiple impact categories, a weighted RSV (W_{RSV}), calculated through eqn. 4, is used to rank the parameters' combined (weighted) influence in all the impact categories assessed:

$$W_{RSV_i} = \sum_{j=1}^{m} \left(\frac{|RSV_{ij}|}{\max\left[|RSV_{1j},\ldots,RSV_{nj}|\right]} \cdot w_j \right) \tag{4}$$

where i and j are the indices for the parameters and impact categories, respectively; n and m are the total number of producer-controlled parameters and impact categories, respectively; and w is the weighting factor assigned to an impact category j (note: $\sum_{j=1}^{m} w_j = 1$). All three impact categories have been given an equal weighting for the current analysis (i.e., $w = 1/3$ for all categories).

Chosen parameters' values for the alternate scenarios are based on production practices of farmers (obtained from sec. 3) with the lowest life cycle impact scores (sec. 4), specifically for GW. The impact distribution for the baseline scenario and the two alternate scenarios is determined by propagating the uncertainty in the scenarios' input parameter space (foreground data (Table B1) + environmental factors (Table E1)) through the LCA model using 10,000 repeated sampling iterations per scenario (i.e., Monte Carlo (MC) method, illustrated in Fig. 3). While these chosen parameters' values are held constant for the proposed alternate scenarios, all remaining parameters are left unperturbed from their baseline distribution. The most-likely impact score for each scenario and the uncertainty associated with it is gauged using the mean and coefficient of variation (COV) of the MC results, respectively.

6.2.1a STATISTICAL METHODS Comparison of impact scores' magnitude or dispersion between scenarios is done simply by comparing percent difference between competing scenarios' mean impact scores or their COV, respectively. Some LCA studies utilizing MC have drawn statistical inferences (e.g., through p-values), but they have done so erroneously, as the assumption of independence cannot be met if the outputs are obtained through deterministic means, and p-values could be inflated simply by increasing the number of simulations (von Brömssen & Röös, 2020; White *et al.*, 2014). Similarly, goodness-of-fits tests (E.g., Chi-square, Anderson-Darling, Kolmogorov-Smirnov, etc.) on the simulated results for each scenario cannot be performed, as the null hypothesis will be rejected due to the large sample size.[22] The same applies for confidence intervals (for mean or standard deviation) which may be artificially decreased / increased simply by increasing / decreasing the sample size of the simulations. Thus, no statistical methods are applied to gauge the significance of differences among competing scenarios' environmental performance.

7 | Environmental framework – Results

Fig. 9 presents the dispersion of life cycle impacts for sheep production using Ontario-specific data distribution on farming practices and Canadian environmental factors. The mean impact scores are 23% and 79% larger than the sample impact scores for the 23 surveyed farms (Table 5) due to the skewness of the impact score dispersion. Only the ED sample impact scores are significantly different from the (simulated) population,

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[22] More specifically, this is due to the increase in the tests' statistical power from a large sample, resulting in detection of the tiniest deviations from the null hypothesis. This is a well-known issue of goodness-of-fit tests, with discussions dating back to 1935 (Pearson *et al.*, 1994)

however ($P < 0.05$); the sample and population GW and WD impacts are consistent with each other. Simulated GW and WD impacts by phase (enteric emissions, feed production, manure management, and farm operations) are also similar ($P < 0.05$) to the respective impacts scores for the samples. For ED, uncertainty results[23] show that the operations-related[24] impacts are the sole contributor to the disparity in the sample and the simulated ED impacts, specifically for impacts related to electricity, fertilization, and diesel inputs (sample and population means of operations are 35.1 and 85.0 MJ/kg LW, respectively). This is partly due to the right skewness in the distribution of these inputs (Fig. B5) and the sensitivity of the parameters related to these inputs.

Parameter screening through RSV is used to identify parameters with a high influence on the impact score. RSV of selected producer-controlled parameters on total global warming (GW), energy demand (ED) and water depletion (WD) impact scores is shown in Fig. 10; Table E2 lists the RSV of all 142 input parameters on the total impact scores in all the impact categories. RSV magnitudes range is 0 – 0.34 for most parameters. Most influential parameters in the 'population / productivity' category are lambs per ewe (lambing rate), livestock body weights, and lamb mortality rate. In the 'dietary inputs' category, daily grain intake, proportion of silage in roughage, and energy content of roughage are the most influential parameters. In the 'farm operations' category, arable outdoor area, fertilizer application, electricity use, and diesel use are the most influential parameters.

Some input parameters have minimal or no direct influence on the impact score. For example, input parameters related to manure management systems (MS), animal activity (as described in Table 2), indoor area of barns / sheds, outdoor pasture area, transport mass or distances, sheep population on farms, grain composition, etc. have a (relatively) low RSV, indicating that the impacts related to these activities, regardless of their proportion relative to the total impact score, are "baked in".

Environment factors, similarly, do not influence the impact score to a large extent (RSV magnitudes' range is 0 – 0.04), with the exception of CH_4 conversion factors for lambs and adult sheep (defined as Y_m in IPCC (2006, Table 10.13)), maintenance net energy (NE) coefficients for lambs and adult sheep (defined as Cf_i in IPCC (2006, Table 10.4)), protein content in meat and wool, energy content in feed (roughages and grains), and ambient temperature (range of RSV magnitudes for these environmental factors is 0.14 – 0.26). The full RSV output[23] by phase shows these influential environmental factors largely affect GW impacts related to livestock emissions: from enteric fermentation and manure. GHG emissions from manure, while highly variable (COV = 65%) make only a 9% on-average contribution to overall GW impacts. GHG Emissions from enteric fermentation, while substantial (contributing to 35% of overall GW impacts), do not contribute to the uncertainty in overall impacts (COV = 15%). Thus, it can be safely stated that i) the role of environmental factors on the overall impact score is also "baked in", and ii) uncertainty in environmental factors should not meaningfully negate any improvements in impact scores made by changing producer-controlled parameters.

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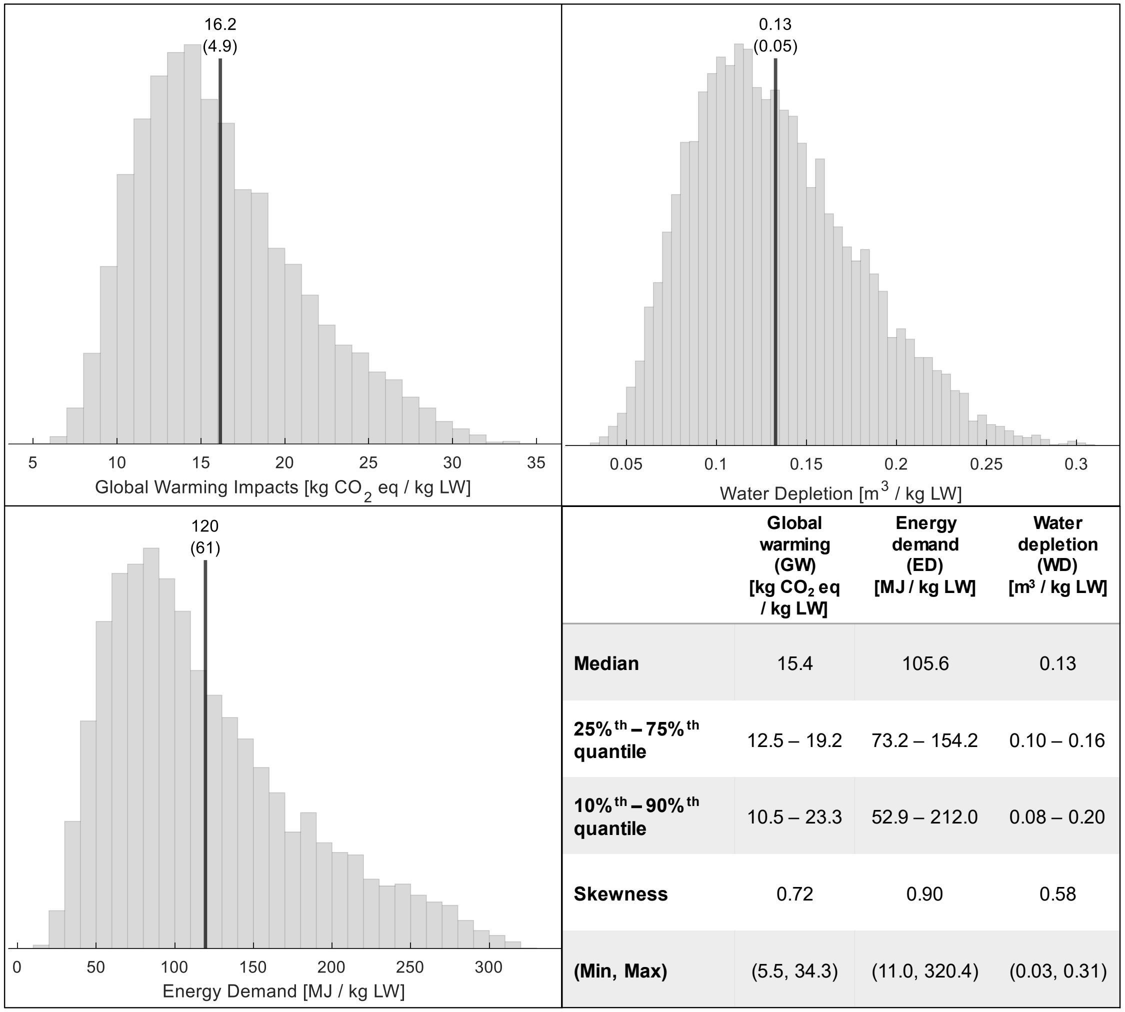
[23] Full sensitivity and uncertainty outputs can be accessed via instructions provided in Appendix E

[24] Read: 'Farm operations and infrastructure' as defined in the LCA system boundary (Fig. 6)

Fig. 9 Dispersion of life cycle impacts in global warming (GW), energy demand (ED), and water depletion (WD), obtained through Monte Carlo uncertainty propagation (10,000 simulations) using Ontario-specific data distribution on farming practices (Table B1) and Canadian environmental factors (Table E1). The vertical line on the histogram indicates the location of the mean; numbers on top of the line display the mean (standard deviation) values. The table lists descriptive statistics for the histograms



	Global warming (GW) [kg CO_2 eq / kg LW]	Energy demand (ED) [MJ / kg LW]	Water depletion (WD) [m^3 / kg LW]
Median	15.4	105.6	0.13
25%th – 75%th quantile	12.5 – 19.2	73.2 – 154.2	0.10 – 0.16
10%th – 90%th quantile	10.5 – 23.3	52.9 – 212.0	0.08 – 0.20
Skewness	0.72	0.90	0.58
(Min, Max)	(5.5, 34.3)	(11.0, 320.4)	(0.03, 0.31)

7.1. SCENARIO ANALYSIS

Among the most influential producer-controlled parameters, 10 parameters are chosen based on their weighted RSV (W_{RSV}; eqn. 4), and their values are varied (from their baseline distribution) in two alternate scenarios representing improved sheep production practices: scenario 1 (SC1) and 2 (SC2). Table 8 lists the chosen parameters and their values for the current baseline (BL) scenario, SC1, and SC2. SC1 focuses strictly on seven input-oriented parameters (i.e., parameters related to on-farm inputs *directly* controllable by producers), while SC2 incorporates all the changes proposed in SC1 in addition to changing three performance-oriented parameters (i.e., input parameters which affect production efficiency but may not be directly controllable by producers; e.g., lambing rate, birth proportion, etc.). As stated in sec. 6.2.1, parameters values for SC1/2 are chosen such that they are within the range of production practices observed in Ontario farms (Tables 2 and 3) associated with the lowest GW life cycle impacts (Fig. 7).[25] While the proposed values of these chosen parameters (described below) are held constant in SC1 and SC2, all remaining parameters remain unchanged from BL.

For input-oriented parameters (SC1), the most influential feed-related parameters were daily grain intake by adult ewes (W_{RSV} = 0.34) and lambs (W_{RSV} = 0.64). Parameters related to grain composition were found to be influential as well (W_{RSV} = 0.11–0.14), but they are not included in SC1, as grain production is already being considered (through the inclusion of daily grain intake parameters). For SC1/2, the value of daily grain intake is proposed to be decreased by ~25% to match the feeding practices of ~40% of sampled farms with a lower grain intake. To compensate, the silage proportion in roughage is increased from 17% to 40%, as it has a relatively lower weighted influence on the impact scores.

Another influential input-oriented parameter, fertilizer application (W_{RSV} = 0.40), is proposed to be decreased by ~60% to match the fertilization practices of ~30% of sampled farms with the lowest fertilization rate.[26] Diesel consumption (W_{RSV} = 0.19) is also decreased by ~25% to match the diesel use of ~50% of farms with more fuel-efficient operations. Lastly, while the per-head bedding straw use parameter is less influential (W_{RSV} = 0.10) compared to other parameters chosen for SC1/2, it is included in scenario analysis due to the relative ease of implementing a stricter measure of on-farm bedding straw usage. In fact, over 75% of sampled farms already meet the bedding straw value proposed in SC1/2.

For performance-oriented parameter (SC2), the three most influential parameters are body weight of lambs at time of slaughter (W_{RSV} = 0.82), lambs per ewe (W_{RSV} = 0.57), and lamb mortality rate (W_{RSV} = 0.19). Their values are proposed to be changed changed such that at least 35% of sampled farms meet the proposed requirements (individually). Note that per-head wool production was another performance-oriented parameter found to be influential (W_{RSV} = 0.22), but it is not included in scenario analysis, as most sheep producers in Ontario do not accurately track wool production (see sec. 3.3.1, par. 6).

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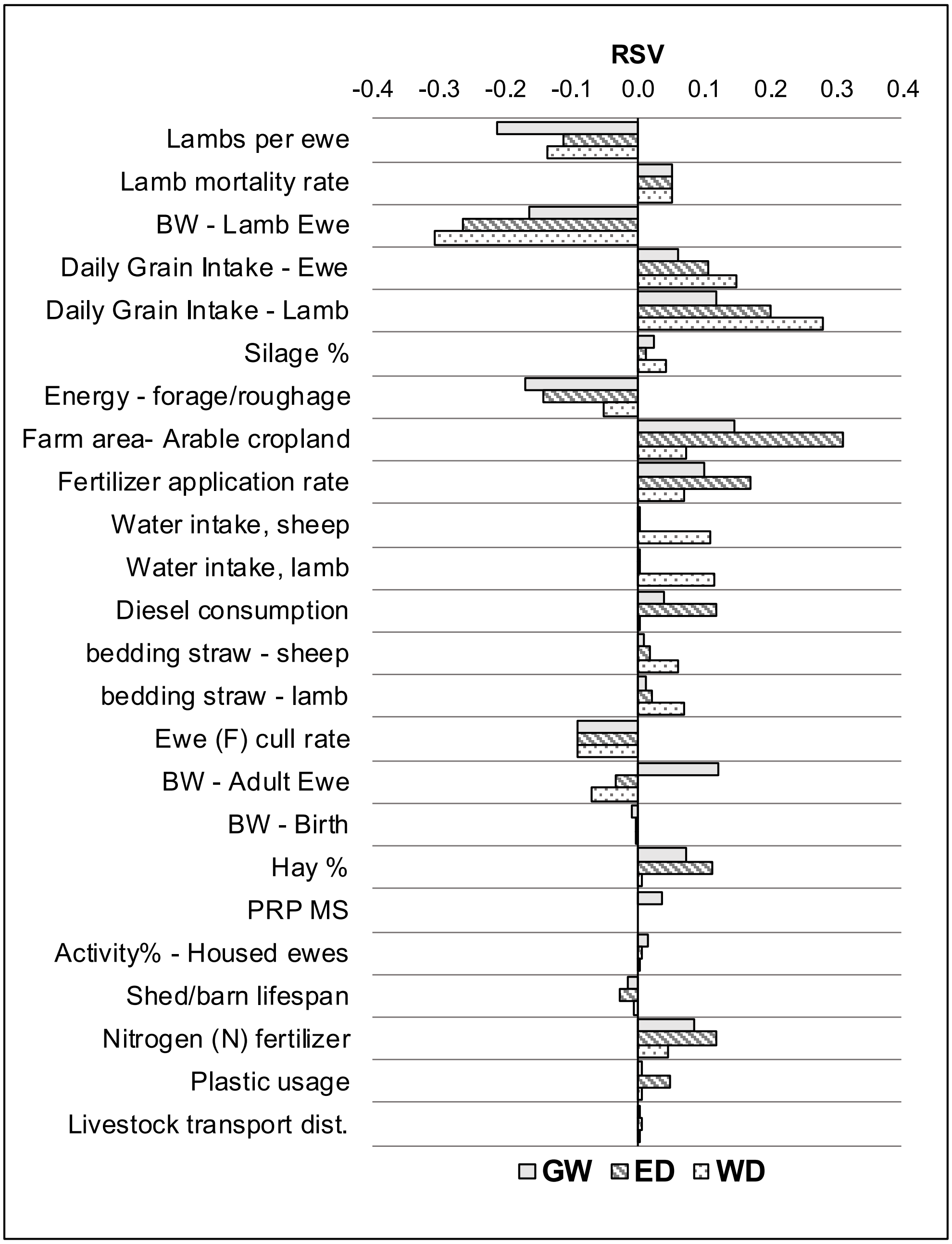
[25] See Appendix C for instructions on viewing full model inputs/outputs for all sampled farms

[26] This 30% percent does not include farms which do not use synthetic fertilizers at all

Fig. 10 Relative sensitivity value (RSV) for selected producer-controlled parameters in the categories of global warming (GW), energy demand (ED), and water depletion (WD). See Table C1 for parameter units



It is important to note that the parameter values chosen for the alternate scenarios (in Table 8) are selected reasonably (i.e., within the range of foreground data presented in sec. 3) but arbitrarily simply to demonstrate the applicability of the methods described here. Upon an actual implementation of an environmental label or claim, the viability of changing the practices reflected by these parameters and the amount by which the chosen parameter values are changed must be assessed by the producers before any change in said practice is recommended / mandated as a criterion. For example, in the current case study, outdoor farm area – a sensitive parameter ($W_{RSV} = 0.62$) – is technically producer-controlled, but producers may not be able to directly control the outdoor area for their operation; hence, this parameter was not chosen for scenario analysis. Scenarios which aim to reduce impacts solely through performance-oriented influential parameters such as lambs per ewe and body weight of lamb instead of more input-oriented parameters (e.g., inputs of feed, electricity, fertilizer, etc.) may also be more difficult to achieve consistently. Consequently, when setting criteria for environmental claims (through scenarios), a discussion on which parameters can be reasonably altered (and by how much) must take place among the stakeholders setting the criteria.

Of course, the number of scenarios or parameters controlled in each scenario can be increased such that producers have more flexibility in choosing which areas of their production they target to achieve emissions reduction. The number of impact categories targeted may also be reduced to provide a more focused, single-issue basis (e.g., carbon footprint) for claims, or alternatively, the weighting factor for each impact category (w_j in eqn. 4) may me modified to reflect the importance placed on each impact type.

Table 9 presents the comparison of life cycle impacts among BL, SC1, and SC2 in all three impact categories (GW, ED, and WD) based on 10,000 simulations. For SC1, ~2/3$^{\text{rd}}$ of all simulations saw a decrease in SC1's life cycle impacts (compared to BL), resulting in a 15% – 24% average reduction in the total impact score in all three impact categories. SC2 saw a net decrease in life cycle impacts in ~3/4$^{\text{th}}$ of all simulations, which resulted in a 25% – 31% average reduction in the total impact score. The largest reduction in impact score was found in operations-related impacts (21% – 29% reduction for SC1, and 30% – 42% reduction for SC2), and smallest reduction was found in enteric emissions (6% for SC1).

The dispersion and statistics of impact scores for all three scenarios can be found in Fig. E3. The uncertainty in total impact scores (measured using COV) of the proposed alternate scenarios decreased by 4%, 18%, and 47% on average in GW, ED, and WD, respectively. Skewness in impact distribution saw a similar decrease: 23%, 12%, and 82% for GW, ED, and WD impacts, respectively. This loss in uncertainty in impacts – measured through COV and skewness – from BL to SC1 & SC2 is due to the reduced effect of outliers in the parameters chosen in Table 8 on the impact score. In other words, the removal of uncertainty in these sensitive parameters understandably reduced the uncertainty in impacts as well.

Table 8 Input parameter values for the current baseline (BL) and the two proposed alternate scenarios (SC1 and SC2)

Parameter	W_{RSV}[a]	Baseline (BL) value[b]	Scenario 1 (SC1) value	Scenario 2 (SC2) value	Unit
Lambs per ewe	0.57	1.8	-	2.0	-
Lamb mortality rate	0.19	0.075	-	0.05	%
Body weight (BW) - Lamb	0.82	38.6	-	40	kg
Daily Grain Intake - Ewe	0.34	0.49	0.35	0.35	kg/head/day
Daily Grain Intake - Lamb	0.64	0.51	0.40	0.40	kg/head/day
Silage %	0.09	0.17	0.40	0.40	%
Fertilizer application rate	0.40	125.45	50	50	kg/ha/year
Diesel consumption	0.19	68.2	50	50	L/ha/year
Bedding straw - sheep	0.10	0.63	0.6	0.6	kg/adult/day
Bedding straw - lamb	0.09	0.43	0.4	0.4	kg/lamb/day

[a] Weighted RSV, determined through eqn. 4, using $w_j = 1/3$

[b] This baseline value only represents the 'most likely' value simulated in the baseline scenario. See Table B1 for the statistical distribution of the baseline input parameters

Table 9 Mean (± standard deviation) life cycle impacts for the baseline scenario (BL) and alternate scenarios 1 (SC1) and 2 (SC2) using Monte-Carlo uncertainty propagation (10,000 simulations)

		Enteric CH_4	Feed production	Manure	Operations	TOTAL	P(BL > SC)[a]	% Reduction[b]
Global warming (GW) [kg CO_2 eq/kg LW]	**BL**	4.9 (± 0.7)	3.5 (± 1.7)	1.5 (± 0.9)	6.3 (± 4.0)	16.2 (± 4.9)	n/a[c]	n/a
	SC1	4.6 (± 0.6)	3.0 (± 0.8)	1.3 (± 0.8)	5.0 (± 2.7)	13.9 (± 3.2)	63%	14.7%
	SC2	3.8 (± 0.4)	2.7 (± 0.7)	1.1 (± 0.7)	4.4 (± 2.4)	12.0 (± 2.7)	77%	24.9%
Energy demand (ED) [MJ/kg LW]	**BL**	n/a	29.8 (± 13)	n/a	89.7 (± 56)	119.5 (± 61)	n/a	n/a
	SC1	n/a	23.8 (± 6)	n/a	67.6 (± 38)	91.4 (± 39)	63%	23.8%
	SC2	n/a	20.2 (± 5)	n/a	59.5 (± 33)	79.7 (± 33)	70%	31.2%
Water depletion (WD) [m^3/kg LW]	**BL**	n/a	0.06 (± 0.04)	n/a	0.07 (± 0.02)	0.13 (± 0.05)	n/a	n/a
	SC1	n/a	0.05 (± 0.02)	n/a	0.05 (± 0.01)	0.10 (± 0.02)	71%	23.1%
	SC2	n/a	0.04 (± 0.01)	n/a	0.04 (± 0.01)	0.09 (± 0.02)	84%	29.9%

[a] Percent of simulations in which the total impact score was observed to be lower for the alternate scenarios (compared to baseline)

[b] Average of percent reduction in total life cycle from baseline to alternate scenarios (achieved using 10,000 simulations per scenario)

[c] Not applicable

7.2. DISCUSSION

In the Canadian context, any self-declared environmental claims (which may or may not use LCA) must meet certain requirements, described in CSA (2008), to comply with the statutes administered by the Competition Bureau Canada. The methodology described here allows Canadian producers to meet these requirements. The framework (sec. 6.2) used to obtain the metrics of environmental performance (sec. 7.1) fully satisfies claim requirement nos. 1 – 6, listed in Table 7, and partially satisfies requirement no. 7, thus meeting its stated goal: that environmental claims are not only easy to understand, but that they meet a bar for accuracy, specificity, and verifiability required for making claims Canada. To meet requirement no. 8, organization(s) making the claim must ensure that the practices reflected in the parameter values proposed in a given scenario are actually being followed through by the producers.

For the present case, the two proposed alternate scenarios, described in Tables 8 and 9 show a clear net improvement in the distribution of environmental performance of sheep production in Ontario. Uncertainty in impact scores were also reduced in SC1/SC2 compared to BL. Producers under SC1 and SC2 can therefore be more confident about any claims they make on their life cycle impacts. A different set of alternate scenarios (with different parameters or parameter values) will, of course, produce a different set of results. But the interpretation of the relationships drawn between the proposed changes in alternate scenarios' parameter values and their effect on the environmental performance should remain unchanged: i.e., "improvements in practices specified in alternate scenarios (e.g., Table 8) has led to an x% improvement in the GW, ED, or WD environmental performance from typical (baseline) practices after accounting for uncertainty," where x is the average percent reduction of impact scores between baseline and alternate scenarios (e.g., '% Reduction' in Table 9).

For the most accurate assessment of impacts, primary data collection on all aspects of production practices must take place; an expensive and a time-consuming endeavour. The method described in this section, however, can be used to forego the need for extensive primary data from *all* participating producers making environmental claims and, consequently, reduce the time spent on auditing and verification.

8 | Conclusions & Recommendations

Environmental footprint, specifically carbon footprint, is receiving more attention from governments, industries, and consumers due to the increasing threat of climate change. Life cycle assessment (LCA) has emerged as one of the most important tools in quantifying and providing pathways for reducing the environmental footprint attributed to human activities. The capacity for consumer purchasing behaviour to mitigate greenhouse gas emissions is acknowledged, but the tools made available to businesses, especially small businesses, for making environmental claims and promote environmentally sustainable commerce are scarce. Additionally, in Canadian sectors, environmental labelling does not always incorporate life cycle thinking, potentially leading to burden-shifting or misleading claims. Where it does, it is often applied inconsistently and opaquely.

This report estimates life cycle impacts of sheep production in Ontario and presents a framework for OSF to make environmental claims on their sheep products. A review on the current state-of-the-art on LCA of sheep farming (sec. 2) is used to create an LCA model (sec. 4) – which uses Ontario-specific primary data on sheep farming, collected specifically for this study (sec. 3) – to output life cycle impacts of sheep production in the categories of global warming, energy demand, and water depletion (sec. 5). A combination of sensitivity, uncertainty, and scenario analysis is used to create a methodology for making environmental claims on sheep products using the impact scores outputted by the LCA model (sec. 6). Finally, scenario analysis is used to demonstrate the applicability of the method in making environmental claims (sec. 7).

The use of LCA and primary foreground data in quantifying the environmental footprint for sheep production satisfies the criteria for scientific rigour, accuracy, transparency, replicability, etc., expected for making environmental claims, but considerable gaps remain. The following recommendations for further refinement are made to LCA practitioners interested in improving the scope of the current model and the framework for implementing environmental labels.

8.1. RECOMMENDATIONS

CARBON SEQUESTRATION The LCA model, in its current state, does not incorporate the effect of carbon sequestration on the overall GW impact score. The uncertainty in currently-utilized carbon sequestration models is high, but for the agricultural sector, the global warming mitigation potential provided by soil carbon sequestration can be substantial (Smith *et al.*, 2014).

Appendix F presents a brief overview of the methods used for estimating carbon sequestration potential from land management changes, with the expectation that it can be used to assist in incorporation of carbon sequestration into the LCA model. A preliminary, back-of-the-envelope estimation of the effects of carbon sequestration on GW impacts of Ontario sheep production, made using the ECCC (2020) method (described in pg. 124), is shown in Table 10. This estimation is made based on an assumption of a land management change in 100% of a 40-hectare outdoor farm area (average arable area for the 23 sheep farms summarized in sec. 3) over 100 years. All other farm inputs and outputs are assumed to be constant throughout this period. The conversion of carbon sequestration potential to the GW impact score (per-functional unit) is done through eqn. F.8 in Appendix F.

A reduction of 2% – 10% (0.29 – 1.40 kg CO_2 eq/kg LW) in the average GW life cycle impact score is observed due to carbon storage from changes in land management or land use. Inclusion of carbon sequestration in the LCA model can highlight potential avenues for further climate change mitigation in sheep production, but further analysis, including sensitivity and uncertainty assessment, is needed.

