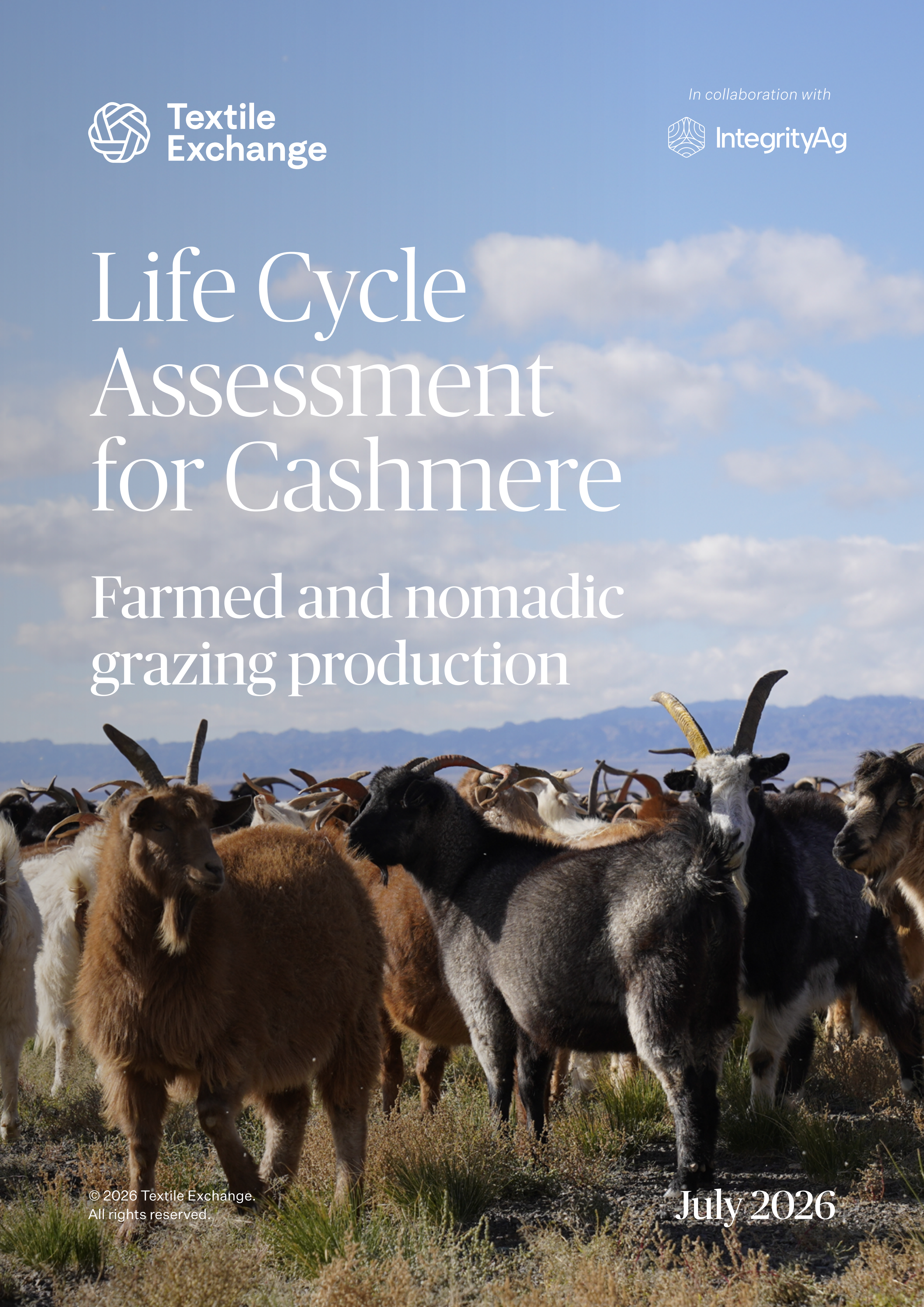
Textile Exchange

In collaboration with IntegrityAg

Life Cycle Assessment for Cashmere

Farmed and nomadic grazing production



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Title: Life Cycle Assessment of Cashmere
Farmed and nomadic grazing production systems

Led by Textile Exchange and prepared by Integrity Ag.

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Textile Exchange is a global non-profit driving beneficial impacts on climate and nature across the fashion, textile, and apparel industry. We guide a growing community of brands, manufacturers, and farmers towards more purposeful production from the very start of the supply chain.

At the heart of our organizational strategy, Climate+, is the goal to help the industry reduce greenhouse gas emissions from fiber and raw material production by 45% by 2030, aligned with the 1.5°C pathway of the Paris Agreement. But our approach goes further, maintaining a holistic and interconnected perspective that aims to improve freshwater, soil health, and biodiversity.

Given Textile Exchange's role and reach in the industry, we believe that we are well-positioned to facilitate the development of Life Cycle Assessment (LCA) studies in a robust and impartial manner, helping to address key data gaps related to the environmental impacts of raw materials and fibers. By engaging stakeholders across and beyond our membership base, we can ensure that different supply chain actors are involved and considered within the LCA development process. Additionally, our LCA+ approach complements LCA results with qualitative insights on biodiversity, soil health, water use, animal welfare, and livelihoods, providing a more complete understanding of material impacts.

In 2022, Textile Exchange launched a series of LCA studies to support the industry in filling key LCA data gaps. Priority studies were identified based on the following criteria: total volume of a fiber or material used by the industry; current availability of impact data; and quality of available impact data.

As a result, seven priority LCA studies were identified: Cotton, Polyester, Leather (hide production), Responsible Wool Standard (RWS) Wool, Responsible Mohair Standard (RMS) Mohair, Nylon, and Cashmere. Each of these studies focuses on the pre-spin stage, or equivalent, impacts of the fiber or material.

For more information on Textile Exchange's position on LCA, please refer to our *Ensuring Integrity in the Use of Life Cycle Assessment Data* paper.

To ensure the LCA studies facilitated by Textile Exchange are robust and credible, we engage with multiple stakeholder groups throughout the study development process:

- **Data collection partners:**
  For example, organizations, schemes, and programs that support the collection and delivery of primary and secondary data.
- **Project sponsors forming a Project Advisory Group:**
  Brands and suppliers that financially support the improvement of LCA data and provide an industry perspective on the LCA needs for a given fiber or material.
- **Material and technical experts forming a Technical Advisory Group:**
  Subject matter experts reviewing initial project outputs ahead of the formal critical review process—helping ensure a robust, transparent, and inclusive review process.
- **Critical reviewers:**
  Independent third-party reviewers assessing the study's alignment with the principles and requirements of the relevant ISO standards.
- **Peer reviewers:**
  For the animal fiber and material LCA studies, peer-reviewed journal articles will be developed to validate and communicate findings.

LCA results are intended to support:	LCA data should not be used for:
✓ Environmental impact reduction strategies ✓ Scope 3 reporting and target-setting ✓ Default or "proxy" data for internal or supply chain-specific LCA studies ✓ Benchmarking and validation within supply chains ✓ Inclusion in LCA databases (for example, Higg MSI, Quantis WALDB) ✓ Holistic understanding of impacts, including social factors	× Public or marketing claims (including on-product labels) × Country-based sourcing or production decisions based solely on LCA averages × Comparisons between fibers or materials. Textile Exchange LCA studies are not comparative studies. They should not be used to investigate the differences in impacts between or within fiber or material types.

When reviewing the Life Cycle Assessment (LCA) results and reports, Textile Exchange advises that the scope of the studies, methodologies applied, and carbon accounting approaches utilized are carefully considered, in particular, biogenic carbon accounting and how this differs between natural and synthetic fibers and materials.

LCA studies assess only those environmental impacts that are anthropogenic in origin, meaning impacts that are caused by human activity.

