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South Africa Wool LCA – Final Report

Cape Wools

Executive summary

This report presents the findings of a pilot life cycle assessment (LCA) of wool produced in South Africa, conducted to provide a transparent and internationally relevant environmental baseline for the sector. The assessment focused on primary production systems and evaluated multiple environmental impact categories to reflect the breadth of sustainability considerations relevant to wool production.

The goal of the study was to quantify the environmental impacts associated with South African wool production, identify the key drivers of impact, and improve understanding of variability between production systems and individual farms. The LCA covered commercial and communal wool production systems and modelled the supply chain from cradle to the primary production gate. Wool and liveweight were treated as co-products, with impacts allocated using a biophysical, protein-based approach to ensure consistency with biological causality and established wool LCA practice. Primary farm data were collected from regions representing the majority of national wool production and were complemented by secondary datasets selected for geographical, technological and temporal relevance.

Primary data were collected from 77 farms across multiple regions and production systems including commercial farms and communal districts. The survey included flock inventories, records of animal weights, grazing areas, and land use data, and was conducted via field visits in the 12-month period from March 2022 to February 2023.

Environmental impact results per kg of greasy wool for the South African average were 28 kg CO_2-e (excl. LU and LUC) (95% C.I 23 and 34 kg CO_2-e), resource use was 7.4 MJ kg greasy wool (95% C.I 6.1 and 8.9 MJ), water consumption was 2117 L (95% C.I 965 and 3850 L) and land occupation was 2730 m^2 (95% C.I 592 and 5486 m^2).

Biogenic carbon emissions and removals from Land Use and Land Use Change were assessed and uncertainty results showed a range of -5 to 5 kg CO_2-e kg greasy wool. This range was developed for the South Africa average; the range for individual farms was not assessed pending further data collection of the main factors influencing emissions and removals, and may be significantly greater than this.

Across all production systems, the results demonstrated that the environmental profile of wool was dominated by biological processes intrinsic to ruminant production. Climate change impacts were primarily driven by enteric methane emissions, with nitrous oxide emissions from manure management and nitrogen cycling forming a secondary contribution. Fossil carbon dioxide emissions represented a relatively small share of total greenhouse gas emissions at the primary production stage, reflecting the low reliance on purchased energy inputs in most systems. Differences in carbon footprint between production systems and farms were explained mainly by variation in productivity and flock efficiency rather than fundamentally different emission pathways.

Commercial farms, which achieved higher wool production and co-product liveweight output per animal, consistently exhibited lower impacts per unit of greasy wool compared with communal farms. This finding highlighted the central role of flock structure, reproductive performance and wool yield in diluting maintenance emissions and reducing environmental intensity. Statistical and sensitivity analyses confirmed that productivity parameters, such as wool cut per head, reproductive rates and feed quality, were the most influential drivers of climate change results. Allocation assumptions were also shown to

affect product-level outcomes, reinforcing the need for careful interpretation of carbon footprint results within the context of methodological choices.

Water consumption results showed substantial variability between farms and systems, driven primarily by differences in water source and the use of irrigation. Fossil energy use increased with greater levels of intensification but remained a minor contributor relative to biological emissions. Land occupation and other impact categories likewise varied between farms, reflecting differences in management, environment and resource availability. Across all indicators, the study identified significant variability at the individual farm level, underlining the importance of site-specific data and cautious use of average values for benchmarking or comparative purposes.

Overall, this study provides a scientifically robust pilot LCA of South African wool. Results were reasonably consistent with previous wool LCAs in comparison countries and within the range reported internationally. The results indicate that meaningful reductions in environmental footprint are most closely linked to improvements in production efficiency at the farm level, rather than changes in emission sources.

The findings support informed decision-making by industry and provide a credible foundation for sustainability reporting, target-setting and future research aimed at improving the environmental performance of wool production systems.

Based on the findings of this study, the following recommendations were identified for producers and the South African industry:

1. At the primary production stage, the most effective opportunities for reducing environmental impacts per kg of wool were associated with improving flock productivity and efficiency. Management strategies that increased wool output per breeding animal, improved reproductive performance, reduced mortality, and limited the proportion of non-productive animals were consistently associated with lower environmental intensities. Continued investment in genetic improvement programs, flock health, and reproductive management, and semi-regular update to the productivity dataset is recommended as a priority pathway for reducing the carbon footprint and other impacts, and for maintaining currency in the future.
2. Interventions aimed solely at reducing inputs without maintaining or increasing output were unlikely to deliver proportional reductions in environmental intensity. As demonstrated by the results, lower production systems frequently exhibited higher impacts per unit of wool because maintenance emissions were distributed over smaller quantities of product. Environmental improvement strategies should therefore focus on output-oriented efficiency gains, rather than on input minimization in isolation.
3. From a methodological and communication perspective, the study highlighted the importance of transparency around allocation assumptions when reporting fibre carbon footprints. While different allocation methods produced substantially different numerical outcomes for wool, the underlying drivers of impact remained unchanged. It was therefore recommended that future communications focus on explaining the biological and management drivers of environmental performance, rather than on comparing point estimates derived using different allocation approaches.
4. The observed variability in environmental performance between farms indicated that best-practice outcomes were already achievable within existing systems. Capturing and sharing knowledge on high-performing farms and integrating environmental

This study revealed the considerable complexity in assessing impacts from wool using multi-indicator LCA and represented a first step in building this knowledge base in South Africa. Further research is needed to:

1. Quantify and improve soil carbon and vegetation modelling to improve the mean and uncertainty results.
2. Evaluate soil carbon and vegetation carbon sequestration under improved grazing practices to identify practices on that lead to removals and demonstrate best practice for wool production in South Africa.
3. Expand regional coverage of farm-level data and repeat the data collection and modelling with the existing farms in 2027/28 to improve understanding of inter-annual variability.
4. Demonstrate how improved breeding and management can lead to better production and environmental outcomes, particularly through increasing fleece yield and meat turnoff from communal areas.
5. Develop ongoing data capture processes to enable LCAs to be updated every 3-5 years. This should include farm mapping to improve vegetation and natural capital assessment.

The scale of the project was enhanced by collaborative work that was done concurrently. The outputs warrant publication in the scientific literature.

Table of Contents

Executive summary i

1. Introduction 1

1.1 Background 1

1.2 Approach and standards used 1

2. Goal of the study 2

2.1 Goal 2

2.2 Intended audience and use 2

2.3 Comparative assertions 2

2.4 Compliance with ISO 14044 2

3. Scope of the study 3

3.1 Product system(s) 3

3.2 Product function(s) and functional unit 3

3.3 System boundary 4

3.4 Impact assessment 5

3.5 Data requirements 5

3.6 Software and database 6

4. Life cycle inventory analysis 7

4.1 Stratification 7

4.2 Primary data collection 8

4.3 Flock model 9

4.4 Validation of data 12

4.5 Modelling approaches 12

4.6 Background databases 17

4.7 Sensitivity analysis 17

4.8 Uncertainty analysis 18

4.9 Statistical analysis 18

4.10 Allocation procedures 18

4.11 Data quality rating method 19

5. Results 21

5.1 Environmental impacts per kg greasy wool 21

5.2 Biogenic carbon flows 23

5.3 Sensitivity analysis 25

5.4 Uncertainty analysis 27

5.5 Statistical analysis of individual producers 30

5.6 Data quality summary and evaluation 30

6. Interpretation 32

6.1 Productivity and flock dynamics 32

6.2 Carbon footprint 33

6.3 Fresh water consumption 35
6.4 Fossil energy use 36
6.5 Land occupation 36
6.6 Assumptions and limitations 37
7. Conclusions and recommendations 39
7.1 Responsible use of results 40
7.2 Recommendations for decision-makers 40
7.3 Recommendations for future research and development 41
8. References 42
Appendix A Additional information on modelling 46
Appendix B Data quality rating method and criteria (PEF/ILCD compliant) 55
Appendix C Supplementary results 57
Appendix D Allocation 61

Table of Tables

Table 1. Impact assessment methods 5
Table 2. Number of farmers surveyed per category 7
Table 3. Land, water and flock characteristics averaged for RWS commercial farms, communal farms and the South Africa average 10
Table 4. Modelled outputs for RWS commercial farms, communal farms and South Africa average based on the primary datasets 11
Table 5. Modelled feed intake, emissions and water for RWS farms, communal farms and the South Africa average 11
Table 6. IPCC land use categories that were detected and assessed 14
Table 7. Assumptions used in the modelling of biogenic carbon flows 16
Table 8. Sensitivity analysis to key parameters for South Africa wool 17
Table 9. Calculation of protein in livestock products 19
Table 10. Environmental impacts per kg of greasy wool for the RWS farms and communal farms 21
Table 11. Environmental impacts per kg of greasy wool for the average of wool from South Africa 22
Table 12. Modelled inputs and outputs associated with biogenic carbon flows for the national average (units in kg C per year) 24
Table 13. Uncertainty analysis on biogenic carbon only for the South Africa average per kg of greasy wool 24
Table 14. Summary table of score against each quality criterion, and global quality score 31
Table 15. Feed intake, livestock greenhouse gas and livestock drinking water prediction methods 46
Table 16. IPCC Tier 1 land use change prediction equations applied for the conversion of forestland to grassland 52
Table 17. Environmental impacts per kg small stocking unit for RWS, Communal and the national average 57
Table 18. Environmental impacts per kg hectare for RWS, Communal and the national average 58
Table 19. Environmental impacts per kg liveweight for RWS, Communal and the national average 58
Table 20. Impact assessment methods used in the Product Environmental Footprint version 3.1 (European Commission Directorate-General for Environment, 2021) 59

Table 21. The environmental impacts reported for the impact categories assessed in the Product Environmental Footprint (PEF) per kg of greasy wool 60
Table 22. Economic data from the primary dataset used in the sensitivity analysis for handling co-production 61
Table 23. Sensitivity analysis of economic and energy allocation approaches per kg of greasy wool for the national average to handle the co-production of wool and liveweight for meat consumption 64
Table 24. Environmental impacts per kg greasy wool using protein (baseline), economic and energy allocation approaches for the national average to handle the co-production of wool and liveweight for meat consumption 64

Table of Figures

Figure 1. Primary production system boundary. System separation was used to divide inputs associated with separate farm sub-systems. 4
Figure 2. Location of surveyed farms 8
Figure 3. Climate change (excl. LU and LUC), land occupation, water consumption fossil resource use for each category (RWS, communal and the national average) 22
Figure 4. Sensitivity analysis of key parameters as a proportion of the baseline environmental impacts per kg of greasy wool. Green bars represent the effect of a 10% increase in the parameter and the red bars represent the 10% decrease in the parameter. Note. The default method was to implement a +/- 10% change in each parameter. In some cases, this was varied to better reflect the likely variation in that parameter in the model. This included empty body weight was varied by +/- 5% and stocking rate was varied by +/- 50%. The sensitivity of fossil resource use, land occupation and water consumption to a 10% change in digestibility was not assessed. Purchased inputs and land occupation parameters are normalized per kg of DMI or per SSU. Since, digestibility influences total DMI and SSU, altering digestibility also alters the normalizing units themselves, obscuring the underlying trend 26
Figure 5. Uncertainty distribution (excluding beta uncertainty) for climate change (excl. LU and LUC), land occupation, water consumption and fossil resource use for RWS farms, communal farms and the ZA average reported per kg of greasy wool (cradle to primary production gate) 28
Figure 6. Uncertainty distribution (including alpha and beta uncertainty) for climate change (excl. LU and LUC), land occupation, water consumption and fossil resource use for the ZA average reported per kg of greasy wool (cradle to primary production gate) 29
Figure 7. Regression of protein per sheep unit and carbon footprint (excl. LU and LUC) (cradle-to-primary production gate) from the results of individual farms analysed in this study 30

1. Introduction

1.1 Background

The global wool industry is the largest contributor to animal fibre production, producing 1.98 million tons of greasy fibre in 2024, representing approximately ~0.9% of total global fibre production (Textile Exchange, 2025). South Africa produces approximately 47,215 tonnes of greasy wool per year, approximately 2% of global wool greasy wool production. Natural fibres, including wool, are facing increasing pressure to align with company emission reduction targets and consumer expectations on sustainability reporting.

Natural fibres, including wool, are facing increasing pressure to align with company emission reduction targets and consumer expectations on sustainability reporting. Supply chain sustainability reporting uses LCA as the foundation for comparing multiple environmental impacts from product systems. Globally, there have been a number of LCA studies published on sheep (Gac et al., 2012; Ibidhi et al., 2017; Mazzetto et al., 2023; Peri et al., 2020; Wiedemann et al., 2016). These studies have typically focused on a select group of countries or regions within countries, and most have focused on a small subset of indicators. These studies provide some insight into the key impact categories, data sources and data collection required for the environmental assessment of wool production systems across a larger geographical region.

Other previous studies on wool (Wiedemann et al. 2020) showed that greenhouse gas (GHG) emissions, land occupation and freshwater consumption were highest at the primary production stage with lower GHG emissions from processing and retail and garment phase. For all animal fibres, fibre production in the animal system is the most significant hotspot for key impacts such as greenhouse gas (GHG) and in some cases other impacts such as eutrophication. To further complicate the supply chain, all animal fibres are one of multiple outputs from a production system which may also deliver meat.

Further challenges were also noted by Watson and Wiedemann (2019) related to the reporting of natural fibres, including outdated or limited datasets and oversimplification of complex impacts. Further, understanding impacts within various natural fibre types is hampered by the uncertainties inherent in natural production systems, making it difficult to evaluate whether impacts are genuinely different from one fibre type to another (Watson & Wiedemann 2019). Addressing these problems requires detailed LCA research into each fibre production system to build the scientific knowledge base for future decision making.

The knowledge gap addressed in this study is the lack of comprehensive, multi-indicator LCA data for South Africa wool. This project provides the first LCA of South Africa wool, quantifying environmental impacts across several environmental impact categories.

1.2 Approach and standards used

This Life Cycle Assessment (LCA) study was conducted in accordance with ISO 14044:2006 *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*. Biogenic carbon was assessed following ISO 14067:2018 and GHG methods used IPCC tier 2 methods.

2. Goal of the study

2.1 Goal

This pilot LCA study investigated the environmental impacts from South Africa wool production to provide information to the global wool industry, consumers, brands and stockholders. The study specifically aimed to quantify impacts from climate change, water and energy use following the requirements of ISO 14040 (ISO, 2006b) and 14044 (ISO, 2006a). Additional, environmental indicators using the indicators used in the PEF framework and the Higg MSI. The study included primary data inventories of production in South Africa. To our knowledge, no peer-reviewed LCA of South African mohair exists; this study addresses that gap by providing the first comprehensive, multi-category LCA.

2.2 Intended audience and use

The results of this study are intended to inform decision-makers in the wool industry, particularly those involved in sustainability, supply chain management, and environmental impact reduction. The findings will be used to improve understanding of the environmental impacts of South African wool production. The study aims to support wool industry stakeholders in making more informed, data-driven decisions about how to reduce supply chain impacts, improve the sustainability of wool production and guide future research.

2.3 Comparative assertions

This study does not constitute a comparative assertion as defined by ISO 14044. The results are specific to South Africa and its production systems and should not be used for direct comparisons with other fibres or between production systems, without careful alignment of functional units, system boundaries, data sources, and methodological assumptions.

Life cycle assessments are inherently sensitive to context-specific factors such as geography, management practices, and input types. Therefore, extending these results to other systems or using them in comparative claims may lead to misleading conclusions. The findings are intended as a foundation for further study, not as a basis for broad generalizations or public environmental claims.

2.4 Compliance with ISO 14044

This study has been conducted in compliance with the principles and requirements outlined in ISO 14044:2006 (Environmental Management – Life Cycle Assessment – Requirements and Guidelines). The standard provides a globally recognized framework that ensures methodological rigor, transparency, and consistency in life cycle assessment.

3. Scope of the study

3.1 Product system(s)

Wool is a natural animal fibre produced by sheep (subspecies Ovis aries), consisting primarily of keratin. Wool is shorn every 6, 8–9 or 12 months depending on the production system, producing greasy wool, which contains raw fibre along with variable proportions of lanolin (wool grease), suint, dirt and vegetable matter. Greasy wool represents one of the first commercial products leaving the farm gate and can be one of the primary co-products of sheep production systems.

This study focuses on wool produced in South Africa from both commercial and communal farming systems. Production systems across South Africa varies in terms of climate, pasture type, stocking rates and management intensity, but are predominantly extensive grazing systems based on managed rangelands or improved pastures.

Commercial wool production in South Africa is conducted on privately owned or leased land, with individually managed flocks and controlled grazing systems. Sheep are typically grazed year-round with limited housing, and purchased inputs are generally low relative to more intensive livestock systems. However, compared with communal systems, commercial farms typically operate with higher input use (e.g. supplementary feeding, veterinary interventions, and infrastructure) and more intensive management, but also deliver higher wool yields and more uniform fibre quality. Supplementary feeding may occur during periods of low pasture availability, such as droughts or winter feed gaps, with the type and quantity of supplementation varying by region and seasonal conditions. Wool production is commonly integrated with meat production, with both outputs forming part of the overall farm system.

Communal wool production in South Africa occurs on shared rangelands, primarily in the Eastern Cape, where land is collectively managed and individual households own small sheep flocks. Unlike commercial systems, grazing is largely continuous and, with limited control over stocking rates and pasture utilisation. Production activities are organised around communal shearing sheds, which function as centralised hubs for shearing, wool classing, baling, and collective marketing. Farmers are typically organised into local associations linked to a shed, enabling aggregation of wool for sale through formal auction systems. While this model improves market access and wool quality through shared infrastructure and training, animal performance and productivity are generally lower and more variable than in commercial systems due to constraints in nutrition, genetics, and animal health management.