Table 10 Change in the global warming (GW) life cycle impact score (from the average GW impact score of 13.2 kg CO_2 eq/kg LW, reported in Table 5) due to carbon sequestration from various changes in land management of a 40-hectare outdoor area. Estimated using ECCC (2020) over a 100 year timeframe

Change in land management	% change in GW impact score
Intensive till → Reduced till	−2.2%
Reduced till → No till	−2.8%
Intensive till → No till	−3.6%
Increased fallow	−8.0%
Reforestation from cropland[a]	−10.6%

[a] Coarse soil assumed

EUTROPHICATION IMPACTS Freshwater eutrophication (ET) impacts from nutrient runoff due to agricultural activities, particularly in the Ontario Great Lakes, remains a pertinent issue. The current LCA model outputs ET impact scores (using the TRACI 2.1 LCIA method (Bare, 2011)) for feed production and farm operations. For the 23 farms sampled in this study, total (feed production + farm operations) ET impacts are in the range of 62 – 140 g nitrogen eq/kg LW, 85% of which, on average, are attributed to feed production. But studies which have incorporated eutrophication in their LCAs have found that nutrient runoff from manure can be a significant source of ET impacts (Bhatt & Abbassi, 2021). On-farm nutrient balance – akin to what was done by O'Brien *et al.* (2016) and Wallman *et al.* (2011) – must be carried out to obtain a complete picture of the ET impacts relevant to Ontario sheep production. From a GW perspective, life cycle impacts of manure may be smaller compared to synthetic fertilization, but manure use can lead to higher source emissions of nutrients, leading to higher ET impacts and degraded water quality. Thus, consideration of ET may also lead to a different set of recommendations for benchmarking criteria of 'ideal' farming practices.

TYPE I / III / IV DECLARATIONS The intended outcome from this study is not only to encourage Canadian producers to properly utilize and take advantage of ISO type II (2016) declarations, but to eventually implement type I (2018) and III (2006a) claims for business-to-consumer and business-to-business communication, respectively, of environmental labels. Producers may also consider implementing a type IV ecolabel newly proposed by Minkov, Lehmann, and Finkbeiner (2020), which aims to combine type I and III labels and create multiple product certifications depending for business-to-business as well as business-to-consumer communication. Development and implementation of PCRs, specifically, can facilitate a more transparent comparison between multiple products' environmental performance.

OTHER SHEEP PRODUCTS 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).

The End

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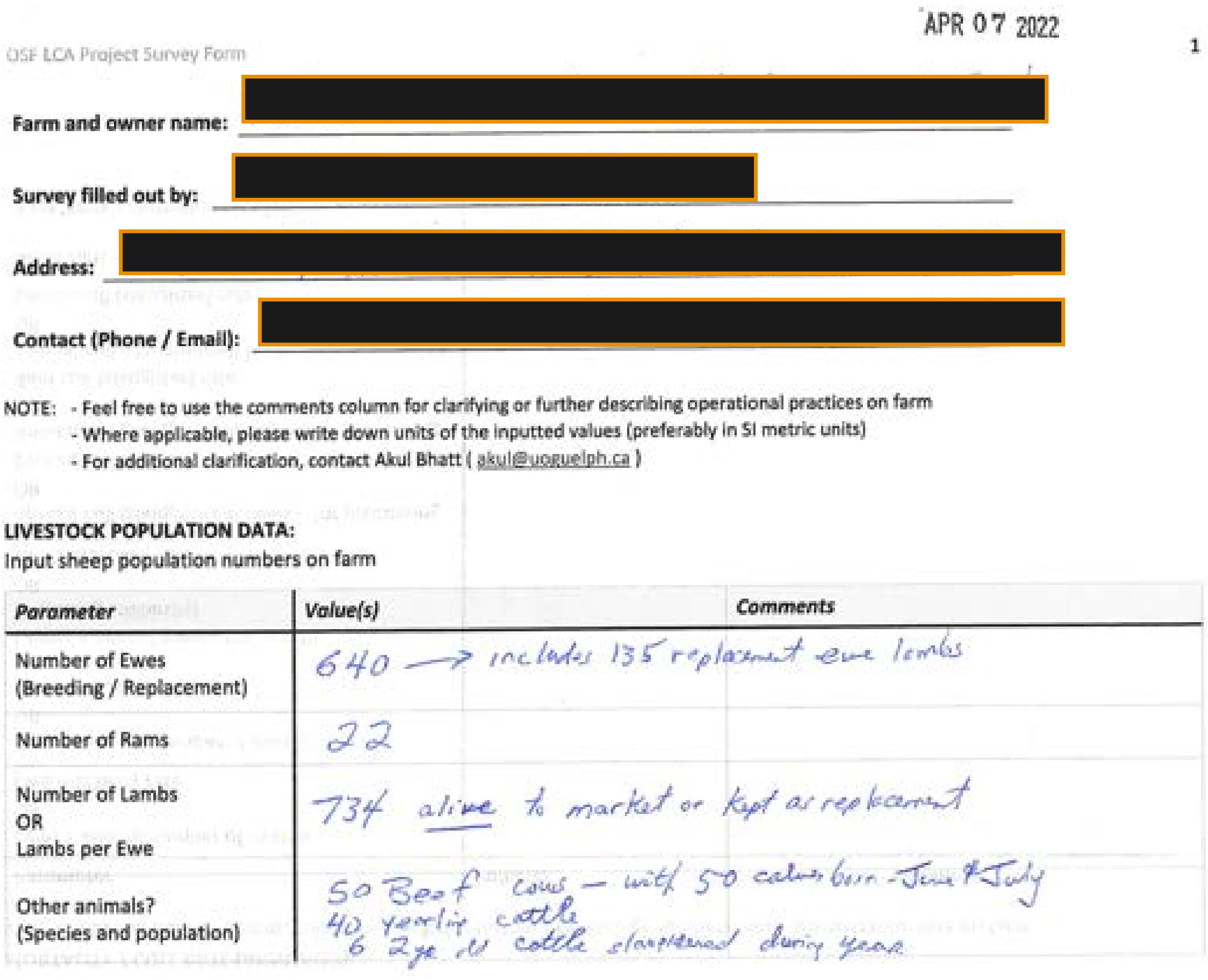
A | Survey form – completed

The following scanned document, completed by a sheep farmer near Lake Timiskawing (Ontario), is a 16-page survey sent to Ontario sheep producers for this study. The statistics on Ontario sheep farming practices presented in sec. 3 are based on 23 such responses obtained from sheep producers who participated in the data collection process. Phone numbers and emails were also exchanged for clarification of questions/ responses and exchanging other documents (e.g., pictures of meter readings, invoices, maps, etc.).

The survey form is comprised of the following sections:

Page(s)	Contents of survey
1	Sheep population on farm
2	Sheep mortality and slaughter rates on farm
3	Distribution of sheep body weights
4-5	Sheep product output on farm
6	Other product outputs on farm
7	Lambing frequency on farm
8	Livestock activity for sheep
9-10	Feed characteristics and grazing practices for sheep on farm
11-12	Manure management system on farm
13	Outdoor farm area, fertilizer, and water application
14	Indoor farm area, electricity, fuel, and plastic use
15	Water and bedding straw consumption by sheep
16	Transportation of livestock, feed, etc. on farm

Appendix B presents the data (once parameterized) from all 23 survey responses.



APR 07 2022

OSF LCA Project Survey Form

1

Farm and owner name: [redacted]

Survey filled out by: [redacted]

Address: [redacted]

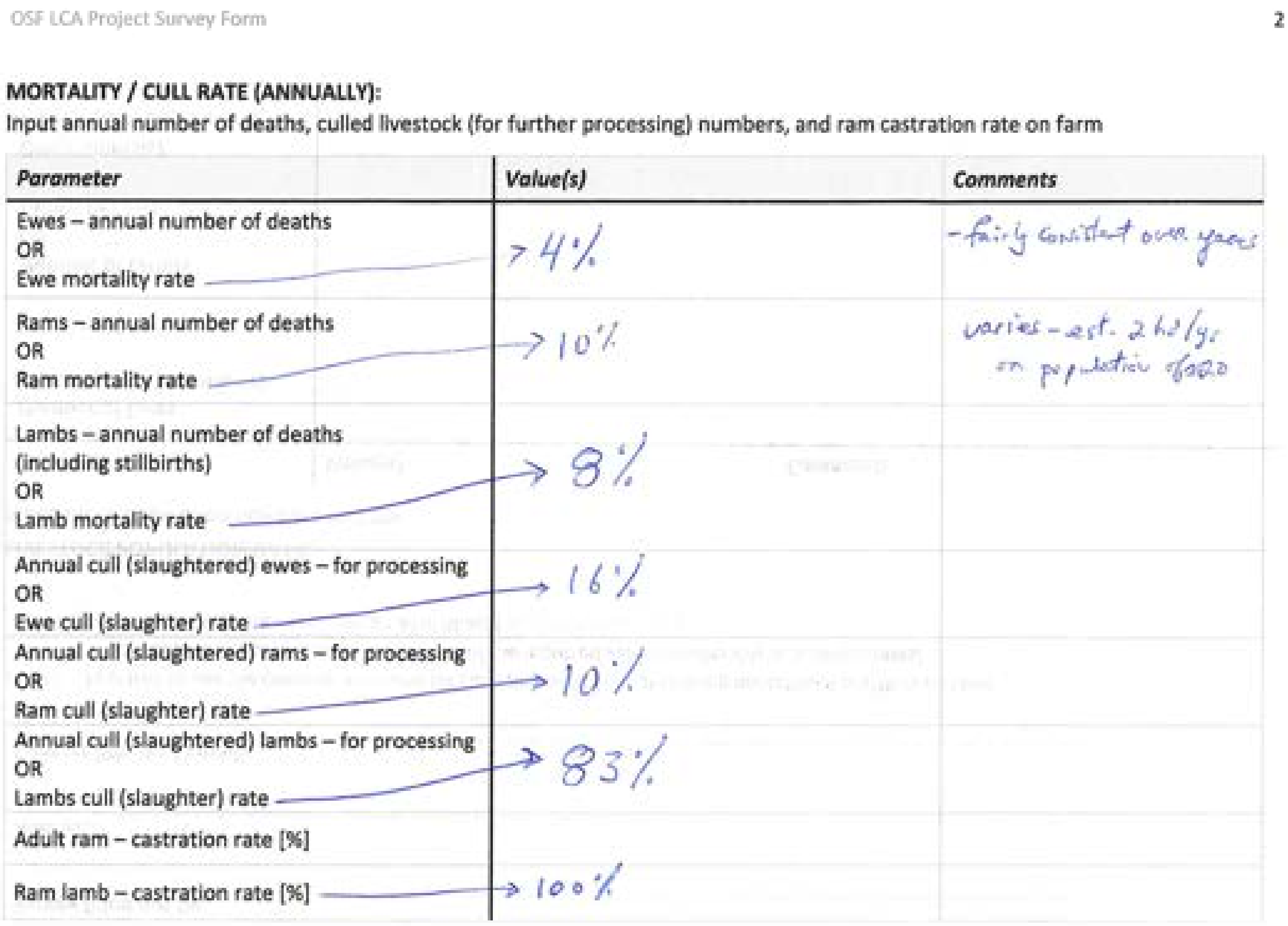
Contact (Phone / Email): [redacted]

NOTE: - Feel free to use the comments column for clarifying or further describing operational practices on farm
- Where applicable, please write down units of the inputted values (preferably in SI metric units)
- For additional clarification, contact Akul Bhatt (akul@uoguelph.ca)

LIVESTOCK POPULATION DATA:

Input sheep population numbers on farm

Parameter	*Value(s)*	*Comments*
Number of Ewes (Breeding / Replacement)	640 → includes 135 replacement ewe lambs	
Number of Rams	22	
Number of Lambs OR Lambs per Ewe	734 alive to market or kept as replacement	
Other animals? (Species and population)	50 Beef cows – with 50 calves born - June & July 40 yearling cattle 6 2yr old cattle slaughtered during year	

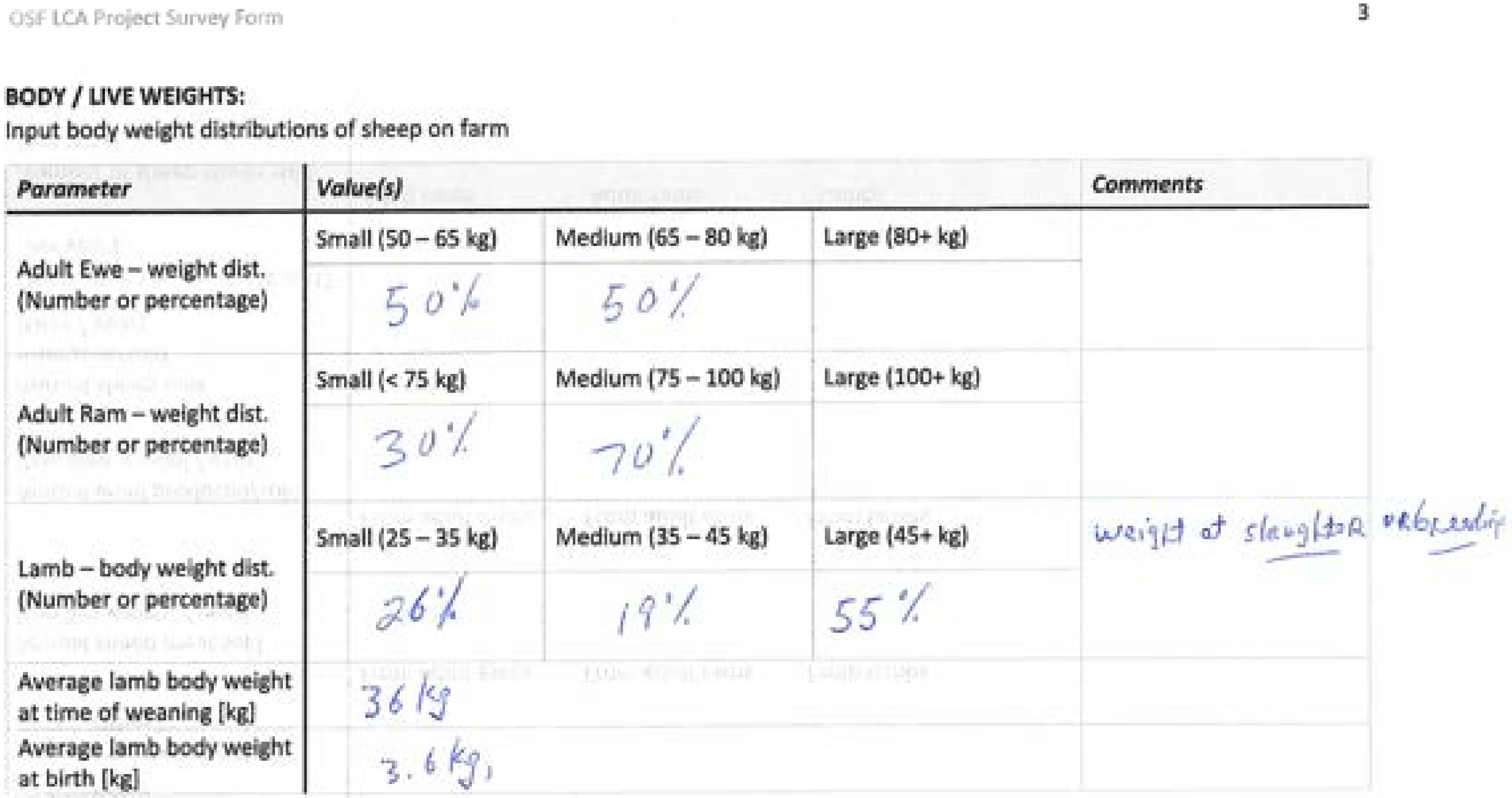


OSF LCA Project Survey Form 2

MORTALITY / CULL RATE (ANNUALLY):

Input annual number of deaths, culled livestock (for further processing) numbers, and ram castration rate on farm

Parameter	*Value(s)*	*Comments*
Ewes – annual number of deaths OR Ewe mortality rate	4%	- fairly constant over years
Rams – annual number of deaths OR Ram mortality rate	10%	varies - est. 2 hd/yr on population of 20
Lambs – annual number of deaths (including stillbirths) OR Lamb mortality rate	8%	
Annual cull (slaughtered) ewes – for processing OR Ewe cull (slaughter) rate	16%	
Annual cull (slaughtered) rams – for processing OR Ram cull (slaughter) rate	10%	
Annual cull (slaughtered) lambs – for processing OR Lambs cull (slaughter) rate	83%	
Adult ram – castration rate [%]		
Ram lamb – castration rate [%]	100%	

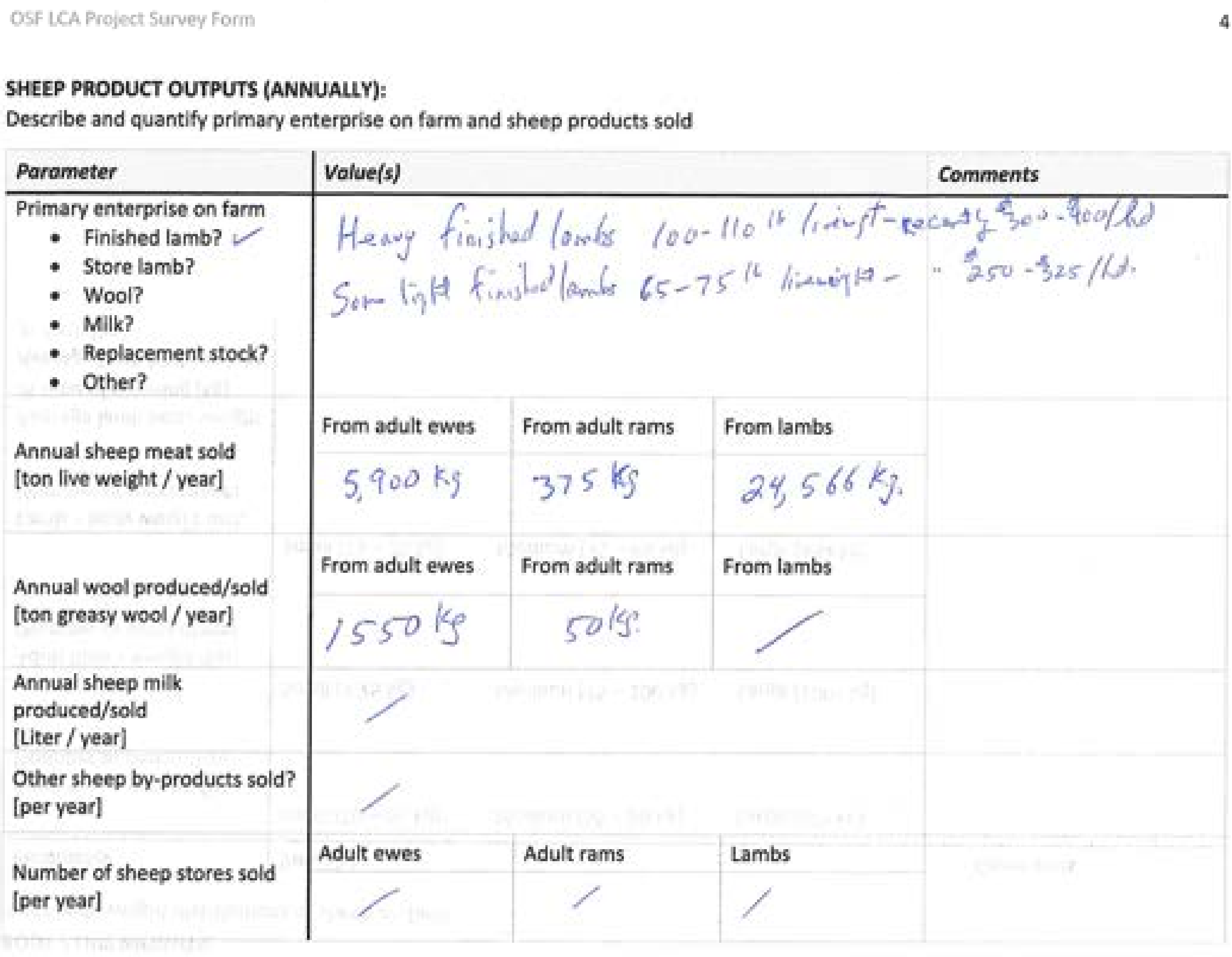


OSF LCA Project Survey Form 3

BODY / LIVE WEIGHTS:

Input body weight distributions of sheep on farm

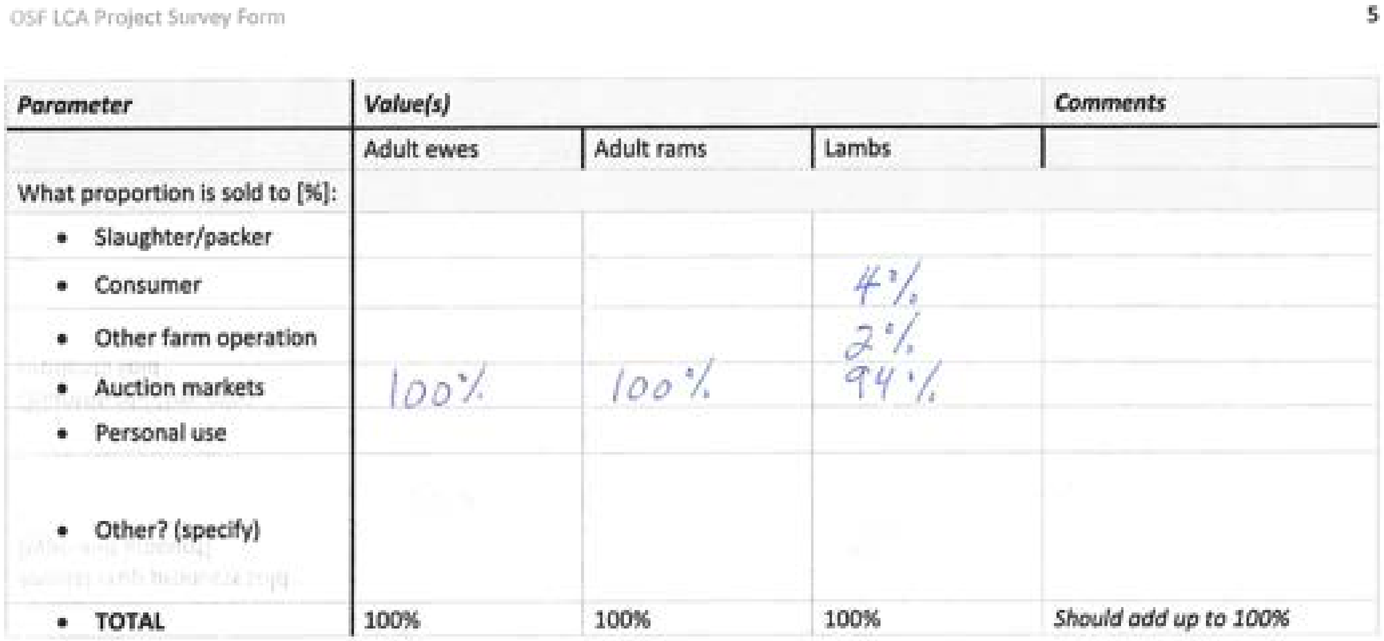
Parameter	*Value(s)*			*Comments*
Adult Ewe – weight dist. (Number or percentage)	Small (50 – 65 kg)	Medium (65 – 80 kg)	Large (80+ kg)	
	50%	50%		
Adult Ram – weight dist. (Number or percentage)	Small (< 75 kg)	Medium (75 – 100 kg)	Large (100+ kg)	
	30%	70%		
Lamb – body weight dist. (Number or percentage)	Small (25 – 35 kg)	Medium (35 – 45 kg)	Large (45+ kg)	weight at slaughter or breeding
	26%	19%	55%	
Average lamb body weight at time of weaning [kg]	36 kg			
Average lamb body weight at birth [kg]	3.6 kg,			



SHEEP PRODUCT OUTPUTS (ANNUALLY):

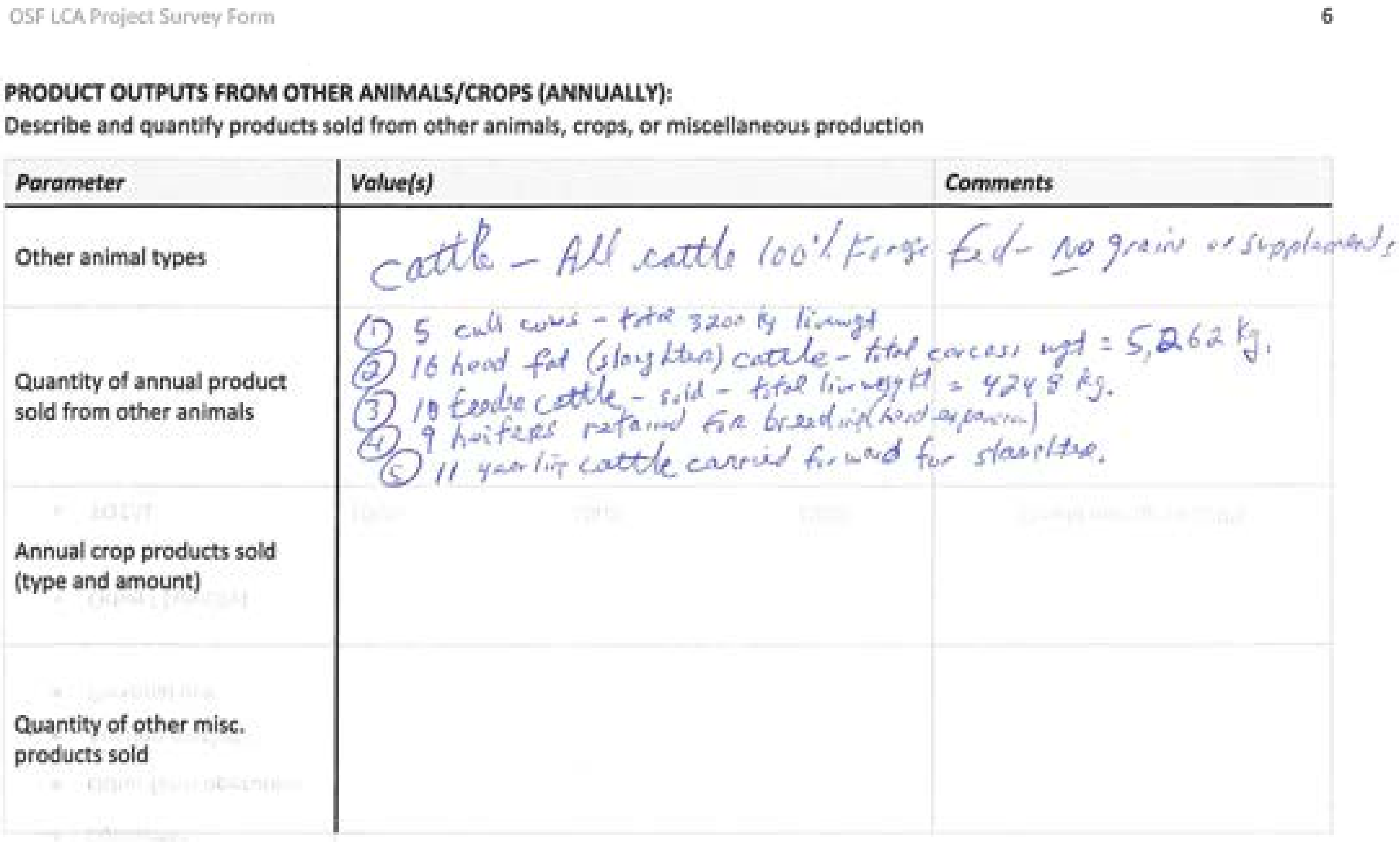
Describe and quantify primary enterprise on farm and sheep products sold

Parameter	*Value(s)*			*Comments*
Primary enterprise on farm • Finished lamb? ✓ • Store lamb? • Wool? • Milk? • Replacement stock? • Other?	Heavy finished lambs 100-110 lb liveweight – receiving $300-$400/hd Some light finished lambs 65-75 lb liveweight –			" $250-$325/hd.
Annual sheep meat sold [ton live weight / year]	From adult ewes	From adult rams	From lambs	
	5,900 kg	375 kg	24,566 kg.	
Annual wool produced/sold [ton greasy wool / year]	From adult ewes	From adult rams	From lambs	
	1550 kg	50 kg.	/	
Annual sheep milk produced/sold [Liter / year]	/			
Other sheep by-products sold? [per year]	/			
Number of sheep stores sold [per year]	Adult ewes	Adult rams	Lambs	
	/	/	/	