For example, in the case of polyester, the LCA boundary begins at the extraction of crude oil, as this marks the point at which human intervention initiates environmental impacts. The geological formation of crude oil itself is not considered within the scope, as it is a natural process not attributable to human activity. The emissions associated with the fossil carbon contained in the oil and therefore the fiber are usually considered at the end-of-life (EoL) stage of the product.

For natural fibers, the starting point of the assessment differs. For animal-based fibers, it begins with animal rearing; for plant-based fibers, it begins with crop cultivation. All upstream activities related to feed and fertilizer production are also included.

In all cases, the associated impacts are allocated across the multiple outputs of the system, a process known as allocation in LCA methodology.

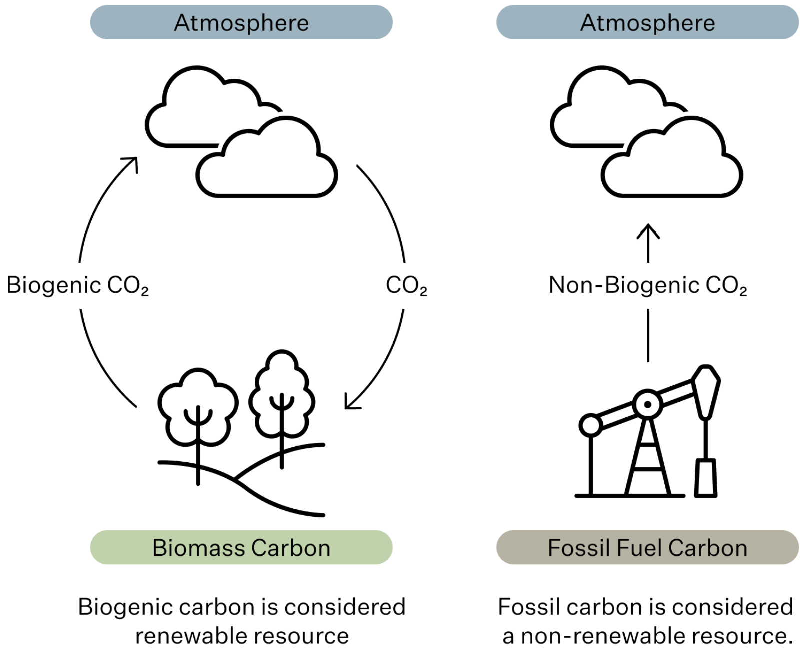
Natural fibers also contain biogenic carbon. Biogenic carbon is absorbed from the atmosphere by plants as they grow and can be released back into the atmosphere later when the plants burn or break down. This is different to fossil carbon that is from fossilized sources in the earth's crust that has formed over millions of years. New fossil material is not formed in natural conditions, so, for example, the incineration of fossil fuels or materials reduces fossil carbon stock and increases atmospheric carbon (never the opposite). Biogenic carbon is considered renewable and fossil carbon is non-renewable. There are several approaches for accounting for biogenic carbon. Its treatment is a critical consideration when comparing fiber types, as inconsistent inclusion or exclusion can lead to misleading or unfair comparisons between biobased and synthetic (fossil-based) materials.

Textile Exchange conducts LCA studies using a cradle-to-gate approach. This means that the studies assess impacts from raw material extraction through to fiber formation. The use phase and EoL stages are not included. However, if EoL were to be included, it would be essential to distinguish between the emissions profiles of biobased and fossil-based materials. For example, synthetic fibers may result in additional greenhouse gas impacts at EoL (for example, due to emissions of fossil carbon from incineration), whereas the emissions occurring from biobased materials are typically considered carbon-neutral at EoL since the emitted carbon was previously absorbed from the atmosphere. See the illustrative example below.

It is important to recognize that the challenge of accounting for biogenic carbon emissions and removals goes beyond carbon stored in the product, and different methods exist for accounting for biogenic carbon. For further guidance, please refer to Textile Exchange's *Biogenic Carbon* guidelines, which outlines recommended practices and considerations for incorporating biogenic carbon into LCA studies. For fossil-based carbon, there are established and standardized accounting methodologies such as the GHG Protocol and ISO guidelines. These methodologies require that emissions and resource use are directly attributable to human activity.

Accounting for Greenhouse Gas (GHG) emissions and the differences between natural and synthetic material production systems is an evolving area with ongoing research and methodology development. Textile Exchange continues to track developments in this area and relevance for its impact data and measurement work.

Illustrative example of natural (crop) vs. synthetic fiber production and the associated carbon cycle:



This study has been led by Textile Exchange in partnership with Integrity Ag.

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Contents

List of Acronyms

ADF	Acid detergent fiber
ADP	Abiotic depletion potential
AE	Accumulated exceedance
AWARE	Available WAter REmanining
AWMS	Animal waste management system
CFC	Chlorofluorocarbon
CML	Center of Environmental Science of Leiden
CN	China
CP	Crude protein
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTUh	Comparative toxic unit for human
DMI	Dry matter intake
DQR	Data quality requirements
EC	Electrical conductivity
EDIP	Environmental design of industrial products
EF	Environmental footprint
EUTREND	Eutrophication trend
FAO	Food and Agriculture Organization
FTE	Full time equivalent
GHG	Greenhouse gas
GIS	Geographical information system
GLO	Global
GWP	Global warming potential
HDPE	High-density polyethylene
IA	Integrity Ag
ICAR	International Committee for Animal Recording
ICP	Inductively coupled plasma
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IWTO	International Wool Textile Organization
LANCA	Land use indicator value calculation
LCA	Life Cycle Assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU and LUC	Land use and land use change
LW	Liveweight
MCF	Methane conversion factor
MSI	Materials sustainability index
MSIS	Mongolian Statistical Information Service
NAMEM	National Agency Meteorology and Environmental Monitoring
NDF	Neutral detergent fiber
NIR	National Inventory Report

NMVOC	Non-methane volatile organic compound
ODP	Ozone depletion potential
PAS standard	Publicly available specifications
PEF	Product environmental footprint
PM	Particulate model
PMA	Protein mass allocation
RoW	Rest of the World
SOC	Soil organic carbon
SQI	Soil quality index
SU	Sheep unit
WMO	World Meteorological Organization

Glossary

Aimag
Province administrative boundary in Mongolia.

Allocation
"Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14040:2006, section 3.17).

Biogenic carbon
Carbon derived from biogenic (plant or animal) sources, excluding fossil carbon.

Critical review
"Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment" (ISO 14044:2006, section 3.45).

Data quality
Characteristics of data that relate to its ability to satisfy stated requirements (as defined in ISO 14044 (2006b)).

Doe cull rate (% of total adult does)
The percentage of adult female goats (does) that are removed from the herd—through sale, slaughter, or consumption.

Dzud
A collective term for a range of extreme winter weather disasters in Mongolia that severely affect livestock survival and pasture access. According to the National Emergency Management Agency (NEMA) of Mongolia, dzud can take multiple forms, including:

- **White dzud (tsagaan zud**): Deep, widespread snowfall covering pastures and blocking access to forage.
- **Black dzud (khar zud):** Absence of snow, leaving dry, frozen ground with no access to water, forcing animals to walk long distances to find snow or water sources.
- **Iron dzud (tömör zud):** A layer of ice forms over the snow or ground, making it extremely difficult for animals to graze.
- **Cold dzud (khyamar zud):** Extremely low temperatures sustained over long periods, causing livestock to freeze or reduce mobility.
- **Storm dzud (shivree zud):** Sudden snowstorms that form deep drifts and hard snow crusts, obstructing grazing and displacing animals.

These events are often preceded or intensified by summer droughts, which reduce available forage and weaken livestock condition before winter.

Farmer
A general term used in China to refers to rural households engaged in agricultural activities, including crop cultivation and/or livestock production. In China, “farmer” may also refer to households primarily involved in livestock herding.