The product system assessed in this study is greasy wool production at the farm gate.

3.2 Product function(s) and functional unit

The primary function of the product studied is to provide greasy wool, which is then processed into textiles for various uses, such as clothing, accessories, and other products. The functional unit was reported to the farm-gate as ‘1 kg of greasy wool at the primary production-gate’.

3.3 System boundary

The system boundary included all supply chain processes associated with the primary production of wool (Figure 1).

The study excluded downstream processes such as primary processing, textile manufacturing, retail, product use and end-of-life disposal. In this report, "primary production stage" refers to the phase within the system boundary that captures all activities occurring on-farm.

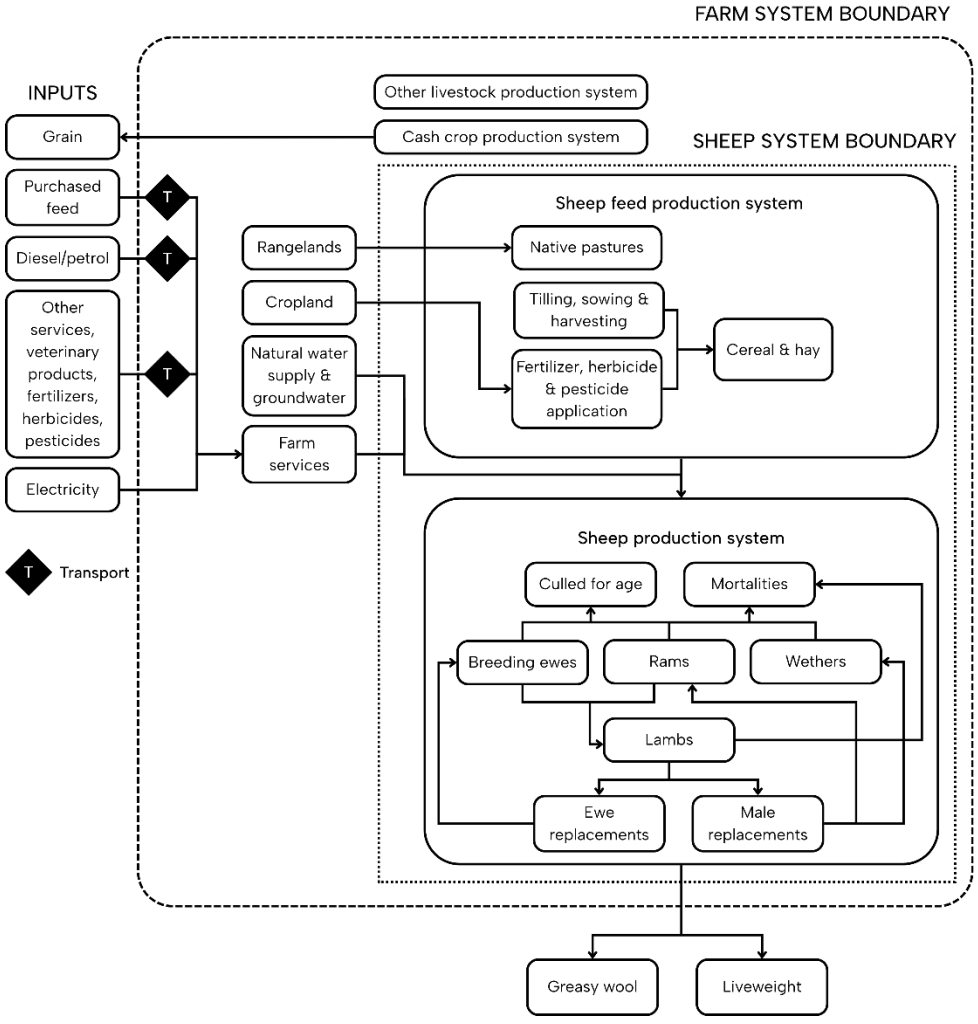


Figure 1. Primary production system boundary. System separation was used to divide inputs associated with separate farm sub-systems.

3.4 Impact assessment

The main impact categories include were climate change, energy, water consumption and land occupation (Table 1).

Additional impact categories included in PEF version 3.1 (European Commission Directorate-General for Environment, 2021) were assessed for alignment with the global RWS LCA that was completed concurrently. These are reported in Appendix C with acknowledged higher uncertainty in this pilot scale study.

Table 1. Impact assessment methods

Impact Category	LCIA method	Unit	Reference
Climate change	Global warming potential (GWP_{100}) AR6	kg CO_2 eq	Bern model - Global warming potentials (GWP) over a 100-year time horizon (based on (IPCC, 2021)
Land occupation	Land area of occupation	m^2	
Water consumption	Water consumption in terms of water use.	m^3 water consumption	
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)18	MJ	van Oers et al. (2002) as in CML 2002 method, v.4.8

3.5 Data requirements

This study defined specific data requirements regarding the types, sources, and quality of data used across the product system. Primary data were collected for wool production in South Africa. This data was sourced directly from farmers using structured surveys conducted by in-country personnel. Data included flock sizes, wool production, meat production, feed practices, land use, energy consumption, water use, and outputs. Secondary data were used to model background processes and upstream activities, such as fuel combustion, transport, chemical production, and general infrastructure. The background data were primarily sourced from the Ecoinvent 3.11 database.

Data quality requirements were established to ensure consistency and relevance across the study, with the aim of meeting the Data Quality Requirements (DQR) set out in the ILCD Handbook. A 12-month production cycle was assessed using survey data collected for livestock, cropping, and purchased inputs covering the period from March 2022 to February 2023. Primary data were validated to ensure biophysical coherence. Outliers were determined as any datapoint that was outside the interquartile range and were checked and corrected where data entry errors were identified. A consistent system boundary and functional unit were applied, and all datasets were assessed for alignment with the study's goal and scope.

The Data Quality Rating (DQR) method was applied to assess each dataset's reliability and appropriateness, with full documentation presented in Appendix A.

Inputs and outputs were excluded from the LCI only when their omission was determined not to significantly affect the overall conclusions of the study. The cut-off criteria was <1% of total environmental significance for any individual input or output and <3% cumulative impact. Inputs excluded based on these criteria included low-volume packaging materials

used during raw fibre transport, administration and overheads, capital infrastructure and maintenance of machinery. These impacts were excluded because their environmental contribution was expected to be minimal due to long operational lifespans and low relative significance. These exclusions were justified through expert review and comparison to previous LCA studies in animal fibre (Wiedemann et al., 2016, 2020)

3.6 Software and database

The life cycle modelling and impact assessment for this study were conducted using SimaPro™ 9.6.0.1 (Pré Consultants, 2024) a widely used software tool for life cycle assessment that supports compliance with ISO 14040 and 14044 standards.

4. Life cycle inventory analysis

4.1 Stratification

Surveys were conducted on 84 farms and communal areas across South Africa. Of these farms, one was excluded as an outlier from the communal average, five were excluded as outliers from the RWS average, and one additional non-RWS farm was excluded from the country-level average, resulting in 77 farms included in the analysis (Table 2). The sample size was stratified by wool production volume, farm size, geographical zone and management practices. The selection farms for data collection considered a balance between sample size with cost, time and logistics in travelling large distances required for primary data collection.

The stratification of regions was reviewed extensively during the scoping phase in consultation with in-country experts, including representatives from Cape Wools and the National Wool Growing Association (NWGA). The final sample size, selected regions, and number of farms per region were agreed upon through this stakeholder engagement process.

A simple (unweighted) average across farms was used to construct the country-level inventory. As a result, the country average underrepresents non-RWS farms, which is an acknowledged limitation of this pilot study. Although RWS farms account for approximately 34% of South African wool production (Textile Exchange, 2025), they are overrepresented in the dataset. Given the small number of non-RWS farms included, applying a weighted average was not considered appropriate.

Results for a non-RWS average were not reported because the sample size was insufficient; nevertheless, non-RWS farms were included in the calculation of the country-level average.

Table 2. Number of farmers surveyed per category

Country	Datasets
RWS commercial farms	66
Non-RWS commercial farms	6
Communal farms	5
Total	**77**

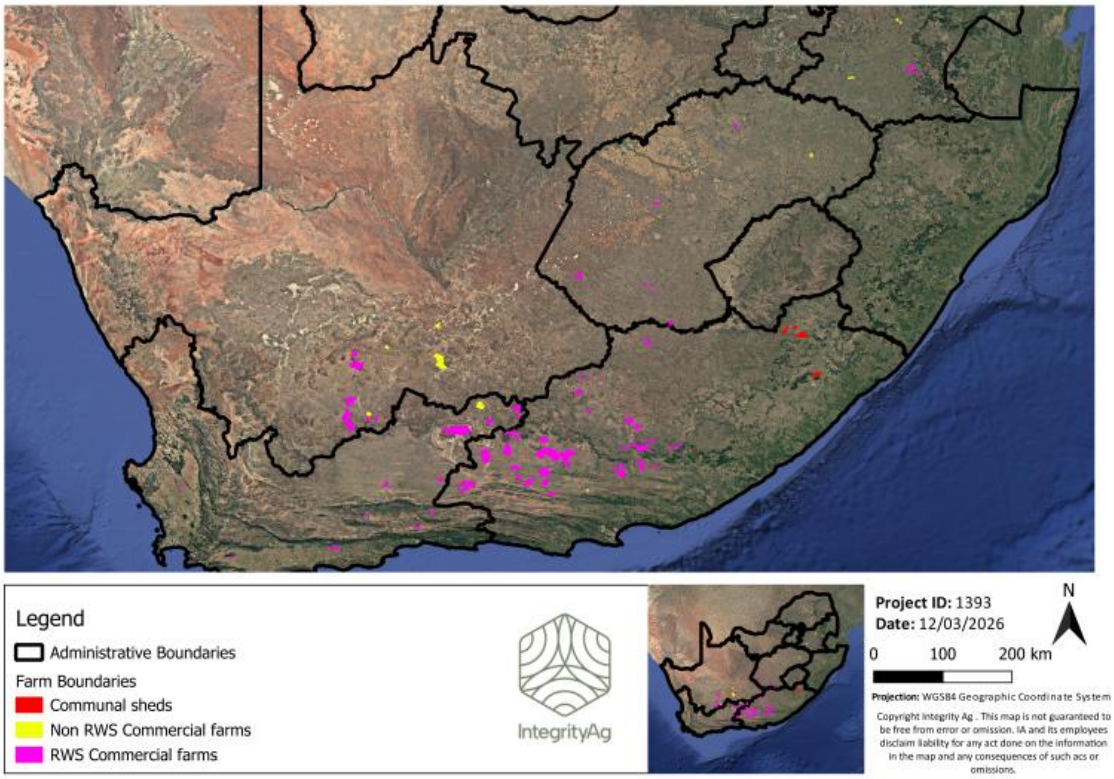


Figure 2. Location of surveyed farms

4.2 Primary data collection

Field visits were conducted to survey flock inventory numbers and animal weights, flock characteristics, grazing areas, crop and fodder production, energy use, water sources, purchased inputs, average price of products sold, goods and services and transport. Surveys and supporting guidance materials were translated from English and made available in other languages, where necessary. For each farm, a single field assessment visit was conducted, during which a minimum of 10 field point surveys were completed for pasture condition. These field point datasets included spatially explicit information on land use classification, land condition score, ground cover, slope, pasture height, and the presence of vegetation. Selection of field points were stratified to ensure coverage of key land and management conditions, and randomized to minimize placement bias. The 12-month survey period for livestock, cropping, and purchased input data was aligned with the production calendar of each country. Data were collected for the 12-month period from March 2022 to February 2023.

The data were reviewed and processed by the research team. Outliers were identified for each parameter and were removed when they did not comply with the structure of the biological model for sheep. For example, when values fell outside the range of biological possibility, or violated mass balance principles, these were considered outliers. In cases where a data point was removed, it was replaced with the normalized mean value for the country to maintain consistency in the dataset.

4.3 Flock model

A flock model was developed based on the IPCC feed intake model which was implemented for each individual class of animals in the flock. Classes modelled included breeding ewes, non-breeding ewes, replacement ewes, bucks, wethers and kids. The flock data were modelled over one complete production cycle from the inventory of breeding ewes, replacement ewes, wethers, rams and lambs. Inventory data were averaged for each production system (Table 3). The outputs from the modelled flock are shown in Table 4 and Table 5. Primary data (flock structure, liveweights, sales/output, inputs, water sources, land, and grazing) were compiled from structured field surveys and case-study assessments. Visual vegetation assessments were combined with laboratory analyses of pasture crude protein (CP), dry matter (DM), neutral detergent fibre (NDF) and acid detergent fibre (ADF) to inform energy quality of diets. The greasy wool indicator was normalized to remove variance in results caused by greater or lesser amounts of contaminants in the wool.

Table 3. Land, water and flock characteristics averaged for RWS commercial farms, communal farms and the South Africa average

Parameters	RWS	Communal	South Africa
Land and water resources			
Stocking rate (SSU/ha)	0.7	1.5	0.7
Grazing area allocated to sheep (ha)	3,978	1,139	3,924
Total cropland allocated to sheep (ha)	129.1	215.9	131.1
Irrigation volume (ML / ha)	3.1	0.0	3.1
Irrigated land (ha)	14.9	0.0	12.8
Natural water supply (%)	10	100	15
Ground water supply (%)	67	0	64
Dam water supply (%)	23	0	21
Flock structure			
Mean flock size (head no.) incl. lambs	3,617	2,747	3,510
Mean flock size (SSU)	2,740	2,001	2,649
Breeding ewes (no. joined)	1,511	1,435	1,478
Non-breeding ewes (head no.)	346	260	348
rams (head no.)	46	61	45
Non-breeding rams (head no.)	35	138	42
Wethers (head no.)	110	391	139
Lambs weaned (head no.)	1,569	462	1,459
Ewe Mature Weight (kg/head)	59	46	58
Rams weight (kg/head)	83	61	82
Ewe cull rate (%)	20	6	20
Weaning rate (% at marking)	104	32	99
adult mortality (%)	2.3	9.9	2.8
Lamb sale weight (kg LW)	35	30	34.4
Lamb sale age (days)	135	275	141
Wool			
Clean wool yield (%)	66	66	66
Feed assumptions			
Crude protein (% of DM)	12	12	12
Digestibility of feed (% of gross energy)	69	69	69
Purchased inputs			
Maize (kg/SU)	9.0	0.0	11.0
Lucerne (kg/ SU)	1.2	0.0	0.4
MAP (kg/SU)	0.8	0.0	0.0
LAN (kg/SU)	1.0	0.0	0.0
Energy			
Diesel (L/SU)	1.8	0.0	1.7
Petrol (L/SU)	0.1	0.0	0.1
Electricity (kwh/SU)	3.9	0.0	3.5
Veterinary products			
Internal parasite treatment (mg/SSU/year)	240	50	226
External parasite treatment (litres/SSU/year)	4328	898	4084

[4] Feed quantities are reported as fed (wet matter), not on a dry matter basis

SSU = small stocking unit

Table 4. Modelled outputs for RWS commercial farms, communal farms and South Africa average based on the primary datasets

Parameters	RWS	Communal	South Africa
Land and water resources			
Wool per sheep shorn (kg/hd/yr)	4.8	2.8	4.4
Total kg liveweight sold or used for consumption (kg LW/yr)	57,948	8,785	52,854
Total greasy wool sold or used for consumption (kg /yr)	10,845	6,543	10,074
Greasy wool sales per breeding ewe (kg/breeding ewe)	7.2	4.6	6.8
Greasy wool sales per SU (kg/SU)	4.0	3.3	3.8
Liveweight sales/consumption per breeding ewe (kg LW/ewe)	38	6	36
Liveweight sales/consumption per SU (kg LW/SSU)	21	4	20
Protein allocation to wool (%)	44	75	44
Protein allocation to meat (%)	56	25	56
Protein per SU (kg protein/SU)	5.2	2.5	5.0
Head sold (hd)	1,420	171	1,298
Head sold (%)	39%	6%	37%

Table 5. Modelled feed intake, emissions and water for RWS farms, communal farms and the South Africa average

Parameters	RWS	Communal	South Africa
Land and water resources			
Total dry matter intake (kg/year)	1,000,060	730,515	966,804
Total flock water intake (L/year)	1,487,570,231	1,257,983,302	1,453,590,886
Total flock land occupation (ha/year)	3,978	1,139	3,924
Total irrigation water volume (m^3/year)	46,812	-	40,201
Total enteric methane (kg CH_4/year)	20,227	15,255	19,607
Total manure methane (kg CH_4/year)	175	128	169
Total direct nitrous oxide from manure and urine (kg N_2O/year)	83	62	80
Total indirect nitrous oxide from ammonia volatilisation from manure and urine (kg N_2O/year)	46	35	45
Total indirect nitrous oxide from leaching and runoff (kg N_2O/year)	101	76	98
Total ammonia from manure and urine (kg NH_3/year)	4,197	3,155	4,073

4.4 Validation of data

Primary data collected directly from stakeholders, were validated through the following steps:

1. Cross-checking against published literature and industry benchmarks, where available.
2. Internal consistency checks (e.g., mass and energy balances, unit conversions).
3. Consultation with data providers to confirm assumptions, fill gaps, and clarify anomalies.
4. Review by the internal LCA team to assess alignment with the goal and scope of the study.