OSF LCA Project Survey Form 5

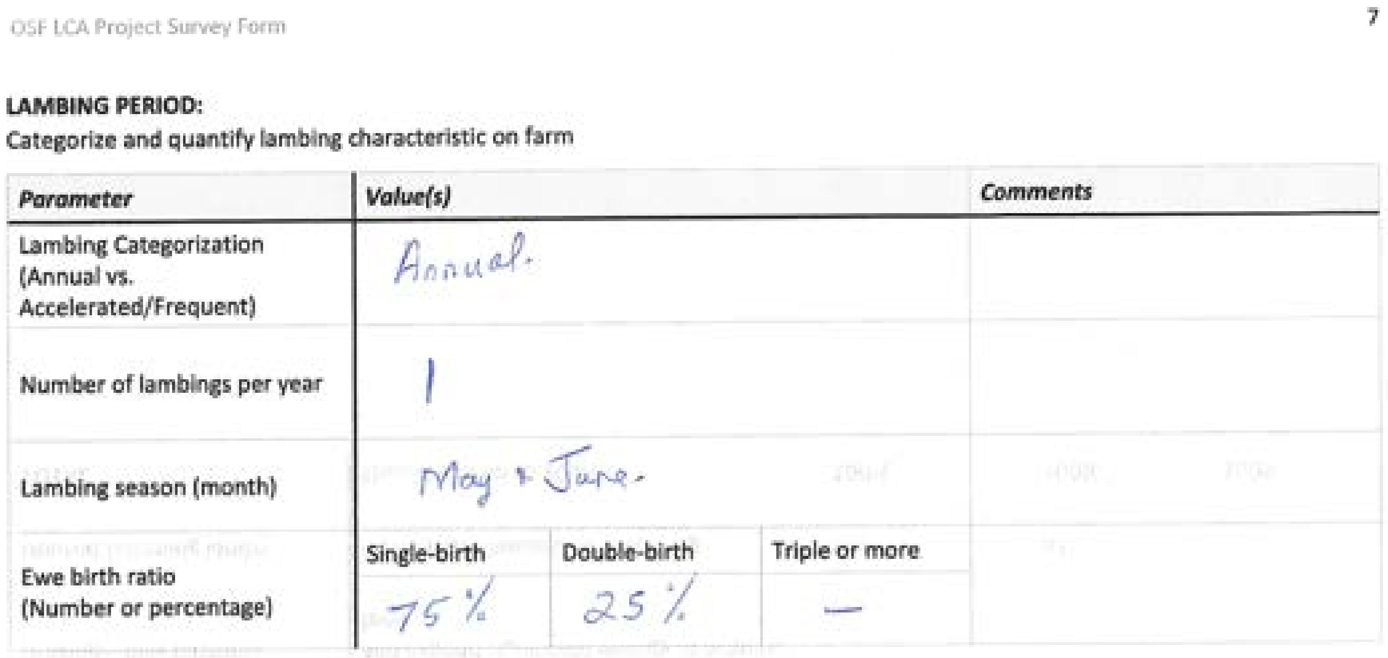
Parameter	**Value(s)**			**Comments**
	Adult ewes	Adult rams	Lambs	
What proportion is sold to [%]:				
• Slaughter/packer				
• Consumer			4%	
• Other farm operation			2%	
• Auction markets	100%	100%	94%	
• Personal use				
• Other? (specify)				
• **TOTAL**	100%	100%	100%	*Should add up to 100%*



PRODUCT OUTPUTS FROM OTHER ANIMALS/CROPS (ANNUALLY):

Describe and quantify products sold from other animals, crops, or miscellaneous production

Parameter	*Value(s)*	*Comments*
Other animal types	cattle – All cattle 100% Forage fed – No grains or supplements	
Quantity of annual product sold from other animals	① 5 cull cows – total 3200 kg liveweight ② 16 head fat (slaughter) cattle – total carcass wgt = 5,262 kg. ③ 18 feeder cattle – sold – total liveweight = 4248 kg. ④ 9 heifers retained for breeding (herd expansion) ⑤ 11 yearling cattle carried forward for slaughter.	
Annual crop products sold (type and amount)		
Quantity of other misc. products sold		



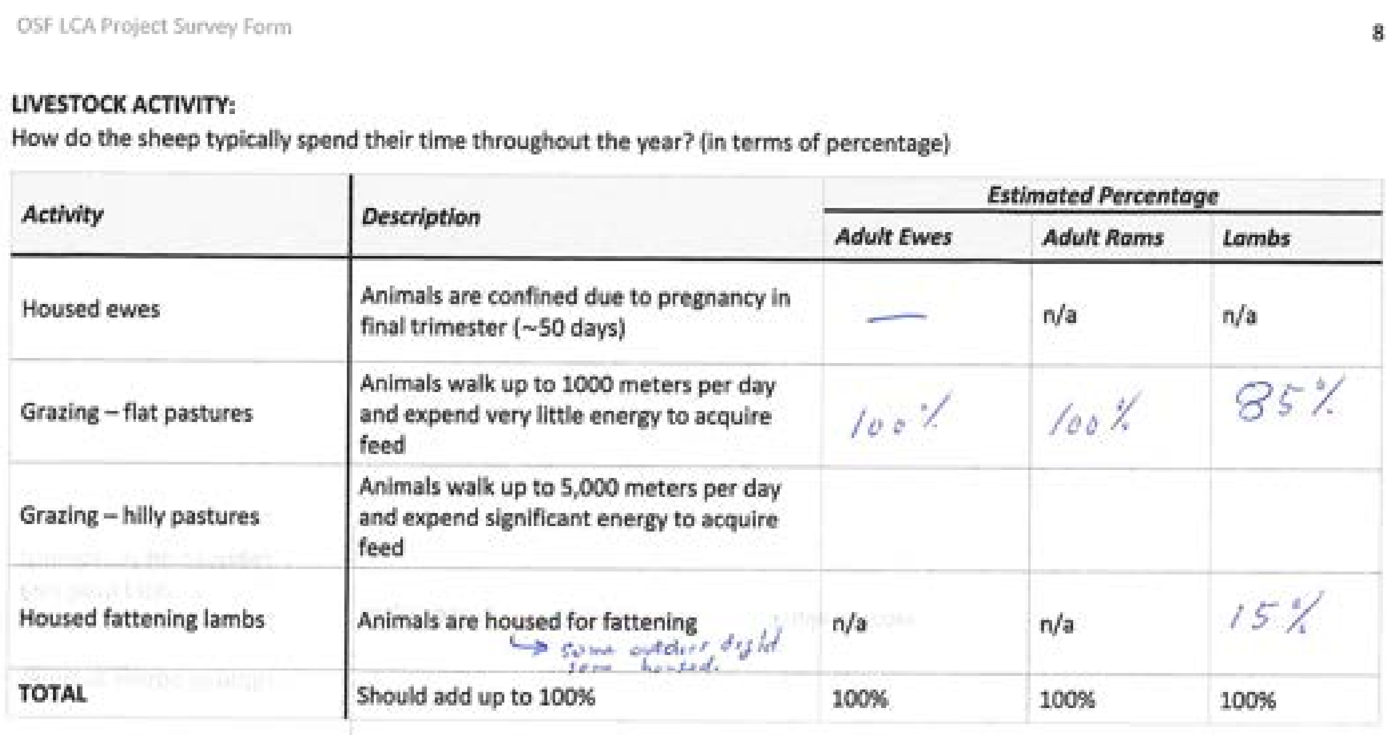
OSF LCA Project Survey Form

7

LAMBING PERIOD:

Categorize and quantify lambing characteristic on farm

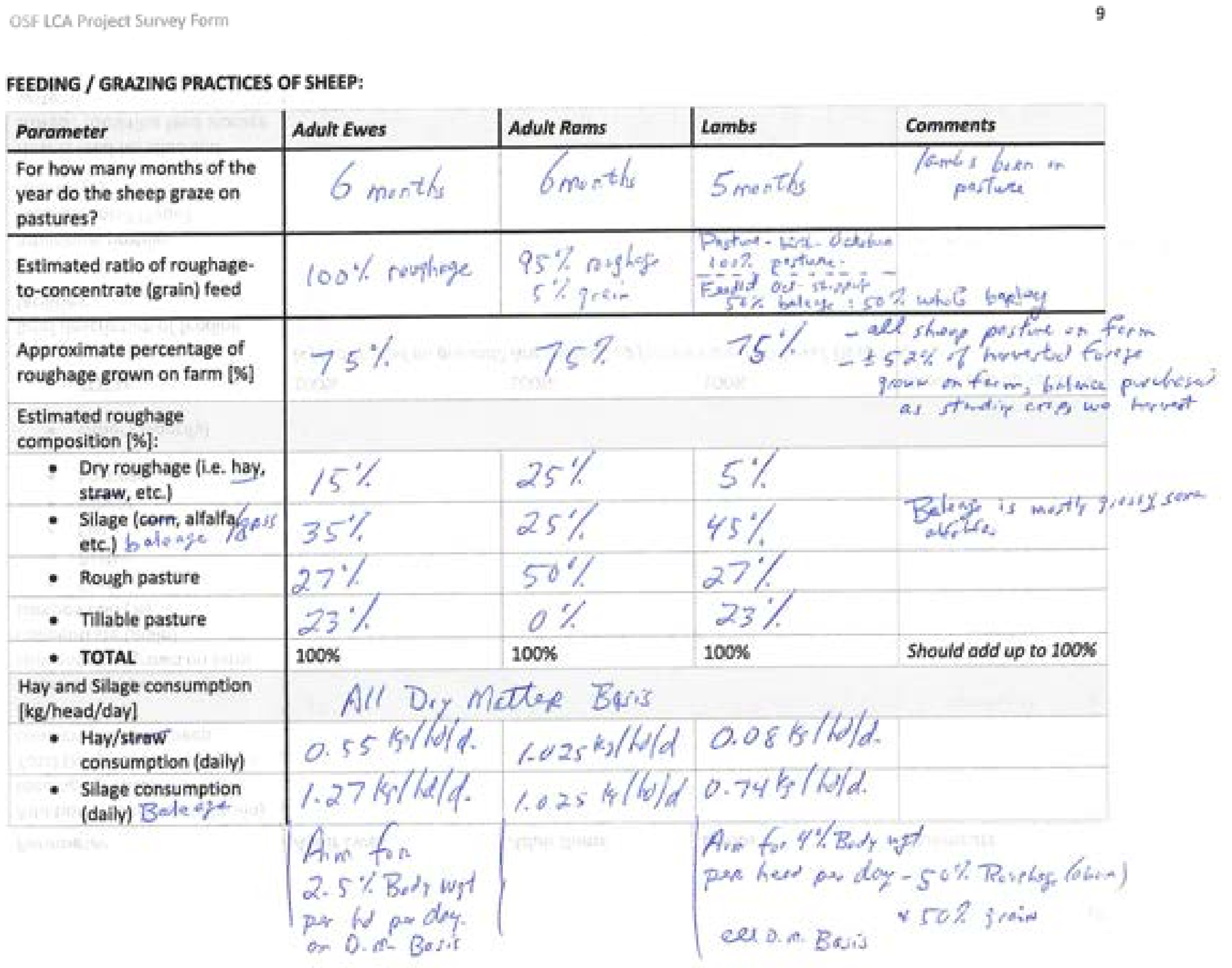
Parameter	*Value(s)*			*Comments*
Lambing Categorization (Annual vs. Accelerated/Frequent)	Annual.			
Number of lambings per year	1			
Lambing season (month)	May + June.			
Ewe birth ratio (Number or percentage)	Single-birth	Double-birth	Triple or more	
	75 %	25 %	—	



LIVESTOCK ACTIVITY:

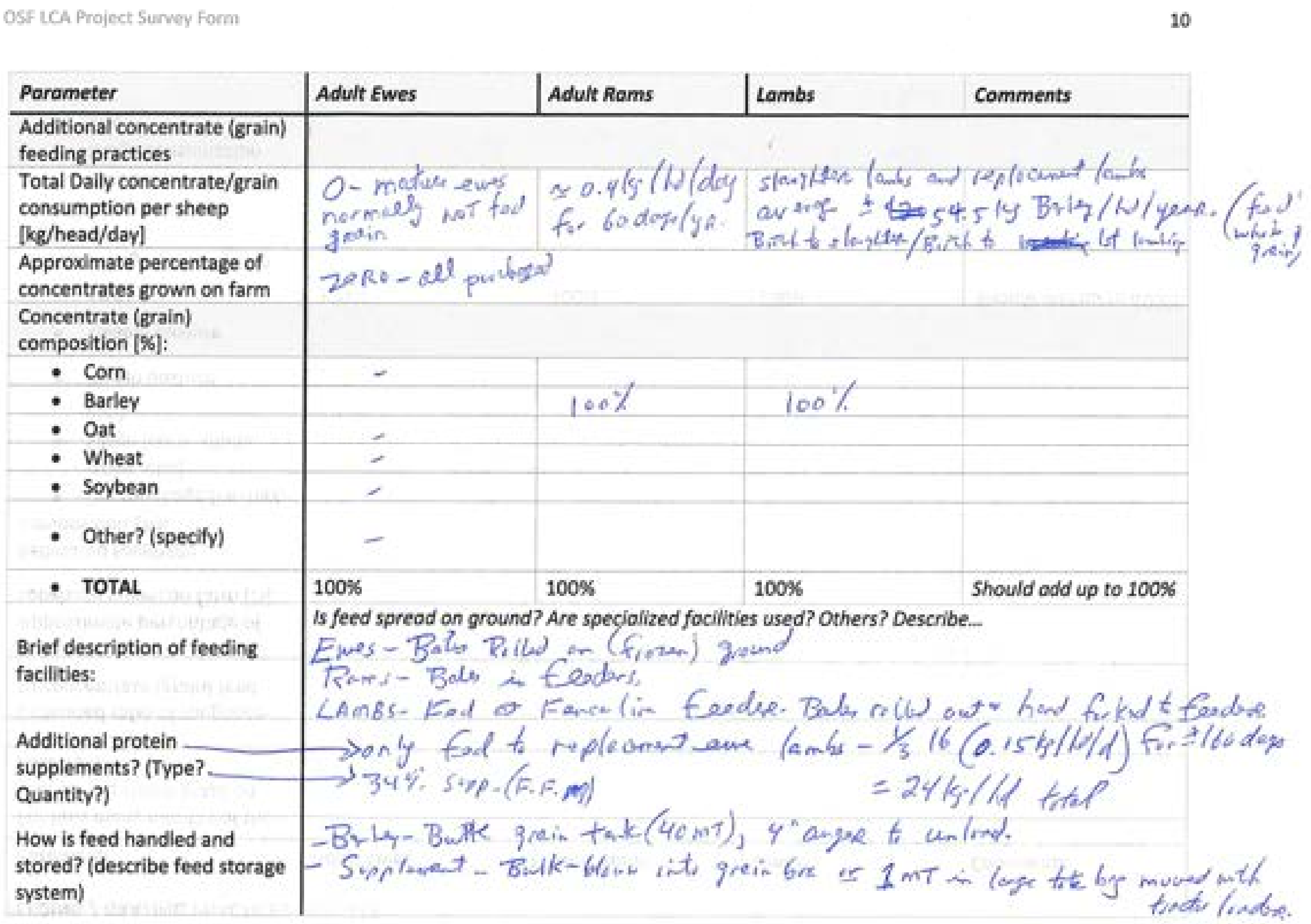
How do the sheep typically spend their time throughout the year? (in terms of percentage)

Activity	Description	Estimated Percentage		
		Adult Ewes	Adult Rams	Lambs
Housed ewes	Animals are confined due to pregnancy in final trimester (~50 days)	—	n/a	n/a
Grazing – flat pastures	Animals walk up to 1000 meters per day and expend very little energy to acquire feed	100%	100%	85%
Grazing – hilly pastures	Animals walk up to 5,000 meters per day and expend significant energy to acquire feed			
Housed fattening lambs	Animals are housed for fattening → some outdoor, dry lot some housed.	n/a	n/a	15%
TOTAL	Should add up to 100%	100%	100%	100%



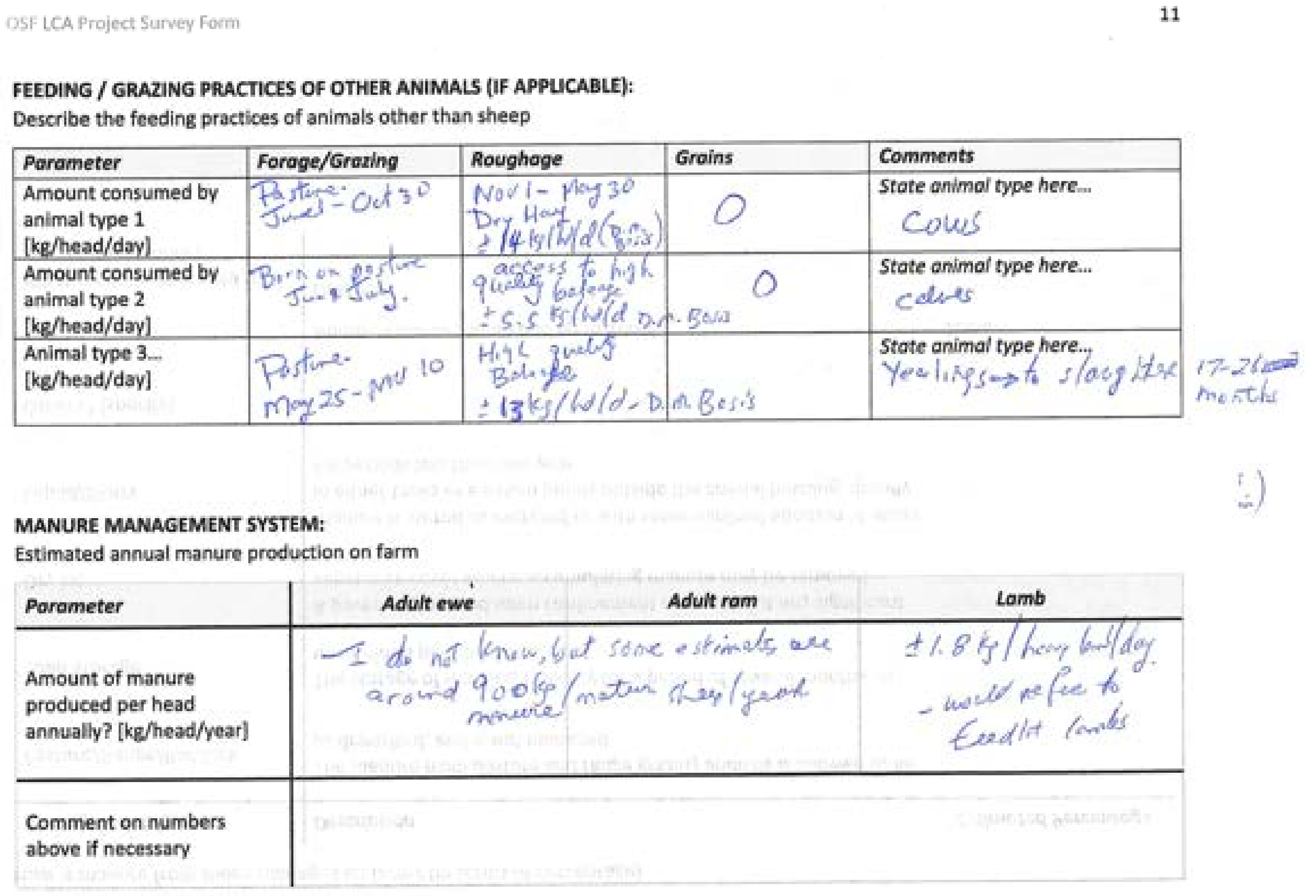
FEEDING / GRAZING PRACTICES OF SHEEP:

Parameter	Adult Ewes	Adult Rams	Lambs	Comments
For how many months of the year do the sheep graze on pastures?	6 months	6 months	5 months	lambs born on pasture
Estimated ratio of roughage-to-concentrate (grain) feed	100% roughage	95% roughage 5% grain	Pasture - ~~Mid~~ - October 100% pasture - Fed Oct - [illegible] 50% baleage : 50% whole barley	
Approximate percentage of roughage grown on farm [%]	75%	75%	75%	- all sheep pasture on farm - ± 52% of harvested forage grown on farm, balance purchased as standing crops we harvest
Estimated roughage composition [%]:				
• Dry roughage (i.e. hay, straw, etc.)	15%	25%	5%	
• Silage (~~corn~~, alfalfa/grass etc.) baleage	35%	25%	45%	Baleage is mostly grassy some alfalfa
• Rough pasture	27%	50%	27%	
• Tillable pasture	23%	0%	23%	
• TOTAL	100%	100%	100%	*Should add up to 100%*
Hay and Silage consumption [kg/head/day]	All Dry Matter Basis			
• Hay/~~straw~~ consumption (daily)	0.55 kg/hd/d.	1.025 kg/hd/d	0.08 kg/hd/d.	
• Silage consumption (daily) Baleage	1.27 kg/hd/d.	1.025 kg/hd/d	0.74 kg/hd/d.	
	Aim for 2.5% Body wgt per hd per day. on D.M. Basis		Aim for 4% Body wgt per head per day - 50% Roughage (baleage) + 50% grain all D.M. Basis	



OSF LCA Project Survey Form 10

Parameter	Adult Ewes	Adult Rams	Lambs	Comments
Additional concentrate (grain) feeding practices				
Total Daily concentrate/grain consumption per sheep [kg/head/day]	0 – mature ewes normally not fed grain	≈ 0.4 kg/hd/day for 60 days/yr.	slaughter lambs and replacement lambs average ± 54.5 kg Barley/hd/year. Birth to slaughter/birth to 1st lambing	(fed whole grain)
Approximate percentage of concentrates grown on farm	ZERO – all purchased			
Concentrate (grain) composition [%]:				
• Corn	–			
• Barley		100%	100%	
• Oat	–			
• Wheat	–			
• Soybean	–			
• Other? (specify)	–			
• **TOTAL**	100%	100%	100%	*Should add up to 100%*
Brief description of feeding facilities:	***Is feed spread on ground? Are specialized facilities used? Others? Describe...*** Ewes – Bales Rolled on (frozen) ground Rams – Bales in feeders. LAMBS – Fed in Fence line feeder. Bales rolled out + hand forked to feeder.			
Additional protein supplements? (Type? Quantity?)	→ only fed to replacement ewe lambs – ⅓ lb (0.15 kg/hd/d) for ±160 days → 34% supp. – (F.F.M) = 24 kg/hd total			
How is feed handled and stored? (describe feed storage system)	– Barley – Butler grain tank (40 MT), 4" auger to unload. – Supplement – Bulk – blown into grain bin or 1 MT in large tote bags moved with tractor loader.			



OSF LCA Project Survey Form

11

FEEDING / GRAZING PRACTICES OF OTHER ANIMALS (IF APPLICABLE):

Describe the feeding practices of animals other than sheep

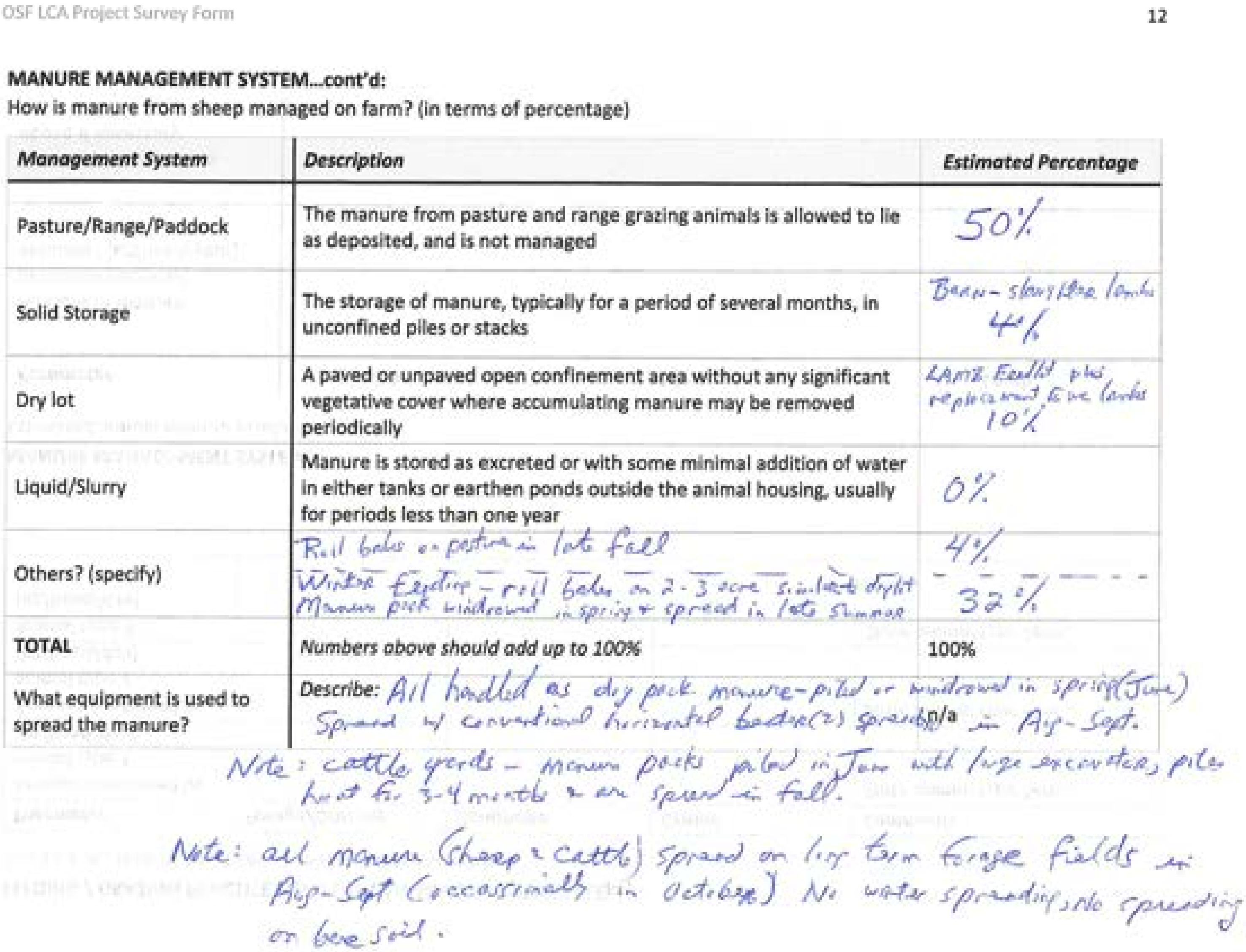
Parameter	*Forage/Grazing*	*Roughage*	*Grains*	*Comments*
Amount consumed by animal type 1 [kg/head/day]	Pasture: June 1 – Oct 30	Nov 1 – May 30 Dry Hay ± 14 kg/hd/d (Basis)	0	*State animal type here...* Cows
Amount consumed by animal type 2 [kg/head/day]	Born on pasture June & July.	access to high quality baleage ± 5.5 kg/hd/d D.M. Basis	0	*State animal type here...* calves
Animal type 3... [kg/head/day]	Pasture May 25 – Nov 10	High quality Baleage ± 13 kg/hd/d – D.M. Basis		*State animal type here...* Yearlings up to slaughter 17-21 months

:)

MANURE MANAGEMENT SYSTEM:

Estimated annual manure production on farm

Parameter	*Adult ewe*	*Adult ram*	*Lamb*
Amount of manure produced per head annually? [kg/head/year]	– I do not know, but some estimates are around 900kg/mature sheep/year manure		± 1.8 kg/head/day. – would refer to Feedlot lambs
Comment on numbers above if necessary			



OSF LCA Project Survey Form 12

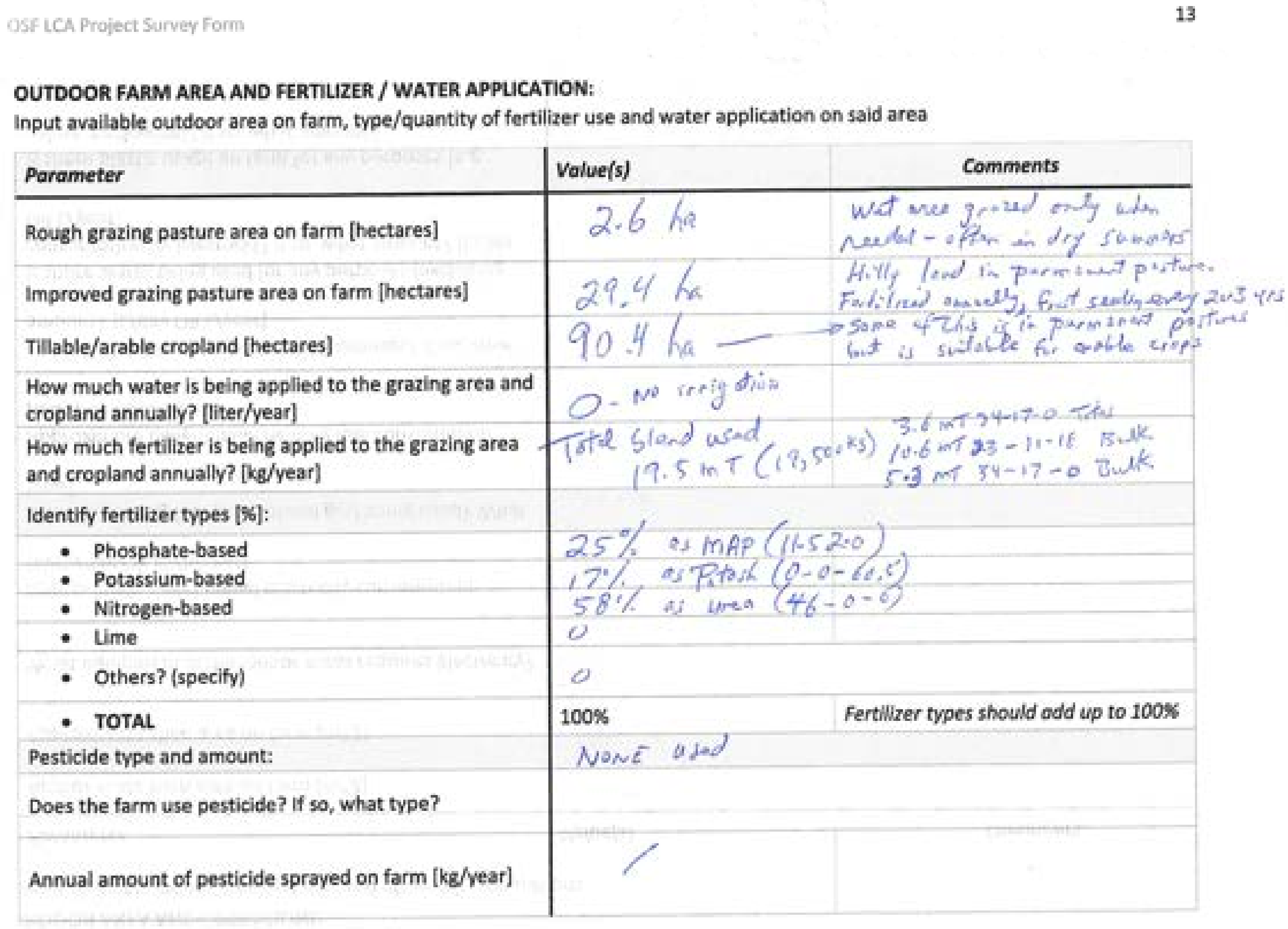
MANURE MANAGEMENT SYSTEM…cont'd:

How is manure from sheep managed on farm? (in terms of percentage)

Management System	*Description*	*Estimated Percentage*
Pasture/Range/Paddock	The manure from pasture and range grazing animals is allowed to lie as deposited, and is not managed	50%
Solid Storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks	Barn – sheep/ewe lambs 4%
Dry lot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically	LAMB Feedlot plus replacement ewe lambs 10%
Liquid/Slurry	Manure is stored as excreted or with some minimal addition of water in either tanks or earthen ponds outside the animal housing, usually for periods less than one year	0%
Others? (specify)	Roll bales on pasture in late fall Winter Feeding – roll bales on 2-3 acre sacrifice drylot Manure pack windrowed in spring + spread in late summer	4% 32%
TOTAL	*Numbers above should add up to 100%*	100%
What equipment is used to spread the manure?	*Describe:* All handled as dry pack manure – piled or windrowed in spring (June) Spread w/ conventional horizontal beater(s) spreader n/a in Aug-Sept.	