Functional unit

Quantified performance of a product system for use as a reference unit (as defined in ISO 14044 (2006b)).

Herder

A person or household primarily engaged in the care and management of grazing livestock such as goats, sheep, cattle, or camels. In Mongolia, this term typically refers to those practicing extensive livestock production systems.

Herder household

A household whose main livelihood is based on livestock herding, including grazing-based management of animals for products such as meat, milk, or fiber (for example, cashmere). While this livelihood is commonly referred to as "herder" in Mongolia and "farmer" in China, the term herder household is used consistently across both geographies.

Protein output

Refers to the total protein produced by the herd across all three products: raw cashmere, milk, and meat.

Protein per sheep unit

Protein per SU refers to the total protein contained in all products leaving the system (for example, protein in raw cashmere, meat, and milk) divided by the total number of sheep units (SU) in the system. It is not the total protein stock on the farm. It is not limited to raw cashmere alone but includes all outputs from the system. This metric provides a standardized way to compare protein productivity across systems of different sizes.

Life cycle

A view of a product system as "consecutive and interlinked stages of a product system from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land, and water.

Life Cycle Assessment (LCA)

Compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle (as defined in ISO 14044 (2006b)).

Life cycle impact assessment (LCIA)

Phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (as defined in ISO 14044 (2006b)).

Life cycle inventory analysis (LCI)

Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (as defined in ISO 14044 (2006b)).

Sheep unit

Sheep unit is a standardized unit used to equate different types of livestock based on the equivalent value or feed requirement of one sheep at 50 kg. Sheep unit is used to standardize the grazing pressure across different animal types, ages, and sizes. This allows for better management and comparison of pasture use, livestock productivity, and carrying capacity across farms or regions.

In this study, we adopted the SU framework for allocating shared inputs (for example, land use, fuel) across species and reporting explanatory variables. However, to reduce the data-collection burden, we simplified the approach by assigning SU values on a per-head basis rather than adjusting for actual live weight. This means that one goat was treated as 0.9SU (or the species-specific equivalent listed below), even though our flock's average weight was below 50 kg. We assumed that if our flock was lighter than the standard SU, other species would also be proportionally lighter, so relative allocations would remain balanced.

This methodology is consistent with Mongolian research practices, including the study by Jargalsaihan et al. (2021), which used sheep equivalents to assess stocking rates and grazing pressure across herders in degraded grasslands. The same approach is also supported in foundational work such as Mearns (1993), which discusses land tenure and herd structure using SU as a comparative unit.

Specifically in this study:

- Sheep = 1.0
- Goats = 0.9
- Breeding does = 1.5
- Horse = 7.0
- Yaks = 6.0
- Cattle = 6.0
- Camels = 5.0

Snow emergency
An extreme winter weather disaster that is often exacerbated by summer droughts followed by harsh winters, and is similar in nature to Mongolia's dzud, though the term is more commonly used in the Chinese context, particularly in pastoral regions of Inner Mongolia.

Wether inclusion rate (% of total breeding does)
The proportion of wethers (castrated male goats) included in the herd relative to the total number of breeding does. This rate influences herd structure. If the wether inclusion rate is greater than 100%, that means there are more wethers than breeding does in the herd.

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1. Executive summary

1.1. Goal and scope

1.1.1. Goal of the study

The textile industry is facing increasing pressure from customers and governments to report and reduce its environmental impacts. The cashmere industry is a high value, natural, and renewable fiber used in the apparel industry. However, there is limited data available that quantifies the environmental impact of cashmere production across multiple impact categories using holistic assessment tools such as Life Cycle Assessment (LCA). Nomadic herders have harvested cashmere and other animal fibers for thousands of years, in systems that have continuously produced fiber, meat, and milk. However, in more recent years, the elevated numbers of livestock have raised concerns about the impact of production on the environment, and research is needed to understand this impact. This study, led by Textile Exchange in partnership with Integrity Ag, aimed to produce a benchmark LCA of cashmere from two major production systems, including assessment using the environmental impact categories in the European Commission's Product Environmental Footprint (PEF) program (European Commission, 2025) (version 3.1) and the Higg MSI (version 2.0). The study included primary data inventories of goat production, and primary processing across two production systems in two major cashmere-producing countries, nomadic grazing systems, and farmed systems. This represents a significant step forward in addressing the critical knowledge gap around the environmental impacts of cashmere, and provides much-needed data to inform more accurate and equitable textile sustainability ratings.

1.1.2. Scope of the study

The system boundary included all supply chain processes associated with the primary production and primary processing of cashmere (Figure 1). The functional unit was reported for each key stage in the supply chain, including the primary production of cashmere to the primary production gate as "1 kg of raw cashmere at the primary production gate," and from the primary production of cashmere through to processing-gate, as "1 kg fine dehaired cashmere." Per-hectare and per-sheep unit results are provided for supplementary insight into whole farm impacts but are not functional units because they do not directly relate to the product function, obscure allocation between co-products, and are highly sensitive to stocking rate. Attribution of soil carbon losses was difficult, so impacts were reported only on a per-hectare basis.

1.2. Inventory data

1.2.1. Description of unit processes

The unit processes considered in this study cover the supply chain from primary production to primary processing. At the primary production stage, cashmere harvesting is supported by a range of production processes, including animal husbandry, pastoral grazing, fodder production, and the production of co-products such as milk and meat. At the primary processing stage, raw cashmere is transported from herder households to specialized processing facilities, where machine-based operations, including scouring and dehairing, are conducted. These processes remove physical contaminants and coarse guard hairs, preparing the fiber for further textile manufacturing.

1.2.2. Data collection and sources

Data was collected from 170 herders and farmers across Mongolia and China, focusing on two major production systems. The survey included herd inventories, animal weights, grazing areas, and land use data, conducted via field visits in Mongolia and China from 2023 to 2024. In Mongolia, case studies were also completed in each region to provide more granular insights. At these sites, additional data was gathered, covering livestock weights, land impacts, and pasture conditions. The sample was stratified by cashmere production volume, household size, geographical zone, and management practices. In Mongolia, a multi-year average dataset was applied, defined as the average of key herd and production parameters over a five-year period (2019–2023). This approach, using regional data, was implemented to account for inter-annual variability and provide a more representative baseline. Primary data was collected from 11 processing facilities in Mongolia and seven in China, focusing on the scouring and dehairing processes. The datasets included purchased inputs, mass flows, and product transformation during primary processing.

1.2.3. Data quality requirements

Data was evaluated for temporal, geographical, and technological representativeness, completeness, and consistency, in line with ISO 14040/14044 (ISO, 2006a, 2006b) requirements (Appendix C–Data quality rating method and criteria (ILCD compliant).

1.3. Modeling and impact assessment methods

The impact assessment included the impact categories listed in PEF v3.1 and the Higg MSI v2.0. Herd inventory, liveweights, and growth rates were used to model gross energy intake from feed and manure production. Gross energy intake and livestock GHG emissions, including enteric methane, were modeled using IPCC Tier II equations, emission factors, and uncertainty from the 2019 refinement (IPCC, 2019b, 2019a). The assessment of LU and LUC GHG emissions was determined using direct LUC methods for the nomadic grazing systems, based on the grazing areas assessed and statistical LUC methods for the farmed system to the nearest jurisdiction. The methodological choices made in this assessment were examined using sensitivity and uncertainty analysis at the primary production and primary processing stages. Comparison of the mean results between systems was based on alpha uncertainties only, and significant differences (95% confidence interval) were determined using the equation reported in Wiltshire et al. (2009), (Appendix D–Uncertainty analysis).

1.3.1. Allocation procedures

Grazing areas were often used for multiple species. Where multiple livestock were managed in the same grazing area, these areas were divided into sub-systems, and the impacts associated with each different production system were attributed accordingly, to avoid allocation.