The data were reviewed and processed by the research team and follow-up questions on the data were reviewed by in-country personnel to ensure the data were complete and properly interpreted. Outliers were identified for each parameter and were only removed when they did not comply with the model structure; for example, where they were outside the range of biological possibility or did not comply with mass balance principles.

Secondary data, sourced from the Ecoinvent 3.11 database, were reviewed for:

- Relevance to the specific geographic, temporal, and technological context of the system under study.
- Consistency with other datasets used in the model.
- Source documentation to verify system boundaries and representativeness.

All data used in the final model were subject to quality assessment using a Data Quality Rating (DQR) framework (see section 4.11).

4.5 Modelling approaches

4.5.1 Feed intake and livestock greenhouse gas emissions

Flock inventory, liveweights and growth rates were used to model gross energy and manure production. Gross energy and livestock GHG emissions were modelled using IPCC Tier II equations, emission factors and uncertainty from the 2019 refinement (IPCC, 2019b, 2019a) (Table 15). The dominant plant communities were assessed visually and pasture characteristics including crude protein, dry matter %, neutral detergent fibre (NDF), acid detergent fibre (ADF) were analysed at the laboratory from samples collected in case studies. NDF and ADF were used to estimate digestible and metabolizable energy of the feed (Minson, 1984).

4.5.2 Land use change modelling and removals

Land use and LUC processes are important considerations for agricultural-based products because these products are inherently land-based. In grazing systems, LUC emissions or removals arise from the conversion of land from one use category to another. Land management practices can also result in LU emissions or removals depending on whether the practices improve or restrict carbon storage in soil and vegetation. The assessment of

LU and LUC GHG emissions was determined using direct LUC methods for the systems based on the grazing areas assessed. The land use types identified included grassland, forest and cropland. The major land use types observed from satellite imagery were forestland and grassland with minor areas for cropping. The Global Forest Watch product (Global Forest Watch, n.d.) was used to assess forest cover loss over the most recent 20-year period (2005–2024) within the grazing regions included in the study. Cropland areas were determined from the areas identified by the farmers. The detected LU and LUC was validated using historical imagery from ESRI World Imagery Wayback. Any forest loss which was a forest plantation, or was a misclassification was excluded.

Land use change GHG emissions and removals were modelled following the PAS standard (BSI, 2011) (to show results that met the requirements of PEF and Higg) and ISO 14067 (ISO, 2018) requirements and both these standards refer to the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006d) for the quantification of LU and LUC emissions, unless otherwise specified. Emissions and removals from indirect LUC were excluded. Removals of atmospheric CO_2 from direct LU and LUC were assessed. Of the six land use categories defined in the (IPCC, 2006d)), forestland, cropland, and grassland were the only land use types identified from the land classification datasets.

Under the IPCC Tier 1 method, carbon pools are generally treated as being at steady state in the absence of land-use or management change (IPCC, 2006b). Accordingly, annual carbon stock change was set to zero for above- and below-ground biomass and dead organic matter in both forestland remaining forestland and grassland remaining grassland. Farms were assessed for evidence of grassland degradation and soil respiration rate was varied in the uncertainty assessment. In the farms assessed land degradation was not observed and soil carbon was therefore considered to be in a steady state (zero carbon stock change). This was tested in the uncertainty analysis.

Of the six land use categories defined in the IPCC 2006, forestland, cropland, and grassland were the only land use types identified from the land classification primary data (Table 6). Land use change GHG emissions from the following carbon pools; biomass, dead organic matter and soils, were assessed following IPCC Tier 1 equations (Table 16). The time period of assessment was the most recent 20-year period (2005-2024) and an equal discounting approach was applied (BSI, 2011). Land use and LUC GHG emissions were reported separately as required by ISO 14067 (ISO, 2018).

Table 6. IPCC land use categories that were detected and assessed

	Forest Land	**Grassland**	**Cropland**	**Wetland**	**Settlement**	**Other Land**
Forest Land	F → F No change detected	F → G Detected, assessed	F → C Not detected	F → W Not detected	F → S Not detected	F → O Not detected
Grassland	G → F Detected, assessed	G → G No change detected	G → C Not detected	G → W Not detected	G → S Not detected	G → O Not detected
Cropland	C → F Not detected	C → G Not detected	C → C Not detected	C → W Not detected	C → S Not detected	C → O Not detected
Wetland	W → F Not detected	W → G Not detected	W → C Not detected	W → W Not detected	W → S Not detected	W → O Not detected
Settlement	S → F Not detected	S → G Not detected	S → C Not detected	S → W Not detected	S → S Not detected	S → O Not detected
Other Land	O → F Not detected	O → G Not detected	O → C Not detected	O → W Not detected	O → S Not detected	O → O Not detected

4.5.3 Resource use, fossil energy and water consumption

Demand for fossil fuel energy was assessed by aggregating all fossil fuel energy inputs throughout the system and reporting these as megajoule (MJ) of energy. The study assessed freshwater use using a water balance method (Bayart et al., 2010) to assess uses and losses throughout foreground and background processes. Forest cover loss was assessed as described in section 4.5.2. Historical LUC from forest to pasture was expected to be low risk for wool production and hence impacts on freshwater consumption as a result of LUC was assumed to be zero. Primary sources of freshwater consumption were livestock drinking water and drinking water supply losses. Drinking water was supplied from natural ways (including rivers, lakes and streams) and groundwater. The proportion of supply from each source was determined from the farm survey. Where losses associated with the supply of water were caused by the production system, they were attributed to livestock production. Losses from livestock drinking troughs were determined from sources of leakage and evaporation.

4.5.4 Land occupation

Land occupation was quantified as the physical area of land required to support wool production over the defined assessment period and was reported in units of square metres (m^2) per greasy wool. The land use assessment was determined based on the farm boundaries assessed. The land use types identified included grassland, forest and cropland. The major land use types observed from satellite imagery were forestland and grassland with minor areas for cropping. Where sheep production also relied on on-farm crop or fodder production, the associated cropland area was included and allocated to sheep based on the proportion of production used within the sheep system. Purchased feed produced off-farm was not assigned land occupation within the system boundary. No differentiation was made between land quality or land management practices within the land occupation indicator itself. The indicator represents land area of occupation only and does not account for potential differences in soil condition, vegetation state, or ecosystem services.

4.5.5 Biogenic carbon flows

Land occupation was quantified as the physical area of land required to support wool production over the defined assessment period and was reported in units of square metres (m^2) per greasy wool. The land use assessment was determined based on the farm boundaries assessed. The land use types identified included grassland, forest and cropland. The major land use types observed from satellite imagery were forestland and grassland with minor areas for cropping.

Generalized biogenic carbon flows associated with pasture were included, based on ISO 14067 clause 6.4.9.3 to provide context for the carbon footprint results. Biogenic carbon flows were modelled using a simplified carbon balance including pasture, livestock and soil interactions but not including trees or LUC (see Table 7). This balance was based on stoichiometric conversion of different flows and stocks including complex carbohydrates, proteins and fat, and gaseous emissions of carbon dioxide (CO_2) and methane (CH_4). Flows were reported as elemental carbon (C) using molecular weights (i.e. 12/44 for CO_2 to C and 12/16 for C from (CH_4).

Impacts on climate were determined from the net change in emissions from the biogenic cycle, representing stock changes in soil and pasture vegetation, and emissions of methane. This was different to the climate change indicator, which included non-carbon emissions of nitrous oxide, and fossil related CO_2 e. Impacts from LUC were also assessed separately. These other emissions were calculated as described in other sections of this report, based on primary inventory data.

Temporary carbon storage in wool and liveweight was included in the assessment, and were classified as delayed emissions as defined by ISO 14067. This was accounted during the assessment period, as required by ISO 14067 (clauses 6.4.8 and 6.4.9.3), which required biogenic carbon stored in a product to be treated as if released at the start of the assessment period, without considering delayed emissions. This is a recognized simplification required by the ISO method. In practice, carbon stored temporarily in liveweight may remain out-of-the-atmosphere for a period of months, but in stable flocks the time period is relatively short. Carbon in wool will likely remain out-of-the-atmosphere for some years, but in a long-term steady state situation, historical emission profiles will be established that diminish the impact of short-term storage (i.e. wool produced 5 years ago may be generating emissions from the end-of-life of garments today, resulting in minimal impact on carbon balances when longer-term equilibriums are used). There are few established ways of determining the effect of this temporary storage on the climate and ISO restricts treating short-term storage as a removal and thus reducing the carbon footprint, though some researchers differ in their interpretation on this point.

Table 7. Assumptions used in the modelling of biogenic carbon flows

Parameter	Value	Uncertainty	Reference
Pasture utilization rate (%)	25	+/- 25%	n.d
Root:shoot ratio	2.4	+/- 25%	Vibart et al. (2025)
Plant respiration rate (%)	50	+/- 10%	Parton et al. (1993)
Carbon content in dry plant biomass (% of DM)	44.73	+/- 10%	Ma et al. (2018)
Carbon content in protein (% of protein)	53	N.A	Rouwenhorst et al. (1991)
Carbon content in fat (% of fat)	75	N.A	Bray & Bouchard (2003)
Carbon in clean fibre (% of clean fibre)	50	N.A	Hawkesworth (1948); Simmonds (1954; 1958); von Bergen (1963)
Carbon in manure (% of volatile solids)	55	+/- 10%	Natural Resources Conservation Service (2025)
Soil respiration rate and organic matter turnover (% of organic material respired)[2]	100	+/- 0.768%	Value based on soil carbon stock change potential determined from the IPCC (2006c)
Fat content in EBW (% of EBW)	21.4	+/- 25%	Sanson et al. (1993)
Vegetable matter base (vmb_content) (% of clean fibre)	0.02	+/- 25%	Assumed value
Grease in raw fibre	21.8	+/- 10%	Mortimer & Atkins (1993) for fine-wool breeds
Suint in raw fibre	8.94	+/- 10%	Mortimer & Atkins (1993) for fine-wool breeds
Carbon content in grease (wax)	75	N.A	von Bergen (1963)
Carbon content in suint	45	N.A	Derived from (Howitt & Preston, 1960)
Fiber regain	16	N.A	Morton & Hearle (2008)

[1] Pasture utilization rates can vary seasonally and between regions, no data were available to determine this.
[2] The IPCC Tier 1 method assumes that there is zero change in soil carbon stocks in grasslands remaining grasslands (IPCC, 2006c). Hence, soil respiration rates are assumed to be 100% as in a steady-state system, the amount of carbon entering those slow pools is roughly balanced by the decomposition of SOC leaving the system.

4.6 Background databases

The background datasets used to estimate the environmental impacts associated with the purchased inputs into the production were sourced primarily from reputable LCI databases such as [e.g., Ecoinvent or Aus LCIV2]. The data include inputs for energy, feed production, water use, chemical inputs, transportation, and infrastructure processes.

4.7 Sensitivity analysis

4.7.1 Sensitivity analysis: key parameters

The sensitivity of the model to key assumptions, data input parameters (Table 8) and methodological decisions were tested. A sensitivity analysis was performed on key model parameters, keeping all other factors constant. This method is useful for identifying which parameters exert the greatest influence on model outputs and, therefore, where improving data quality would have the greatest effect on reducing uncertainty. However, due to the non-linear structure of the model and potential correlations among parameters, these results should not be interpreted as predictive of system behaviour when multiple parameters change simultaneously. Instead, they indicate relative importance for prioritizing data refinement. The default method was to implement a +/- 10% change in each parameter. In some cases, this was varied to better reflect the likely variation in that parameter in the model.

Table 8. Sensitivity analysis to key parameters for South Africa wool

Parameters	-10%	Baseline value	+10%
Clean wool yield (%)	59%	66%	72%
Protein in empty body weight (%)	15%	16%	18%
Empty body weight as a proportion of liveweight (% of liveweight)[1]	81%	85%	89%
Proportion of grease in wool (% of greasy wool)	20%	22%	24%
Digestibility (% of gross energy)	62%	69%	76%
Weaning Rate (%)	89%	99%	109%
Mortality Rate (%)	6%	7%	8%
Average adult weight (kg LW)	52	58	64
Average lamb weight at weaning (kg LW)	18	20.0	22
Stocking rate (SSU ha^{-1})[2]	0.3	0.7	1.0
Wether inclusion (% of breeding ewes)	5%	9%	14%
Greasy wool per head (kg GW hd^{-1} yr^{-1})	4.0	4.4	4.9
Purchased Energy (MJ SSU^{-1})	118	131	144
Irrigation rate (ML ha^{-1})	2.8	3.1	3.5

[1] *Empty body weight was varied by +/- 5%*
[2] *Stocking rate was varied by +/- 50%*

4.7.2 Sensitivity to allocation approach

The sensitivity of results to the allocation method was tested by considering energy allocation methods and economic allocation. These were explored in Section D.1 of Appendix D.

4.8 Uncertainty analysis

Alpha and beta uncertainties were assessed via Monte Carlo analysis (1000 iterations) using SimaPro™ 9.6.0.1 (Pré Consultants, 2024). Results were presented using the mean ± 2S.D.

Two types of uncertainty were distinguished: α (alpha) uncertainty, which represents variation between farm input data and reflects variability in the primary datasets, and β (beta) uncertainty, which represents model-related uncertainty including prediction of feed intake, application of emission factors, and uncertainty in background datasets. Uncertainty was reported based only on α, because β uncertainty is shared across systems and doesn't affect relative differences. The uncertainty analysis excluding beta uncertainties (shared model uncertainties) were calculated to determine statistically significant differences. As beta uncertainty was shared by all systems, comparison of the mean results between production systems was based on alpha uncertainties only.

For the mean results for South Africa, both alpha and beta uncertainties were combined.

4.9 Statistical analysis

4.9.1 Regression model of individual flocks

For climate change (excl. LU and LUC) a statistical analysis was conducted by analysing each flock individually. A regression model was fitted and grouped by country. The dependent variable was climate change impacts (excl. LU and LU), and the independent variable was protein per sheep unit. The regression analysis was applied to examine the relationship between protein per SU and climate impact (excl. LU and LUC). The regression was linear in the transformed variable stocking units per protein.

4.10 Allocation procedures

Allocation was applied where processes resulted in multiple co-products and the environmental burdens could not be assigned solely to the product under study. All allocation procedures used in this study follow the hierarchy set out in ISO 14044:2006, whereby subdivision of processes or system expansion is preferred. Where subdivision was not feasible and a single function could not be isolated, allocation was based on a relevant physical property or economic relationship, in line with sector-specific best practice and data availability.

Sheep farms typically operate mixed farming operations which can include goats and cattle and may also produce grains or other crops. The presence of multiple production systems was handled by system sub-division and accounting for the wool production

system separately. Shared inputs between livestock species including land area and energy use were divided and attributed to each system based on stocking rates. Manure deposited to grazing land was an internal flow and impacts (emissions) were attributed to the grazing system. Handling co-production of wool and liveweight for meat consumption was modelled using protein allocation methods based on (Wiedemann et al., 2015). For comparison, energy allocation methods and economic allocation were used in the sensitivity analysis.

The protein mass of greasy wool was estimated by multiplying the greasy wool mass by the clean wool content assuming a protein content of 100% for dry, clean wool (Table 9). Dry, clean wool content was estimated from the clean wool yield using the Schlumberger Combed Dry (1.0 % Total Fatty Matter) calculation (Australian Wool Education Trust, 2008). The clean wool yield (% of greasy wool) was 67% (average of the datasets), the vegetable matter base was assumed to be 2%. The protein content of empty body weight (EBW) was assumed to be 16.4% and EBW as a proportion of liveweight was assumed to be 85% (based on Sanson et al. (1993)). The protein allocation method involves calculating the amount of protein in each product (Table 9). Comparison methods using economic and energy allocation were used and are shown in the Appendix for context.

Table 9. Calculation of protein in livestock products

Parameter	Equation
Total protein in liveweight[1]	Total liveweight sold x proportion of EBW in LW/100 x protein content in EBW
Theoretical fibre yield[1]	(2.5+(5.2-(40.6/(7.8+vmb_content*100)))+(reported_clean_wool_yield*100))/100
wool base (% of greasy wool)	theoretical_fibre_yield/1.207
Protein in clean dry scoured fibre (%)	100%
Total protein in wool top (kg) – dry basis	Total greasy wool (kg) x wool base (%) x protein in clean dry fibre (%)

[1] *The clean wool yield (% of greasy wool) was 66%.*

4.10.1 Allocation for secondary data

All background processes were sourced predominantly from Ecoinvent 3 using the allocation cut-off by classification model (Table 8). The allocation approaches documented in the respective datasets were retained. No user modifications to allocation procedures were made.

4.11 Data quality rating method

4.11.1 Overview

The quality of input data used in this LCA study was assessed using the Data Quality Rating (DQR) approach. This evaluation considered key criteria in accordance with ISO 14044 (2006b), and aligned with ILCD Handbook. Each dataset was scored based on its performance across Technological Representativeness (TeR), Geographical

Representativeness (GR), Time-related Representativeness (TiR), Completeness (C) and Precision/Uncertainty (P).

4.11.2 Scoring system

Each criterion was rated from 1 (high quality) to 5 (low quality). The overall DQR score was calculated as the arithmetic mean of the four individual scores. A lower DQR indicates better overall quality. Data quality assessment was carried out at the process level. Detailed scoring and interpretation are provided in section 5.6.