Note: cattle yards – manure packs piled in June with large excavator, piles heat for 3-4 months & are spread in fall.

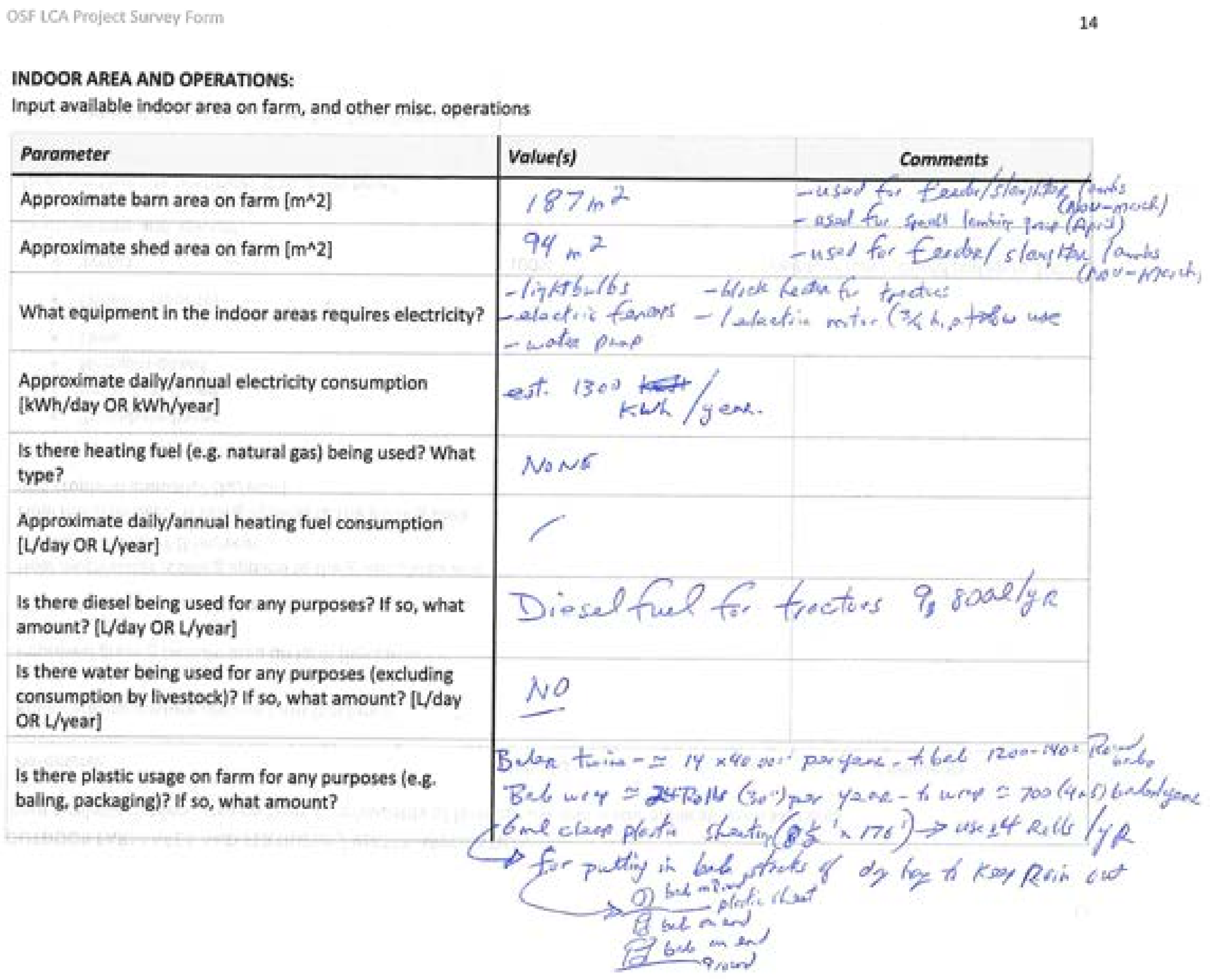
Note: all manure (sheep & cattle) spread on long term forage fields in Aug-Sept (occasionally in October) No winter spreading, no spreading on bare soil.



OUTDOOR FARM AREA AND FERTILIZER / WATER APPLICATION:

Input available outdoor area on farm, type/quantity of fertilizer use and water application on said area

Parameter	*Value(s)*	*Comments*
Rough grazing pasture area on farm [hectares]	2.6 ha	Wet area grazed only when needed – often in dry summers
Improved grazing pasture area on farm [hectares]	29.4 ha	Hilly land in permanent pasture. Fertilized annually, frost seeding every 2or3 yrs
Tillable/arable cropland [hectares]	90.4 ha ⟶	Some of this is in permanent pasture but is suitable for arable crops
How much water is being applied to the grazing area and cropland annually? [liter/year]	0 - no irrigation	
How much fertilizer is being applied to the grazing area and cropland annually? [kg/year]	Total blend used 19.5 mT (19,500 kgs)	3.6 mT 34-17-0 Tote 10.6 mT 23-11-18 Bulk 5.3 mT 34-17-0 Bulk
Identify fertilizer types [%]:		
• Phosphate-based	25% as MAP (11-52-0)	
• Potassium-based	17% as Potash (0-0-60.5)	
• Nitrogen-based	58% as urea (46-0-0)	
• Lime	0	
• Others? (specify)	0	
• **TOTAL**	100%	*Fertilizer types should add up to 100%*
Pesticide type and amount:	None used	
Does the farm use pesticide? If so, what type?		
Annual amount of pesticide sprayed on farm [kg/year]	/	



OSF LCA Project Survey Form 14

INDOOR AREA AND OPERATIONS:

Input available indoor area on farm, and other misc. operations

Parameter	*Value(s)*	*Comments*
Approximate barn area on farm [m^2]	187 m 2	- used for feeder/slaughter lambs (Nov-march) - used for spring lambing prep (April)
Approximate shed area on farm [m^2]	94 m 2	- used for feeder/ slaughter lambs (Nov-March)
What equipment in the indoor areas requires electricity?	- lightbulbs - electric fencers - water pump	- block heater for tractors - 1 electric motor (3/4 h.p [illegible] use
Approximate daily/annual electricity consumption [kWh/day OR kWh/year]	est. 1300 ~~kwh~~ KWh / year.	
Is there heating fuel (e.g. natural gas) being used? What type?	NONE	
Approximate daily/annual heating fuel consumption [L/day OR L/year]	/	
Is there diesel being used for any purposes? If so, what amount? [L/day OR L/year]	Diesel fuel for tractors 9,800L/yR	
Is there water being used for any purposes (excluding consumption by livestock)? If so, what amount? [L/day OR L/year]	NO	
Is there plastic usage on farm for any purposes (e.g. baling, packaging)? If so, what amount?	Baler twine - ≈ 14 x 40,000' per year - to bale 1200-1400 Round bales Bale wrap ≈ ~~24~~ 25 Rolls (30") per year - to wrap ≈ 700 (4x5) bales/year 6 ml clear plastic sheeting (32' x 170') → use 4 Rolls /YR	

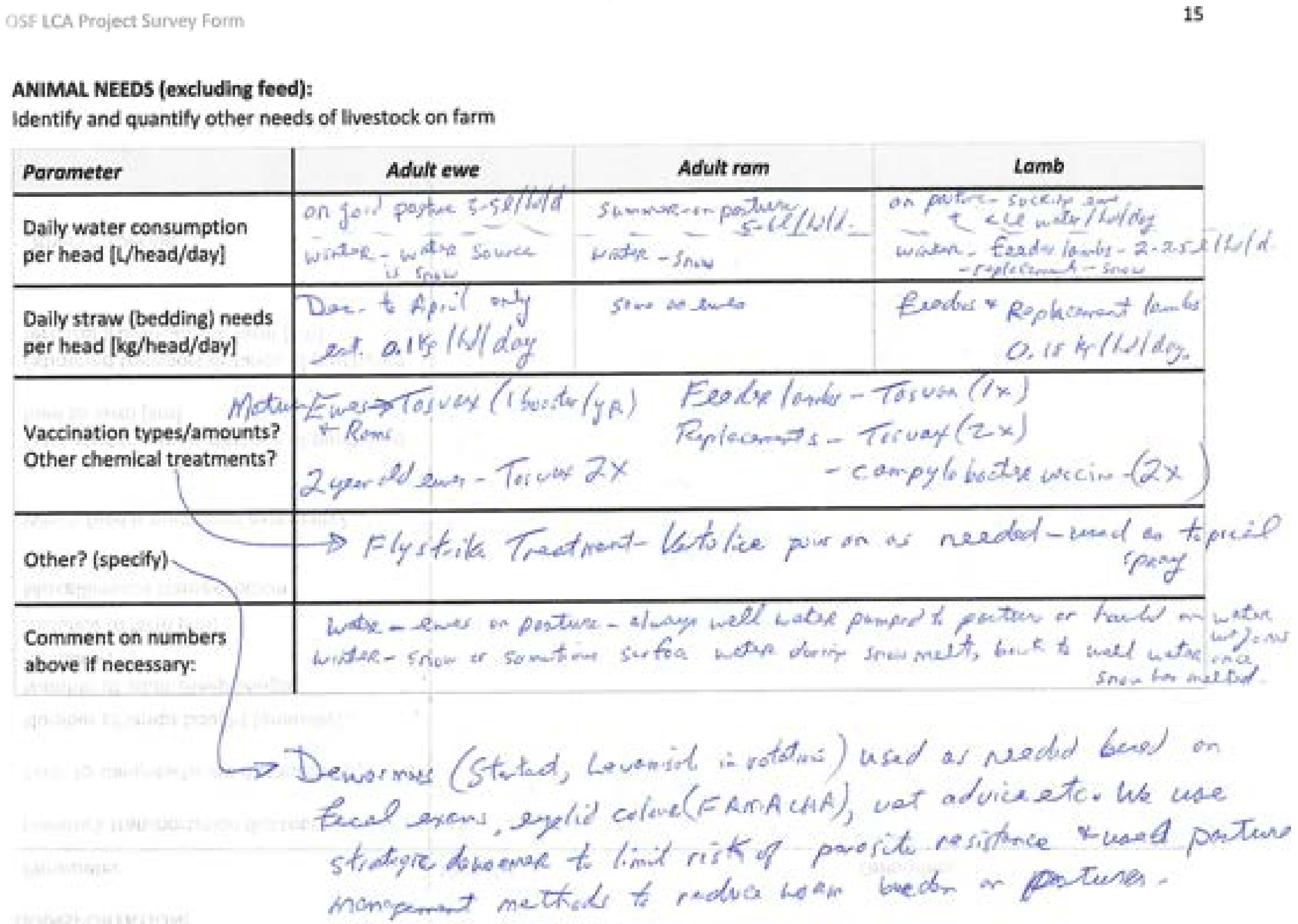
→ for putting in bale stacks of dry hay to keep Rain out

bale in plastic sheet

bale on end

bale on end

ground

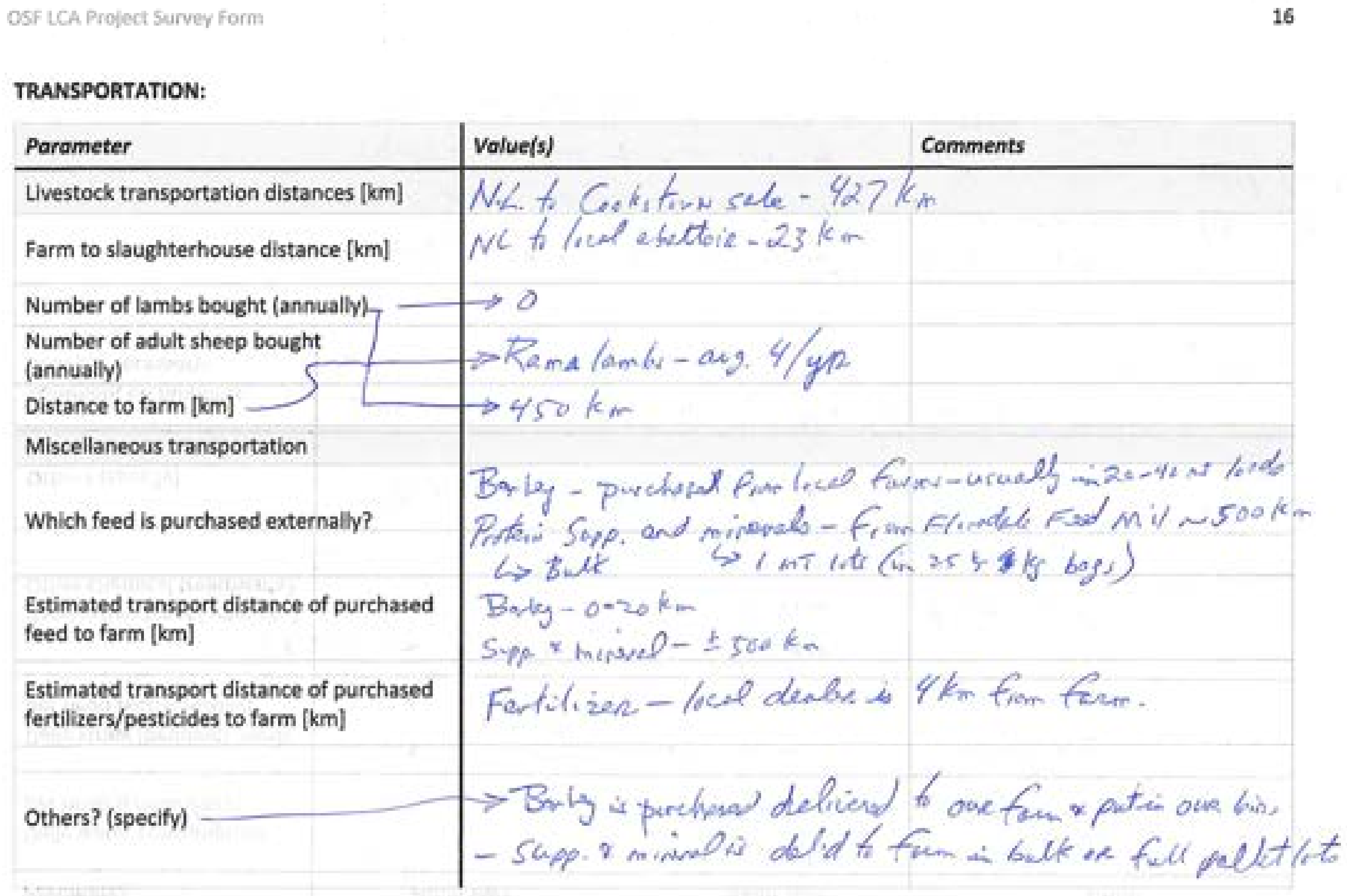


ANIMAL NEEDS (excluding feed):

Identify and quantify other needs of livestock on farm

Parameter	*Adult ewe*	*Adult ram*	*Lamb*
Daily water consumption per head [L/head/day]	on good pasture 5-8 l/hd/d winter - water source is snow	Summer - on pasture 5-6 l/hd/d winter - snow	on pasture - suckling and < 1 l water/hd/day winter - Feeder lambs - 2-2.5 l/hd/d. - replacements - snow
Daily straw (bedding) needs per head [kg/head/day]	Dec. to April only est. 0.1 kg/hd/day	Same as ewes	Feeders + Replacement lambs 0.15 kg/hd/day.
Vaccination types/amounts? Other chemical treatments?	Mature Ewes → Tasvax (1 booster/yr) + Rams 2 year old ewes - Tasvax 2X	Feeder lambs - Tasvax (1x) Replacements - Tasvax (2x) - campylobacter vaccine (2x)	
Other? (specify)	→ Flystrike Treatment - Vetrolice pour on as needed - used as topical spray		
Comment on numbers above if necessary:	water - ewes on pasture - always well water pumped to pasture or hauled in water w/cans winter - snow or sometimes surface water during snow melt, back to well water once snow has melted.		

→ Dewormers (Startect, Levamisole in rotation) used as needed based on fecal exams, eyelid colour (FAMACHA), vet advice etc. We use strategic deworming to limit risk of parasite resistance + used pasture management methods to reduce worm burden on pastures.



TRANSPORTATION:

Parameter	Value(s)	Comments
Livestock transportation distances [km]	NL to Cookstown sale – 427 km	
Farm to slaughterhouse distance [km]	NL to local abattoir – 23 km	
Number of lambs bought (annually)	→ 0	
Number of adult sheep bought (annually)	→ Ram lambs – avg. 4/yr	
Distance to farm [km]	→ 450 km	
Miscellaneous transportation		
Which feed is purchased externally?	Barley – purchased from local farmers – usually in 20–40 MT loads Protein Supp. and minerals – from Floradale Feed Mill ~500 km ↳ Bulk ↳ 1 MT lots (in 25 & kg bags)	
Estimated transport distance of purchased feed to farm [km]	Barley – 0–20 km Supp. & mineral – ± 500 km	
Estimated transport distance of purchased fertilizers/pesticides to farm [km]	Fertilizer – local dealer is 4 km from farm.	
Others? (specify)	→ Barley is purchased delivered to our farm & put in our bins. – Supp. & mineral is deliv'd to farm in bulk or full pallet lots	

B | Input parameter statistical distributions

The following statistics are obtained from the primary data on Ontario-specific sheep farming practices, collected specifically for this study through surveys/questionnaires (Appendix A).

Figs. B1 and B2 present XY (scatter) plots for various farm input-outputs through which correlation among foreground data is visually gauged. Statistical inferences on correlation are drawn through regression analysis, however, using MATLAB (sec. C2). Figs. B3 and B4, respectively, show the Q-Q plots and boxplots for the sample data ($n = 23$) collected through surveys. These plots are used to visually assess the normality of the sample data, but the goodness of fit is assessed through the Anderson-Darling (AD) test using MATLAB (sec. 3.3).

Table B1 lists the details on statistical distribution fitted to the sample data. Fig. B5 plots the statistical distributions (listed in Table B1) overlaying the histogram of the sample data. Note that while the probability distribution curves exclude the outliers, the histogram includes all the sample data, including the outliers.

The description, units, and associated MATLAB variable for the parameters listed in the aforementioned figures and tables can be found in sec. C2.

Fig. B1 XY plots of productivity and feed-related parameters

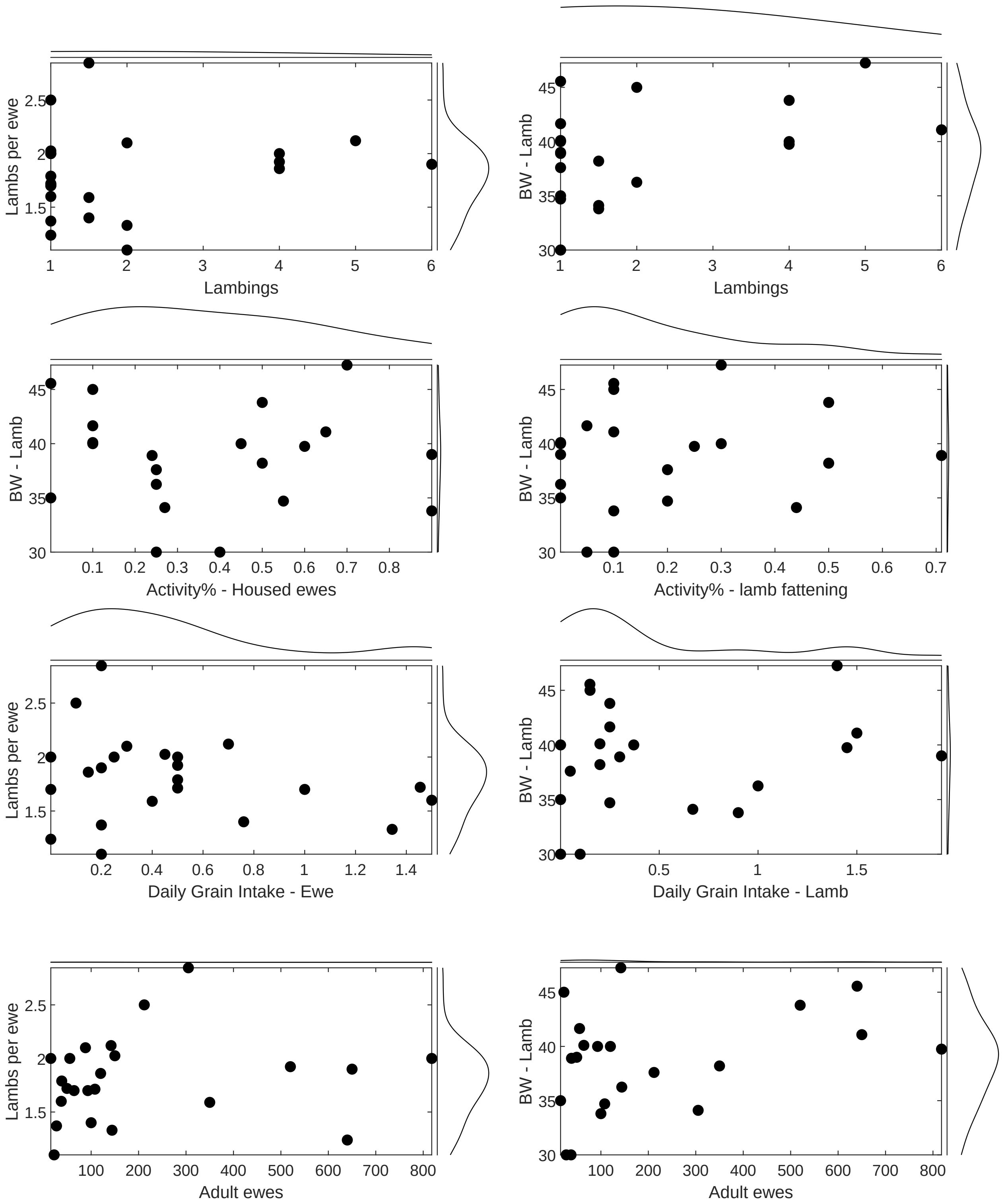


Fig. B2 XY plots of farm infrastructure and transportation-related parameter (red data-points are outliers)