Cashmere primary production yields three products: raw cashmere, liveweight for meat consumption, and milk for dairy products. Allocation was performed using the protein allocation method (Wiedemann et al., 2015), with energy allocation methods FAO (2016), and economic allocation, used for sensitivity analysis.

At the primary processing stage, the output product was fine, dehaired cashmere. This process removes coarse fibers and grease. Grease was entrained in wastewater and treated as waste. Coarse hair was used either as a feedstock for compost or as a material for low-value purposes. It was treated as a residual.

1.4. Environmental impact assessment results

Impact categories were selected based on their relevance to the production regions, and their material contribution to overall environmental outcomes. The environmental impact categories of highest relevance to these systems included land use, climate change, fossil resource use, water use, and ecotoxicity (Figure 5). Selected environmental impact results per kg of clean, dehaired cashmere for the nomadic grazing system and farmed system were 183 kg CO_2-eq and 155 kg CO_2-eq GHG emissions (excluding land use and land use change (LU and LUC)), 233,313 Pt and 127,992 Pt land use impact, 144 and 109 MJ fossil resource use, 46 m^3 and 83 m^3 deprived water use, and 415 CTUe and 535 CTUe ecotoxicity impacts, respectively. The primary production stage accounted for over 75% of the total impact across five of the six most relevant indicators: climate change, water use, ecotoxicity, particulate matter, and land use. The occupation of livestock grazing contributed >99% of land use impacts. With respect to LU and LUC, impacts from vegetation change were not material, but soil carbon loss risks were reported in the literature. Attribution of soil carbon losses was difficult because research indicates that the effects of climate change have resulted in soil carbon loss, together with impacts from overgrazing. Impacts were reported on a per hectare basis. As a result, a sensitivity test for SOC is included in the main report.

Climate change impacts were not significantly different between management systems when reported per kg of raw or clean, dehaired cashmere. The farmed system showed significantly higher impacts in water use compared to the nomadic system per kg of clean, dehaired cashmere. At the primary production stage, the nomadic system showed significantly higher land use impacts when reported per kilogram of raw cashmere and per kg of clean, dehaired cashmere. When reported per hectare, results were higher for the farmed system at the primary production stage compared to the nomadic grazing system. This illustrates a trade-off: results were similar per unit of cashmere, but farmed systems were more resource-intensive and had higher impacts per hectare for important indicators such as climate change. Improvements, such as better winter nutrition and enhanced genetics, could potentially enable both systems to achieve lower impacts through generating higher turn-off of other products, such as meat and milk. The key impact categories at the primary processing stage were fossil resource use, water use arising from process steam, thermal energy from natural gas, and electricity from the grid.

1.5. Limitations

The study collected primary data from 170 different production sites across two major cashmere-producing nations and two common, contrasting, production systems. There are over 195,750 herder households in Mongolia (National Statistics Office of Mongolia, 2024a), and approximately 16 million in northern and western China (Ho, 2016) (though not all are involved in cashmere production). In the present study, the variation between agroecological zones in Mongolia was not pronounced, suggesting reasonable representativeness, though larger sample sizes are needed to confirm this. The results calculated for the farmed systems in China were not representative of the semi-nomadic grazing practices found across large areas of Inner Mongolia, which are likely to yield outcomes more comparable to those observed in Mongolia. For this reason, the results should not be interpreted as being representative of either Mongolia or China, and should not be used for comparison between these countries. Future studies are needed to expand coverage of different agroecological zones, examine variations in management practices, and examine a broader spectrum of climatic conditions to build the knowledge base regarding the impacts of cashmere production. Cashmere production has a history spanning thousands of years in these regions, but further research is needed to quantify the impact of practice change in recent decades, particularly with respect to higher stocking rates. It would be informative for the industry to have a comparison between the findings of the present study and traditional practices in order to examine the marginal changes that have occurred and the environmental impacts of these changes. This could also be informed through using a consequential LCA approach.

Data collection in China presented significant challenges that impacted the scope and representativeness of the study. While logistical constraints, such as geographic remoteness and limited infrastructure, played a role, the most substantial barrier stemmed from regulatory restrictions tied to national data security laws. These laws, which classify certain data as sensitive or state-controlled, limit the ability to access some farm-level information and conduct on-site land assessments. In practice, this meant that even with in-country field staff, permissions to collect primary data were often delayed, denied, or restricted to aggregated data with no geo-specificity.

The choice of allocation method had a large impact on the results of the study, and uncertainty exists in how to apply the energy methods used for the sensitivity analysis. The approach here was consistent with LCA guidance, but different schools of thought exist on the most appropriate allocation method. We note that the PEF method requires energy-based allocation (as used in the sensitivity analysis), but this method has a range of potential assumptions that could be applied, which have a material impact on the final result.

1.6. Conclusion and recommendations

Cashmere production has historically been practiced within nomadic grazing systems that deliver fiber, meat, and milk, with low external inputs. However, recent increases in livestock numbers and changing land use pressures have raised concerns about sustainability. Adapting traditional grazing practices to modern societal demands and practices, while responding to external pressures regarding sustainability outcomes, remains a challenge for the cashmere sector. This study represents the first comprehensive Life Cycle Assessment (LCA) of cashmere production across multiple environmental impact categories, offering critical insights for the industry to prioritize emission reduction strategies. The findings highlight that there were no significant differences in greenhouse gas emissions (climate change impacts) between the production systems per kg of clean, dehaired cashmere (primary processing gate). However, at the primary production stage, the farmed systems, due to higher productivity and efficiency, generally exhibit lower greenhouse gas emissions compared to nomadic grazing systems (per kg of raw cashmere at the primary production gate). Land use impacts were more complex, with nomadic systems showing higher impacts per kilogram of product, while farmed systems show higher impacts per hectare due to intensified stocking rates. The limitations of the LANCA model in accurately capturing land use impacts, especially in rangeland contexts, underscore the need for improved methodologies and region-specific data.

Variation in carbon footprint for cashmere was explained by differences in herd management and productivity, both between individual herds within the same production system (for example, between different nomadic herds), and between the two main production systems (nomadic grazing and farmed). The analysis indicated that differences in productivity at the herd level, within a given production system, had as much or greater influence on carbon footprint as the difference between the two production systems themselves. Therefore, management practices and productivity at the herd level were more significant drivers of environmental impact than the distinction between production systems alone. These suggested interventions, including better herd management, selective culling, and supplementary feeding, offer viable pathways to reduce environmental impacts, potentially without compromising income. This is particularly relevant in China, where live animals were sold at higher prices per kilogram of liveweight, resulting in greater returns for producers. These interventions would be effective for both grazing systems. Systematic changes in nomadic systems, such as improved market access for the sale of animals for meat, may encourage more focus on animal turn-off, and improve herd output and incomes with fewer livestock. It is also important to acknowledge the trade-off between environmental impacts. Efficiency gains may increase resource intensity as observed in the farmed systems. Grazing pressure contributed to two distinct categories of land-related impacts: (1) land use impacts, as assessed using the LANCA model, which evaluates changes in soil quality and ecosystem functions due to land occupation and management; and (2) land use greenhouse gas (GHG) impacts associated with soil carbon loss. Although not the primary focus of this study, climatic factors, such as reduced rainfall, play a significant role in these impacts, making it difficult to attribute them solely to cashmere production. While it is difficult to disaggregate these multiple cause-and-effect relationships, the imperative to reduce grazing pressure while improving livelihoods is a key outcome of this study, and the solutions to this challenge are multifaceted. Long-term sustainability may be achieved through a combination of ancient grazing practices at sustainable stocking rates, combined with interventions, such as the use of purchased feed for winter management, to improve overall environmental outcomes while also generating income for herders.