4.11.3 Scope of assessment

Key unit processes assessed were the sheep production unit process, including farm services, drinking water model and flock production model.

5. Results

5.1 Environmental impacts per kg greasy wool

The environmental impacts per kg of normalized greasy wool (cradle to primary production-gate) are reported in Table 10, Table 11 and Figure 3.

The results for average of South Africa based on all production systems were calculated inclusive of uncertainty and showed a coefficient of variation of 14% in the carbon footprint results inclusive of land use and land use change. This indicated there was a 95% probability the carbon footprint was between 21 to 36 kg CO_2-e kg greasy wool. The mean uncertainty results were higher for water and land occupation than an average of the RWS and communal farms would suggest, because of the uneven distributions displayed in the uncertainty analysis of these results indicating higher land area and water was more probable than an equal range of above-and-below mean results. Results were between systems excluding shared model uncertainty for comparison between the systems only (see Figure 3). These results were different for land and water in the South Africa average to those including shared uncertainty (Table 11). The results in Table 11 were used as overall reported results.

Table 10. Environmental impacts per kg of greasy wool for the RWS farms and communal farms

Impact category	Units	RWS	Communal
Climate change (excl. LU and LUC)	kg CO_2 eq	26	53
Climate change – Biogenic	kg CO_2 eq	24	53
Climate change – Fossil	kg CO_2 eq	1.7	0.0
Climate change – Land use and land use change (excl. impacts from soil carbon stock change)	kg CO_2 eq	<0.01	<0.01
Resource use, fossils	MJ	7.9	0.2
Water consumption	l	2660	294
Land occupation	m^2	1659	1572

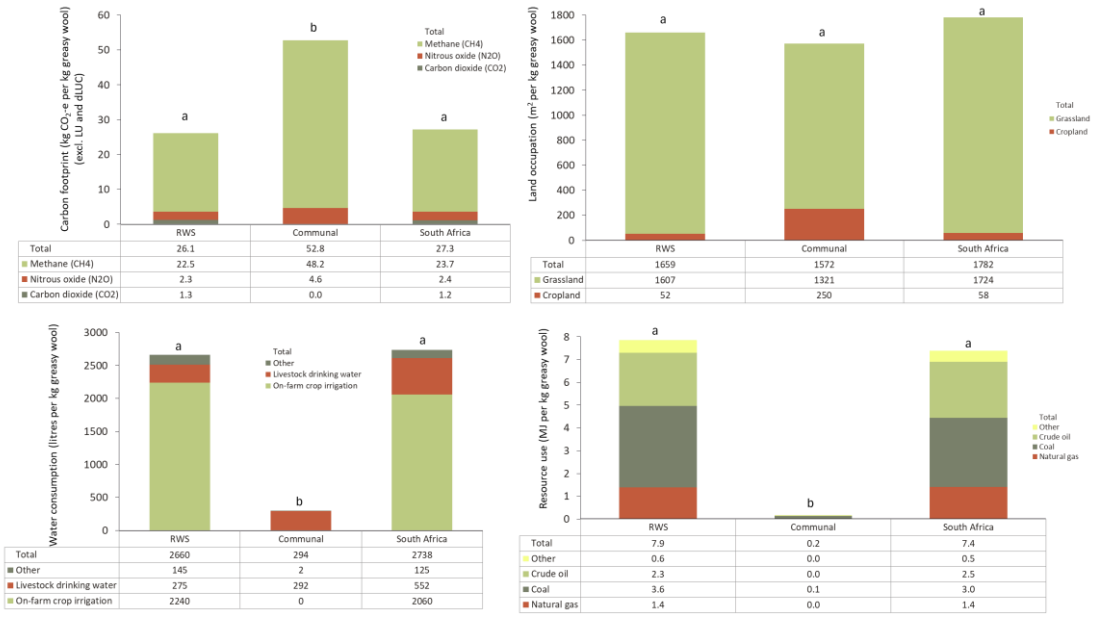


Figure 3. Climate change (excl. LU and LUC), land occupation, water consumption fossil resource use for each category (RWS, communal and the national average)

Table 11. Environmental impacts per kg of greasy wool for the average of wool from South Africa

Notes: Uncertainty analysis including alpha and beta uncertainties (shared model uncertainties)

		Mean	Median	SD	CV	Confidence interval	
Impact category	**Units**					**0.025**	**0.975**
Climate change (incl. LU and LUC)	kg CO_2 eq	28	28	3.8	14%	21	36
Climate change (excl. LU and LUC)	kg CO_2 eq	28	28	2.8	10%	23	34
Climate change – Biogenic	kg CO_2 eq	26	26	2.7	10%	22	32
Climate change – Fossil	kg CO_2 eq	1.5	1.5	0.2	10%	1.2	1.9
Climate change – Land use and land use change	kg CO_2 eq	-0.1	0.0	2.7	-3220%	-5.3	5.1
Resource use, fossils	MJ	7.4	7.3	0.7	10%	6.1	8.9
Water consumption	l	2117	2035	744	35%	965	3850
Land occupation	m^2	2730	2575	1319	48%	592	5486

5.2 Biogenic carbon flows

The biogenic carbon flows in pasture, not associated with LUC are reported in Table 12. The net carbon balance was zero indicating no transfer of carbon flows to or from permanent soil carbon stocks (temporary stocks in livestock products were treated as resulting in equivalent emissions). As a result, the only biogenic carbon flow (excluding LUC) that contributed to the climate change indicator was methane arising from enteric and manure processes. A Monte Carlo uncertainty analysis was undertaken to evaluate the sensitivity of climate change results to key parameters influencing the biogenic carbon balance. The analysis was deliberately constrained to parameters associated with the biogenic carbon balance (Table 7), reflecting the high uncertainty and potential bidirectional nature of soil carbon fluxes under grazing systems. All other inventory parameters were held constant.

The uncertainty analysis demonstrated that climate change impacts (incl. LU and LUC) were most sensitive to the soil respiration rate (the inverse of the change in soil carbon stocks). Variation in this parameter resulted in substantial changes to the net biogenic carbon balance, with soil carbon acting either as a net source or a net sink of carbon dioxide depending on the direction and magnitude of soil organic carbon change.

Across the Monte Carlo simulations, climate change impacts of biogenic carbon flows ranged from 18 to 29 kg CO_2-e per kg of greasy wool, expressed as a 95% confidence interval. This excluded fossil carbon dioxide, purchased input emissions and land use change from land conversion. Lower-bound results corresponded to scenarios in which soils were accumulating carbon, whereas upper-bound results reflected scenarios where soils were losing carbon. These results highlight the dominant influence of soil carbon assumptions on total climate change outcomes for wool production systems. This was considered a reasonable calculation of the uncertainty in global wool, produced across many different regions where long-term soil carbon may vary slightly either above or below zero. It is not representative of any single country, region or farm, where the range in possible soil carbon change and respiration is much greater.

The uncertainty analysis indicates the potential for soil carbon sequestration to materially reduce net climate change impacts or to increase impacts. The inclusion of removals in reported results is contingent on the ability to demonstrate permanence (GHG Protocol, 2026) and ISO 14067. This could not be demonstrated at the scale of the current assessment, but may be achieved with additional farm-scale assessment. Consistent with the Land Sector and Removals Standard (GHG Protocol, 2026) additional mechanisms such as long-term monitoring and verification frameworks would be required to verify and assure the durability of soil carbon stocks before removals could be robustly accounted for. The uncertainty in the biogenic results, reported per kilogram of greasy wool, are shown in Table 13. These results indicate that within the current bounds of the uncertainty assessment, impacts from LULUC had a mean of 0 (no emissions, no removals) and a range of -5 to 5 kg CO_2-e kg greasy wool. This indicated there was a 95% probability the LULUC impacts were within this range. This does not suggest that individual farms may not be significantly outside this range in response to localised management such as improved soil management leading to removals from soil carbon. It indicates that as an average for South African wool, the results were expected to be within this range.

Table 12. Modelled inputs and outputs associated with biogenic carbon flows for the national average (units in kg C per year)

Carbon balance	South Africa
Plant	**kg C**
Pasture CO_2 assimilation	11,931,137
Autotrophic respiration (pasture respiration)	5,965,569
Annual dry matter production	1,740,248
Livestock dry matter intake	435,062
Pasture senesced leaf, stem	1,305,186
Pasture senesced root material	4,225,321
Livestock	
Animal respiration	240,722
Enteric methane	14,706
Manure methane	127
Manure excreted	163,777
Carbon embedded in liveweight	11,129
Carbon embedded in wool	4,602
Soil	
Carbon added in the soil	5,694,283
Soil respiration	5,694,283
Carbon Balance	
Annual pasture uptake of carbon	-11,931,137
Autotrophic respiration (pasture respiration)	5,965,569
Respired by livestock	240,722
Eructated as methane	14,706
Manure methane	127
Embedded in livestock products (liveweight and wool)	15,731
Soil respiration	5,694,283
Carbon balance	**0 (-114,083 to 106,641)**

[1]*Uncertainty analysis on the carbon balance with 95% confidence intervals*

Table 13. Uncertainty analysis on biogenic carbon only for the South Africa average per kg of greasy wool

		Mean	Median	SD	CV	Confidence interval	
Impact category	Units					0.025	0.975
Climate change – biogenic emissions and removals incl. Land use and land use change	kg CO_2 eq	23	23	2.6	11%	18	29
Climate change - Biogenic	kg CO_2 eq	23	23	0.0	0%	23	24
Climate change - Land use and land use change	kg CO_2 eq	0	0	2.6	-3718%	-5	5

5.3 Sensitivity analysis

5.3.1 Sensitivity analysis: key parameters

A sensitivity analysis was performed on key model parameters. Flock productivity parameters including weaning rate, greasy wool production (kg hd^{-1} yr^{-1}) and feed digestibility were identified as some of the most influential factors affecting environmental impacts. Increasing weaning rate from 99% to 109% (+10% change) reduced climate change impacts (excl. LU and LUC) by 4%. Simultaneous improvements across multiple productivity parameters can lead to non-linear reductions in environmental impacts, particularly when starting from a low-productivity baseline. This effect is primarily driven by substantial increases in protein output. For example, scenarios involving a higher number of lamb survival per breeding female, lower mortality rates, and a reduced ratio of non-breeding to breeding animals can collectively enhance system efficiency and reduce per-unit environmental burdens. Since the LANCA model, and carbon stock change model, is a function of land area, a decrease in stocking rate increases environmental impacts as there is less product being produced from the same land area. These results should be interpreted with caution since this outcome contrasts with conventional land management and grazing principles, which typically associate lower stocking rates with reduced environmental pressure.

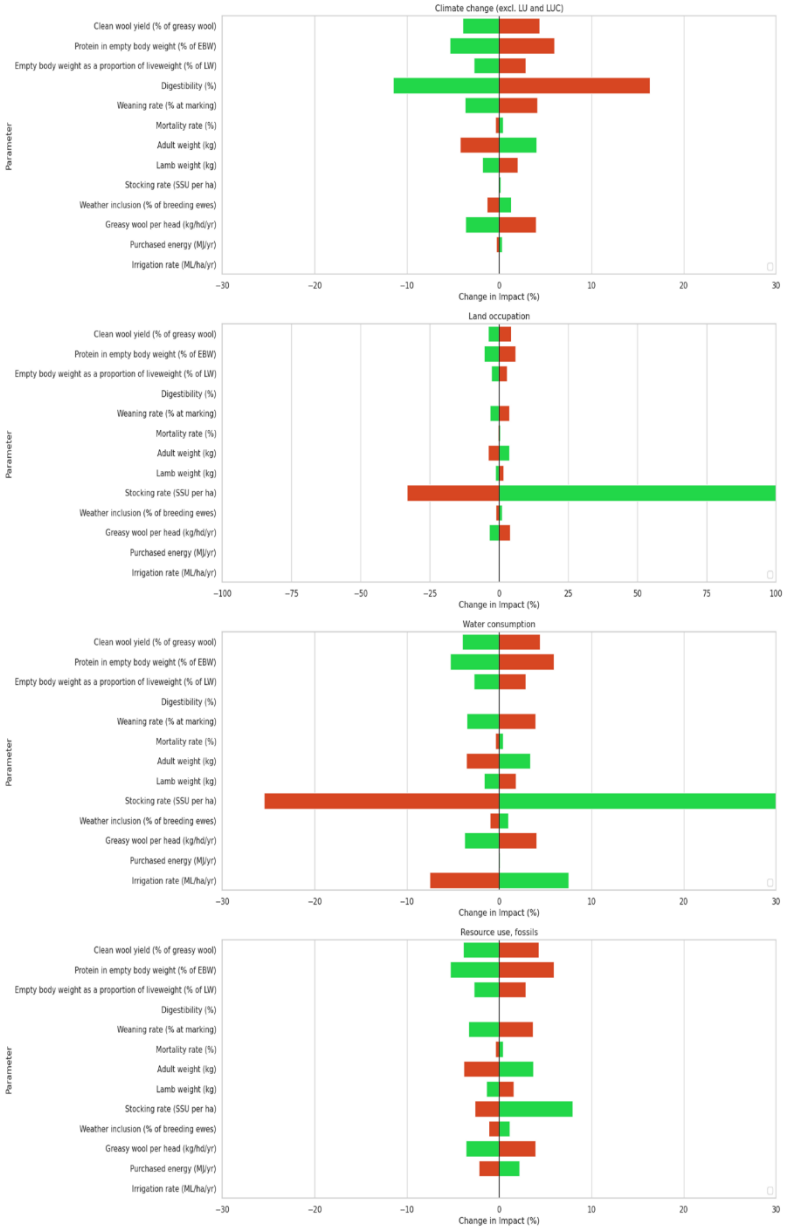


Figure 4. Sensitivity analysis of key parameters as a proportion of the baseline environmental impacts per kg of greasy wool. Green bars represent the effect of a 10% increase in the parameter and the red bars represent the 10% decrease in the parameter. Note. The default method was to implement a +/- 10% change in each parameter. In some cases, this was varied to better reflect the likely variation in that parameter in the model. This included empty body weight was varied by +/- 5% and stocking rate was varied by +/- 50%. The sensitivity of fossil resource use, land occupation and water consumption to a 10% change in digestibility was not assessed. Purchased inputs and land occupation parameters are normalized per kg of DMI or per SSU. Since, digestibility influences total DMI and SSU, altering digestibility also alters the normalizing units themselves, obscuring the underlying trend

5.3.2 Sensitivity to allocation approach

The choice of allocation method had a large influence on the environmental impacts of wool.

Economic allocation

The sensitivity analysis using an economic allocation for the handling of co-production of wool and liveweight for meat consumption decreased the environmental impacts for wool compared to the baseline results (Table 10), by up to 35% (see Appendix D, Table 23).

Using economic allocation, changes in market prices alone can cause the wool carbon footprint to change substantially, despite no biophysical change in the system and no change in gross emissions from sheep farming. The price data applied in this study were representative of 2023 conditions, characterized by comparatively low greasy wool prices and elevated lamb prices, which shifted a greater proportion of impacts towards liveweight and away from wool. An additional comparison was undertaken (results not shown) using 2026 prices which suggested that higher wool prices have now re-balanced the impacts, generating allocations to wool that were similar to those obtained using protein allocation.

Energy allocation

The sensitivity analysis energy allocation methods for the handling of co-production of wool and liveweight for meat consumption resulted in lower and higher allocations to wool depending on the implementation, compared to the protein allocation method. While not the focus of the study, this method demonstrated the uncertainty and sensitivity of assumptions used in the PEF system, which required energy allocation. This is discussed in 8.Appendix D. This is discussed in Appendix D. Further method development work is needed before there would be confidence in using an energy-based allocation method.

5.4 Uncertainty analysis

An uncertainty analysis was run using Monte Carlo simulation (n = 1,000) to investigate variability in the impact assessment results across all categories and to evaluate the significance of differences between production systems and to generate a confidence interval for the results. Uncertainty was associated with variation in inputs and sheep flock performance and attributes. Key contributors to uncertainty included parameter uncertainty in the livestock model associated with variation in production across the surveyed farms and regions, soil carbon change assumptions, purchased supplementary feed, wool yield and fossil resource use at the farm stage and primary processing stage.