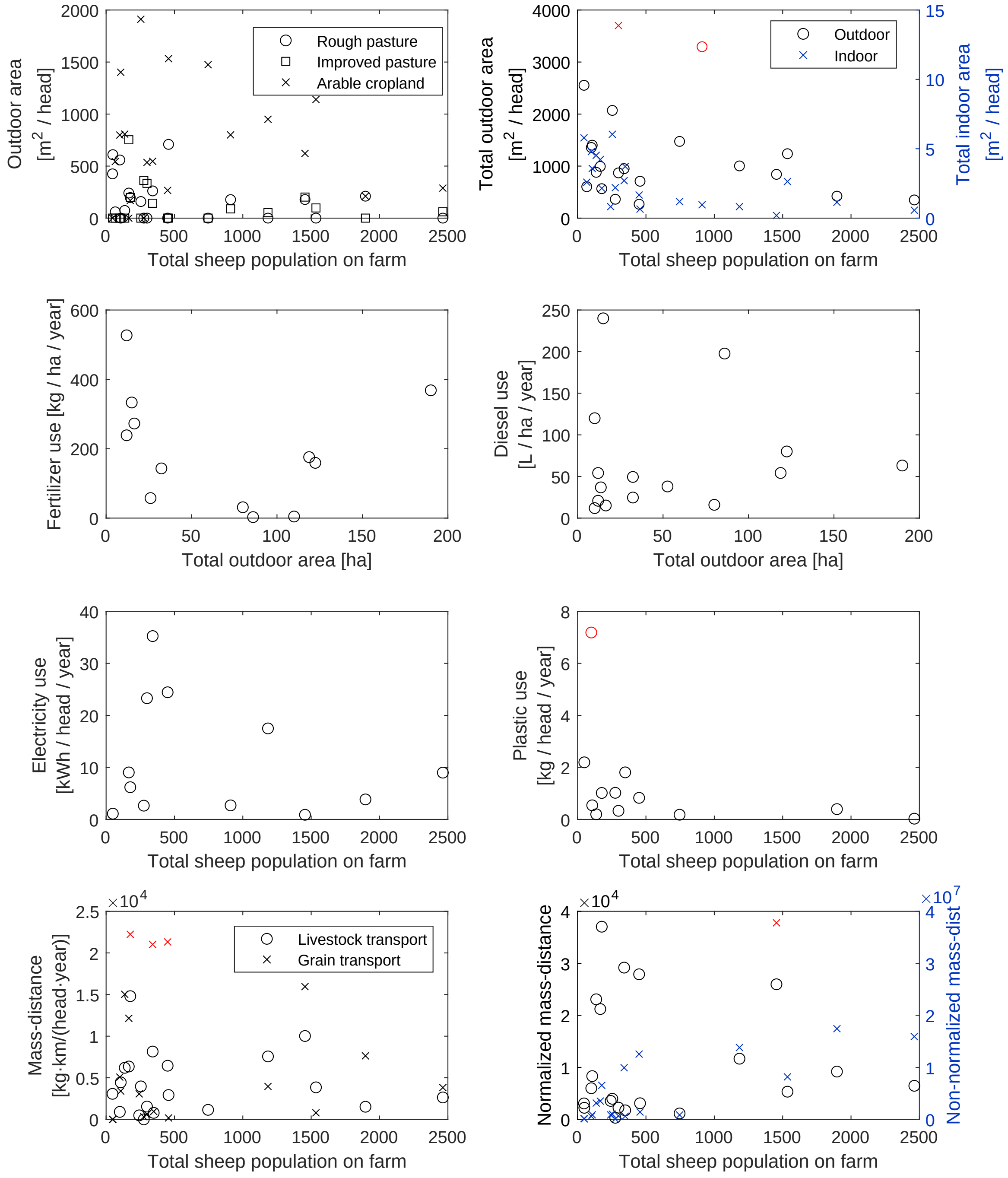


Fig. B3 Normal Q-Q plots of sample data collected from surveys

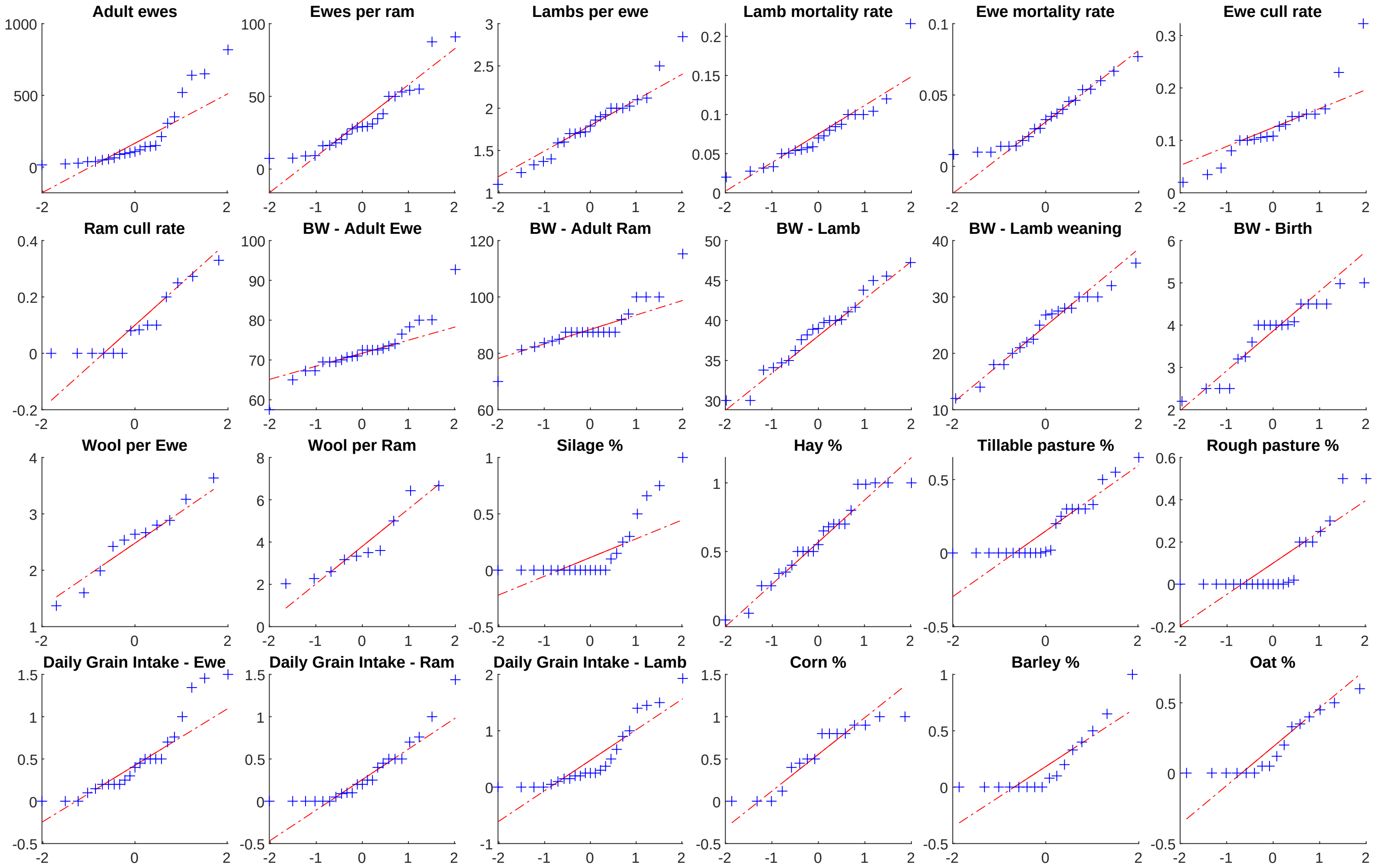


Fig. B3 *(continued)*: Normal Q-Q plots of sample data collected from surveys

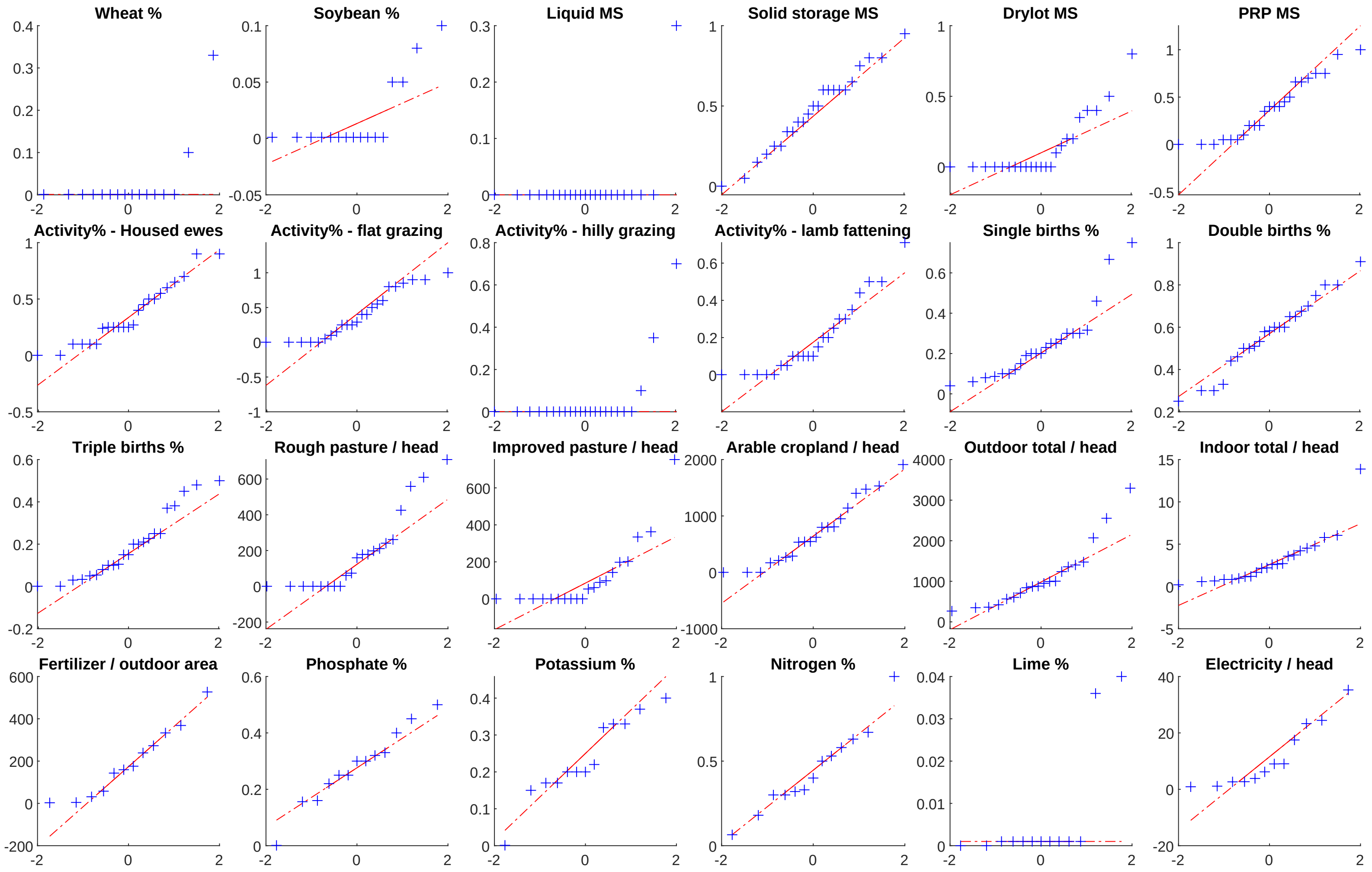


Fig. B3 *(continued)*: Normal Q-Q plots of sample data collected from surveys

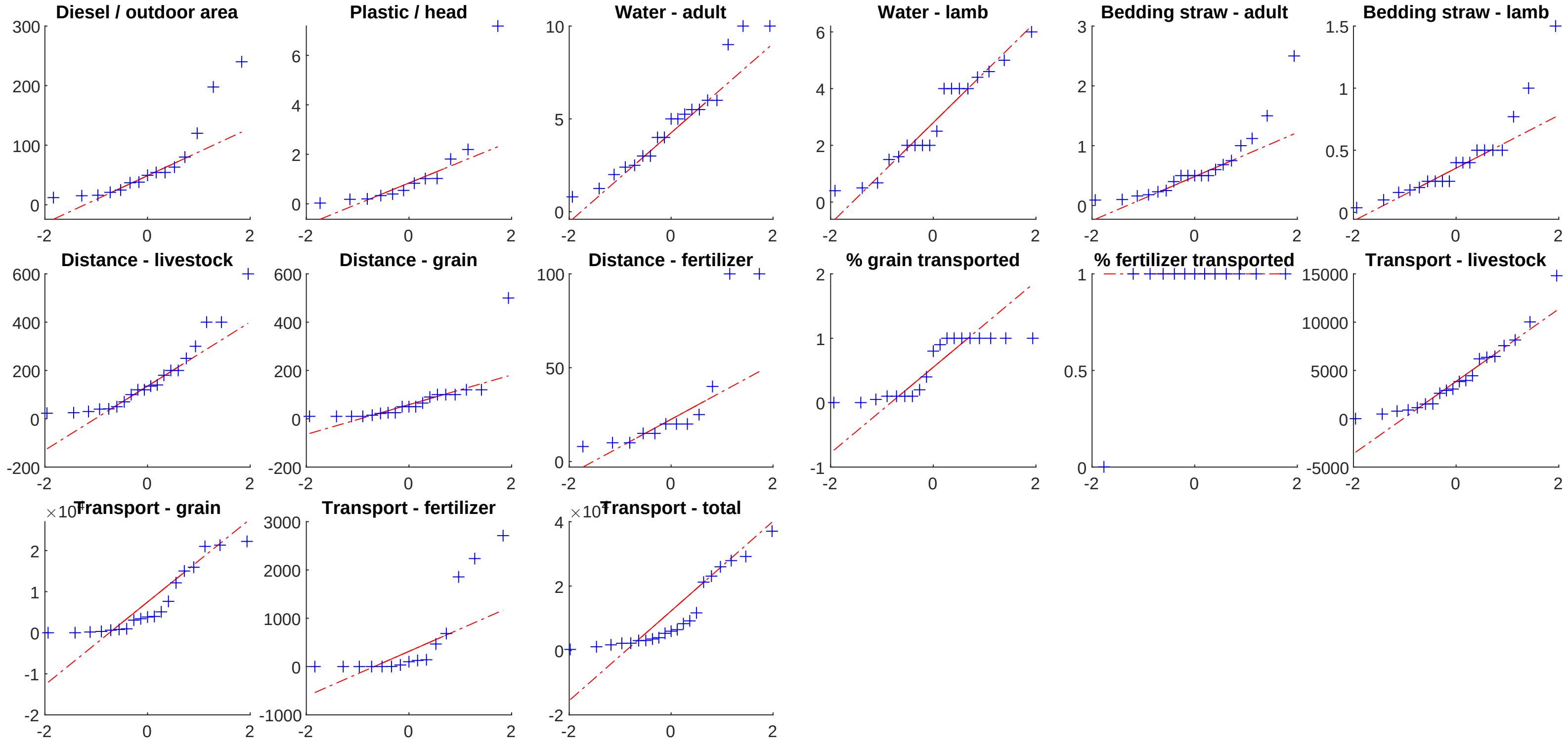


Fig. B4 Boxplots of sample data collected from surveys

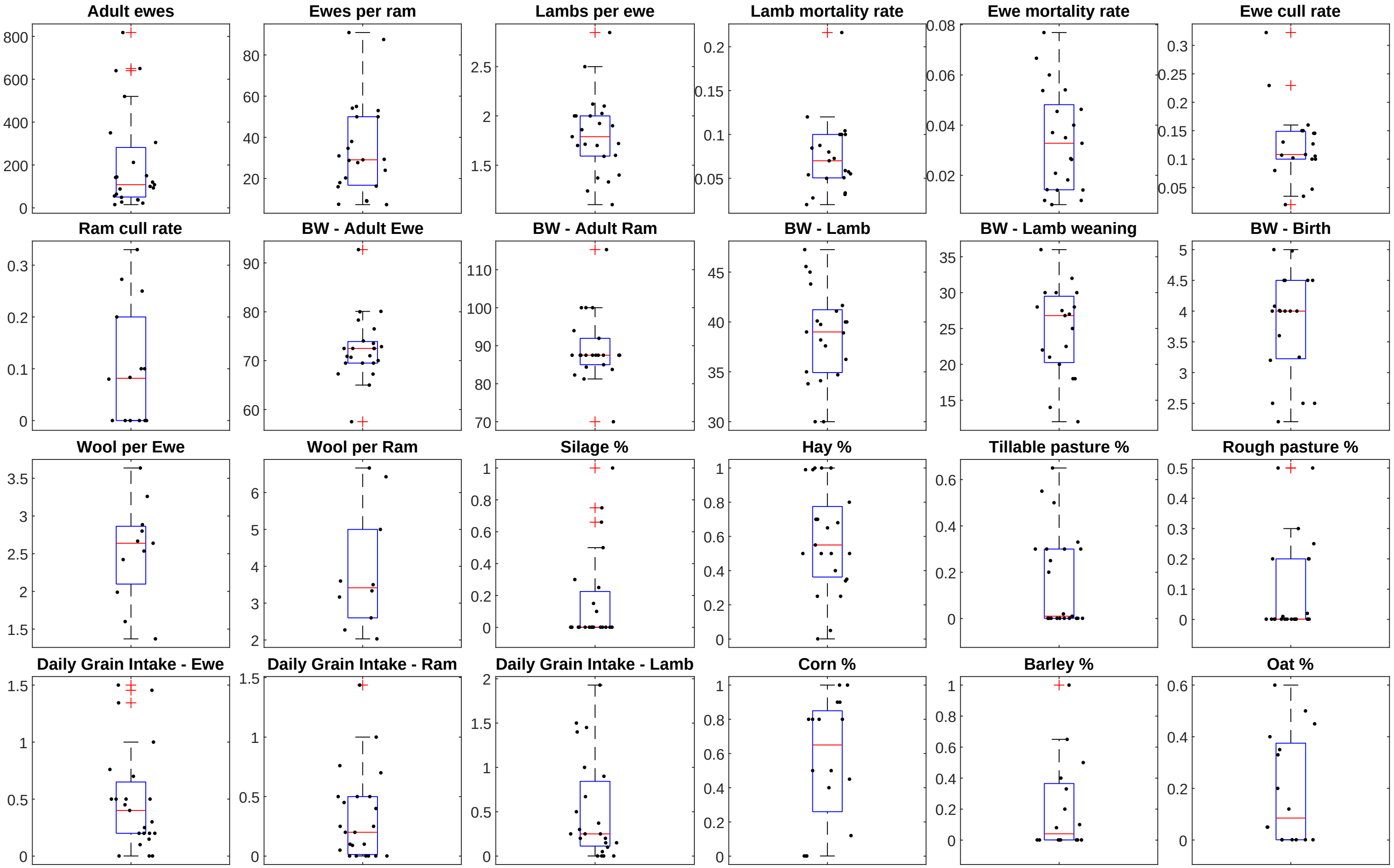


Fig. B4 *(continued)*: Boxplots of sample data collected from surveys

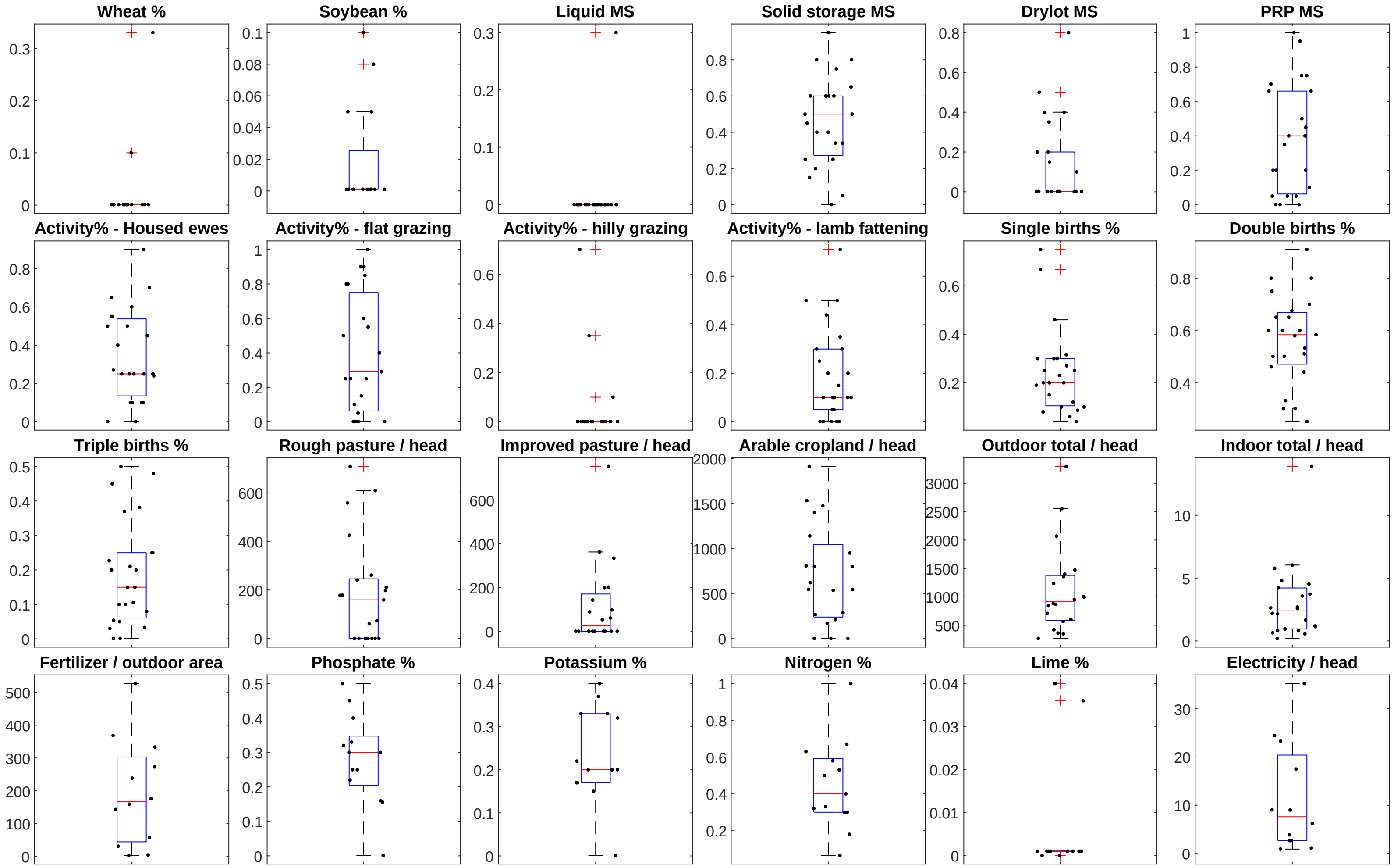


Fig. B4 *(continued)*: Boxplots of sample data collected from surveys

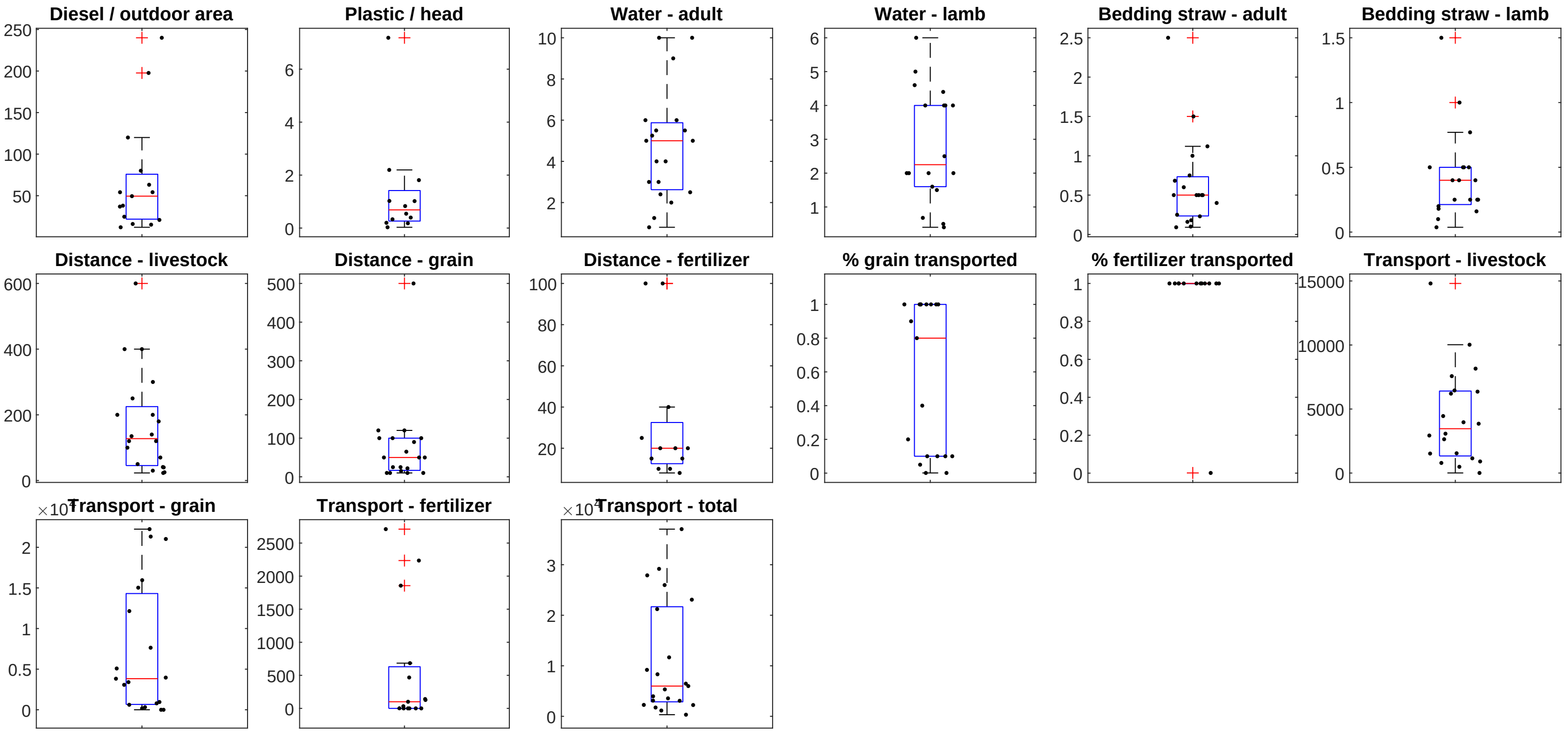


Table B1 Distribution type and parameter values of distributions fitted to farm sample data

Variable name	Distribution type	Parameter value 1	Parameter value 2	Parameter value 3	AD test[a] *p*-value
Adult ewes	Burr	95.290	1.638	0.843	0.98
Ewes per ram	Lognormal	3.300	0.731		0.88
Lambs per ewe	Normal	1.805	0.397		0.89
Lamb mortality rate	Lognormal	-2.732	0.553		0.92
Ewe mortality rate	Weibull	0.038	1.795		0.93
Ewe cull rate	Generalized Extreme Value	-0.033	0.053	0.096	0.71
Ram cull rate	Exponential	0.101			0.08
BW - Adult Ewe	Normal	71.114	4.725		0.24
BW - Adult Ram	Normal	89.220	8.835		0.17
BW - Lamb	Normal	38.655	4.692		0.98
BW - Lamb weaning	Normal	24.621	6.316		0.93
BW - Birth	Weibull	4.112	5.715		0.52
Wool per Ewe[b]	Normal	4.800	1.000		n/a
Wool per Ram[b]	Normal	6.400	1.500		n/a
Silage %	Exponential	0.162			0.09
Hay %	Generalized Extreme Value	-0.607	0.335	0.527	0.42
Tillable pasture %	Exponential	0.162			0.07
Rough pasture %	Exponential	0.138			0.12
Daily Grain Intake - Ewe	Exponential	0.487			0.23
Daily Grain Intake - Ram	Exponential	0.326			0.06

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[a] Anderson-Darling test

[b] Range of values obtained from Brock *et al.* (2013), Eady *et al.* (2012), and Jones *et al.* (2014) (normal distribution assumed). These are reflected in the wool production distributions plotted in Fig. B5 as well.

Table B1 – *Continued from previous page*

Variable name	**Distribution type**	**Parameter value 1**	**Parameter value 2**	**Parameter value 3**	**AD test *p*-value**
Daily Grain Intake - Lamb	Exponential	0.505			0.06
Corn %	Extreme Value	0.745	0.181		0.05
Barley %	Logistic	0.152	0.152		0.18
Oat %	Rayleigh	0.199			0.00
Wheat %	Birnbaum Saunders	0.004	1.904		0.13
Soybean %	Weibull	0.008	0.491		0.07
Liquid MS	Uniform	0.000	0.010		0.00
Solid storage MS	Normal	0.469	0.248		0.99
Drylot MS	Weibull	0.039	0.373		0.02
PRP MS	Weibull	0.352	0.798		0.23
Activity% - Housed ewes	Loglogistic	-1.306	0.761	3.000	0.17
Activity% - flat grazing	Gamma	0.487	0.807		0.14
Activity% - hilly grazing	Beta	0.206	3.054		0.72
Activity% - lamb fattening	Generalized Extreme Value	0.476	0.103	0.081	0.63
Single births %	Loglogistic	-1.622	0.407		0.91
Double births %	Logistic	0.569	0.097		0.98
Triple births %	Loglogistic	-2.028	0.781		0.39
Rough pasture / head	Logistic	133.071	113.354		0.21
Improved pasture / head	Gamma	0.125	795.377		0.07
Arable cropland / head	Normal	608.604	573.954		0.75
Outdoor total / head	Logistic	868.295	418.776		0.34
Indoor total / head	Loglogistic	0.641	0.769		0.60
Fertilizer / outdoor area	Weibull	187.887	0.931		0.72
Phosphate %	Generalized Extreme Value	-0.422	0.135	0.244	0.98

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Table B1 – *Continued from previous page*

Variable name	**Distribution type**	**Parameter value 1**	**Parameter value 2**	**Parameter value 3**	**AD test *p*-value**
Potassium %	Generalized Extreme Value	-0.543	0.116	0.212	0.70
Nitrogen %	Generalized Extreme Value	-0.094	0.202	0.347	0.99
Lime %	Generalized Extreme Value	1.103	0.001	0.001	0.12
Electricity / head	Lognormal	1.858	1.219		0.97
Diesel / outdoor area	Lognormal	3.829	0.906		0.99
Plastic / head	Loglogistic	-0.478	0.755		1.00
Water - adult	Normal	4.747	2.698		0.75
Water - lamb	Extreme value	3.667	1.549		0.60
Bedding straw - adult	Lognormal	-0.802	0.881		0.93
Bedding straw - lamb	Weibull	0.471	1.370		0.83
Distance - livestock	Burr	809.124	1.271	7.409	0.97
Distance - grain	Loglogistic	3.761	0.633		0.68
Distance - fertilizer	Lognormal	3.101	0.828		0.66
% grain transported	Uniform	0.750	1.000		n/a
% fertilizer transported	Uniform	0.900	1.000		n/a
Transport - livestock	Weibull	4382.920	1.026		0.95
Transport - grain	Exponential	7239.210			0.34
Transport - fertilizer	Weibull	46.829	0.192		0.21
Transport - total	Generalized Extreme Value	0.728	4340.140	4147.830	0.92

Fig. B5 Histogram of sample data (includes outliers) and fitted distributions (excludes outliers)