The study emphasized that extreme climatic events (dzuds) increase environmental impacts per kg of cashmere, primarily due to reduced productivity and higher mortality. Enhancing resilience through better dzud management and infrastructure could mitigate these effects. While the study provides a foundational understanding, it also acknowledges limitations in data representativeness, translation accuracy, and legal constraints on data access. Future research should aim to refine land use impact models, expand regional data collection, and investigate interventions that improve environmental outcomes and social and economic well-being. This study did not assess animal welfare. Further research is also needed to expand and test the outcomes of this study, to support sustainable transformation in the cashmere industry.

1.7. Intended use and communication of study results

The study aimed to provide data-driven insights for decision-makers in the cashmere industry, guiding efforts to reduce environmental impacts and support emission reduction practices. Additionally, the findings will help shape future research and raise consumer awareness about the environmental footprint of cashmere. The findings indicate the risks to environmental outcomes associated with overgrazing, and suggest that herd productivity improvements through improved winter nutrition could improve the environmental impact results across indicators such as climate change and land use, irrespective of the production system.

The results of this study should not be used for direct comparisons between cashmere and other fibers, or comparisons between Mongolia and China, or for procurement decisions between production systems. The results are not considered suitable for procurement decisions without considering the specificities of supply chains and the differences in impacts from year to year. Further, the multiple indicator results show that trade-offs exist between production systems, introducing the risk of unintended consequences if one system was favored over another.

Care should be taken when using these results for broader generalizations, as Life Cycle Assessment (LCA) results are highly sensitive to the specific boundaries, data quality, and methodological choices made in the study. The LCI dataset results generated from this study are intended to be made available through platforms such as the Product Environmental Footprint (PEF), Higg MSI, WALDB, and the Textile Exchange data library, but this does not imply comprehensiveness or representativeness.

2. Introduction

2.1. Background

The global cashmere industry has experienced significant growth over the last decade, producing 25,611 tons of greasy fiber in 2023, representing approximately ~0.02% of global fiber production (Textile Exchange, 2024). The majority of cashmere is produced by low-income herders and farmers in remote, semi-arid areas in China and Mongolia, representing 58% (National Bureau of Statistics of China, 2024) and 39% (National Statistics Office of Mongolia, 2024b) of annual global cashmere production, respectively. Natural fibers, including cashmere, are facing increasing pressure to align with company emission reduction targets and consumer expectations on sustainability reporting; however, there is a paucity of studies, particularly in cashmere, resulting in knowledge gaps for reporting.

Supply chain sustainability reporting uses LCA as the foundation for comparing multiple environmental impacts from product systems. Globally, there are many LCA studies published on small-ruminant systems. However, most studies have focused on sheep (Gac et al., 2012; Ibidhi et al., 2017; Mazzetto et al., 2023; Wiedemann et al., 2016), or dairy goat farming systems (Cabral et al., 2020; Gutiérrez-Peña et al., 2019; Pardo et al., 2016; Robertson et al., 2015; Zucali et al., 2020). These studies have typically been in farmed production systems in developed countries. The dairy goat systems were intensively managed with much greater reliance on feed inputs and fertilizer than nomadic and pastoral cashmere goat herds. Nonetheless, these studies provide some insight into the key impact categories, data sources, and data collection required for the environmental assessment of cashmere goat production systems. Climate change, land use, water use, eutrophication, and fossil resource depletion were identified as key impact categories across the LCA studies cited above.

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 the processing, retail, and garment phases. In comparison, fossil fuel usage was much greater in the processing phase, and the retail and garment phases, than in the primary production stage (Wiedemann et al., 2020). Given the similarities across the wool and cashmere supply chain, including extensive grazing systems for small ruminant production and the scouring process during primary processing, the hotspots identified in the wool supply chain will provide insight for cashmere. That noted, key differences also exist, including the ratio of fiber, meat, and milk, and the different yield losses across the processing supply chain, which can be expected to have a large influence on the environmental impact of the fiber.

Addressing the research gap remains a challenge for cashmere, because of the complexity in the primary production system, which can lead to high degrees of variability because of seasonal impacts (Ahearn, 2018; Crook et al., 2020; Engler et al., 2021; Tachiiri et al., 2017). This can create significant variation in production quantity and quality across management systems and regions.

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

While cashmere is highly valued as a luxury fiber, there are concerns regarding the sustainability of production, particularly through rangeland degradation (Chan et al., 2023; Densambuu et al., 2018; Hilker et al., 2014; Jamsranjav et al., 2018; Sainnemekh & Aduut, 2022; Sheehy & Damiran, 2016), and impacts associated with climate change (Morton et al., 2024; Namkhainyam et al., 2024). The knowledge gap addressed in this study is the lack of comprehensive, multi-indicator LCA data for cashmere production systems. This project provides the first LCA of cashmere, quantifying environmental impacts across several environmental impact categories. While the LCA does not directly measure rangeland degradation, it offers critical insights into the broader environmental footprint of cashmere production, thereby supporting more informed sustainability assessments and decision-making.

2.2. 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* (ISO, 2006b). The study has undergone a critical review by an independent expert panel to ensure conformity with the ISO standard and the scientific robustness of the results. In addition, an external stakeholder group, comprising representatives from cashmere initiatives, cashmere industry stakeholders, and LCA experts, was established to provide ongoing guidance and input throughout the study.

While this study's LCA focuses on environmental impact categories, it does not assess social impacts—such as those related to workers, communities, or human rights. It is important to consider both environmental and social impacts for the responsible sourcing of raw materials. Textile Exchange and its project partners have developed an addendum to this study, focused on a social livelihood survey conducted with participating data providers, and a review of literature on current cashmere production practices. This addendum is an illustration of Textile Exchange's "LCA+" approach, which acknowledges the need for a holistic understanding of impact beyond what is covered in traditional LCA methodology. Although this addendum does not provide a quantitative assessment of social impacts, it highlights the importance of considering social issues alongside environmental ones, and offers a foundational overview of the key human rights risks associated with cashmere production systems. This study does not assess animal welfare.

3. Goal of the study

3.1. Goal

The study investigated the environmental impacts of cashmere production to provide information to the global cashmere industry, consumers, brands, and stakeholders. The study specifically aimed to quantify these impacts following the requirements of ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b). The study included primary data inventories of production and primary processing in each country.

3.2. Intended audience and use

The results of this study are intended to inform decision-makers in the cashmere 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 cashmere production. The study aims to support cashmere industry stakeholders in making more informed, data-driven decisions about how to reduce supply chain impacts, improve the sustainability of cashmere production, and guide future research.

Additionally, the findings will contribute to the development of more accurate environmental performance benchmarks for the cashmere industry, and provide insights into best practices for sustainable production. The study will be communicated through various channels, including reports, presentations, industry meetings, and academic publications, to ensure wide dissemination of the results and foster dialogue on how to address the challenges identified.

The LCI dataset results generated from this study are intended to be submitted to established platforms such as the Environmental Footprint (EF) database, Higg Material Sustainability Index (Higg MSI), World Apparel and Footwear LCA Database (WALDB), and the Textile Exchange data library, subject to alignment with each platform's submission criteria and approval processes. The method documented and applied in this report is the preferred approach for interpreting the results, but we acknowledge that some databases have proscriptive requirements covering some aspects of the study. If method differences exist between databases, it is possible that the results will also differ despite utilizing the LCI dataset from the present study.

3.3. Comparative assertions

This study does not constitute a comparative assertion as defined by ISO 14044 (ISO, 2006b). The results are specific to the studied regions and production systems, and should not be used for direct comparisons with other fibers or between production systems without careful alignment of functional units, system boundaries, data sources, and methodological assumptions.

Life Cycle Assessment studies 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.

3.4. 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* (ISO, 2006b). The standard provides a globally recognized framework that ensures methodological rigor, transparency, and consistency in Life Cycle Assessment.