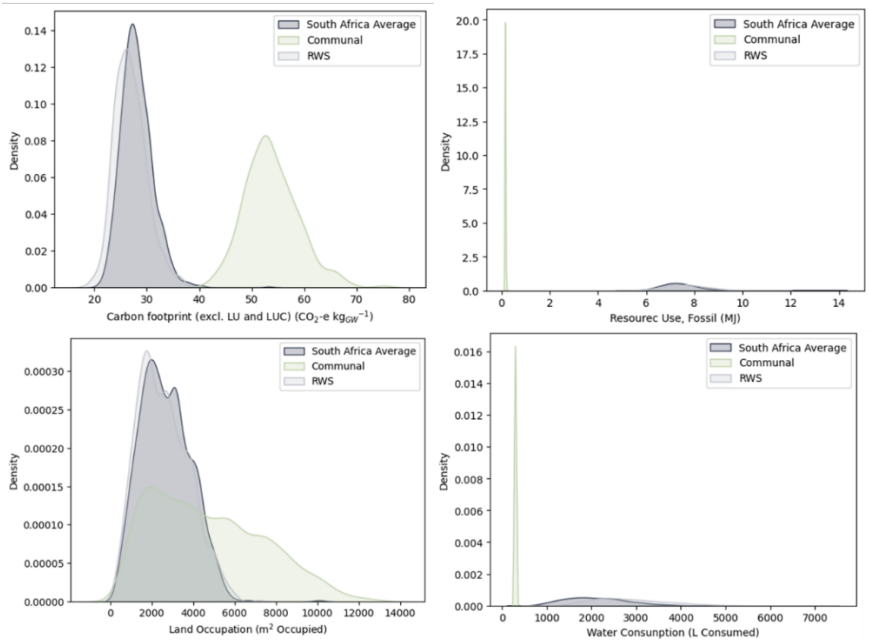


Figure 5. Uncertainty distribution (excluding beta uncertainty) for climate change (excl. LU and LUC), land occupation, water consumption and fossil resource use for RWS farms, communal farms and the ZA average reported per kg of greasy wool (cradle to primary production gate)

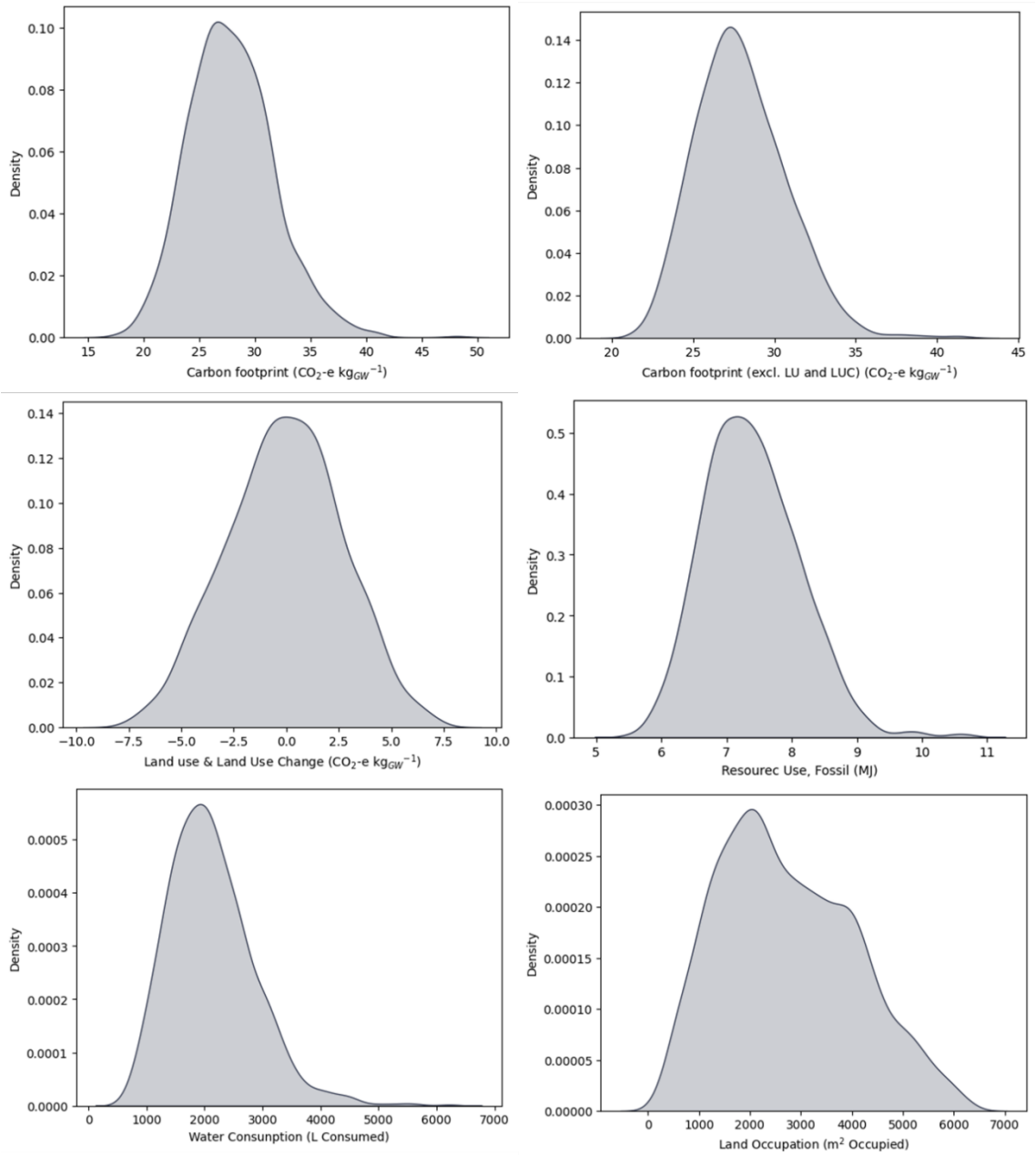


Figure 6. Uncertainty distribution (including alpha and beta uncertainty) for climate change (excl. LU and LUC), land occupation, water consumption and fossil resource use for the ZA average reported per kg of greasy wool (cradle to primary production gate)

The uncertainty analysis on the biogenic carbon footprint was reported in Table 13. This excluded carbon dioxide from fossil fuels and nitrous oxide emissions.

5.5 Statistical analysis of individual producers

Climate change impact (excl. LU and dLUC) per kg of greasy wool for each farm were plotted against the total protein output standardized per livestock unit (sheep unit). An inverse linear model was fit (Figure 7) showing a strong regression relationship. The regression analysis showed the carbon footprint exponentially increased with decreasing protein output per livestock unit. This showed flock productivity, measured in terms of output per stocking unit, was the primary determinant of variation in carbon footprint between farms.

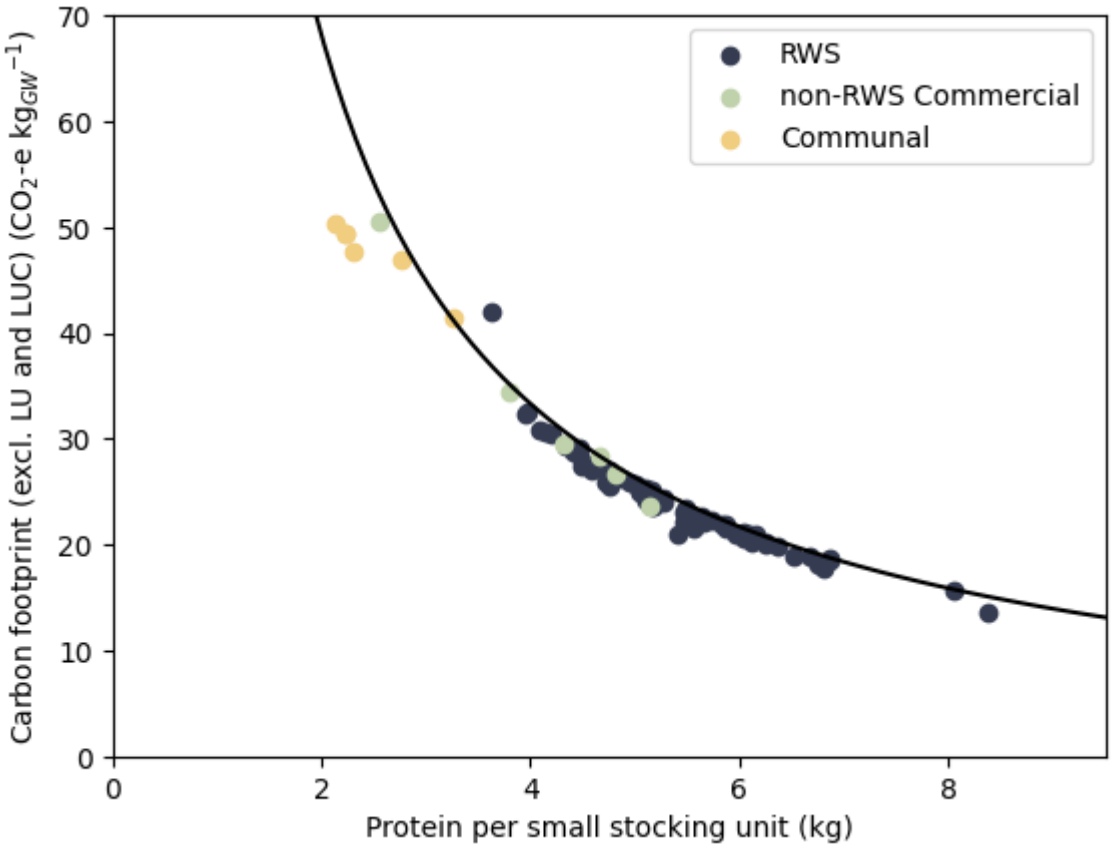


Figure 7. Regression of protein per sheep unit and carbon footprint (excl. LU and LUC) (cradle-to-primary production gate) from the results of individual farms analysed in this study

5.6 Data quality summary and evaluation

This study met ISO 14040/14044 data quality requirements using region-specific, up-to-date, and methodologically consistent data. Primary data were collected from the regions that make the highest contribution of South Africa wool production, with technological relevance to current wool production systems and processing practices. Secondary data were sourced from peer-reviewed literature and the Ecoinvent 3 database and were assessed for temporal (within the past 10 years), geographical, and technological relevance. All data were checked for completeness, internal consistency, and

transparency, ensuring the study can be reproduced and verified in line with ISO 14044 Section 4.2.3.6.

5.6.1 Data quality rating

The data quality rating (DQR) scores for the major system processes are summarized in Table 14. Each dataset was assessed using five ILCD-recommended criteria. Scores range from 1 (high quality) to 5 (low quality), with the average score used to derive the DQR. The study average a data quality rating score of 1.7 (Table 14). This indicates overall good quality data, with consistently strong geographical and technological representativeness and moderate variability in precision and completeness. Further detail is provided in Appendix B.

Table 14. Summary table of score against each quality criterion, and global quality score

Process	TeR	GR	TiR	C	P	DQR (avg)
Sheep production system	1	1.5	2	2	2	1.7

TER = Technological representativeness
GR = Geographical representativeness
TIR = Time-related representativeness
C = Completeness
P = Precision

6. Interpretation

6.1 Productivity and flock dynamics

The results of this study indicated that variation in flock productivity and flock structure was a principal driver of environmental impact intensity when reported per kilogram of greasy wool. Opportunities for impact reduction across multiple impact categories were associated with producing more saleable output with the same or fewer inputs, and the South African results demonstrated this relationship clearly through the contrast between RWS commercial and communal production systems.

The protein output per small stocking unit (protein per SSU) provided an integrated measure of whole-flock productivity encompassing both wool and liveweight outputs. At the national level, South Africa achieved 5.0 kg protein SSU^{-1}, though this figure masked substantial heterogeneity between production systems. RWS commercial farms recorded 5.2 kg protein SSU^{-1}, a value comparable with Australia (data not shown), whereas communal farms produced only 2.5 kg protein SSU^{-1}. This divergence was consistent with the approximately two-fold difference in climate change impact intensity between the two systems.

Across wool life cycle assessments, a consistent finding has been that environmental impacts per unit of fibre are highly sensitive to how much saleable output is generated per animal. Wiedemann et al. (2016) demonstrated that total greenhouse gas emissions per flock were broadly similar across contrasting sheep systems, but that impacts per kilogram of wool varied substantially depending on how effectively wool and meat production diluted maintenance requirements such as enteric methane, basal feed intake, and land occupation.

Protein production was a function of both wool yield and liveweight yield, and was driven by flock productivity factors including wool cut per sheep, liveweight sold per breeding ewe, and reproductive performance. RWS farms produced 4.8 kg of greasy wool per sheep shorn compared with 2.8 kg for communal farms, and greasy wool sales per breeding ewe were 7.2 kg and 4.6 kg, respectively. Liveweight sales per breeding ewe exhibited an even more pronounced disparity, at 38 kg LW for RWS farms versus only 6 kg LW for communal farms with the low value from the communal farms being caused by the low reproductive performance and higher mortality rates, resulting in low volumes of sheep for sale. These differences in output collectively determined the protein allocation shares: RWS farms allocated 44% of total protein to wool and 56% to meat, whereas communal systems allocated 75% to wool and only 25% to meat. The high wool allocation share in communal systems reflected the very low liveweight turnoff rather than high fibre output, and indicated that these systems were less effective at diluting maintenance-related emissions across multiple product streams.

Flock structure was identified as a key explanatory variable for the observed differences in environmental performance. In wool production systems, higher proportions of adult animals maintained for fibre without contributing proportionally to liveweight output — have been shown to increase impacts per kilogram of wool by elevating feed demand and enteric emissions with lower saleable product because of live weight sales. The communal system carried proportionally more wethers (391 head) relative to breeding ewes (1,435 head) than the RWS system (110 wethers relative to 1,511 breeding ewes).

Reproductive efficiency was a central driver of the productivity differential between the two systems. The weaning rate for RWS farms was 104%, compared with 32% for communal farms — a three-fold difference that profoundly influenced liveweight turnoff. Higher weaning rates increased meat output per breeding ewe, thereby lowering emissions per kilogram of fibre. Conversely, the low weaning rate in communal systems indicated that a large proportion of breeding ewes were maintained without producing a weaned lamb, increasing the number of animals sustained without contributing to saleable output. This effect was compounded by higher adult mortality rates in communal flocks (9.9%) relative to RWS farms (2.3%), further reducing the efficiency with which feed inputs were converted to marketable products. The sensitivity analysis confirmed that weaning rate was among the most influential parameters: increasing the national average weaning rate from 99% to 109% reduced climate change impacts (excluding LU and LUC) by approximately 4%, and simultaneous improvements across multiple productivity parameters were shown to produce non-linear reductions in environmental impacts, particularly when starting from a low-productivity baseline.

Collectively, these flock dynamics indicated that the environmental intensity gap between RWS and communal systems was attributable predominantly to differences in reproductive efficiency, flock composition, and animal performance, rather than to differences in per-animal emissions. This was supported by the farm-level regression analysis conducted in this study, which identified a strong inverse association between protein per SSU and climate change impact intensity across individual producers. Protein productivity thus functioned as an integrating metric for overall system efficiency, linking animal performance directly to environmental intensity, and identifying reproductive performance and flock structure as the most tractable levers for reducing the carbon footprint of South African wool production.

6.2 Carbon footprint

Variation in the reported carbon footprint between RWS commercial and communal production systems was primarily explained by the differences in production efficiency described above, rather than by fundamentally different emission profiles. Climate change impacts per SSU were broadly comparable between systems (237 and 229 kg CO_2-e SSU^{-1} for RWS and communal farms, respectively), yet impacts expressed per kilogram of greasy wool showed significant differences; 26 kg CO_2-e for RWS and 53 kg CO_2-e for communal farms (excluding LU and LUC). This pattern confirmed that systems with higher wool production and liveweight turnoff allocated a smaller proportion of maintenance-related emissions to each unit of wool as discussed above.

The emission profile was dominated by biogenic methane, arising largely from enteric fermentation associated with ruminant digestion. Biogenic climate change contributions accounted for 24 and 53 kg CO_2-e per kg greasy wool for RWS and communal systems, respectively, representing approximately 94% and over 99% of total climate change impacts in each system. Nitrous oxide emissions, primarily linked to manure management and nitrogen cycling in grazing systems, formed the next most important contribution. Fossil carbon dioxide emissions represented a comparatively minor share of total greenhouse gas emissions at the primary production stage (1.7 and <0.1 kg CO_2-e per kg greasy wool for RWS and communal farms), reflecting the low purchased input intensity of both systems and the near-complete absence of fossil energy use in communal production. This emissions profile highlighted that the carbon footprint of South African greasy wool was governed mainly by biological processes intrinsic to ruminant systems

rather than by energy consumption or other purchased inputs, consistent with findings from Australian wool LCAs (Brock et al., 2013; Wiedemann et al., 2016).

The sensitivity analysis demonstrated that flock productivity parameters — including weaning rate, greasy wool production per head, and feed digestibility — exerted the greatest influence on climate change results as noted in the previous section. The sensitivity of results to allocation method was also substantial. Economic allocation redistributed impacts between co-products without altering gross system emissions, producing shifts in the apparent carbon footprint of wool in the absence of any biophysical change. These findings reinforced the importance of interpreting carbon footprint results in conjunction with allocation assumptions and supported the use of protein-based biophysical allocation as a stable and biologically meaningful baseline for reporting.

Land use and land use change contributions to climate change were associated with higher uncertainty and were influenced by assumptions regarding pasture management and soil carbon dynamics. Vegetation related LULUC impacts were difficult to assess because of limitations in the methods available for satellite based detection. Low removals were observed in the current study, suggested that available datasets may underestimate actual removals, and consequently overestimate net LULUC impacts where regionally specific data were unavailable.

Acknowledging methodological differences in allocation approaches, the South African RWS results were broadly consistent with previous LCAs of Australian wool (Brock et al., 2013; Eady et al., 2012; Wiedemann et al., 2016) and were within the range of international studies. Overall, the climate change results indicated that meaningful reductions in the carbon footprint of South African wool were most closely linked to improvements in production efficiency at the primary production stage — strategies that increased fibre and co-product output per breeding animal, reduced the proportion of non-productive stock, and improved reproductive performance, as identified in the productivity analysis above.

6.2.1 Soil carbon impacts

Soil carbon stock change has the potential to represent a substantial source of greenhouse gas emissions or removals in grazing-based wool production systems. However, quantifying soil carbon change and attributing it specifically to wool production remains highly uncertain, particularly in extensive rangeland systems where soil carbon dynamics are influenced by climate variability, historic land use, and long-term grazing management interactions operating over large spatial and temporal scales. In this study, a soil respiration rate of 100% was applied. This represents the proportion of carbon respired relative to carbon added to soil annually from all sources and indicates no change in soil carbon stocks. This is consistent with the IPCC and land condition assessment undertaken as part of this study indicated generally good ground cover and land condition across participating farms, providing no evidence of systematic soil degradation. With respect to removals that occurred on farms, there was no systematic way of determining whether these removals had occurred, or whether they would be permanent, making it difficult to justify their inclusion under ISO 14067.