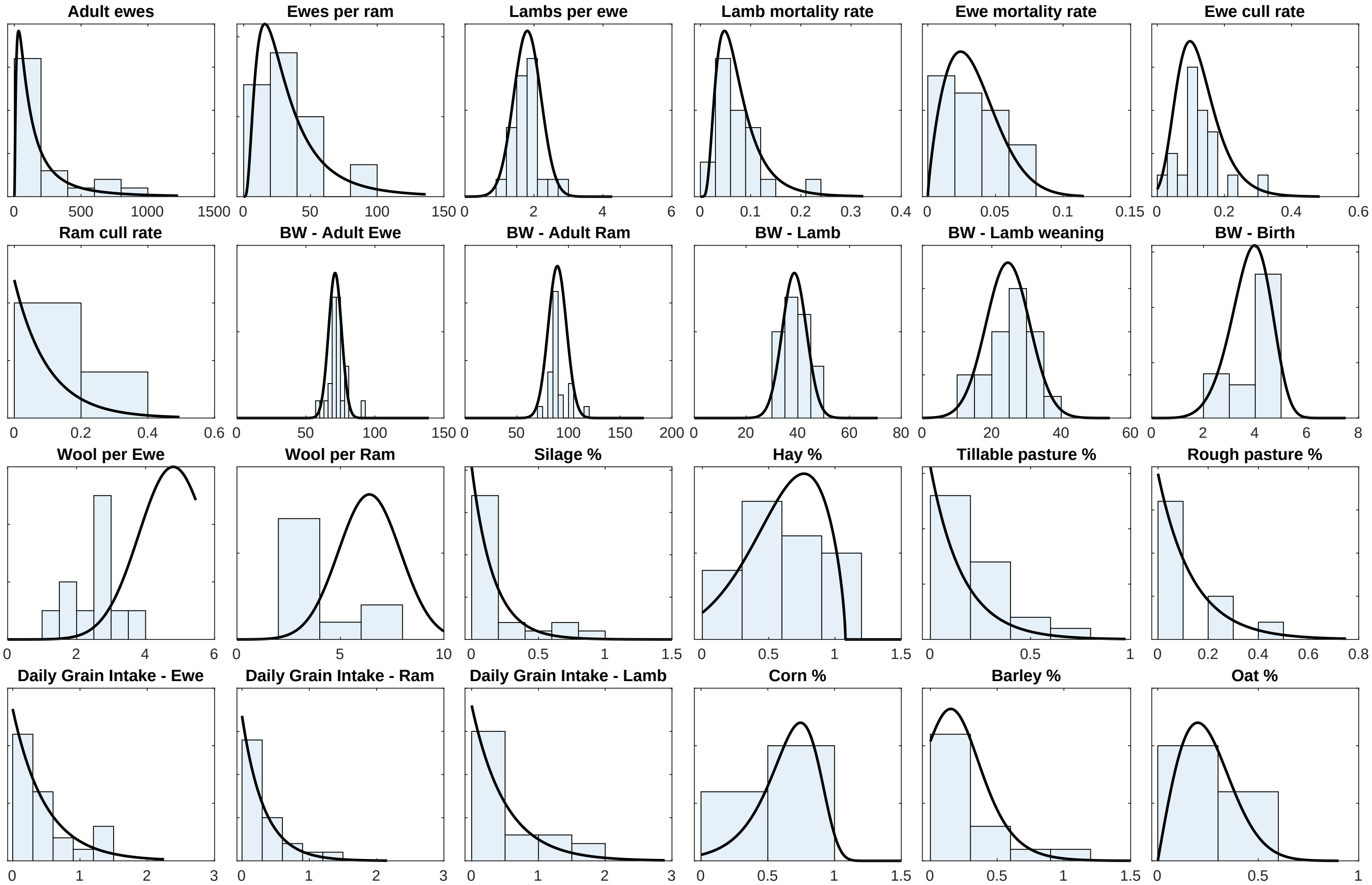


Fig. B5 *(continued)*: Distributions fitted over histograms of sample data

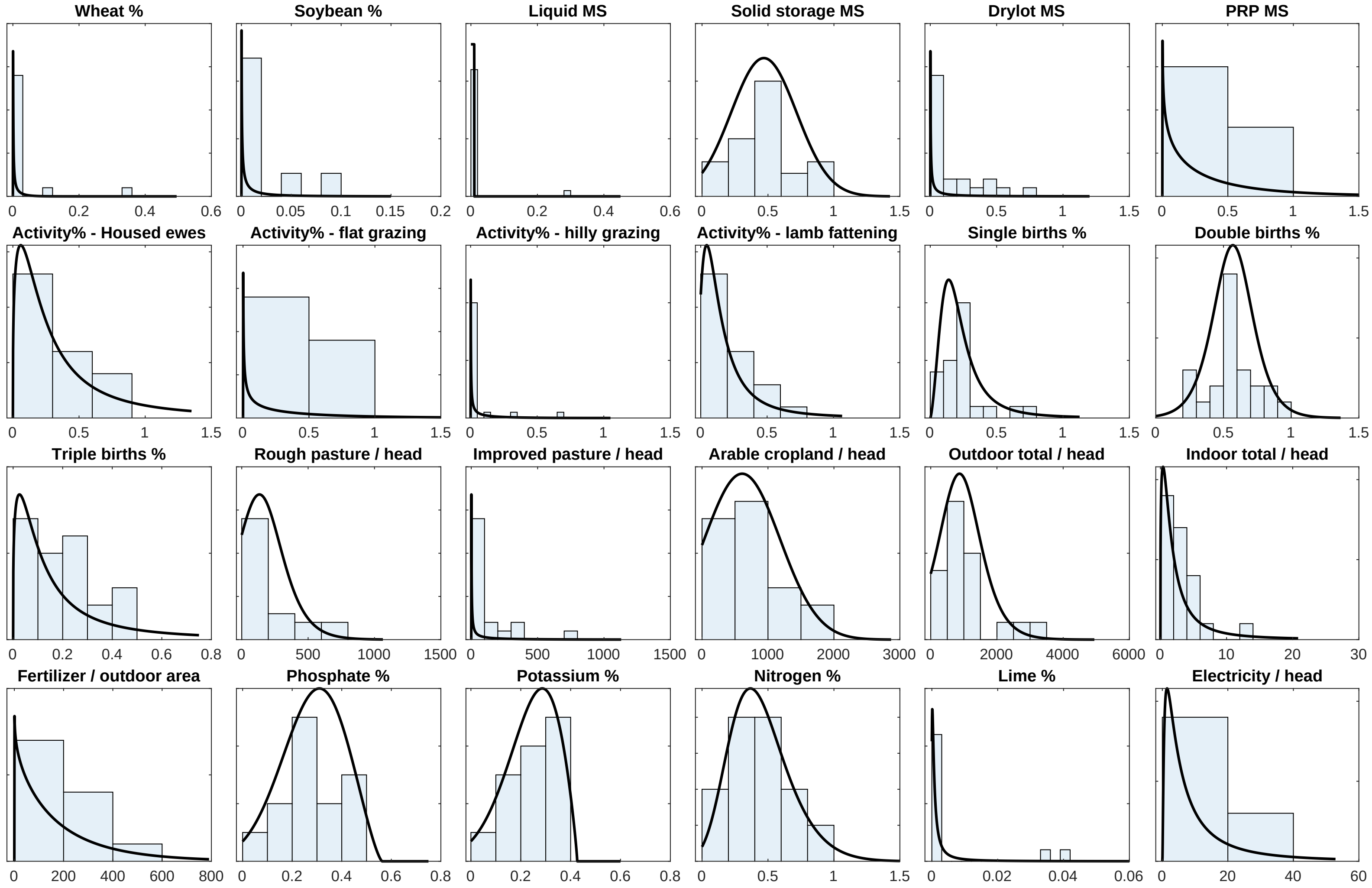
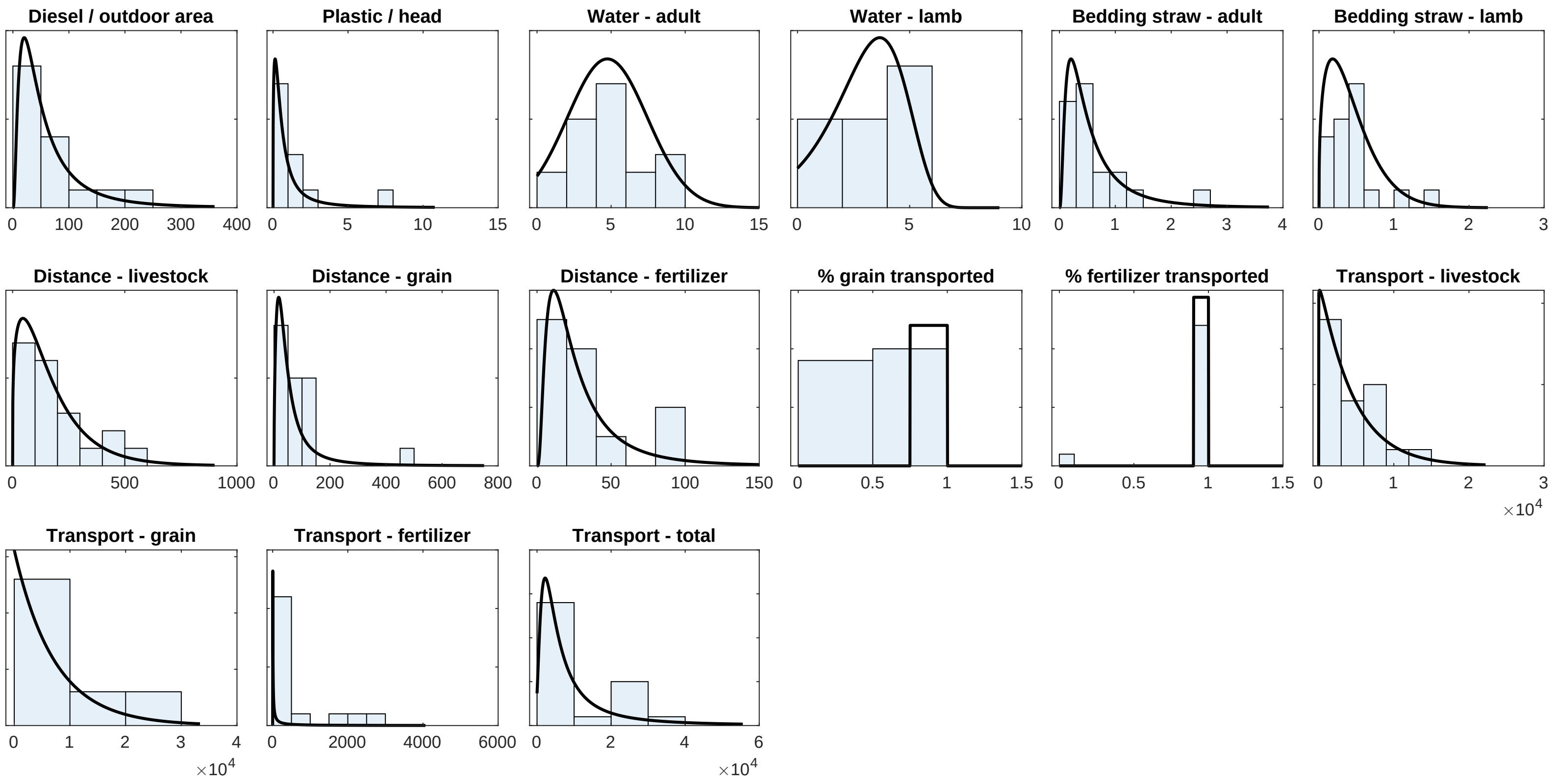


Fig. B5 *(continued)*: Distributions fitted over histograms of sample data



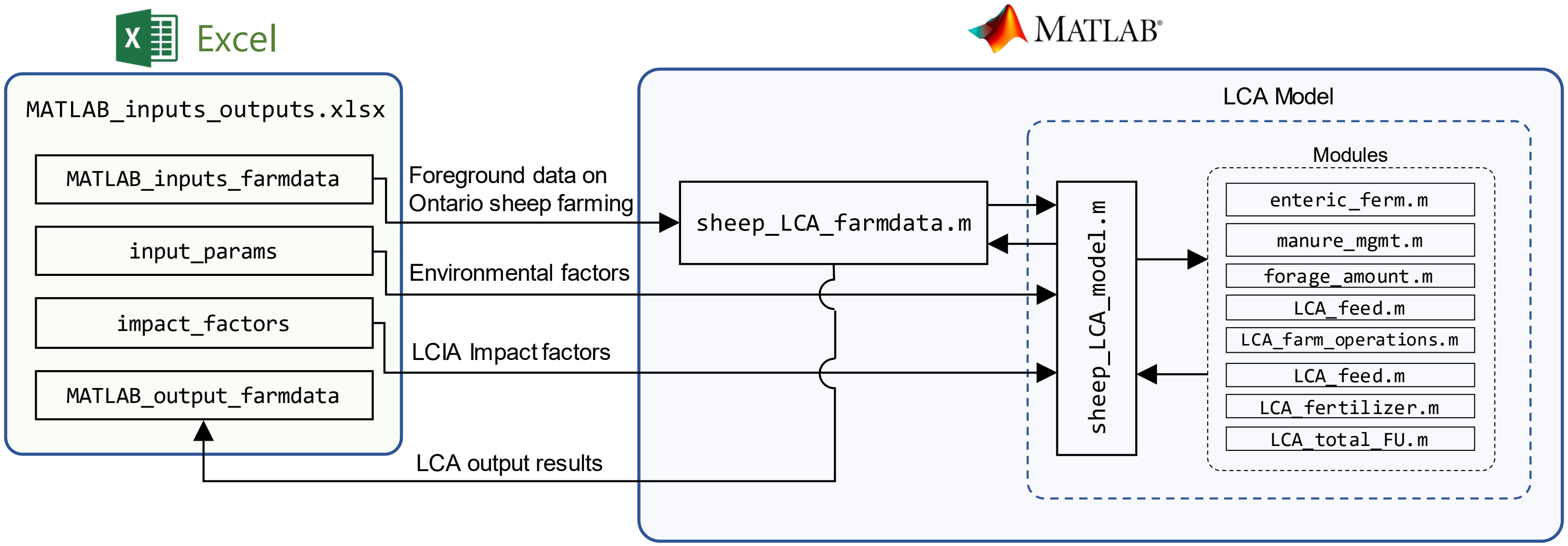
C | Sheep LCA model – additional details

The full LCA outputs for the LCA results presented in sec. 4, LCA model code files, and instructions on executing the code can be accessed and used under the General Public License (GPL v3.0) on GitHub: **github.com/akoolbhatt/ON-sheep-LCA**.

The LCA results shown in sec. 4 can be replicated by executing the MATLAB script `sheep_LCA_farmdata.m`. Fig. C1 shows the MATLAB-Excel interaction during code execution. Script (`sheep_LCA_farmdata.m`) execution will import (from the spreadsheet `MATLAB_inputs_outputs.xlsx`) the foreground data on sheep farming practices as well as relevant environmental factors and impact factors into the LCA model. It will also export the LCA outputs back into the spreadsheet.

The LCA model consists of eight scripts which accept 142 input parameters representing farming practices and environmental factors. Sec. C1 contains the description of the function of these scripts. Sec. C2 contains description, baseline values, units, and associated MATLAB variable for all 142 parameters. It also includes the sources from which environmental factor values were obtained.

Fig. C1 Conceptualization of MATLAB-Excel interaction in LCA model code execution



C1. LCA MODEL MATLAB SCRIPTS

The model consists of the following MATLAB scripts:

Script name	**Script function**
`sheep_LCA_model.m`	This script does the following: • Combines related variables into arrays, • Displays error, aborts calculations if invalid inputs are detected, • Estimates forage amount through iterative energy balance, and • Runs subsequent scripts in 'Modules' to determine cradle-to-gate life cycle impacts
`enteric_ferm.m`	Calculates livestock's net energy (NE) and gross energy (GE) requirements, and per-head enteric CH_4 emissions
`forage_amount.m`	Estimates DMI from roughage/grazing
`manure_mgmt.m`	Estimates manure CH_4 emissions and nitrogen-based GHG emissions (through nitrogen balance)
`LCA_feed.m`	Tallies the total feed intake and calculates impacts of feed production
`LCA_fertilizer.m`	Calculates impacts of fertilizer production and fertilization
`LCA_farm_operations.m`	Calculates impacts of farm infrastructure (outdoor area, barns/sheds, etc.) and misc. farming operations (water, electricity, heating fuel, diesel, tilling, plastic, and transportation)
`LCA_total_FU.m`	Calculates allocation factor and estimates life cycle impacts per functional unit

This script package imports parameter values (representing farming practices and environmental factors) and LCIA impact factors stored in `MATLAB_inputs_outputs.xlsx` and stores them as MATLAB variables. The variables are used as input arguments in the LCA model (`sheep_LCA_model.m`), which outputs life cycle impacts in the categories of global warming (GW), energy demand (ED), and water depletion (WD).

The live script `sheep_LCA_IO.mlx` may be used as an example to see how input arguments in `MATLAB_inputs_outputs.xlsx` can be passed on to the LCA model. Model results deemed important (e.g., life cycle impacts per functional unit, total daily dry matter intake (DMI), etc.) are also tabulated at the end of this live script.

C2. LCA MODEL INPUT PARAMETERS

Notes:
1. Input parameter values shaded in **orange** cells are obtained from surveys. Unshaded values are environmental parameters obtained from external sources
2. Baseline values represent average Ontario sheep farming practices
3. If 'SOURCE' in table below is blank, value is obtained from surveys

Table C1 List of input parameters, description, units, baseline value and the associated MATLAB variable in the LCA model

VARIABLE NAME	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
	POPULATION				
`ewes`	Adult ewes (F)	#	*Number of adult ewes on farm(s)*	206	
`ewes_per_ram`	Ewes per ram	#	*Number of ewes per ram*	34	
`lambs_per_ewe`	Lambs per ewe	-	*Average number of lambs per ewe*	1.8	
`P_male_lambs`	Lamb M:total ratio	%	*Proportion of rams in lamb population*	50%	
`lamb_mortality`	Lamb mortality rate	%	*Proportion of lambs which do not survive*	7.50%	
`ewe_mortality`	Ewe (F) mortality rate	%	*Proportion of ewes which do no survive*	3.50%	
`ewe_cull`	Ewe (F) cull rate	%	*Proportion of ewes culled*	12.40%	
`ram_cull`	Ram (M) cull rate	%	*Proportions of rams culled*	10.10%	
	AVERAGE BODY WEIGHTS (BW)				
`BW_ewe`	BW - Adult Ewe	kg	*Average body weight of adult ewe*	72.4	
`BW_ram`	BW - Adult Ram	kg	*Average body weight of adult ram*	89.2	
`BW_lamb_ewe`	BW - Lamb Ewe	kg	*Average body weight of lamb ewe at age 1y*	38.6	
`BW_lamb_ram`	BW - Lamb Ram	kg	*Average body weight of lamb ram at age 1y*	38.6	
`BW_weaning`	BW - Lamb weaning	kg	*Average body weight of lamb at time of weaning*	24.6	
`BW_birth`	BW - Birth	kg	*Average body weight of lamb at time of birth*	3.8	
	PRODUCTS				

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Table C1 – *Continued from previous page*

VARIABLE NAME	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
`BW_LW_ewe`	BW –>LW Ewe	%	*% of inputted BW which translates to LW for ewes*	100%	
`BW_LW_ram`	BW –>LW Ram	%	*% of inputted BW which translates to LW for lambs*	100%	
`BW_LW_lamb`	BW –>LW Lamb	%	*% of inputted BW which translates to LW for lambs*	100%	
	Annual wool production her head				
`wool_per_ewe`	Wool per Ewe	kg wool/ewe/year	*Average annual wool produced by ewe*	4.8	Brock *et al.* (2013), Eady *et al.* (2012), and Jones *et al.* (2014)
`wool_per_ram`	Wool per Ram	kg wool/ram/year	*Average annual wool produced by ram*	6.4	
`wool_per_lamb`	Wool per Lamb	kg wool/lamb/year	*Average annual wool produced by lamb*	1	
	Annual milk production her head				
`milk_per_ewe`	Milk per Ewe	kg milk/ewe/year	*Average annual milk produced by ewe*	100	IPCC (2006)
	DIET INPUTS				
	Mass proportion of diet based on roughage / foraging				
`P_forage_adult_ewe`	Forage% - Adult Ewe	%	*Proportion of adult ewes' diet from foraging*	77.10%	
`P_forage_adult_ram`	Forage% - Adult Ram	%	*Proportion of adult rams' diet from foraging*	84.15%	
`P_forage_lamb_ewe`	Forage% - Lamb Ewe	%	*Proportion of lamb ewes' diet from foraging*	58.91%	
`P_forage_lamb_ram`	Forage% - Lamb Ram	%	*Proportion of lamb rams' diet from foraging*	58.84%	
	Roughage / forage type composition (by mass)				
`forage_corn_silage`	Silage %	%	*Percent of corn (maize) in roughage / forage*	17%	
`forage_hay`	Hay %	%	*Percent of hay in roughage / forage*	58%	
`forage_tillable_pasture`	Tillable pasture %	%	*Percent of tillable pasture in roughage / forage*	16%	
`forage_rough_pasture`	Rough pasture %	%	*Percent of rough pasture in roughage / forage*	9%	
-	Sum Check	%	*Should equal 100%*	100%	

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Table C1 – *Continued from previous page*

VARIABLE NAME	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
	Daily grain intake per head				
`grain_amount_ewe`	Daily Grain Inktake - Ewe	kg/head/day	*Daily grain (concentrate) intake per adult ewe*	0.49	
`grain_amount_ram`	Daily Grain Inktake - Ram	kg/head/day	*Daily grain (concentrate) intake per adult ram*	0.33	
`grain_amount_lamb`	Daily Grain Inktake - Lamb	kg/head/day	*Daily grain (concentrate) intake per lamb*	0.51	
`feeding_practice`	Feeding practice	logical	*Feeding practice: 0 = specialized facilities (5% wastage); 1 = feed spread on ground (20% wastage)*	0	
	Grain composition (by mass)				
`grain_corn`	Corn %	%	*Percent of corn (maize) in grain*	55%	
`grain_barley`	Barley %	%	*Percent of barley in grain*	20%	
`grain_oat`	Oat %	%	*Percent of oat in grain*	20%	
`grain_wheat`	Wheat %	%	*Percent of wheat in grain*	3%	
`grain_soybean`	Soybean %	%	*Percent of soybean in grain*	2%	
-	Sum Check	%	*Should equal 100%*	100%	
	Energy content of dry matter intake				
`DMI_energy_forage`	Energy - forage/roughage	MJ/kg	*Energy content of roughage/forage*	12	AHDB (2018)
`DMI_energy_grain`	Energy - Grain concentrate	MJ/kg	*Energy content of grain concentrates*	18.45	AHDB (2018) and IPCC (2006)
	Nitrogen content of feed				
`N_silage`	N content - silage	kg N/kg feed	*Nitrogen content of silage*	0.022	FAO (2018)
`N_hay`	N content - hay	kg N/kg feed	*Nitrogen content of hay*	0.01	FAO (2018)
`N_till_pasture`	N content - Tillable pasture	kg N/kg feed	*Nitrogen content of tillable pasture*	0.035	FAO (2018)
`N_rough_pasture`	N content - Rough pasture	kg N/kg feed	*Nitrogen content of rough pasture*	0.035	FAO (2018)
`N_corn`	N content - Corn	kg N/kg feed	*Nitrogen content of Corn*	0.02	FAO (2018)
`N_barley`	N content - Barley	kg N/kg feed	*Nitrogen content of Barley*	0.02	FAO (2018)
`N_oat`	N content - Oat	kg N/kg feed	*Nitrogen content of Oat*	0.02	FAO (2018)

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Table C1 – *Continued from previous page*

VARIABLE NAME	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
`N_wheat`	N content - Wheat	kg N/kg feed	*Nitrogen content of Wheat*	0.035	FAO (2018)
`N_soybean`	N content - Soybean	kg N/kg feed	*Nitrogen content of Soybean*	0.02	FAO (2018)
	MANURE MANAGEMENT INPUT				
	Manure Management System				
`MS_liquid`	Liquid MS	%	*Proportion of manure managed using liquid systems*	0%	
`MS_solid`	Solid storage MS	%	*Proportion of manure managed using solid storage systems*	46%	
`MS_drylot`	Drylot MS	%	*Proportion of manure deposited on drylot*	14%	
`MS_PRP`	PRP MS	%	*Proportion of manure deposited on pasture, range and paddock (PRP)*	40%	
-	Sum Check	%	*Should equal 100%*	100%	
	Nitrogen Content in Products				
`N_meat`	N content in Meat	kg N / kg LW	*Nitrogen content in meat*	0.034	FAO (2016)
`N_wool`	N content in Wool	kg N / kg wool	*Nitrogen content in wool, assuming 16% of greasy wool is water*	0.134	FAO (2016)
`N_milk`	N content in Milk	kg N /L milk	*Nitrogen content in milk*	0.013	FAO (2016)
	Methane Conversion Factors (MCF)				
`MCF_liquid`	Liquid MCF	%	*MCF for liquid sys.*	25.00%	ECCC (2020)
`MCF_solid`	Solid storage MCF	%	*MCF for solid sys.*	2.00%	ECCC (2020)
`MCF_drylot`	Drylot MCF	%	*MCF for drylot sys.*	1.00%	ECCC (2020)
`MCF_PRP`	PRP MCF	%	*MCF for pasture/range/paddock (PRP) sys.*	1.00%	ECCC (2020)
	Manure CH_4 Parameters				
`UE`	Urinary Energy	%	*Urinary energy (UE) as a fraction of gross energy (GE)*	4.00%	IPCC (2006)
`ASH`	Ash content	%	*Manure ash content*	8.00%	ECCC (2020)

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Table C1 – *Continued from previous page*

VARIABLE NAME	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
`Bo`	Bo	m^3 CH_4 / kg VS	*Max CH_4 production capacity of manure*	0.19	IPCC (2006)
	Direct N_2O Emissions Parameters				
`N_excr`	Nitrogen Excr. Rate	kg N / day / 1000 kg	*Daily Nitrogen excretion rate (Table 10.19)*	0.42	IPCC (2006)
`EF3_liquid`	Liquid EF3	kg N_2O-N/kg N	*Direct N_2O emission factor for liquid manure management*	0	ECCC (2020)
`EF3_solid`	Solid EF3	kg N_2O-N/kg N	*Direct N_2O emission factor for solid manure management*	0.005	ECCC (2020)
`EF3_drylot`	Drylot EF3	kg N_2O-N/kg N	*Direct N_2O emission factor for drylot manure management*	0.02	ECCC (2020)
`EF3_PRP`	PRP EF3	kg N_2O-N/kg N	*Direct N_2O emission factor for PRP (urine/dung) manure management*	0.01	ECCC (2020)
	Indirect Volatization N_2O Emissions Parameters				
`FracGas_liquid`	%N vol. - liquid MS	%	*Fraction of manure that volatizes as NH_3 and Nox in liquid MS*	0	ECCC (2020)
`FracGas_solid`	%N vol. - solid MS	%	*Fraction of manure that volatizes as NH_3 and Nox in solid MS*	0.12	ECCC (2020)
`FracGas_drylot`	%N vol. - drylot MS	%	*Fraction of manure that volatizes as NH_3 and Nox in drylot MS*	0.12	ECCC (2020)
`FracGas_PRP`	%N vol. - PRP	%	*Fraction of manure that volatizes as NH_3 and Nox in PRP MS*	0.2	ECCC (2020, Table A3.4-22)
`EF4`	EF4	kg N_2O-N/(kg NH_3-N+NOx-N)	*Emission factor from atm. Deposition*	0.01	IPCC (2006, ch.11)
	Indirect Leaching N_2O Emissions Parameters				
`FracLeach_liquid`	%N leach - liquid MS	%	*Fraction of manure N loss through leaching/runoff from liquid MS*	0.00%	ECCC (2020)
`FracLeach_solid`	%N leach - solid MS	%	*Fraction of manure N loss through leaching/runoff from solid MS*	15.00%	ECCC (2020)

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Table C1 – *Continued from previous page*

VARIABLE NAME	**PARAMETER**	**UNIT**	*COMMENTS*	**BASELINE VALUE**	**SOURCE**
`FracLeach_drylot`	%N leach - drylot MS	%	*Fraction of manure N loss through leaching/runoff from drylot MS*	15.00%	ECCC (2020)
`FracLeach_PRP`	%N leach - PRP	%	*Fraction of manure N loss through leaching/runoff from PRP MS*	0.00%	ECCC (2020)
`EF5`	EF5	kg N_2O-N/(kg N leaching)	*Emission factor from N leaching/runoff*	0.0075	IPCC (2006, ch.11)
	GROSS ENERGY / ENT.FERM INPUTS				
	Castrated% and Ambient Temperature inputs				
`castrated_ram`	castrated% - Adult ram	%	*Percent of adult rams castrated*	90.00%	
`castrated_ram_lamb`	castrated% - Lamb ram	%	*Percent of lamb rams castrated*	80.00%	
`Tamb`	Annual Ambient. Temp	degC	*Annual average ambient temperature*	15	
	Net energy for activity (NEa) inputs				
`P_housed_ewe`	Activity% - Housed ewes	%	*Proportion of time livestock is confined due to pregnancy*	35%	
`P_flat`	Activity% - flat grazing	%	*Proportion of time animals walk up to 1000m for feeding*	40%	
`P_hilly`	Activity% - hilly grazing	%	*Proportion of time animals walk up to 5000m for feeding*	5%	
`P_fatten`	Activity% - lamb fattening	%	*Proportion of time animals are housed for fattening*	20%	
-	Sum Check	%	*Should add up to 100%*	100%	
	Net energy for pregnancy (NEp) inputs				
`P_gestation`	Gestation / birth %	%	*Proportion of adult ewes that give birth / go through gestation*	80%	
`P_single`	Single births %	%	*Proportion of single births*	35%	
`P_double`	Double births %	%	*Proportion of double births*	55%	
`P_triple`	Triple births %	%	*Proportion of triple births*	10%	
-	Sum Check	%	*Should add up to 100%*	100%	

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Table C1 – *Continued from previous page*