The following key aspects of ISO 14044 (ISO, 2006b) were applied.

3.4.1. Goal and scope definition

The study clearly defined its objective, system boundaries, functional unit, and the intended use of the results. These elements were tailored to the specific context of cashmere production in Mongolia and China, ensuring the relevance and robustness of the assessment.

3.4.2. Inventory analysis

Inventory data was collected and processed in accordance with ISO 14044 (ISO, 2006b) requirements for data quality and representativeness. Regional and production-specific data was used where possible, and data sources and assumptions were transparently documented.

3.4.3. Impact assessment

The selection and application of impact categories followed ISO 14044 (ISO, 2006b) guidelines, ensuring that the relevant environmental aspects were appropriately assessed. The chosen categories reflected the study's goals and the environmental relevance of key processes. The selection criteria for impact categories included both key environmental indicators commonly reported in other livestock LCA studies. The impact assessment included impact categories listed in the Product Environmental Footprint (PEF) and Higg MSI methodologies.

3.4.4. Interpretation

Results were interpreted in line with ISO 14044 (ISO, 2006b) provisions, including identification of limitations, key assumptions, and sources of uncertainty. These were clearly communicated to support informed use of the results and to avoid misinterpretation.

By following ISO 14044 (ISO, 2006b), this study ensures that its approach, findings, and conclusions meet internationally accepted standards for quality and transparency in LCA.

4. Scope of the study

4.1. Product system(s)

Cashmere goats are a breed of domestic goat (subspecies *Capra aegagrus hircus*) that produce a coarse outer coat (guard hair) and fine undercoat. The latter grows during summer, ahead of the winter months, when it provides thermal insulation for the animal (Nocelli et al., 2020). The undercoat of cashmere fiber is used in garment making. Cashmere is typically harvested by combing or shearing. The subsequent processing includes cleaning and scouring to remove dirt and grease, as well as dehairing to remove residual guard hair (Hunter, 2012).

Cashmere production systems vary across ecological regions and cultures (Morton et al., 2024), and can be broadly grouped into nomadic, sedentary extensive grazing systems, and farmed systems. Nomadic grazing systems are typically characterized by extensive grazing practices and often operate without formal land tenure arrangements, where herders move their herds seasonally to access fresh pastures, a practice known as transhumance. Most nomadic herders have fixed shelters for winter and spring, which they may use for up to six months to protect their livestock from cold winter conditions. Purchased inputs into the system are typically very low, with some herders purchasing a small amount of feed for the winter and cutting hay in the autumn to provide supplementary feed. Sedentary grazing systems are based on fixed, privatized land and typically involve housing animals in permanent shelters for at least three months during winter, often due to seasonal grazing bans. Lastly, farmed systems represent a more intensive management approach where goats are kept in enclosures for more than three months of the year and provided with supplementary feed, and grazing of pastures occurs for a shorter period from late spring to autumn, matching the period of peak pasture availability. Typically purchased inputs for farmed systems include fertilizer, corn, and hay.

Both Mongolia and China experience extreme winter weather events (known as dzuds in Mongolia and snow emergencies in China), which are often exacerbated by summer droughts followed by harsh winters. These conditions can lead to significant livestock mortalities and pose challenges to maintaining livestock productivity. These weather events occur sporadically, and their management has a significant impact on long-term livestock numbers, live animal sales, and productivity.

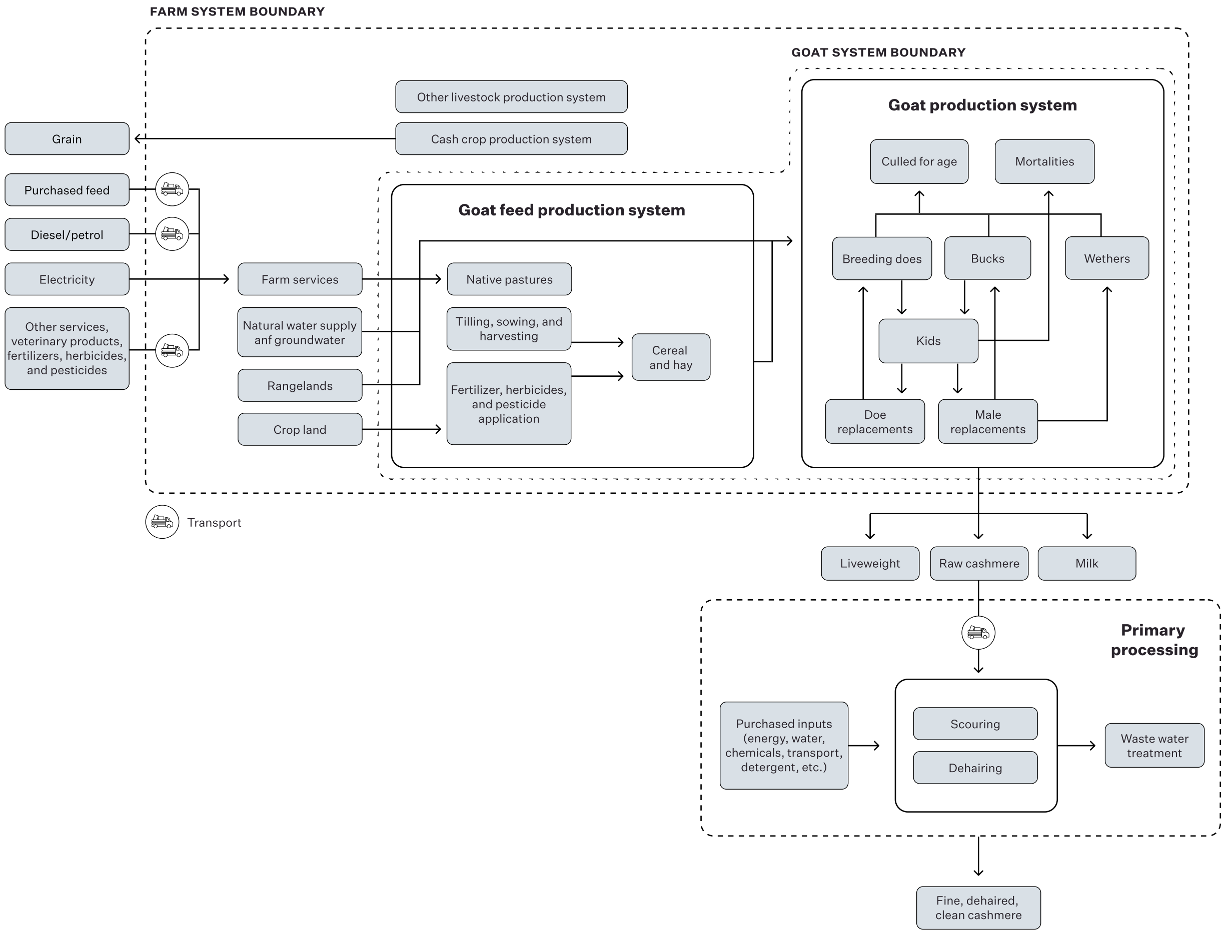
4.2. Product functions(s) and functional unit

The primary function of the product studied is to provide clean, dehaired cashmere fiber, which is then processed into textiles for various uses, such as clothing, accessories, and other products. The functional unit was reported for each key stage in the supply chain, including the primary production of cashmere to the farm-gate (or herder-household gate), as “1 kg of raw cashmere at the primary production gate” and, from the primary production of cashmere through to processing-gate, as “1 kg of fine dehaired cashmere.”

4.3. System boundary

The system boundary included all supply chain processes associated with the primary production and primary processing of cashmere (Figure 1). The study excluded downstream processes such as 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, regardless of production system type. This is distinct from "farmed system," which specifically describes one of the production systems characterized by enclosed management and higher input use.