Nevertheless, soil carbon stock change remains an important consideration for land-based climate outcomes. When included in the uncertainty assessment, this resulted in a 95% Confidence interval of -5 to 5 kg CO_2-e kg greasy wool, indicating that soil carbon emissions or removals could change the carbon footprint in the order of 20% above or below the reported value, with modest changes in soil carbon stocks.

It is important to note that this result is not representative of any single farm, where the potential magnitude of soil carbon change and soil respiration may be substantially greater and carbon footprints could vary outside this range.

Further research incorporating long-term, region-specific soil carbon measurements, together with improved methods for attributing soil carbon change to grazing systems, and validation methods to ensure soil carbon permanence would be beneficial, to enable soil carbon stock changes to be included in baseline wool LCA results.

6.3 Fresh water consumption

There was a substantial variation in water consumption between farms and between production system types, primarily associated with differences in water source and whether irrigation was used. RWS commercial farms recorded 2,660 L per kg greasy wool which was significantly higher than the communal farms which used 294 L per kg greasy wool. The RWS farms sourced drinking water predominantly from groundwater (67%) and farm dams (23%), with only 10% derived from natural surface water supplies. These farms also applied irrigation at an average rate of 3.1 ML per hectare across an average of 14.9 hectares of irrigated land per farm. This masked greater differences between RWS farms, which included some farms that relied substantially on irrigation and other farms that used no irrigation. Communal farms, by contrast, relied entirely on natural water sources and used no irrigation, which reduced the water consumption very significantly. The South Africa average results were 2117 L but this was highly uncertain, reflecting the large variation in results caused by the presence or absence of irrigation water use.

Wiedemann et al. (2016) reported no Australian farms in their study that used irrigation water for pasture production, and fresh water consumption in those systems was dominated by supply losses — principally evaporative losses from farm dams — and to a lesser extent by direct livestock drinking water requirements. The markedly higher water consumption observed in the South African production system reflected the contribution of irrigation water, which was largely absent from both the communal and the Australian systems studied to date.

When water consumption was expressed using the AWARE deprivation-weighted characterisation method (see 8.Appendix C, Supplementary results), RWS farms recorded 83.3 m^3 of deprived water per kg greasy wool, compared with 12.2 m^3 for communal farms. The elevated water scarcity footprint for RWS farms reflected both the higher volumetric consumption from irrigation and the water stress characterisation factors applied to the relevant catchments. Wiedemann et al. (2016) used different indicators and was therefore not directly comparable; they also showed a wide range in stress-weighted water use values and the large influence of regional water stress characterisation in generating the final result.

This supported a broader observation from multi-country assessments that water results were more strongly influenced by country-level characterisation factors and irrigation practices than by the flock productivity drivers that predominantly determined climate change impacts, as discussed in the preceding sections.

6.4 Fossil energy use

Fossil resource use per kilogram of greasy wool differed markedly between South African production systems, reflecting the contrasting levels of management intensity. RWS commercial farms recorded 7.9 MJ per kg greasy wool, whereas communal farms were significantly lower, with only 0.2 MJ per kg greasy wool, yielding a national average of 7.4 MJ per kg greasy wool. The near-zero fossil energy demand in communal systems was consistent with the absence of purchased fuel, electricity, fertiliser, and supplementary feed inputs reported in the inventory. In these areas, wool production was integrated into the life of the community and much of the work was done manually. On the RWS farms, while still extensively managed, diesel (1.8 L SSU^{-1}), electricity (3.9 kWh SSU^{-1}), and modest quantities of supplementary feed and fertiliser were used, which collectively accounted for the higher fossil resource demand.

The South African RWS result was notably lower than the range reported by Wiedemann et al. (2016) for Australian wool, where fossil fuel energy demand ranged from 12.5 ± 4.1 MJ per kg greasy wool in the southern pastoral zone to 22.5 ± 6.2 MJ per kg greasy wool in the Western Australian wheat-sheep zone. In the Australian study, fossil energy demand varied significantly in response to production intensity, with the highest values observed where fertiliser and pesticide inputs associated with improved pastures and forage crops were substantially greater. Farm energy demand — comprising fuel and electricity — was the largest contributor across all Australian regions, followed by fertiliser and pesticide inputs and animal health services. The lower fossil energy intensity observed in South African RWS systems was therefore consistent with the comparatively low use of inorganic fertilisers, the potentially lower utilisation of sown pasture improvement relative to Australian systems operating in higher-rainfall or mixed-farming zones.

6.5 Land occupation

Total land occupation per kilogram of greasy wool was 1,659 m^2 for RWS commercial farms and 1,572 m^2 for communal farms, which were not significantly different. Although RWS farms operated at a substantially lower stocking rate (0.7 SSU ha^{-1}) than communal farms (1.5 SSU ha^{-1}), the higher productivity per animal in the RWS system — as outlined in the productivity discussion above — offset the larger grazing area per stocking unit, resulting in broadly comparable land occupation when normalised to the functional unit. This outcome reinforced the finding that production efficiency moderated the influence of extensive land use on per-unit environmental impacts. National average results were higher because of the uncertainty analysis which had a log-normal distribution, increasing the predicted likelihood of higher land occupation in the national flock. This resulted in a national average of 2730 m^2.

The South African results were within the wide range reported by Wiedemann et al. (2016) for Australian wool, where land occupation varied more than any other impact category across the three regions assessed. In that study, non-arable pasture land occupation ranged from 92 m^2 per kg greasy wool in the Western Australian wheat-sheep zone to over 9,000 m^2 per kg greasy wool in the South Australian southern pastoral zone, driven by large differences in the underlying land resources available for sheep production. The South African systems were predominantly based on extensive grazing of rangelands with some intensification through the use of irrigated land, with relatively smaller areas of cropland allocated to sheep production (129 ha for RWS and 216 ha for communal farms).

Wiedemann et al. (2016) noted that non-arable grazing land was generally less suitable for alternative agricultural production and that occupation of such land does not result in as high a degree of modification to the natural ecosystem as cropping. This distinction is relevant to the interpretation of land occupation results in South Africa, where the grazing land base was composed predominantly of managed rangelands. The land occupation indicator as applied in this study represented physical area only and did not differentiate between land quality, vegetation condition, or ecosystem service provision.

6.6 Assumptions and limitations

The scope of this study was defined by the available resources, time constraints, and the specific objectives set by the commissioning parties. Limitations are discussed in the following sections.

6.6.1 Sampling limitations

The selection regions and farms for data collection considered a balance between a representative sample with cost, time and logistics in travelling large distances required for primary data collection. None-the-less, the sample size was comparatively large and provided meaningful results within the stated uncertainty.

6.6.2 Representativeness

This study relied on primary data collected over a single production year covering one cycle of production. This time period does not represent the full range of climatic conditions that influence the primary production system in each country. Extending this data collection period would improve the representativeness but was not possible in the current project scope. To address this limitation, both the sensitivity and uncertainty analysis considered the impact of variables most likely to change from year to year in response to climate variation; namely flock productivity measures, and purchased inputs. The sensitivity analysis used a single-parameter approach, in which each key production parameter was adjusted by 10% individually (i.e., not simultaneously). This showed that a 10% change in an individual parameter could alter the results by up to 16% in either direction for most parameters. Further studies would benefit from extending the timeframe for data collection to two years in preference to the one year of the present study.

6.6.3 Data quality

Data collection was completed by in-country extension experts. In-person and online meetings were conducted to explain the data collection methodologies and survey questions and to mitigate the risk of misunderstanding key concepts. However, limitations and language barriers may have impacted the data quality in some instances. The research team worked to mitigate this risk by verifying the plausibility of the data using first principles in considering flock performance, population and dynamics.

6.6.4 LCA modelling

There are several measurement and modelling challenges to assess the impacts on SOC stock change as discussed in section 6.2.1. This study completed an uncertainty analysis

on soil respiration rate that influenced soil carbon stocks to assess the range in plausible estimates.

7. Conclusions and recommendations

This study provided the first life cycle assessment of South African wool from primary production using primary data and up-to-date methods. While the project was intended as a pilot study, the reasonably large dataset collected enabled a robust and internationally relevant baseline across multiple environmental impact categories.

The assessment demonstrated that the environmental profile of wool in South Africa was dominated by different factors depending on the indicator. Carbon footprint was driven by biological emissions intrinsic to ruminant production systems, particularly enteric methane. Differences in climate impacts between production systems were explained primarily by variation in productivity and flock efficiency rather than by fundamentally different emission pathways. Commercial farms, which produced higher quantities of wool and co-product liveweight relative to the number of small stock units consistently exhibited lower impacts per unit of fibre compared to communal farms, reflecting more efficient production and dilution of maintenance emissions. This finding was consistent with previous wool LCAs and reinforced the central role of flock structure, reproductive performance, wool yield and lamb performance in determining environmental intensity. Water consumption was predominantly driven by variation in irrigation water use and to a lesser extent, supply losses for drinking water. Fossil energy use was directly proportional to the level of intensification used, which was much lower from communal production.

Across all impact categories, substantial variability was observed between individual farms. This variability indicated that current production systems already operated in such a way that delivered a wide range of environmental performance outcomes, suggesting that significant reductions in environmental intensity were achievable using existing management practices and technologies. Sensitivity analyses further demonstrated that methodological choices, particularly allocation between wool and meat, influenced the distribution of impacts between co-products but did not alter the underlying drivers of environmental performance.

Overall, the results confirmed that wool production systems in South Africa shared many of the same environmental characteristics and challenges identified in previous wool LCAs.

7.1 Responsible use of results

This study represents a novel contribution to the field but is subject to several acknowledged limitations:

As shown from the uncertainty and sensitivity analysis, the influence of small changes in soil carbon on the carbon footprint is material. Further research is needed to quantify these impacts across the major production regions in South Africa, and to develop suitable assessment methods together with management practices that can ensure permanent increases in carbon stocks in soil or vegetation. Considering the uncertainty, we recommend using the carbon footprint results without amalgamating these with the emissions from soil or vegetation LULUC until a higher degree of certainty in the findings can be achieved through further research. Climate change (excl. LU and LUC) results are presented separately from LU and LUC throughout the report, and we advise maintaining this distinction until further research improves confidence in soil carbon modelling. These results should be used for indicative purposes not procurement decisions or choices between production systems.

While the study had a relatively large dataset, it could not be guaranteed to be representative of South African wool. The sampled farms were selected to capture typical production conditions, but they do not capture the full range of possible production systems, climatic conditions, or management intensities that may exist.

The results presented in this study were based on biophysical allocation, specifically using protein product allocation, to allocate impacts between the main co-products: liveweight and greasy wool. This approach followed established LCA guidance. A sensitivity analysis using economic allocation revealed differing trends in some impact categories and lower and higher reportable impacts for wool depending on the assumptions used. This highlighted the significant influence that allocation choice can have on comparative outcomes.

While the findings offer valuable insights into environmental hotspots and system-level dynamics, they are not suited for direct comparison with other fibre LCAs unless methodological alignment is ensured. Stakeholders are encouraged to interpret the results in context and avoid overgeneralization or fibre substitution decisions based on isolated values without considering the broader sustainability profile and uncertainties involved.

7.2 Recommendations for decision-makers

Practical, evidence-based guidance for primary producers and industry organizations, is summarized below.

Based on the findings of this study, the following recommendations were identified for producers and the South African industry:

1. At the primary production stage, the most effective opportunities for reducing environmental impacts per kg of wool were associated with improving flock productivity and efficiency. Management strategies that increased wool output per breeding animal, improved reproductive performance, reduced mortality, and limited the proportion of non-productive animals were consistently associated with lower environmental intensities. Continued investment in genetic improvement programs, flock health, and reproductive management, and semi-regular update to the

productivity dataset is recommended as a priority pathway for reducing the carbon footprint and other impacts, and for maintaining currency in the future.

2. Interventions aimed solely at reducing inputs without maintaining or increasing output were unlikely to deliver proportional reductions in environmental intensity. As demonstrated by the results, lower production systems frequently exhibited higher impacts per unit of wool because maintenance emissions were distributed over smaller quantities of product. Environmental improvement strategies should therefore focus on output-oriented efficiency gains, rather than on input minimization in isolation.
3. From a methodological and communication perspective, the study highlighted the importance of transparency around allocation assumptions when reporting fibre carbon footprints. While different allocation methods produced substantially different numerical outcomes for wool, the underlying drivers of impact remained unchanged. It was therefore recommended that future communications focus on explaining the biological and management drivers of environmental performance, rather than on comparing point estimates derived using different allocation approaches.
4. The observed variability in environmental performance between farms indicated that best-practice outcomes were already achievable within existing systems. Capturing and sharing knowledge on high-performing farms and integrating environmental efficiency metrics into extension activities, is recommended to support ongoing reductions in the environmental footprint over time.

7.3 Recommendations for future research and development

This study revealed the considerable complexity in assessing impacts from wool using multi-indicator LCA and represented a first step in building this knowledge base in South Africa. Further research is needed to:

- Quantify and improve soil carbon and vegetation modelling to improve the mean and uncertainty results.
- Evaluate soil carbon and vegetation carbon sequestration under improved grazing practices to identify practices on that lead to removals and demonstrate best practice for wool production in South Africa.
- Expand regional coverage of farm-level data and repeat the data collection and modelling with the existing farms in 2027/28 to improve understanding of inter-annual variability.
- Demonstrate how improved breeding and management can lead to better production and environmental outcomes, particularly through increasing fleece yield and meat turnoff from communal areas.
- Develop ongoing data capture processes to enable LCAs to be updated every 3-5 years. This should include farm mapping to improve vegetation and natural capital assessment.

The scale of the project was enhanced by collaborative work that was done concurrently. The outputs warrant publication in the scientific literature.

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Appendix A Additional information on modelling

Feed intake and livestock GHG emissions were modelled using IPCC Tier II equations from the 2019 refinement (IPCC, 2019b, 2019a) (Table 15).

Table 15. Feed intake, livestock greenhouse gas and livestock drinking water prediction methods

<table>
<tr><th>Prediction method</th><th>Factor/prediction equation</th><th>Reference</th></tr>
<tr><td>Net energy for maintenance (MJ day^{-1})</td><td>$NE_m = Cf \times$ average liveweight$^{0.75}$

Cf = coefficient MJ day^{-1}kg^{-1}

For lambs (< 1 year) Cf = 0.236 and for sheep > 1 year = 0.217</td><td>Equation 10.3 IPCC Volume 4, Chapter 10 (IPCC, 2019a)</td></tr>
<tr><td>Net Energy for activity (MJ day^{-1})</td><td>$NE_a = C_a \times$ average liveweight

C_a = coefficient corresponding to animal's feeding situation MJ d^{-1} kg^{-1}.

Grazing flat pasture (<1000 metres a day) = 0.0107

Grazing hilly pasture (> 5000 meters a day) = 0.024

<table><tr><th>Country</th><th>Grazing flat pasture</th><th>Grazing hilly pasture</th></tr><tr><td>South Africa</td><td>12%</td><td>88%</td></tr></table></td><td>Equation 10.5 IPCC Volume 4, Chapter 10 (IPCC, 2019a)</td></tr>
<tr><td>Net Energy for lactation (MJ day^{-1})</td><td>$\mathrm{NE_l} = Milk \times \mathrm{EV_{milk}}$

Where:

Milk = amount of milk produced, kg of milk day^{-1}

This was estimated to be 1.2 kg day^{-1} (McGregor, 2018)

$\mathrm{EV_{milk}}$ = the energy required to produce 1 kg of milk (MJ kg $^{-1}$). Assumed 4.6 MJ kg $^{-1}$ for sheep and 3 months lactating</td><td>Equation 10.10 IPCC Volume 4, Chapter 10 (IPCC, 2019a)</td></tr>
<tr><td>Net energy to produce wool (MJ day^{-1}) approx 0.08 MJ day^{-1} for wool</td><td>$\mathrm{NE_{wool}} = \frac{\mathrm{EV_{wool}} \times \mathrm{PR_{wool}}}{365}$

Where:

$\mathrm{EV_{wool}}$ = the energy value of each kg of wool produced (MJ kg $^{-1}$). Assumed to be 24 MJ kg clean dry wool.