VARIABLE NAME	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
	Coefficient for Net Energy for Maintenance (NEm)				
`Cfi_0_adult`	Default Cfi - Adult ewe	MJ/kg/day	*Coefficient for calculating NE_m in adult sheep*	0.217	ECCC (2020)
`Cfi_0_lamb`	Default Cfi - Lamb ewe	MJ/kg/day	*Coefficient for calculating NE_m in lamb sheep*	0.236	ECCC (2020)
	Coefficient for Net Energy for Activity (NEa)				
`Ca_housed_ewe`	Ca - Housed ewe	MJ/kg/day	*Coefficient for calculating NE_a for housed ewes*	0.009	ECCC (2020)
`Ca_flat`	Ca - flat grazing	MJ/kg/day	*Coefficient for calculating NE_a for flat grazing sheep*	0.0107	ECCC (2020)
`Ca_hilly`	Ca - hilly grazing	MJ/kg/day	*Coefficient for calculating NE_a for hilly grazing sheep*	0.024	ECCC (2020)
`Ca_fatten`	Ca - fattening lambs	MJ/kg/day	*Coefficient for calculating NE_a for housed fattening lambs*	0.0067	ECCC (2020)
	Coefficient for Net Energy for Growth (NEg)				
`a0_intact`	a’ - intact males	MJ/kg	*a’ coefficient for intact male lambs*	2.5	ECCC (2020)
`a0_castr`	a’ - castr males	MJ/kg	*a’ coefficient for castrated male lambs*	4.4	ECCC (2020)
`a0_female`	a’ - female males	MJ/kg	*a’ coefficient for female lambs*	2.1	ECCC (2020)
`b0_intact`	b’ - intact males	MJ/kg^2	*b’ coefficient for intact male lambs*	0.35	ECCC (2020)
`b0_castr`	b’ - castr males	MJ/kg^2	*b’ coefficient for castrated male lambs*	0.32	ECCC (2020)
`b0_female`	b’ - female males	MJ/kg^2	*b’ coefficient for female lambs*	0.45	ECCC (2020)
	Coefficient for Net Energy for Lactation (NEl)				
`EV_milk`	EV milk	MJ/kg milk	*Energy req’d for milk*	4.6	IPCC (2006)
	Coefficient for Net Energy for Wool (NEw)				

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Table C1 – *Continued from previous page*

VARIABLE NAME	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
`EV_wool`	EV wool	MJ/kg wool	*Energy req'd for wool*	24	IPCC (2006)
	Coefficient for Net Energy for Pregnancy (NEp)				
`Cp_single`	Cp - single birth	-	*Coefficient for calculating NE_a for single birth*	0.077	IPCC (2006)
`Cp_double`	Cp - double birth	-	*Coefficient for calculating NE_a for double birth*	0.126	IPCC (2006)
`Cp_triple`	Cp - triple birth	-	*Coefficient for calculating NE_a for triple or more birth*	0.15	IPCC (2006)
	Coefficient for Gross Energy (GE)				
`DE_grain`	DE - Grain	%	*Digestible energy for sheep on grain diet*	74.00%	ECCC (2020)
`DE_forage`	DE - Forage/Roughage	%	*Digestible energy for sheep on roughage diet*	65.00%	ECCC (2020)
	Ent.Ferm convserion factor, Ym				
`Ym_adult`	CH_4 conversion - Adult sheep	%	*Methane conversion factor for adult sheep*	6.50%	IPCC (2006)
`Ym_lamb`	CH_4 conversion - Lambs	%	*Methane conversion factor for lambs*	4.50%	IPCC (2006)
	FARM OPERATION INPUTS				
	Farm area/size				
`area_out_rough`	Farm area - Rough	m^2/head	*Rough outdoor grazing area per population on farm*	184	
`area_out_imprvd`	Farm area - Improved	m^2/head	*Improved outdoor grazing area per population on farm*	117	
`area_out_arable`	Farm area- Arable cropland	m^2/head	*Arable cropland area per population on farm*	700	
`area_in`	Farm area - indoors	m^2/head	*Indoor farm area (barns, sheds, etc.) per population on farm*	3	
`shed_lifespan`	Shed/barn lifespan	y	*Average lifespan of shed/barn on farm*	50	

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Table C1 – *Continued from previous page*

VARIABLE NAME	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
	Fertilizer Inputs				
`fert_per_area`	Fertilizer application rate	kg/ha/year	*Annual application of fertilizer (combined weight) per outdoor area*	125.45	
`fert_P`	Phosphate (P) fertilizer	%	*Proportion of fertilizer that is phosphate-based*	28.00%	
`fert_K`	Potassium (K) fertilizer	%	*Proportion of fertilizer that is potassium-based*	24.00%	
`fert_N`	Nitrogen (N) fertilizer	%	*Proportion of fertilizer that is nitrogen-based*	45.00%	
`fert_lime`	Lime	%	*Proportion of fertilizer that is lime*	3.00%	
-	Sum Check	%	*Should equal 100%*	100%	
	Water Inputs				
`water_sheep`	Water intake, sheep	L/adult/day	*Daily water intake per adult sheep*	4.75	
`water_lamb`	Water intake, lamb	L/lamb/day	*Daily water intake per lamb*	2.84	
`water_misc`	Water intake, misc.	L/day	*Daily water intake for other miscellaneous tasks*	50	
	Electricity / heating consumption				
`electricity_in`	Electricity consumption	kWh/head/year	*Annual electricity consumption per population*	11.3	
`heating_fuel_in`	Heating fuel consumption	L/day	*Daily fuel (natural gas) used for heating*	50	
`diesel_in`	Diesel consumption	L/ha/year	*Annual diesel consumption on farm per outdoor area*	68.2	
`diesel_HV`	Diesel heating value	MJ/L	*Heating value of diesel*	38.6	
	Other misc. operational inputs				
`bedding_in_adult`	bedding straw - sheep	kg/adult/day	*Daily bedding straw req'd per adult sheep*	0.63	
`bedding_in_lamb`	bedding straw - lamb	kg/lamb/day	*Daily bedding straw req'd per lamb*	0.43	
`plastic_in`	Plastic usage	kg/head/year	*Annual plastic (LDPE) usage per population on farm*	1.31	
	Transportation inputs				

Continued on next page...

Table C1 – *Continued from previous page*

`VARIABLE NAME`	PARAMETER	UNIT	*COMMENTS*	BASELINE VALUE	SOURCE
`p_ewe_transport`	#ewes transport	/year	*Percent of adult ewes bought/transported annually*	10.00%	
`p_ram_transport`	#rams transport	/year	*Percent of adult rams bought/transported annually*	10.00%	
`p_lamb_transport`	#lambs transport	/year	*Percent of lambs bought/transported annually*	100.00%	
`dist_livestock`	Livestock transport dist.	km	*Average transportation distance of livestock*	171	
`P_transport_grain`	%grain transported	%	*Percent of grain bought/transported externally*	55.00%	
`dist_grain`	Grain transport dist.	km	*Average transport distance of grain*	78	
`P_transport_fert`	%fertilizer transported	%	*Percent of fertilizers bought/transported externally*	92.00%	
`dist_fert`	Fertilizer transport dist.	km	*Average transport distance of fertilizers*	30	
`mass_transport_other`	Other transport mass	kg/year	*Other major mass transported annually*	5000	
`dist_other`	Other transport dist.	km	*Average transportation distance of other mass*	100	
	PROTEIN CONTENT OF PRODUCTS				
`protein_LW`	Meat (LW) - protein content	kg protein / kg LW	*Protein content of live weight meat*	0.18	FAO (2016) and Wiedemann *et al.* (2015)
`protein_wool`	Wool - protein content	kg protein / kg wool	*Protein content of wool*	0.65	FAO (2016) and Wiedemann *et al.* (2015)

D | LCA and environmental labelling

The shifting focus towards better environmental management was originally one of the main motivations behind conceptualization of life cycle assessment (LCA) in the 1970s. But LCA was intended to be an approach for businesses and policymakers to quantify and reduce the environmental impacts of industrial activities (Guinée *et al.*, 2011). Its immediate application in guiding consumer behaviour was not as successful, as its approaches (and results) were often difficult to communicate to an audience of average consumers (i.e., laypersons).[27] Metrics such as carbon footprint, reported using ISO standards specifically for communicating footprints (e.g., as done by Lo-Iacono-Ferreira *et al.* (2021)), satisfies the test of scientific rigour but do not always provide an intuitive assessment to consumers of their decisions' environmental implications.

In the 1980s-90s, various ecolabelling programs emerged (mostly through governmental bodies) to promote sustainable consumption among consumers.[28] During this period, the US Society of Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO) were in the process of formalizing and standardizing LCA. The need for standardization (internationally) of environmental labelling, especially using a life cycle approach, was also recognized during these talks (Neitzel, 1997; USEPA, 1993, pp.7-10), leading to the creation of various international standards for making environmental claims or declarations.

It was argued that the value of environmental claims rests on the assurance that the information conveyed by a claim must be i) accurate, ii) reliable, and iii) easy to understand by the consumer(s). A set of standards for making claims must not only protect consumers from misleading claims but create fair and consistent rules for industries and businesses in all sectors to promote their products / services through environmental claims. This led to the creation of the ISO 14020 (2000) series of standards for environmental labels and declarations (Arratia, 2017; Münch, 2012).

d1. ISO 14020 SERIES FOR ENVIRONMENTAL LABELLING

ISO has categorized environmental labelling schemes into three types, described in Table D1, in its 14020 (2000) 'Environmental Labels and Declarations' series. All three label types are created with the similar intent of facilitating and encouraging the demand and supply of products / services with a lower environmental footprint. ISO,

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[27] This is an ongoing discussion in the LCA community; e.g., see Klöpffer (2014, Ch.4, sec.4) for a discussion on improvements in communication of LCA to various audiences

[28] *EcoLogo* (Canada, 1988); *EcoMark* (Japan, 1989); *Umweltzeichen* (Austria, 1991); *EU Flower* (European Union, 1992); *NF Environment* (France, 1992); *Blue Angel* (Germany, 1978); *Nordic Swan* (Nordic countries, 1989); *Green Seal* (USA, 1991)

in an effort to link environmental labelling to LCA, also requires life cycle "considerations" for all three types of labels (although only type III declarations require ISO 14040 (2006b) standard LCA). Type I and II environmental declarations, communicated via symbols or texts, are targeted towards consumers in a retail environment. Type III declarations, called environmental product declarations (EPDs), are created for industry-to-industry exchanges to convey the life cycle environmental loads associated with products through data sheets using well-defined product category rules (PCRs)[29] and LCA. Type III EPDs, unlike type I and II claims, require the use of ISO 14040 (2006b) standard LCA to meet the criteria of 'science-based' and 'comparability' (Rubik & Frankl, 2017).

Type I labels are awarded to products which fulfill certain environmental criteria as verified by independent (third party) governmental or private organizations accredited by the ISO. Businesses wishing to employ type I schemes must comply with the official standards set by the governing bodies (which follow requirements specified in ISO (2018)) before they can use the associated symbols (e.g., *EcoLogo* in Canada, *Blue Angel* in Germany, *Energy Star* for appliances and electronics, etc.) on their products. Type I claims can thus also be classified as binary pass-fail systems, where producers must only meet the threshold set by the bodies and (often) have no incentives for improvement beyond the threshold (Minkov, Lehmann, & Finkbeiner, 2020). Type I claims, due to their requirement of ecolabelling bodies, can also pose a barrier to sectors for which governing bodies have not created criteria; e.g., ecolabelling bodies in Canada (Government of Canada, 2022b) do not currently have a certification program for Canadian producers in the agrifood sector reducing the GHG emissions of their products through process improvement or better land management (carbon sequestration). Type II labels were created for such instances.

Type II environmental declarations are any claims 'self-declared' by manufacturers or producers, in which the claimant(s) can set their own scope and benchmarking criteria for environmental performance without prior approval from an independent body. Self-declared environmental claims made by a company can be difficult to verify or substantiate, and – if implemented poorly – prevent consumers from making informed purchasing decisions. In an effort to minimize the risks of companies using self-declared environmental claims to mislead consumers ("greenwashing"), ISO 14021 (2016) includes requirements on transparency, verifiability and specificity for claims to be categorized as type II (e.g., making ambiguous claims such as "green", "environmentally friendly", "sustainable", etc. is prohibited). ISO also puts the onus on government bodies to prosecute companies making misleading type II claims; *Competition Bureau Canada* serves this purpose in Canada (see the section below).

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[29] See Ingwersen *et al.* (2013) for PCR development guide, and IFIF and FEFENA (2015) for an example of a PCR for livestock feed products in accordance with LEAP (sec. 4.1)

Table D1 Three types of environmental labels / declarations under ISO 14020 (2000) series

Type [ISO Standard]	Description
Type I [14024 (2018)]	• Called *Environmental labelling program* or *Ecolabelling* • Requires verification from an independent, license-granting body • Communicated through symbols (logos) • Requires life cycle consideration • ISO standard LCA is recommended, but not required • E.g., EcoLogo® certification in Canada
Type II [14021 (2016)]	• Called *Self-declared environmental claims* • Does not require 3rd party verification • Communicated through text or symbols (logos) • Requires life cycle consideration (but not necessarily an LCA) • E.g., environmental claims made by smartphone manufacturers (e.g., SONY, Google, Apple, etc.) • The 'Mobius loop' used to indicate product recyclability
Type III [14025 (2006a)]	• Called *Environmental Product Declarations (EPDs)* • Requires verification from an independent, license-granting body • Requires life cycle consideration • Requires ISO 14040 (2006b) LCA • Communicated through data sheets using product category rules (PCRs; Ingwersen *et al.* (2013)) • E.g., LEED certification in Canada (Gelowitz & McArthur, 2018) • E.g., EPDs from Canadian manufacturers of steel, concrete, flooring, etc.

D2. TYPE II ENVIRONMENTAL CLAIMS IN CANADA

Type II claims, due to their low barrier of entry, have become popular, particularly in Europe (Rubik & Frankl, 2017, pp.75–77, 164) and Asia (Lee & Uehara, 2003, pp.96–123). In North America, however, implementation of self-declared environmental claims in consumer goods is sporadic (Curran, 2012, Ch.22).[30] For Canada, data on consumer perception, trust, and purchasing behaviour regarding environmental claims is also underrepresented (relative to Europe) in the literature. There is a paucity of resources available for producers, specifically small businesses, wishing to engage in 'green marketing'. The sole Canadian guide for self-declared environmental claims available to Canadian producers is the Canadian Standard Association's (CSA's) *Environmental claims: a guide for industry and advertisers* (CSA, 2008).

The CSA (2008) guide was created as a "best practice guide" for the application of ISO 14021 in the Canadian marketplace and to assist industries and advertisers making type II self-declared environmental claims in complying with the Canadian Competition Act,[31] the Consumer Packaging and Labelling Act,[32] and the Textile Labelling Act.[33] The guide was created to i) decrease the risk of communicating misleading environmental claims, ii) provide an incentive for producer to improve environmental performance, and iii) increase opportunities for consumers to purchase products with a lower environmental footprint.

Although the guide does explicitly state that, "if the principles and specific requirements of [ISO 14021]...are complied with, it is *unlikely* [emphasis added] that environmental claims...would raise concerns under the statutes administered by the Competition Bureau", the guide itself is not a regulation. It is intended to serve as a proactive measure for businesses to avoid making misleading – and potentially lawbreaking[34] – environmental claims. It does not relate the ISO 14021 requirements to the legal standards that apply to misleading environmental claims prosecuted by the Bureau. The Canadian Bar Association (CBA, 2007), in its comment on the final draft of CSA (2008), also raised concerns about vague definitions of "preferred" or "discouraged" claims, unclear comments on the nature of proof required to substantiate environmental claims, and lack of clarity on how strictly the Competition Bureau enforces prosecution of claims that the guide "discourages". CBA concludes by stating that the CSA (2008) report is better described as, "a best practices document, rather than a 'guide' or 'guideline'."

Despite these ambiguities, the CSA (2008) report nonetheless remains a valuable guide for producers to reduce the risk of making unwarranted environmental claims.

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[30] Which is not to say that environmental labels in North America do not exist. Meléndez (2010) found 171, 64, and 161 ecolabels approved in Canada, Mexico, and the US, respectively; but the vast majority of them, especially in the agrifood sector, do not incorporate life cycle considerations

[31] Competition Act: R.S., 1985, c. C-34, s. 1R.S., 1985, c. 19 (2nd Supp.), s. 19 (current to Nov. 2022)

[32] Consumer Packaging and Labelling Act: 1970-71-72, c. 41, s. 1 (current to Nov. 2022)

[33] Textile Labelling Act: R.S. 1985, c. 46 (1st. Supp.), s. 1 (current to Nov. 2022)

[34] Specifically as they apply to the three aforementioned acts; see Government of Canada (2022a) for the Bureau's stance on "greenwashing"

The guide was archived by the Competition Bureau in Nov. 2021 and may not reflect its latest standards, but to date, it remains one of the *only* comprehensive resources freely available to Canadian businesses for making type II claims. For further assurance, industries may also seek a binding written opinion on any proposed environmental claim(s) through the Bureau's Program of Advisory Opinion.[35]

Currently, any environmental claim which does not require independent verification falls under a type II claim, and the scope given for type II claims by ISO 14021 (2000) is wide (Minkov, Lehmann, Winter, & Finkbeiner, 2020); agruably too wide for businesses to independently make environmental claims which would lead to outcomes desired of ecolabelling (i.e., more sustainable products should be promoted; "greenwashing" should be deterred; etc.). Type II claims – due to their self-declared nature – are easy to implement, particularly for small businesses, but there is a higher chance of their implementation being error-prone, as individual producers may have differing interpretations of the principles specified by ISO regarding type II claims. Furthermore, a point of ambiguity regarding consideration of product life cycle in type II claims still remains: the few examples of type II claims found in literature do not always incorporate life cycle thinking despite the requirement of 'life cycle considerations' explicitly stated in ISO 14021 (2000) and CSA (2008).[36]

Canadian small producers wishing to make self-declared environmental claims, with or without LCA, must contend with these complexities. This difficulty is further compounded by an absence of case studies which showcase a proper implementation of type II environmental claims and their enforcement by authorities, especially in a Canadian context. By extension, it is also difficult to find a framework for producers to create environmental benchmarking criteria and potentially form a ground-up, independent organization for making certified type I or III claims for their own sectors.

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[35] See *Competition Bureau Fee and Service Standards Handbook for Written Opinions* for more information

[36] The ambiguity on 'life cycle consideration' was another issue brought forward by CBA (2007) in their critique of the CSA (2008) document

E | Sensitivity / uncertainty modelling

Additional details

The full LCA outputs for the LCA results presented in sec. 7, LCA model code files, and instructions on executing the code can be accessed and used under the General Public License (GPL v3.0) on GitHub: **github.com/akoolbhatt/ON-sheep-LCA**.

The sensitivity / uncertainty results shown in sec. 7 can be replicated by executing the scripts `sheep_LCA_RSV.m` and `sheep_LCA_MC.m` in MATLAB. Fig. E1 shows the MATLAB-Excel interaction during code execution. Executing `sheep_LCA_RSV.m` will import (from the spreadsheet `MATLAB_inputs_outputs.xlsx`) the baseline parameter values for foreground data on sheep farming practices as well as relevant environmental factors, export the RSV sensitivity outputs back into the spreadsheet, and plot the sensitivity graphs. Executing `sheep_LCA_MC.m` will import the statistical distributions of all parameters into the LCA model for uncertainty analysis, export the LCA outputs back into the spreadsheet, and plot the dispersion of the impact scores.

Table E1 lists the statistical distribution of the environmental factors used for uncertainty analysis. The statistical distributions for the foreground primary data collected and analyzed in sec. 3 are presented in Table B1.

Fig. E2 shows the one-at-a-time (OAT) sensitivity of "population / products" input parameter category (as illustrated in Fig. 4) on global warming (GW) impacts. See the document `OAT_sensitivity_figures.pdf` (on GitHub) for the OAT sensitivity graphs in all five parameter categories and all three impact categories.

Table E2 lists the parameter Relative Sensitivity Value (RSV) on total life cycle impacts. See the Excel worksheet `MATLAB_RSV_Output` in `MATLAB_inputs_outputs.xlsx` for RSV results breakdown in all the impact categories by life cycle phase.

Fig. E3 presents the impact dispersion and descriptive statistics of life cycle impacts for the three scenarios discussed in sec. 6. See the worksheet `MATLAB_MC_Output` in `MATLAB_inputs_outputs.xlsx` for the LCA outputs of all 10,000 MC simulations. The script `sheep_LCA_MC.m` may also be modified to output the uncertainty in intermediary LCA outputs (e.g., net energy (NE) requirements, as presented in Table 6).

The description, units, and associated MATLAB variable for the parameters listed in the aforementioned figures and tables can be found in sec. C2.

Fig. E1 Conceptualization of MATLAB-Excel interaction in sensitivity & uncertainty analysis

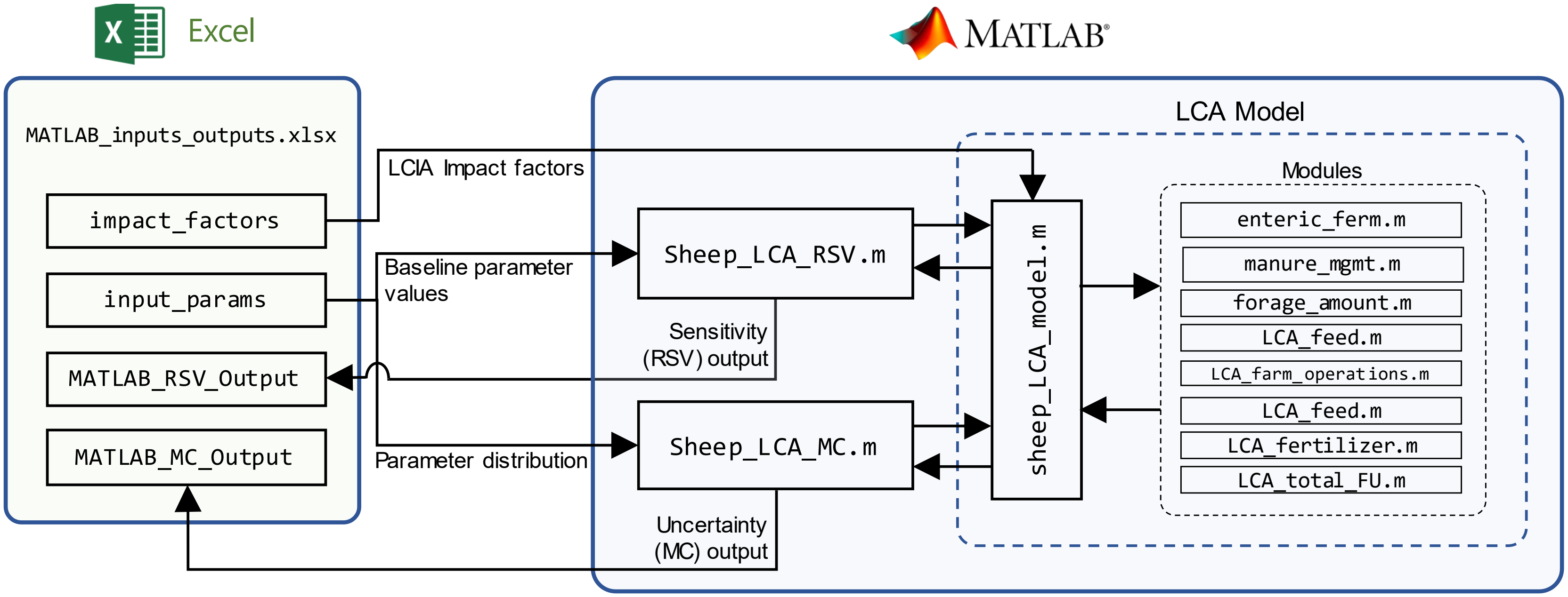

Table E1 Statistical distributions of environmental factors

Environmental factor	Distribution type	Parameter value 1	Parameter value 2	Parameter value 3	Source
Liquid MCF	Normal	25.0%	3.8%		ECCC (2020)
Solid storage MCF	Normal	2.0%	0.3%		ECCC (2020)
Drylot MCF	Normal	1.0%	0.2%		ECCC (2020)
PRP MCF	Normal	1.0%	0.2%		ECCC (2020)
Bo	Triangular	0.19	0.275	0.36	ECCC (2020)
Nitrogen Excr. Rate	Normal	0.42	0.07		ECCC (2020)
Solid EF3	Triangular	0.0027	0.005	0.01	IPCC (2006)
Drylot EF3	Triangular	0.01	0.02	0.04	IPCC (2006)
PRP EF3	Triangular	0.003	0.0165	0.03	IPCC (2006)
%N vol. - solid MS	Triangular	5.00%	12.00%	20.00%	ECCC (2020)
%N vol. - drylot MS	Triangular	5.00%	12.00%	20.00%	ECCC (2020)
%N vol. - PRP	Triangular	5.00%	20.00%	50.00%	ECCC (2020)
EF4	Triangular	0.20%	2.60%	5.00%	IPCC (2006)
%N leach - solid MS	Triangular	5.00%	12.50%	20.00%	ECCC (2020)
%N leach - drylot MS	Triangular	5.00%	12.50%	20.00%	ECCC (2020)
EF5	Triangular	0.0005	0.0075	0.025	IPCC (2006)
Default Cfi - Adult ewe	Uniform	0.20615	0.22785		IPCC (2006)
Default Cfi - Lamb ewe	Uniform	0.2242	0.2478		IPCC (2006)

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Table E1 – *Continued from previous page*

Environmental factor	**Distribution type**	**Parameter value 1**	**Parameter value 2**	**Parameter value 3**	**Source**
Ca - Housed ewe	Uniform	0.00855	0.00945		IPCC (2006)
Ca - flat grazing	Uniform	0.010165	0.011235		IPCC (2006)
Ca - hilly grazing	Uniform	0.0228	0.0252		IPCC (2006)
Ca - fattening lambs	Uniform	0.006365	0.007035		IPCC (2006)
a' - intact males	Uniform	2.375	2.625		IPCC (2006)
a' - castr males	Uniform	4.18	4.62		IPCC (2006)
a' - female males	Uniform	1.995	2.205		IPCC (2006)
b' - intact males	Uniform	0.3325	0.3675		IPCC (2006)
b' - castr males	Uniform	0.304	0.336		IPCC (2006)
b' - female males	Uniform	0.4275	0.4725		IPCC (2006)
Cp - single birth	Uniform	0.07315	0.08085		IPCC (2006)
Cp - double birth	Uniform	0.1197	0.1323		IPCC (2006)
Cp - triple birth	Uniform	0.1425	0.1575		IPCC (2006)
DE - Grain	Normal	74.0%	3.0%		ECCC (2020)
DE - Forage/Roughage	Normal	65.0%	3.0%		ECCC (2020)
CH_4 conversion - Adult sheep	Triangular	5.50%	6.50%	7.50%	IPCC (2006)
CH_4 conversion - Lambs	Triangular	3.50%	4.50%	5.50%	IPCC (2006)

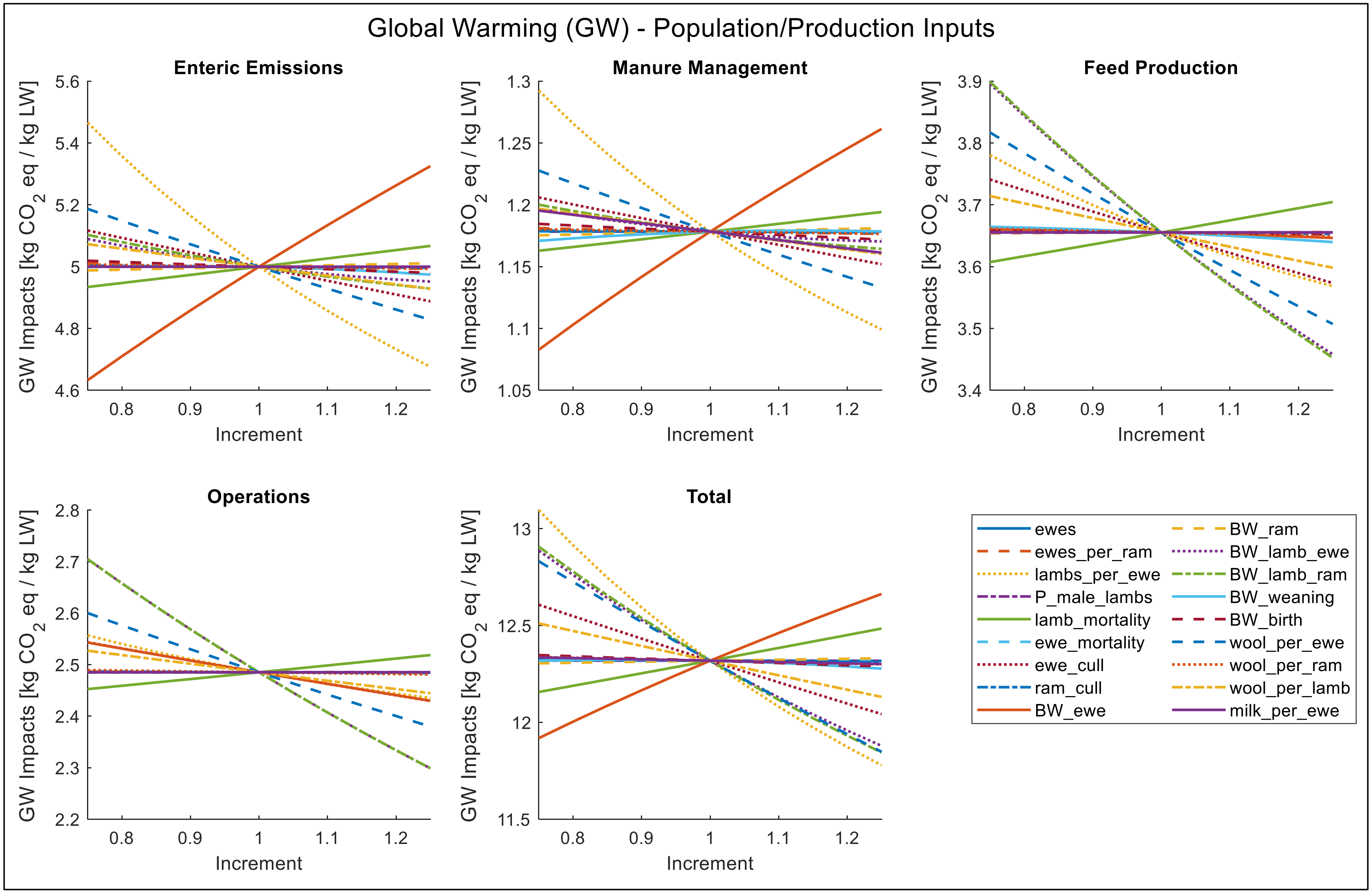
Global Warming (GW) - Population/Production Inputs
Enteric Emissions
Manure Management
Feed Production
Operations
Total
GW Impacts [kg CO_2 eq / kg LW]
Increment
0.8
0.9
1
1.1
1.2
4.6
4.8
5
5.2
5.4
5.6
1.05
1.1
1.15
1.2
1.25
1.3
3.4
3.5
3.6
3.7
3.8
3.9
2.2
2.3
2.4
2.5
2.6
2.7
2.8
11.5
12
12.5
13
ewes
ewes_per_ram
lambs_per_ewe
P_male_lambs
lamb_mortality
ewe_mortality
ewe_cull
ram_cull
BW_ewe
BW_ram
BW_lamb_ewe
BW_lamb_ram
BW_weaning
BW_birth
wool_per_ewe
wool_per_ram
wool_per_lamb
milk_per_ewe