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



4.4. Allocation

At the primary production stage, there are a number of co-products, including milk, live animals for meat consumption, and cashmere. Cashmere herders typically operate mixed species herds, which can include sheep, cattle, yaks and/or camels and, in China, herders may also produce grains or other crops. These mixed production systems were handled by system sub-division, and accounting for the cashmere goat production system separately where possible. Shared inputs between livestock species, including land area and energy use, were divided based on stocking rates derived from livestock units (in this case, sheep units) as a standardized measure, and the total number of head of each animal species reported from the survey. To reduce the burden of data collection, only total head numbers were requested for non-goat species. The subdivision of resources was conducted assuming similar sex and age structures across species.

Handling co-production of cashmere, liveweight for meat consumption, and milk for dairy products, was modeled using a biophysical method based on protein, similar to the method recommended for wool (International Wool Textile Organisation (IWTO, 2016)) developed by Wiedemann et al. (2015). Biophysical methods based on the energy requirements of the animal, and economic allocation, were used for sensitivity analysis. The application of a biophysical method based on energy requirements follows recommendations in FAO (2016) and PEF (European Commission Directorate-General for Environment, 2021). However, the available guidance for implementing energy allocation is not sufficiently specified or operationalized to ensure consistent application. To maintain transparency and scientific defensibility, this study evaluated several applications of the energy allocation approach and presents the results in the sensitivity analysis. The unresolved methodological issues surrounding energy allocation extend beyond the scope of this LCA and are more appropriately addressed in a dedicated methodological paper, where the options, assumptions, and implications can be fully documented and tested.

At the primary processing stage, no other co-products were identified. Waste products were disposed of via municipal waste treatment routes or was managed as a residual with no environmental impact. All impacts at the primary processing stage were allocated to the clean, dehaired fiber.

Further details are provided in section 5.11 Allocation procedures.

4.5. Impact assessment

The impact assessment included categories in PEF version 3.1 (European Commission Directorate-General for Environment, 2021) (Table 1) and the Higg MSI version 2.0 (Cascale, 2024) (Table 2).

Table 1: 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 (GWP100) AR6	kg CO2 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

Impact category	LCIA method	Unit	Reference
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	Dimension less (pt)	LANCA version 2.5 (Horn & 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 2: Impact assessment methods used in the Higg MSI version 2.0

Impact category	LCIA method	Unit	Reference
Climate change	IPCC AR6 GWP 100, excluding biogenic CO2	kg CO2 eq	Intergovernmental Panel on Climate 100, excluding biogenic change. IPCC Sixth Assessment Report (IPCC, 2021)
Eutrophication	CML—IA baseline 2013	kg PO4- eq	Center of Environmental Science of Leiden University (CML), 2013. CML-IA Baseline (CML, 2016)
Abiotic resource depletion, fossil fuels	CML—IA baseline 2013	MJ	Center of Environmental Science of Leiden University (CML), 2013. CML-IA Baseline (CML, 2016)
Water resources depletion/scarcity	AWARE EF Method*	m3	Available WAter REmaining (AWARE) model (Boulay et al., 2018; UNEP/SETAC, 2016)
Chemistry	Semi-quantitative impacts (Usetox) + qualitative modifiers	Chemistry units	USEtox (2024) and SAC Chemistry Task Team, 2018 (Cascale, 2024)

4.6. Assumptions and limitations

The scope of this study reflects constraints related to available resources, time, and the objectives defined by the commissioning parties.

The data collection period overlapped the 2022–2023 Mongolian dzud, which was not a typical year. To reduce inter-annual variability, regionalized data was used to calculate five-year averages; however, this remains a limitation.

The stratification of regions was reviewed extensively during the scoping phase, in consultation with in-country experts, including representatives from the Mongolian National Federation of Pasture User Groups (NFPUGs), the Sustainable Fibre Alliance (SFA), Good Growth, and the Mongolian Academy of Sciences. Sampling was based on a balance between representativeness and logistical feasibility, which limited dataset size and may reduce the representativeness of results. In China, data was collected predominantly from farmed systems and was not representative of some of the major production regions, such as Inner Mongolia.

The survey data relied on translation and expert facilitation. However, potential issues in translating technical terms, and the absence of record keeping among herders, may have affected data accuracy. Responses were verified for plausibility, but estimation bias may remain.

Due to China's data security laws (National People's Congress, 2023), spatial data was unavailable, and case studies could not be conducted. This limits the resolution of land use, and land use change assessments, and increases uncertainty in associated impact models. These constraints are not unique to this study.

In the Cashmere LCA study, the project team invested significant time attempting to establish relationships with Chinese universities. However, the recent data security laws remained a substantial barrier to progress. This context is essential to understanding the limitations of the current LCA and the uncertainty associated with Chinese data inputs. Future studies would benefit from structured collaborations with Chinese institutions, long-term engagement strategies, and clearer data-sharing agreements to improve transparency and data quality. Input data was collected by trained in-country field staff, but herders typically maintained few auditable records. Data was independently collected and cross-checked with regional averages, and corrected where outliers were observed. Nonetheless, limitations in data quality existed, resulting in quantified uncertainty in the results. Further research with larger, more diverse samples, and case study visits in China, would improve the representativeness of results for the industry.

Additionally, cashmere production has a history spanning thousands of years in these regions, but it is acknowledged that practices have changed in recent decades, particularly with respect to higher stocking rates. It would be informative for the industry to have a comparison between the findings of the present study and traditional practices in order to examine the marginal changes that have occurred and the environmental impacts of these changes.

This study uses background datasets from the Ecoinvent 3 database for purchased feed processes and purchased inputs into both the primary production and primary processing stages to estimate environmental impacts. There were no Mongolia-specific processes available and only a limited number of China-specific datasets. When country-specific data was unavailable, global (GLO) or "rest of world" (ROW) datasets were used instead. The representativeness of these substitute datasets is unknown.

There was a range of methodological limitations with respect to soil carbon assessment. The IPCC Tier 1 stock change framework was adopted to ensure consistency across management systems and transparency in assumptions, although it applies generalized factors that do not capture local heterogeneity or management nuance, potentially over- or understating impacts.

Beyond the accounting method used, further limitations existed with the attribution of soil carbon loss to the grazing system because of the influence of climate change on soil carbon losses. This is discussed and examined in the sensitivity analysis.

4.7. Data requirements

This study defined specific data requirements regarding the types, sources, and quality of data used across the product system. Primary data was collected for cashmere production and primary processing in China and Mongolia. This data was sourced directly from herders and processing facilities, using structured surveys conducted by in-country personnel. Data included herd sizes, cashmere production, milk and meat production, feed practices, land use, energy consumption, water use, and outputs. Secondary data was used to model background processes and upstream activities, such as fuel combustion, transport, chemical production, and general infrastructure. The background data was primarily sourced from the Ecoinvent 3 database.

Data quality requirements were established to ensure consistency and relevance across the study, with the aim of meeting the data quality requirements set out in the International Reference Life Cycle Data System (ILCD) Handbook (European Commission—Joint Research Centre—Institute for Environment and Sustainability, 2010). Primary data from farms or herders was collected for the September 2022 to August 2023 production year through field surveys and interviews. To improve representativeness for Mongolia, and account for inter-annual variability, regional datasets (for example, from the Mongolian Statistical Information Service) were averaged over a five-year period (2019–2023). Data quality was assessed separately for primary and regional data sources, and the combined data quality rating reflected the weighted contribution of each, as detailed in Appendix C–Data quality rating method and criteria (ILCD compliant). Primary data was validated against industry averages and expert input. A consistent system boundary and functional unit were applied, and all datasets were assessed for alignment with the study's goal and scope.