$\mathrm{PR_{wool}}$ = annual wool production per sheep kg yr $^{-1}$</td><td>Equation 10.12 IPCC Volume 4, Chapter 10 (IPCC, 2019a)</td></tr>
</table>

<table>
<tr><th>Prediction method</th><th>Factor/prediction equation</th><th>Reference</th></tr>
<tr><td>Net energy for pregnancy (MJ day^{-1})</td><td>$$\mathrm{Ne_p} = \mathrm{C_{pregnancy}} \times \mathrm{NE_m}$$
Where:
$C_{pregnancy}$ = 0.077 for single births
$C_{pregnancy}$ = 0.126 for twin births
Assumed to be single births.
A sensitivity analysis revealed that the difference between assuming single births versus twin births was not material (<1% difference in the results).
NE_m = net energy for maintenance (equation 10.3)</td><td>Equation 10.13 IPCC Volume 4, Chapter 10 (IPCC, 2019a)</td></tr>
<tr><td>Net energy for growth (MJ day^{-1})</td><td>$$\mathrm{NE_g} = \frac{\mathrm{WG}_{lamb} \times (\mathrm{a} + 0.5\mathrm{b}(\mathrm{BW_i} + \mathrm{BW_f}))}{365}$$
Where:
WG_{kid} = BW_f – BW_i kg yr^{-1}
BW_i = live bodyweight at weaning kg yr $^{-1}$
BW_f = live bodyweight at 1 yr or at slaughter if slaughtered prior to 1 year of age, kg
a, b = constants MJ kg^{-1}
This equation was modified from Equation 10.7 IPCC Volume 4, Chapter 10, to model the net energy for growth in each animal class. The starting weight and final weight of each animal class was used.
<table><tr><th>Category</th><th>a</th><th>b</th></tr><tr><td>Intact males</td><td>2.5</td><td>0.35</td></tr><tr><td>Castrates</td><td>4.4</td><td>0.32</td></tr><tr><td>Females</td><td>2.1</td><td>0.45</td></tr></table></td><td>Equation 10.7 IPCC Volume 4, Chapter 10 (IPCC, 2019a)</td></tr>
<tr><td>Gross energy (MJ day^{-1})</td><td>$$GE = \frac{\left(\frac{\mathrm{NE_m} + \mathrm{NE_a} + \mathrm{NE_l} + \mathrm{NE_{work}} + \mathrm{NE_p}}{\mathrm{REM}}\right) + \left(\frac{\mathrm{NE_g} + \mathrm{NE_{wool}}}{\mathrm{REG}}\right)}{\mathrm{DE}}$$
Where:
NE_m = net energy required by the animal for maintenance (Equation 10.3) MJ day $^{-1}$
NE_a = net energy for animal activity (Equation 10.4) MJ day^{-1}
NE_l = net energy for lactation (Equation 10.10) MJ day $^{-1}$
NE_{work} = net energy for work (Equation 10.11) MJ day $^{-1}$</td><td>Equation 10.16 IPCC Volume 4, Chapter 10 (IPCC, 2019a)</td></tr>
</table>

Prediction method	Factor/prediction equation	Reference
	NE_p = net energy for pregnancy (Equation 10.13) MJ day $^{-1}$ NE_g = net energy for growth (Equation 10.7) MJ day $^{-1}$ REG = ratio of net energy available for growth in a diet to digestible energy consumed (Equation 10.15) REM = ratio of net energy available for maintenance in a diet to maintenance energy consumed (Equation 10.14) NE_{wool} = net energy required to produce a year of wool (Equation 10.12) MJ day^{-1} DE = digestibility of feed expressed a as fraction of gross energy (digestible energy/gross energy)	
Ratio of net energy available for maintenance in a diet to digestible energy consumed	$$\text{REM} = 1.123 - (4.092 \times 10^{-3} \times DE) + (1.126 \times 10^{-5} \times (DE)^2) - (\frac{25.4}{DE})$$ Where: DE = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy)	Equation 10.14 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Ratio of net energy available for growth in a diet to digestible energy consumed	$$1.164 - (5.16 \times 10^{-3} \times DE) + (1.308 \times 10^{-5} \times (DE)^2) - (\frac{37.4}{DE})$$ Where: DE = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy)	Equation 10.15 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Dry matter intake	$$\text{DMI} = \frac{\text{GE}}{18.45}$$ Where: 18.45 = assumption of the gross energy content of cellulose fibers (MJ kg DM^{-1})	(CSIRO, 2007)
Volatile solid excretion rates	$$VS = \left[\text{GE} \times \left(1 - \frac{\text{DE}}{100}\right) + (\text{UE} \times \text{GE})\right] \times [\frac{1 - \text{ASH}}{18.45}]$$ Where: GE = gross energy intake (MJ day^{-1}) DE = digestibility of the feed as a percent of gross energy UE × GE = urinary energy excretion expressed as a fraction of GE. Assumption 0.04 (4%) of gross energy. ASH = the ash content of feed as a fraction of DMI. Assumption 0.1 (10%) of DMI.	Equation 10.24 IPCC Volume 4, Chapter 10 (IPCC, 2019a)

Prediction method	Factor/prediction equation	Reference
	18.45 = conversion factor for dietary GE per kg of dry matter (MJ kg^{-1}). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.	
Methane emissions from manure	$$EF = (VS * 365) * [B_0 \times 0.67 \times \sum \frac{MCF_{S,k}}{100} \times AWMS_{(T,S,K)}]$$ Where: EF = annual CH_4 manure emission factor (kg CH_4 hd^{-1} $year^{-1}$) VS = daily volatile solid excreted (kg DM hd^{-1} $year^{-1}$) B_0 = maximum methane producing capacity for manure produced by goats (m^3 CH_4 kg^{-1} of VS excreted). 0.67 = conversion factor of m^3 $_{CH4}$ to kg CH_4 MCF = methane conversion factors for each manure management system (S) by climate region (k) AWMS = fraction of manure handled using animal waste management system (S) in climate region (k)	Equation 10.23 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Maximum methane producing capacity for manure (B_0)	Pasture Range and Paddock MCFs must always be used in conjunction with a B_0 value of 0.19 m^3 CH4 kg^{-1} of VS excreted.	Table 10.16 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Methane conversion factor (MCF)	"Pasture/range/paddock" MCF = 0.47%	Table 10.17 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Animal waste management system (AWMS)	100 % of animal waste is deposited on "Pasture/range/paddock".	
Nitrogen intake (kg N hd^{-1} day^{-1})	$$\text{N intake} = \frac{GE}{18.45} \times (\frac{\frac{CP\%}{100}}{6.25})$$ Where: N intake = daily N consumed (kg N hd^{-1} day^{-1}) GE = gross energy intake (MJ hd^{-1} day^{-1}) 18.45 = conversion factor for dietary GE per kg of dry matter (MJ kg^{-1}). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock. CP% = percent crude protein in dry matter 6.25 = conversion from kg of dietary protein to kg of dietary N	Equation 10.32 IPCC Volume 4, Chapter 10 (IPCC, 2019a)

Prediction method	Factor/prediction equation	Reference
Nitrogen excretion (kg N hd $^{-1}$ day^{-1})	$$\text{Nex} = (\text{N intake} - \text{N retention})$$ Where: Nex = daily N excretion rates (kg N hd^{-1} day^{-1}) N intake = daily N intake (kg N hd^{-1} day^{-1}) N retention = daily N intake that is retained by the animal (kg N hd^{-1} year^{-1})	Equation 10.31A IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Nitrogen retention	$$\text{N retention} = \frac{\text{Pwool} + \text{Pliveweight}}{6.25}$$ Where: N retention = total N that is retained in the animal for the production of meat and wool P wool = amount of protein contributing to greasy wool production (kg protein hd^{-1} day^{-1}). Assumption that 100% dry clean wool is protein. P liveweight = amount of protein contributing to liveweight growth (kg protein hd^{-1} day^{-1}). Assumption that 18% of liveweight is protein.	
Direct nitrous oxide emissions from manure management (kg N_2O hd^{-1} day^{-1})	$$N_2O = \text{Nex} \times EF_3 \times \frac{44}{28}$$ Where: dN_2O = direct N_2O emissions from manure management (kg N_2O hd^{-1} day^{-1}) Nex = nitrogen excretion (kg N hd^{-1} day^{-1}) EF_3 = emission factor direct N_2O emissions from • "sheep and others" deposited on "pasture/range/paddocks" =0.003 (kg N_2O – N (kg N)$^{-1}$). Uncertainty range = 0.000 – 0.010. $\frac{44}{28}$= conversion of N_2O – N to N_2O	Equation 10.25 IPCC Volume 4, Chapter 10 (IPCC, 2019a) Table 11.1 IPCC Volume 4, Chapter 11 (IPCC, 2019b)
Indirect N_2O emissions due to volatilization of N from manure management	$$iN_2O = \text{N volatilsation} \times EF_4 \times \frac{44}{28}$$ Where: iN_2O = indirect N_2O emissions due to volatilization of N from manure management (kg N_2O hd^{-1} yr^{-1}) N volatilization = amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils and manure management systems (kg N_2O – N hd^{-1} yr^{-1}) EF_4 = emission factor N volatilization and redeposition kg N_2O–N. For dry climates = 0.005. South Africa was characterized as a dry	Equation 10.28 IPCC Volume 4, Chapter 10 (IPCC, 2019a) Table 11.3 IPCC Volume 4, Chapter 11 (IPCC, 2019b)

Prediction method	Factor/prediction equation	Reference
	climate. It was assumed 67% of farms were dry climates and 33% of farms were wet climates.	
N_2O from atmospheric deposition of N volatilized from managed soils	$$\text{N volatilisation} = \sum_S [\text{Nex} \times \text{AWMS(s)} \times \text{Frac}_{\text{GASM}}]$$ Where: N volatilization = amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils (kg N_2O – N hd^{-1} yr^{-1}) Nex = daily N excretion rates (kg N hd^{-1} day^{-1}) AWMS(s) = fraction of manure handled using animal waste management system (S) in climate region (k) $Frac_{GASM}$ • fraction of urine and dung N deposited by grazing animals that volatilizes as NH_3 and NO_x (kg N volatilized) = 0.11. Uncertainty = 0.02 – 0.33. Uncertainty range is based on the 2.5th to 97.5th percentile.	Equation 11.9 IPCC Volume 4, Chapter 11 (IPCC, 2019b)
Indirect N_2O emissions from leaching	$$iN_2Oleach = Nex \times Frac_{leach} \times EF_5 \times \frac{44}{28}$$ Where: iN_2O_{leach} = amount of N_2O emissions produced from leaching and runoff of N (kg N_2O hd^{-1} day^{-1}) $Frac_{leach}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg N additions or deposition by grazing animals)$^{-1}$ = 0.24. The $Frac_{leach}$ only applies to wet climates. For dry climate, the default $Frac_{leach}$ is zero. Uncertainty 0.00 – 0.31. Uncertainty range is based on the 2.5th to 97.5th percentile. It was assumed 67% of farms had dry climates and 33% of farms were wet climates. Nex = daily N excretion rates (kg N hd^{-1} day^{-1}) EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff) $\frac{44}{28}$ = conversion of N_2O – N to N_2O	Equation 10.27 IPCC Volume 4, Chapter 10 (IPCC, 2019a) Equation 11.10 IPCC Volume 4, Chapter 11 (IPCC, 2019b) Table 11.3 IPCC Volume 4, Chapter 11 (IPCC, 2019b)
Ammonia emissions	$$NH_3 = Nex \times 0.197 \times 1.215$$ Where: NH_3 = amount of ammonia emissions from N excreted (kg NH_3 hd^{-1} day^{-1}) 0.197 = emission factor for NH_3–N from manure	Table 8A.1 IPCC Volume 4, Chapter 11 (IPCC, 2019b)

Prediction method	Factor/prediction equation	Reference
	1.215 = conversion factor from NH_3–N to NH_3	
Livestock drinking water intake	$$Drinking\ water\ intake = 0.1911t - 2.882$$ For a 45kg adult merino wether Where: T = average maximum daily temperature This was adjusted to the weight of each animal class.	CSIRO 2007 Nutrient Requirements of Domesticated Ruminants (CSIRO, 2007)

Table 16. IPCC Tier 1 land use change prediction equations applied for the conversion of forestland to grassland

Carbon pool	Prediction equation	Reference
Soil carbon	Annual change in organic carbon stocks in mineral soils $$\Delta C_{\text{mineral}} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$ $$SOC = \sum (SOC_{REF} \times F_{LU} \times F_{MG} \times F_I \times A$$ Where: $\Delta C_{Mineral}$ = annual change in carbon stocks in mineral soils (tons C yr^{-1}) SOC_0 = soil organic carbon stock in the last year of an inventory time period (tons C) $SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory time period (tons C) D = Time dependence of stock change factors which is the default time period for transition between equilibrium SOC values, yr (Commonly 20 years and this has been applied) SOC_{REF} = the reference carbon stock (tons C ha^{-1}) South Africa = 41.12 t C ha^{-1} The two main soil types were identified as high activity mineral clays and rocky areas. The average value was used Table 6.5 (DFFE, 2024) F_{LU} = stock change factor for land-use systems or sub-system for a particular land-use (dimensionless) South Africa = 1 (Table 6.2 IPCC 2006 Chapter 6, IPCC)	Equation 2.25 IPCC 2006, Volume 4, Chapter 2 (IPCC, 2006c)

Carbon pool	Prediction equation	Reference
	F_{MG} = stock change factor for management regime (dimensionless) South Africa = 1 (nominally managed grasslands representing non-degraded and sustainably managed grassland, but without significant management improvements) FI = stock change factor for input of organic matter (dimensionless) no input applied (only applied to improved grasslands South Africa= 1 A = land area (hectares)	
Biomass	Initial change in biomass carbon stocks on land converted to another land category $$\Delta C_{\text{conversion}} = \sum\{(B_{AFTER} - B_{BEFORE}) \times \Delta A_{TO_OTHERS}\} \times CF$$ Where: $\Delta C_{CONVERSION}$ = initial change in biomass carbon stocks on land converted to another land category (tons C yr^{-1}) B_{AFTER} = biomass stocks on land type immediately after the conversion, (tons d.m. ha^{-1}). As a simplification for Tier 1, it is assumed that all biomass is lost immediately from the previous ecosystem after conversion even when there is no abrupt change, and residual biomass is thus assumed to be zero, (i.e., the land is cleared of all vegetation before grassland vegetation is established). B_{BEFORE} = biomass stocks on land type *i* before the conversion (tons d.m. ha^{-1}) South Africa = 100 t DM ha^{-1} Temperate ecological zone was selected for South Africa. Table 4.4 (IPCC, 2006b) ΔA_{TO_OTHERS} = area of land use converted to another land-use category in a certain year (ha yr^{-1}) CF = carbon fraction of dry matter, (ton C tons d.m.$^{-1}$) type of land use converted to another land-use category. South Africa = 0.47 t C t DM^{-1} Table 4.3 (IPCC, 2006b)	Equation 2.16 IPCC 2006, Volume 4, Chapter 2 (IPCC, 2006a)
Dead organic matter	Annual change in carbon stocks in dead wood and litter due to land conversion $$\Delta C_{\text{DOM}} = \frac{(C_n - C_o) \times A_{on}}{T_{on}}$$	Equation 2.23 IPCC 2006 Volume 4, Chapter 2 (IPCC, 2006c)

Carbon pool	Prediction equation	Reference
	Where: ΔC_{DOM} = annual change in carbon stocks in dead wood or litter, (tons C yr^{-1}) C_o = dead wood/litter stock, under the old land-use category (tons C ha^{-1}) The Tier 1 default assumes removal of all dead wood and litter during conversion and that there is no dead wood or litter that remains or accumulates in Land Converted to Grassland and hence C_0 = zero C_n = dead wood/litter stock, under the new land-use category (tons C $ha^{-1)}$ The Tier 1 default assumes removal of all dead wood and litter during conversion and that there is no dead wood or litter that remains or accumulates in Land Converted to Grassland A_{on} = area undergoing conversion from old to new land-use category (ha) T_{on} = time period of the transition from old to new land-use category, yr. The Tier 1 default is 20 years for carbon stock increases and 1 year for carbon losses and hence T_{on} = zero.	

Appendix B Data quality rating method and criteria (PEF/ILCD compliant)

To ensure robustness and transparency, the quality of input data used in this LCA study was assessed using the Data Quality Rating (DQR) approach. This evaluation considered key criteria in accordance with ISO 1404 (2006b), and aligned with ILCD Handbook. Each dataset was scored based on its performance in line with ISO, p. (2006b, p. 10), which mandates specification of data quality in terms of temporal, geographical, and technological coverage, along with precision, completeness, and consistency.

B.1 Rationale for process-level data quality rating

In this study, DQR were assigned at the process level, encompassing distinct supply chain stages including sheep production. This approach was chosen to balance the need for transparency and detail with practical constraints related to available resources and project scope. Aggregating data quality assessments by process rather than by individual inventory flows allows for a manageable yet meaningful evaluation of data representativeness and reliability across key system components. This method reflects the overall data quality for each stage while avoiding excessive complexity that could obscure interpretation. This approach aligns with ISO 14044 guidelines, which do not mandate a specific level of granularity for data quality assessment, and with ILCD recommendations that encourage detailed evaluation where feasible but allow flexibility based on study goals and constraints.

B.2 Time-related representativeness

In the time-related representativeness criterion, the goal is to ensure the inventory reflects typical, or "steady state," conditions rather than anomalous years that could skew results.

To ensure the LCA inventory reflects typical production conditions rather than an anomaly, a complete production cycle was modelled and adjusted for changes in inventory to achieve a steady state. This approach enhances the time-related representativeness of the inventory data by aligning it with steady-state production conditions. A complete production cycle refers to all lifecycle stage required for the animal to produce one unit of greasy wool. For sheep, this is generally considered to be 12 months, as animals may be shorn up to twice annually and lambs are produced annually. The complete production cycle in this study was based on the primary data collected across the 84 farms during the survey period. Using only one year of data is acknowledged as a limitation of the study. The scope, time, and budget constraints of this study did not allow for multi-year averaging of primary data and national statistics with granular flock-level data were not available to supplement this analysis.

B.3 Mean DQR score

The overall project-level DQR was calculated as the arithmetic mean of the process-level DQR scores without weighting by environmental impact contributions. Process level refers to on-farm and post-farm process. This approach was chosen to maintain simplicity and transparency in the aggregation method.