Table E2 Relative sensitivity value (RSV) of input parameters on total impacts. Blank values imply that the parameter does not have an effect on the impact category

Input parameter	Relative sensitivity value (RSV) – Total impacts		
	Global warming (GW)	Energy demand (ED)	Water depletion (WD)
Adult ewes (F)	0.00	0.00	-0.01
Ewes per ram	0.00	0.00	0.00
Lambs per ewe	-0.21	-0.11	-0.14
Lamb M:total ratio	0.00	0.00	0.00
Lamb mortality rate	0.05	0.05	0.05
Ewe (F) mortality rate			
Ewe (F) cull rate	-0.09	-0.09	-0.09
Ram (M) cull rate	0.00	0.00	0.00
BW - Adult Ewe	0.12	-0.03	-0.07
BW - Adult Ram	0.00	0.00	0.00
BW - Lamb Ewe	-0.16	-0.26	-0.31
BW - Lamb Ram	-0.17	-0.27	-0.31
BW - Lamb weaning	-0.01	-0.01	0.00
BW - Birth	-0.01	0.00	0.00
Wool per Ewe	-0.16	-0.17	-0.18
Wool per Ram	-0.01	-0.01	-0.01
Wool per Lamb	-0.06	-0.06	-0.07
Milk per Ewe	-0.01		
Forage% - Adult Ewe	0.00	0.00	0.00
Forage% - Adult Ram	0.00	0.00	0.00
Forage% - Lamb Ewe	0.00	0.00	0.00
Forage% - Lamb Ram	0.00	0.00	0.00
Silage %	0.03	0.01	0.04
Hay %	0.07	0.11	0.00
Tillable pasture %	0.02		
Rough pasture %	0.01		
Daily Grain Inktake - Ewe	0.06	0.11	0.15
Daily Grain Inktake - Ram	0.00	0.00	0.00
Daily Grain Inktake - Lamb	0.12	0.20	0.28
Feeding practice			
Corn %	0.07	0.03	0.08
Barley %	0.04	0.06	0.00
Oat %	0.04	0.05	0.01
Wheat %	0.01	0.01	0.05
Soybean %	0.02	0.01	0.02

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Table E2 – *Continued from previous page*

Input parameter	**Relative sensitivity value (RSV) – Total impacts**		
	Global warming (GW)	**Energy demand (ED)**	**Water depletion (WD)**
Energy - forage/roughage	-0.17	-0.14	-0.05
Energy - Grain concentrate	-0.08	-0.07	-0.03
N content - silage	0.01		
N content - hay	0.02		
N content - Tillable pasture	0.02		
N content - Rough pasture	0.01		
N content - Corn	0.02		
N content - Barley	0.01		
N content - Oat	0.01		
N content - Wheat	0.00		
N content - Soybean	0.00		
Liquid MS			
Solid storage MS	0.04		
Drylot MS	0.02		
PRP MS	0.04		
N content in Meat	-0.02		
N content in Wool	0.00		
N content in Milk	-0.01		
Liquid MCF			
Solid storage MCF	0.01		
Drylot MCF	0.00		
PRP MCF	0.01		
Urinary Energy	0.00		
Ash content	0.00		
Bo	0.02		
Nitrogen Excr. Rate			
Liquid EF3			
Solid EF3	0.02		
Drylot EF3	0.02		
PRP EF3	0.03		
%N vol. - liquid MS			
%N vol. - solid MS	0.00		
%N vol. - drylot MS	0.00		
%N vol. - PRP	0.01		
EF4	0.01		

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Table E2 – *Continued from previous page*

Input parameter	**Relative sensitivity value (RSV) – Total impacts**		
	Global warming (GW)	**Energy demand (ED)**	**Water depletion (WD)**
%N leach - liquid MS			
%N leach - solid MS	0.00		
%N leach - drylot MS	0.00		
%N leach - PRP			
EF5	0.00		
castrated% - Adult ram	0.00	0.00	0.00
castrated% - Lamb ram	-0.01	0.00	0.00
Annual Ambient. Temp	-0.14	-0.04	-0.02
Activity% - Housed ewes	0.02	0.00	0.00
Activity% - flat grazing	0.02	0.01	0.00
Activity% - hilly grazing	0.01	0.00	0.00
Activity% - lamb fattening	0.01	0.00	0.00
Gestation / birth %	0.02	0.01	0.00
Single births %	0.01	0.00	0.00
Double births %	0.01	0.00	0.00
Triple births %	0.00	0.00	0.00
Default Cfi - Adult ewe	0.24	0.06	0.02
Default Cfi - Lamb ewe	0.19	0.07	0.03
Ca - Housed ewe	0.02	0.00	0.00
Ca - flat grazing	0.02	0.01	0.00
Ca - hilly grazing	0.01	0.00	0.00
Ca - fattening lambs	0.01	0.00	0.00
a' - intact males	0.00	0.00	0.00
a' - castr males	0.01	0.00	0.00
a' - female males	0.00	0.00	0.00
b' - intact males	0.00	0.00	0.00
b' - castr males	0.01	0.00	0.00
b' - female males	0.02	0.01	0.00
EV milk	0.05	0.01	0.01
EV wool	0.03	0.01	0.00
Cp - single birth	0.01	0.00	0.00
Cp - double birth	0.01	0.00	0.00
Cp - triple birth	0.00	0.00	0.00
DE - Grain	-0.41	-0.17	-0.06
DE - Forage/Roughage	-0.78	-0.23	-0.08

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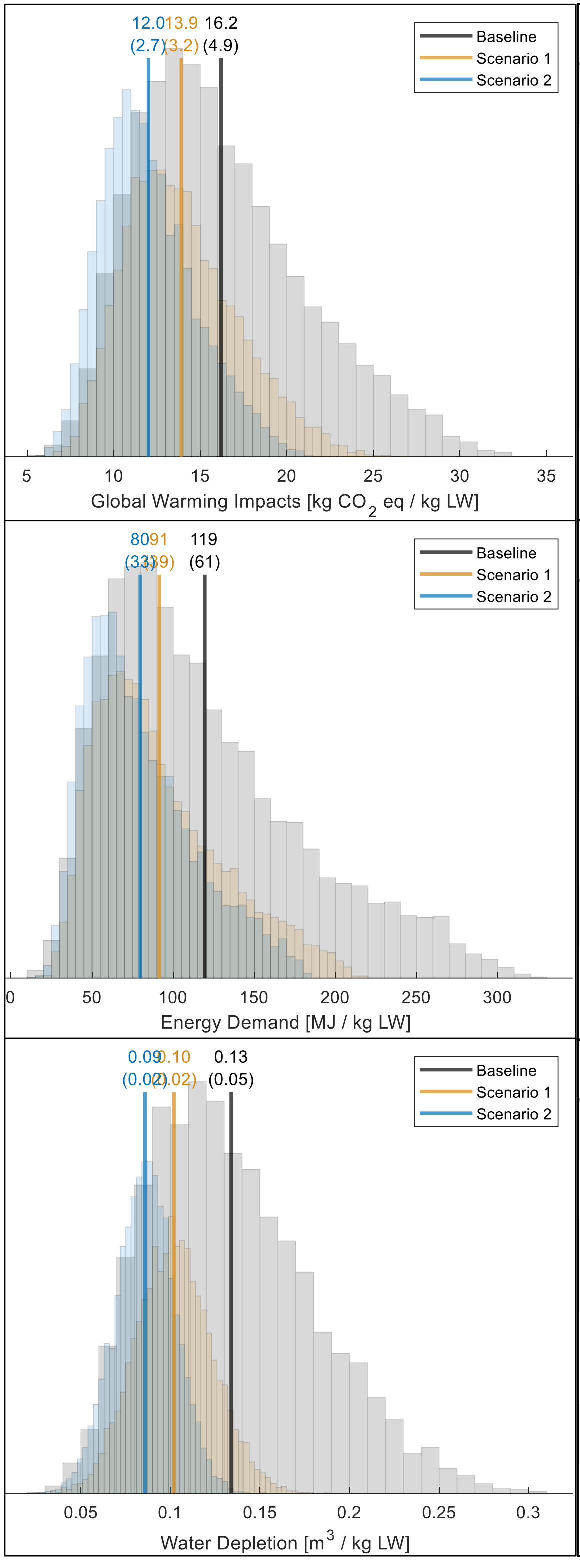
Table E2 – *Continued from previous page*

Input parameter	**Relative sensitivity value (RSV) – Total impacts**		
	Global warming (GW)	**Energy demand (ED)**	**Water depletion (WD)**
CH4 conversion - Adult sheep	0.24		
CH4 conversion - Lambs	0.17		
Farm area - Rough			
Farm area - Improved			
Farm area- Arable cropland	0.15	0.31	0.07
Farm area - indoors	0.02	0.03	0.01
Shed/barn lifespan	-0.02	-0.03	-0.01
Fertilizer application rate	0.10	0.17	0.07
Phosphate (P) fertilizer	0.01	0.04	0.02
Potassium (K) fertilizer	0.00	0.01	0.00
Nitrogen (N) fertilizer	0.08	0.12	0.05
Lime	0.00	0.00	0.00
Water intake, sheep	0.00	0.00	0.11
Water intake, lamb	0.00	0.00	0.11
Water intake, misc.	0.00	0.00	0.01
Electricity consumption	0.01	0.06	0.04
Heating fuel consumption	0.00	0.00	0.00
Diesel consumption	0.04	0.12	0.00
Diesel heating value	0.04	0.12	0.00
bedding straw - sheep	0.01	0.02	0.06
bedding straw - lamb	0.01	0.02	0.07
Plastic usage	0.01	0.05	0.00
#ewes transport	0.00	0.00	0.00
#rams transport	0.00	0.00	0.00
#lambs transport	0.00	0.00	0.00
Livestock transport dist.	0.00	0.00	0.00
%grain transported	0.00	0.01	0.00
Grain transport dist.	0.00	0.01	0.00
%fertilizer transported	0.00	0.00	0.00
Fertilizer transport dist.	0.00	0.00	0.00
Other transport mass	0.00	0.00	0.00
Other transport dist.	0.00	0.00	0.00
Meat (LW) - protein content	0.26	0.26	0.26
Wool - protein content	-0.25	-0.25	-0.25

Fig. E3 Dispersion of life cycle impacts in global warming (GW), energy demand (ED), and water depletion (WD) using Monte Carlo (MC) uncertainty propagation (10,000 simulations) for all three scenarios discussed in sec. 7. The vertical line on the histogram indicates the location of the mean; numbers on top of the line display the mean (standard deviation) values. The table lists descriptive statistics for the histograms



Global warming (GW) [kg CO_2 eq / kg LW]			
	Baseline	**Scenario 1**	**Scenario 2**
Median	15.4	13.5	11.6
25%th – 75%th quantile	12.5 – 19.2	11.5 – 15.9	10.0 – 13.7
10%th – 90%th quantile	10.5 – 23.3	10.1 – 18.4	8.8 – 15.8
Skewness	0.72	0.55	0.57
(Min, Max)	(5.5, 34.3)	(5.8, 26.6)	(5.5, 22.7)

Energy demand (ED) [MJ / kg LW]			
	Baseline	**Scenario 1**	**Scenario 2**
Median	105.6	82.7	72.5
25%th – 75%th quantile	73.2 – 154.2	61.7 – 114.8	54.1 – 99.4
10%th – 90%th quantile	52.9 – 212.0	48.0 – 149.7	42.5 – 129
Skewness	0.90	0.79	0.79
(Min, Max)	(11.0, 320.4)	(15.8, 220.0)	(10, 183.4)

Water depletion (WD) [m^3 / kg LW]			
	Baseline	**Scenario 1**	**Scenario 2**
Median	0.13	0.10	0.09
25%th – 75%th quantile	0.10 – 0.16	0.09 – 0.11	0.07 – 0.10
10%th – 90%th quantile	0.08 – 0.20	0.08 – 0.13	0.06 – 0.10
Skewness	0.58	0.10	-0.05
(Min, Max)	(0.03, 0.31)	(0.04, 0.19)	(0.02,0.15)

F | Carbon sequestration modelling

Overview

Livestock LCA studies often do not incorporate the impact of soil carbon stock changes on the carbon footprint of their production, as there is a lack of consensus on accuracy of methods used to predict changes in soil carbon. Despite this uncertainty, soil carbon sequestration is suspected to be a critically important process for accurately evaluating the global warming potential of agricultural activities.

The following sections provide a brief overview of some existing methods for estimating changes in soil carbon storage, including methods prescribed by the IPCC and the ECCC. A comparison of soil carbon estimations among these two methods is also provided.

INTRODUCTION

Soils have the ability to sequester ~20,000 Mt of carbon over a period of 25 years (more than 10% of all GHG emissions) (FAO, 2017).The inclusion of carbon sequestration for GHG estimations of ruminant supply chains has been proposed by multiple organizations (ECCC, 2020; FAO, 2016; IPCC, 2006; UECBV, 2019). A brief review of the literature indicates that there are various mathematical models for quantifying the carbon sequestration potential of grasslands and changes in crop management practices. Soussana *et al.* (2010), for example, uses a mass balance of carbon fluxes for estimating the annual changes is soil carbon in managed grasslands. The mass balance considers the exchange of trace gases (CO_2, CH_4, and VOCs) within the atmosphere, carbon inputs from manure, emissions from fires, export of farm products, leaching of carbon from soil, and lateral losses of carbon from erosion. Soussana *et al.* (2010) suggested the following relationship be used to estimate the net carbon storage (NCS):

$$\begin{aligned} NCS = &\left(F_{CO_2} - F_{CH_4} - F_{VOC} - F_{fire}\right) \\ &+ \left(F_{manure} - F_{harvest} - F_{animal\text{-}products}\right) \\ &- (F_{leach} + F_{erosion}) \end{aligned} \tag{F.1}$$

where F represents the carbon flux from each activity specified by the subscript. The obvious disadvantage of this method is the need for direct measurements of site-specific carbon fluxes and the frequency with which measurements must be taken. Soussana *et al.* (2010) acknowledge the need to collect data annually in order to understand changes in soil carbon over the course of years or decades.

Vleeshouwers and Verhagen (2002), a study on European agricultural land use, used the CESAR (**C**arbon **E**mission and **S**equestration by **A**g**R**icultural land use) model to assess the average annual sequestration potential and emission potential of grasslands and arable land, respectively, across numerous sites in Europe between the years of 2008 and 2012. The CESAR model is relatively complex, and it can be used to simulate changes in the soil carbon of plant production systems, taking into consideration crop species, crop yields, climate, and soil characteristics. The study found that, under 'business as usual' circumstances, the conversion of arable land to grassland offered an average carbon flux of 1.44 t C/year/ha to the soil, averaged over Europe for the period of 2008 – 2012. While this study concluded that grasslands are generally effective for sequestering carbon, it also recognized the need to understand the long-term carbon sequestration potential of grasslands and other land uses.

An alternative approach to quantifying carbon sequestration is offered by Petersen *et al.* (2013), in which the C-Tool, a soil carbon turnover simulation tool, is used in conjunction with the Bern Carbon Cycle Model. This method was used to compare the changes in soil carbon and generation of CO_2 that would occur from removal of straw from agricultural soils (soybean production) for bioenergy use and leaving the straw on the field. It found a reduction of GHG emissions of ~10% over 100 years. The study also concluded that the choice of time perspective in modelling carbon sequestration had a large effect on the LCA impact score and recommended that a 100-year time perspective be used for LCA studies.

The IPCC (2006)[37] and ECCC (2020) documents, heavily used in the creation of the LCA model for this study, also offer methods for quantifying carbon sequestration. Both these organizations' methods are intended to compute soil carbon stock changes over time after land use or land management changes occur, be it a change in crop management practices or the conversion of existing natural habitat to cropland.

IPCC METHOD

The IPCC method, found in vol.4, Ch.2 of Eggleston (2006), estimates annual changes in soil carbon by considering the difference in the expected equilibrium soil carbon stocks prior to and after a change in land management. Equilibrium soil carbon stocks are calculated with consideration of the native soil properties, existing land use, management practices, and input of organic matter. The IPCC method operates under two assumptions that set it apart from other soil carbon models: i) soil carbon stocks transition to a new state of equilibrium in a linear fashion; however, literature supports the supposition that changes in soil carbon between equilibria are characterized by curvilinearity (Janzen, 1998); and ii) a new state of equilibrium is reached 20 years after the land use change has taken place, which has a direct impact on the magnitude of the expected annual carbon flux. It is commonly asserted, however, that it can take over 100 years in some scenarios to achieve equilibrium after a land use change occurs. Petersen *et al.* (2013) recommend using a 100-year time perspective, and they also anticipate that the IPCC method may not describe soil loss adequately in the long-term.

Using the IPCC method, the equilibrium carbon stock of mineral soils can be estimated to be:

$$SOC = \sum_{c,s,i} \left(SOC_{REF_{c,s,i}} \cdot F_{LU_{c,s,i}} \cdot F_{MG_{c,s,i}} \cdot F_{I_{c,s,i}} \cdot A_{c,s,i} \right) \tag{F.2}$$

where SOC is the soil organic carbon stock; SOC_{REF} is the reference (or default) organic carbon stock; F_{LU} is the stock change factor for a particular land use; F_{MG} is the stock change factor for management regime; F_I is the stock change factor for input of organic matter; A is the area of the land undergoing land use change; c represents climate zones; s represents soil types, and i represents the set of management systems present. Eqn. F.2 can be used to calcualte the expected soil carbon stocks under equilibrium conditions for pre-change and post-change land use. The annual carbon flux between equilibria can then be calculated to be:

$$\Delta C_{mineral} = \frac{SOC_0 - SOC_{(0-T)}}{D} \tag{F.3}$$

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[37] Subset of Eggleston (2006)

where $SOC_{(0-T)}$ is the soil organic carbon stock at the beginning of the inventory time period (prior to the land use change); SOC_0 is the soil organic carbon stock in the last year of an inventory time period (after the land use change); D is the default time period for the transition between equilibrium (assumed to be 20 years by the IPCC); $\Delta C_{mineral}$ is the annual change in carbon stocks in mineral soils. This change in soil carbon can be directly converted to the mass flux of CO_2 by multiplying the change in carbon stock by the ratio of molar masses of CO2 and C:

$$\Delta CO_2 = -\frac{44}{12} \cdot \Delta C_{mineral} \tag{F.4}$$

where ΔCO_2 is the resultant total mass flux of CO_2. The sign of the flux is important: a decrease in soil carbon storage generates an increase in atmospheric CO_2. Despite its unconventional assumptions, the IPCC method provides a straightforward set of formulae for quantifying changes in soil carbon. It should also be noted that the use of this method would constitute as a tier 1 approach for quantifying soil carbon changes unless additional information is acquired on stock change factors and reference stocks for native Ontario soil.

ECCC METHOD

ECCC (2020) does not offer a single method for computing differences in soil carbon storage. Instead, ECCC used simulations with the Century Model to form empirical curvilinear (first-order decay) equations for the prediction of soil carbon changes after the conversion of grasslands and forest to cropland. The Century model was also used to derive an empirical equation for changes in soil carbon with changes in cropland management practices. These equations also predict that new equilibria are often reached more than 100 years after land use changes occur. For example, their Century Model simulations for the conversion of forest to cropland found that only about 25% of carbon losses occurred in the first 20 years and about 90% of carbon losses occur within 100 years. Eqns. F.5, F.6, and F.7 are the empirical equations for soil carbon changes due to land management changes (i.e., changes in tilling practices), grassland conversion to cropland, and forest conversion to cropland, respectively:

$$\Delta C_{LMC}(t) = \Delta C_{LMC_{max}} \cdot \left(1 - e^{-kt}\right) \tag{F.5}$$

$$\Delta C(t) = 0.28 \cdot SOC_{agric} \cdot \left(1 - e^{-0.12t}\right) \tag{F.6}$$

$$\Delta C(t) = 0.284 \cdot SOC_{agric} \cdot \left(1 - e^{-0.0262t}\right) \tag{F.7}$$

where $\Delta C_{LMC}(t)$ is the change in soil organic carbon due to land management change; $\Delta C_{LMC_{max}}$ is the maximum possible change in soil organic carbon due to land management change (dependent on land management change and zone); $\Delta C(t)$ is the change in soil organic carbon t years after land conversion; k is the rate constant (dependent on land management change and zone); SOC_{agric} is the soil carbon of agricultural soil at a maximum depth of 30 cm (values found in ECCC (2020, Table A3.5-9)); and t is the time since the land management change has occurred. The coefficients 0.28 and 0.284 in eqns. F.6 and F.7, respectively, represent the proportion of maximum soil carbon loss from land conversion; and the coefficients 0.12 and 0.0262 in eqns. F.6 and F.7, respectively, represent the rate constant (y^{-1}) for the decay. Canada-specific coefficient values for eqn. F.5 can be found in ECCC (2020, Table A3.5-8). Conversion of ΔC to ΔCO_2 can be done through the molar mass ratio (eqn. F.4).

Eqn. F.5 can be utilized to predict changes in soil carbon after any change in tilling practices, either more or less intensive. It should be noted, however, that the ECCC equations only calculate the change in soil carbon after conversion to cropland. It is unknown whether the same method can be used to directly predict the carbon sequestration potential of converting cropland back into grassland or forest overtime. If it can be safely assumed that the magnitude of the change in soil carbon stocks between two states of equilibrium is the same regardless of which state occurred first, the maximum change in soil carbon can be used to calculate annual CO_2 emission or sequestration.

Two important advantages of the ECCC method are i) their consideration of curvilinearity over a longer 100-year timespan, and ii) the fact that these empirical relationships were specifically formulated to represent conditions of Canadian soil. Thus, the ECCC method may be more applicable for the current study compared to the alternatives.

Carbon sequestration per functional unit

Once a method for calculating carbon sequestration potential is chosen, it is necessary to determine how these impacts will be allocated per functional unit. Based on the literature reviewed, it is reasonable to expect that a time-perspective of 20 – 100 years can be used to annualize emissions or sequestration potential. These impacts can then be divided by the annual production of the functional unit. Assuming that kg live weight (LW) is the functional unit, the resultant increase or reduction in the global warming impact score from N land management or land use changes over T years can be estimated to be:

$$I = \frac{1}{T}\int_{t=1}^{T} \frac{\sum_{i=1}^{N}\left(\Delta CO_{2_i}(t)\cdot A_i\right)}{P(t)}\,\mathrm{d}t \approx \sum_{t=1}^{T} \frac{\sum_{i=1}^{N}\left(\Delta CO_{2_i}(t)\cdot A_i\right)}{P(t)} \tag{F.8}$$

where I [kg CO_2 eq/kg LW] is the resultant global warming impact score attributed to carbon sequestration potential; ΔCO_2 [kg CO_2/ha/y] is the CO_2 mass flux from carbon sequestration; A [ha] is the land area; and P [kg LW/y] is the annual product output.

COMPARISON OF ΔC USING ECCC AND IPCC

A preliminary comparison between the IPCC and the ECCC methods was performed to determine how differently each method predicts changes in soil carbon. Three scenarios were modelled: management change from intensive tillage to no tillage, land use change from forest to cropland, and land use change from grassland to cropland. Tables F1 and F2 list the values used for each method, selected to reasonably represent conditions that could be found in Ontario. Chs. 4, 5, and 6 (of vol. 4) in Eggleston (2006) were consulted for the F_{LU}, F_{MG}, and F_I values in Table F2. It should be recognized that changes in these input parameters may result in modest variations in the reported changes in soil carbon.

Fig. F1 shows the comparison of changes in soil carbon storage between the ECCC and the IPCC methods after significant land management or land use changes have occurred. In all scenarios, the IPCC method overestimates the change in soil carbon storage over a premature equilibrium time (20 y) compared to the ECCC method. The ECCC method shows that both these assumptions do not hold true when curvilinearity is taken into account.

Table F1 ECCC (2020) values for estimating change in carbon stocks

Land Use/Management Change	k [/year]	$C_{LMC_{max}}$ [Mg/ha]	SOC_{agric} [Mg C/ha]
Intensive till → No till	0.025[a]	5[b]	-
Forest → cropland	-	-	77[c]
Grassland → cropland	-	-	77[c]

[a] Decay constant for East Central Canada
[b] Maximum change for East Central Canada
[c] Medium cropland soil

Table F2 IPCC (2006) values for estimating change in carbon stocks

Land Use	SOC_{REF} [t C/ha]	F_{LU} [-]	F_{MG} [-]	F_I [-]
Intensive Till	95.0[a]	0.69[b]	1.00[c]	1.00[d]
No Till	95.0[a]	0.69[b]	1.15[e]	1.00[d]
Grasslands	95.0[a]	1.00[f]	0.95[g]	1.00[h]
Forest	95.0[a]	1.00[i]	1.00[i]	1.00[i]

[a] Soils with high activity clay – cold, temperate, and moist climate
[b] Long-term cultivation in a moist, temperate climate
[c] Substantial soil disturbance
[d] Crop residue is returned to the field, or manure is added
[e] Direct seeding in moist, temperate climate
[f] All permanent grassland has an FLU factor of 1.00
[g] Moderately degraded grassland receiving no management inputs
[h] Improved Grassland where no additional management inputs are used
[i] All stock change factors are 1.00 for forest

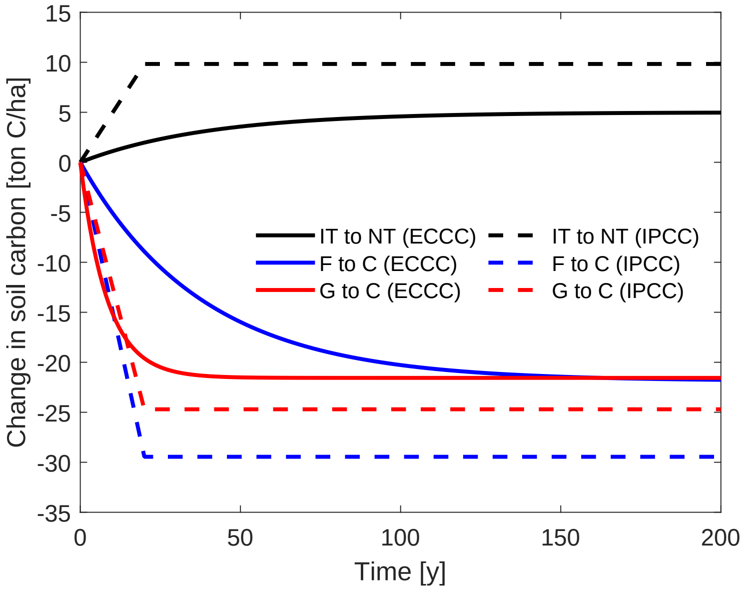

Fig. F1 Comparison of change in soil carbon storage between the ECCC and the IPCC methods from land management changes of intensive tilling (IT) to no tilling (NT), forest (F) to cropland (C), and grassland (G) to cropland (C)

READER NOTES:

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