Appendix C Supplementary results

C.1 Environmental impacts per small stocking unit (cradle to farm-gate)

Environmental impacts were reported per stocking unit (Table 17) to provide supplementary insights into the sheep farm system, independent of allocation. It is not appropriate as a functional unit as it does not directly link to the function of the product. Reporting impacts per small stocking unit is useful for comparing systems with different stocking densities, eliminates the need to allocate emissions between coproducts and considers animal-level GHG emissions. However, it does not accurately reflect the system's productivity.

Table 17. Environmental impacts per kg small stocking unit for RWS, Communal and the national average

Impact category	Units	RWS	Communal	South Africa
Climate change (excl. LU and LUC)	kg CO_2 eq	237	229	235
Climate change - Biogenic	kg CO_2 eq	222	228	222
Climate change - Fossil	kg CO_2 eq	15.11	0.18	12.93
Climate change - Land use and land use change (excl. impacts from soil carbon stock change)	kg CO_2 eq	0.02	0.00	0.02
Resource use, fossils	MJ	71	0.7	64
Water consumption	l	24093	1271	23584
Land occupation	m^2	15029	6801	15351

C.2 Environmental impacts per hectare (cradle to farmgate)

Environmental impacts were reported per hectare (Table 18) to provide supplementary insights into the sheep farm system, independent of allocation. It is not appropriate as a functional unit as it does not directly link to the function of the product. When impacts are reported per hectare, the results primarily reflect the stocking rate or intensity of the production system, which can be misleading if considered alone. Reporting impacts per kg of product normalizes these impacts by productivity and reduces variability caused by differences in stocking rates.

Table 18. Environmental impacts per kg hectare for RWS, Communal and the national average

Impact category	Units	RWS	Communal	South Africa
Climate change (excl. LU and LUC)	kg CO_2 eq	163	402	159
Climate change – Biogenic	kg CO_2 eq	153	401	150
Climate change – Fossil	kg CO_2 eq	10.4	0.3	8.7
Climate change – Land use and land use change (excl. impacts from soil carbon stock change)	kg CO_2 eq	0.02	0.00	0.02
Resource use, fossils	MJ	49	1.2	43.0
Water consumption	l	16596	2234	15920
Land occupation	m^2	10352	11950	10362

C.3 Environmental impacts per kg of liveweight (cradle to farm-gate)

Supplementary results were reported per kg of liveweight sold. This functional unit reflects the environmental impacts allocated to meat after the protein allocation to wool, divided by the total liveweight sold (or consumed) of animals leaving the system. When impacts are expressed per kg of liveweight, sheep meat shows substantially lower environmental impacts (Table 19) than wool (per kg of greasy raw fibre) within the same system. This is because a sheep produces a large amount of liveweight but only a small amount of wool each year. As a result, system inputs and emissions are spread across many kilograms of meat but very few kilograms of fibre. Although greasy wool is allocated only a slightly lower share of total impacts (44%) than liveweight (56%), those impacts are distributed over a much smaller output quantity, leading to higher impacts per unit of greasy wool.

Table 19. Environmental impacts per kg liveweight for RWS, Communal and the national average

Impact category	Units	RWS	Communal	South Africa
Climate change (excl. LU and LUC)	kg CO_2 eq	6.3	12.7	6.6
Climate change – Biogenic	kg CO_2 eq	5.9	12.7	6.2
Climate change – Fossil	kg CO_2 eq	0.4	0.0	0.4
Climate change – Land use and land use change (excl. impacts from soil carbon stock change)	kg CO_2 eq	0.0	0.0	0.0
Resource use, fossils	MJ	1.9	0.0	1.8
Water consumption	l	641	71	660
Land occupation	m^2	400	379	430

C.4 Environmental impacts used in the Product Environmental Footprint (PEF) 3.1

The environmental impact assessment methods used are reported in Table 20 and the results are reported in Table 21.

Table 20. Impact assessment methods used in the Product Environmental Footprint version 3.1 (European Commission Directorate-General for Environment, 2021)

Impact Category	LCIA method	Unit	Reference
Climate change	Global warming potential (GWP_{100}) AR6	kg CO_2 eq	Bern model - Global warming potentials (GWP) over a 100-year time horizon (based on (IPCC, 2021)
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11 eq	EDIP model based on the ODPs of the World Meteorological Organization (WMO) over an infinite time horizon (WMO, 2014)+ integrations
Human toxicity, cancer	Comparative toxic unit for humans (CTUh)	CTUh	Based on USEtox2.1 model (Fantke et al., 2017), adapted as in Saouter et al. (2018)
Human toxicity, non-cancer	Comparative toxic unit for humans (CTUh)	CTUh	Based on USEtox2.1 model (Fantke et al., 2017), adapted as in Saouter et al. (2018)
Particulate matter	Impact on human health	Disease incidence	PM model (Fantke et al., 2016)
Ionizing radiation, human health	Human exposure efficiency relative to U235	kBq U235 eq	Human health effect model as developed by (Dreicer et al., 1995)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm et al., 2008) as applied in ReCiPe 2008
Acidification	Accumulated exceedance (AE)	mol H^+ eq	Accumulated exceedance (Posch et al., 2008; Seppälä et al., 2006)
Eutrophication, terrestrial	Accumulated exceedance (AE)	mol N eq	Accumulated exceedance (Posch et al., 2008; Seppälä et al., 2006)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al., 2009) as applied in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al., 2009) as applied in ReCiPe
Ecotoxicity, freshwater	Comparative toxic unit for ecosystems (CTUe)	CTUe	based on USEtox2.1 model (Fantke et al., 2017), adapted as in Saouter et al. (2018)
Land use	Soil quality index	Dimensionless (pt)	LANCA version 2.5 (Horn and Maier, 2018)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 water eq of deprived water	Available WAter REmaining (AWARE) model (Boulay et al., 2018; UNEP/SETAC, 2016)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	van Oers et al. (2002) as in CML 2002 method, v.4.8
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)18	MJ	van Oers et al. (2002) as in CML 2002 method, v.4.8

Table 21. The environmental impacts reported for the impact categories assessed in the Product Environmental Footprint (PEF) per kg of greasy wool

Impact category (PEF)	Units	RWS	Communal	South Africa
Acidification	mol H^+ eq	0.02	0.01	0.02
Climate change	kg CO_2 eq	26.1	52.8	27.3
Climate change – (excl. LULUC)	kg CO_2 eq	26.1	52.8	27.3
Climate change – Biogenic	kg CO_2 eq	24.5	52.8	25.8
Climate change – Fossil	kg CO_2 eq	1.7	0.0	1.5
Climate change – LULUC	kg CO_2 eq	0.0	0.0	0.0
Ecotoxicity, freshwater	CTUe	96	56	100
Particulate matter	disease inc.	3.7E-06	7.7E-06	3.9E-06
Eutrophication, marine	kg N eq	0.02	0.03	0.02
Eutrophication, freshwater	kg P eq	4.5E-04	9.1E-06	4.3E-04
Eutrophication, terrestrial	mol N eq	0.3	0.5	0.3
Human toxicity, cancer	CTUh	1.5E-09	6.3E-12	1.5E-09
Human toxicity, cancer – inorganics	CTUh	1.1E-09	3.2E-12	1.1E-09
Human toxicity, cancer – organics	CTUh	4.0E-10	3.1E-12	4.0E-10
Human toxicity, non-cancer	CTUh	4.7E-08	1.9E-09	4.0E-08
Human toxicity, non-cancer – inorganics	CTUh	4.2E-08	8.6E-10	3.4E-08
Human toxicity, non-cancer – organics	CTUh	4.7E-09	8.1E-10	5.0E-09
Ionizing radiation	kBq U-235 eq	0.03	0.00	0.03
Land use	Pt	86421	80359	92803
Ozone depletion	kg CFC11 eq	6.16E-08	1.56E-10	6.58E-08
Photochemical ozone formation	kg NMVOC eq	0.02	0.02	0.02
Resource use, fossils	MJ	7.9	0.2	7.4
Resource use, minerals and metals	kg Sb eq	8.32E-06	1.06E-07	7.29E-06
Water depravation	m^3 depriv.	83.3	12.2	77.5

Appendix D Allocation

D.1 Sensitivity to allocation approach: methods

The sensitivity of results to the allocation method was tested by considering energy allocation methods and economic allocation.

Economic allocation (a)

The economic allocation was determined using the average price multiplied by the modelled output of each co-product (Table 22).

Table 22. Economic data from the primary dataset used in the sensitivity analysis for handling co-production

Parameters	South Africa
Wool price ($USD/kg greasy wool)	$6.92
Liveweight price ($USD/kg LW)	$3.28
Economic allocation wool (%)	29
Economic allocation liveweight (%)	71

Modelled energy allocation

The sensitivity of results to allocation was performed using the energy allocation method (LEAP, 2015). However, the guidance for implementing energy allocation between meat and fibre is not sufficiently specified or operationalized for consistent implementation. A sensitivity analysis was conducted study using five alternative approaches to the energy allocation as described below.

Energy allocation (b)

For each animal class, the energy to produce wool, for liveweight growth and for lactation was calculated following the IPCC 2019 Volume 4, Chapter 10 net energy equations (Table 15). Energy for liveweight, growth and lactation were calculated relative to the output of these products from the flock. Products grown but not exported from the flock were considered as part of flock maintenance energy requirements. The energy allocation for wool was then determined as follows:

$$\text{Energy allocation to wool \%} = \frac{\text{Net energy to produce wool (MJ)} \times \frac{\text{wool sold (kg)}}{\text{wool grown (kg)}}}{\left(\text{Net energy to produce wool} \times \frac{\text{wool sold (kg)}}{\text{wool grown (kg)}} + \text{net energy for growth} \times \frac{\text{liveweight sold(kg)}}{\text{liveweight gain (kg)}}\right)\text{(MJ)}}$$

$$\text{Energy allocation to liveweight \%} = \frac{\text{Net energy for growth} \times \frac{\text{liveweight sold(kg)}}{\text{liveweight gain (kg)}}}{\left(\text{Net energy to produce wool} \times \frac{\text{wool sold (kg)}}{\text{wool grown (kg)}} + \text{net energy for growth} \times \frac{\text{liveweight sold(kg)}}{\text{liveweight gain (kg)}}\right)\text{(MJ)}}$$

$$\text{The net energy to produce wool} = 24\ \text{MJ} \times \text{clean dry wool (kg)} + 38\ \text{MJ} \times \text{greasy wool (kg)} \times \text{grease content}$$

Where: grease content = 21.8% of greasy wool (Table 7).

Energy value of each kg of wool produced = 24 MJ per kg reported in IPCC (2019a).

Energy allocation (c)

This approach followed the same methodology as Energy Allocation (b), with two key differences: (1) the energy associated with lactation and pregnancy was also attributed to liveweight, (2) net energy for growth was not adjusted according to the proportion of liveweight sold. The energy allocation for wool was then determined as follows:

$$\text{Energy allocation to wool \%} = \frac{\text{Net energy to produce wool (MJ)} \times \frac{\text{wool sold (kg)}}{\text{wool grown (kg)}}}{\left(\text{Net energy to produce wool} \times \frac{\text{wool sold (kg)}}{\text{wool grown (kg)}} + \text{Net energy for growth} + \text{net energy for lactation} + \text{net energy for pregnancy}\right)\text{(MJ)}}$$

$$\text{Energy allocation to liveweight \%} = \frac{\text{Net energy for growth} + \text{net energy for lactation (excluding milk sales)} + \text{net energy for pregnancy}}{\left(\text{Net energy to produce wool} \times \frac{\text{wool sold (kg)}}{\text{wool grown (kg)}} + \text{Net energy for growth} + \text{net energy for lactation} + \text{net energy for pregnancy}\right)\text{(MJ)}}$$

Energy allocation (d)

This approach followed energy allocation (c), and applied a fixed net energy requirement for wool production of 130 MJ/kg greasy wool. This value was reported in CSIRO (2007), which stated that the metabolizable energy (ME) requirement can be estimated as 0.13 MJ per gram (g) of dry greasy wool fleece growth (sheep). This value was derived from sheep producing approximately 6 g of dry greasy wool per day (equivalent to about 2.2 kg per year of clean fibre plus wax and suint). It includes the maintenance energy required for skin and follicle growth.

Energy allocation (e)

This approach followed energy allocation (c), and applied a fixed net energy requirement for wool production of 157 MJ/kg greasy wool. This value is inclusive of maintenance energy requirements for skin and follicle growth and was derived from an angora goat study (Luo et al., 2004). This value is applied in the energy allocation in the PEF methodology (European Commission Directorate-General for Environment, 2021).

Energy allocation (f)

This approach followed energy allocation (c), and applied a fixed net energy requirement for wool production of 65.5 MJ/kg greasy wool. This value was calculated using the equation reported in CSIRO (2007): ME for wool (MJ/d) = 0.13(FL – 6), where FL is greasy fleece growth in grams per day. This equation may be used to determine fibre growth beyond maintenance requirements and was included to provide an indication of "fibre only" requirements. A merino sheep for wool production on average produces 4.4kg wool per year (Table 3) equivalent to approximately 12.1 grams per day. This yields an ME for wool (MJ/d) = 0.13(12.1-6) = 0.79MJ/day equivalent to 65.5 MJ/kg greasy wool. This example illustrates the implementation of the equation when maintenance energy requirements are excluded. This wool-based estimate was used as a proxy and included in the sensitivity analysis to explore its potential influence.

D.2 Sensitivity to allocation approach: results

Across both production systems, the choice of allocation method had a large influence on the environmental impacts of greasy wool.

Economic allocation

Using an economic allocation for the handling of co-production of greasy wool and liveweight for meat consumption substantially decreased the environmental impacts for greasy wool by 35% (Table 23 and Table 24).

Using economic allocation, changes in market prices alone can cause the wool carbon footprint to change substantially, despite no biophysical change in the system and no change in gross emissions from sheep farming. The price data applied in this study were representative of 2023 conditions, characterized by comparatively low greasy wool prices and elevated lamb prices, which shifted a greater proportion of impacts towards liveweight and away from wool. An additional comparison was undertaken (results not shown) using 2026 prices (i.e. \$14 USD kg greasy wool^{-1} and \$3.4 USD kg liveweight^{-1}), which had the effect of generating allocations to wool that were 53% higher than 2023, and that were similar to those obtained using protein allocation.

Energy allocation

The sensitivity analysis energy allocation methods for the handling of co-production of wool and liveweight for meat consumption resulted in lower and higher allocations to wool depending on the implementation, compared to the protein allocation method.

The first two implementations of the energy allocation method, (b) and (c), using an energy value of 24 MJ per kg of clean wool (i.e. less the grease content) and 38 MJ in grease, showed impacts were higher for fibre using the protein method, because fibre has a very high proportion of protein (clean, dry fibre is 100% protein) while live weight is proportionally lower in protein than in energy. On an energy basis, live weight has a larger amount of energy associated with the meat and animal fat, which resulted in proportionally higher burdens allocated to live weight for the energy method compared to the protein method. However, when the energy required to produce wool was increased to 130 MJ and 157 MJ per kg of greasy wool the impacts to wool were up to 87% higher than the protein allocation method. These higher energy values were derived from published wool energy estimates that include maintenance energy requirements associated with skin and follicle growth. When the energy requirements of wool only growth was examined (f) using 60.5MJ kg greasy wool-1 the results were 5% lower than the protein allocation method. The results of these allocation approaches are reported per kg of greasy wool in Table 23 and Table 24.

Table 23. Sensitivity analysis of economic and energy allocation approaches per kg of greasy wool for the national average to handle the co-production of wool and liveweight for meat consumption

Farm Gate	Units	Headline Protein	(1) Economic	(2) Energy	(3) Energy	(4) Ener	(5) Energy	(6) Energy
Total greenhouse gas emissions (excl. LU and LUC)	kg CO_2-e/kg greasy wool	622962				828795	879841	706713
Total greasy wool sold or used for consumption	kg	10074						
Total kg liveweight sold or used for consumption	kg	52854						
% allocation to greasy wool	%	44%	29%	22%	18%	54%	58%	37%
% allocation to liveweight	%	56%	71%	78%	82%	46%	42%	63%
Climate change (excl. LU and LUC) -greasy wool	kg CO_2-e/kg greasy wool	27.2	17.7	13.8	10.9	44.2	51.0	25.9
Climate change (excl. LU and LUC) - meat	kg CO_2-e/kg liveweight	6.6	8.4	9.1	9.7	7.3	6.9	8.4

Table 24. Environmental impacts per kg greasy wool using protein (baseline), economic and energy allocation approaches for the national average to handle the co-production of wool and liveweight for meat consumption

Impact category	Units	Headline protein	(1) Economic	(2) Energy	(3) Energy	(4) Energy	(5) Energy	(6) Energy
Climate change (excl. LU and LUC)	kg CO_2 eq	28	17.8	13.9	11.0	44.3	51.1	26.0
Climate change - Biogenic	kg CO_2 eq	26	16.8	13.1	10.4	41.9	48.3	24.6
Climate change - Fossil	kg CO_2 eq	1.5	1.0	0.8	0.6	2.5	2.8	1.4
Climate change - Land use and land use change (excl. impacts from soil carbon stock change)	kg CO_2 eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Resource use, fossils	MJ	7.4	4.8	3.8	3.0	12.1	13.9	7.1
Water consumption	l	2117	1785	1393	1099	4241	4849	2550

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