Insights from the Fourth National Communication of Mongolia (Ministry of Environment and Tourism of Mongolia, 2024) and the UNFCCC Report from China Convention to combat desertification (Government of China, 2023), including reported degradation levels, were incorporated where relevant. However, due to the lack of additional spatial data, a uniform distribution of degradation levels across all agroecological zones was assumed for Mongolia. This is recognized as a limitation of the analysis.

The data quality rating (DQR) method was applied to assess each dataset's reliability and appropriateness, with full documentation presented in Appendix C–Data quality rating method and criteria (ILCD compliant).

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 were <1% of the 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 fiber 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 fiber (Wiedemann et al., 2016, 2020).

4.8. Software and database

The life cycle modeling 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 (ISO, 2006a) and 14044 (ISO, 2006b) standards.

4.9. Critical review

This study underwent an external critical review in accordance with ISO 14071 (ISO, 2024), fulfilling the requirement to ensure adherence to the relevant standards outlined in ISO 14044 (ISO, 2006b). The critical review was conducted by qualified, independent experts who were not involved in the study. Their role was to assess the transparency, consistency, and scientific rigor of the methods, data, assumptions, and results. The review focused on evaluating the goal and scope definition, methodology, data quality, allocation methods, and interpretation of findings. Recommendations arising from the review process were addressed in the final report to enhance its accuracy, robustness, and compliance with ISO standards. The final critical review letter is provided in Appendix A–Critical review statement.

4.10. Intended audience and use

The intended use of the study has shaped several aspects of its methodological design. Given its role in supporting both internal sustainability insights and communication with external stakeholders, the study has adopted primary data for key processes, complemented by secondary datasets. Although not intended to support comparative assertions between fibers, the study has been designed with transparency and reproducibility in mind to enable meaningful interpretation of the results. In line with ISO 14044 (ISO, 2006b), no public comparisons with other products are made, and the study does not support claims of superiority unless methodological equivalence is established. The intended use also informs the need for clear communication of assumptions, limitations, and uncertainties within the results.

This report is structured as a full technical report intended for expert review and internal use, with sections suitable for external communication where appropriate.

5. Life cycle inventory analysis

5.1. Stratification

Data was collected from 170 herders and farmers across Mongolia and China across two production systems (Table 5). A small number of semi-nomadic farms were also assessed, but considering the small sample size (n = 4), they were combined with the farmed systems for analysis. The sample size was stratified by cashmere production volume, herder household size, geographical zone, and management practices. The study included only regions where cashmere was produced for international markets. In Mongolia, it was assumed that all provinces produce cashmere for international markets. In China, the major cashmere regions for international markets include Inner Mongolia, Shaanxi and Ningxia. The selection of provinces, and subsequently herder households and farms for data collection, considered a balance between sample size and 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 the Mongolian National Federation of Pasture User Groups (NFPUG), the Sustainable Fibre Alliance (SFA), Good Growth, and the Mongolian Academy of Sciences. The final sample size, selected aimags/provinces, and number of herders per region, were agreed upon through this stakeholder engagement process, which aimed to balance geographic diversity, production relevance, and feasibility of data collection. Some cashmere-producing regions have been excluded, and this is a limitation of the study.

5.1.1. Selection of provinces (Mongolia)

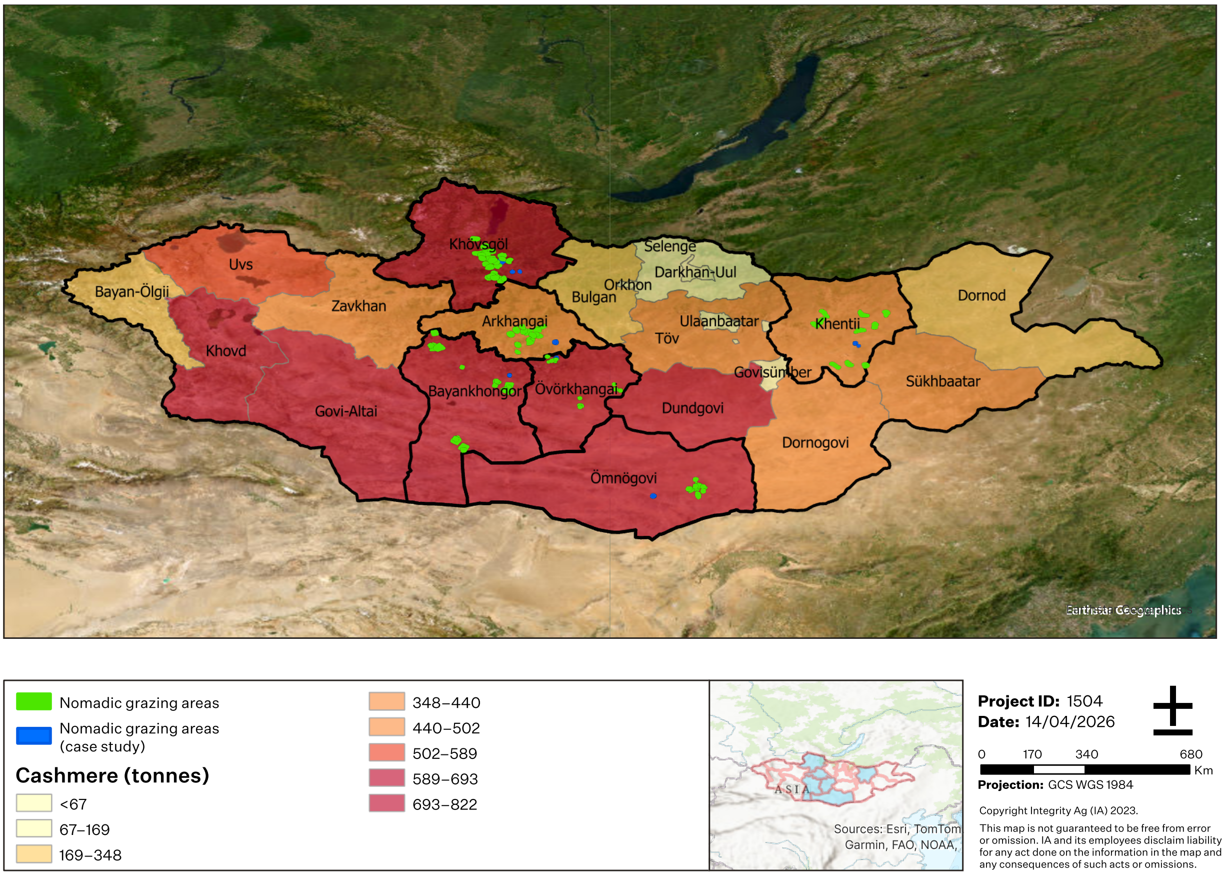
The following process was used for the selection of provinces:

1. Provinces that produced less than 4% of total cashmere production for Mongolia were screened out.
2. The geographical zones for the remaining provinces were compared. The three main geographical zones in Mongolia include the Forest Steppe, Steppe, and Desert Steppe.

The six selected provinces represent 47% of Mongolian cashmere production in 2023.

The provinces selected in this study include Arkhangai, Bayankhongor, Khentii, Khövsgöl, Ömnögovi and Övörkhangai (Figure 2). The herders were then selected and asked to participate in the study (Table 3).

Figure 2: Geographical regional (aimag/province) hotspot analysis of cashmere production volumes in 2023.



The color scale from yellow, orange to red indicates regions from low to high volumes of raw cashmere production. The provinces selected in this study include Khövsgöl, Arkhangai, Bayankhongor, Övörkhangai, Ömnögovi, and Khentii, and are outlined in black.

Table 3: Number of herders surveyed per aimag in the nomadic grazing system

Aimag	Sample size
Arkhangai	16
Bayankhongor	21
Khentii	11
Khövsgöl	26
Ömnögovi	15
Övörkhangai	21

5.1.2. Selection of provinces (China)

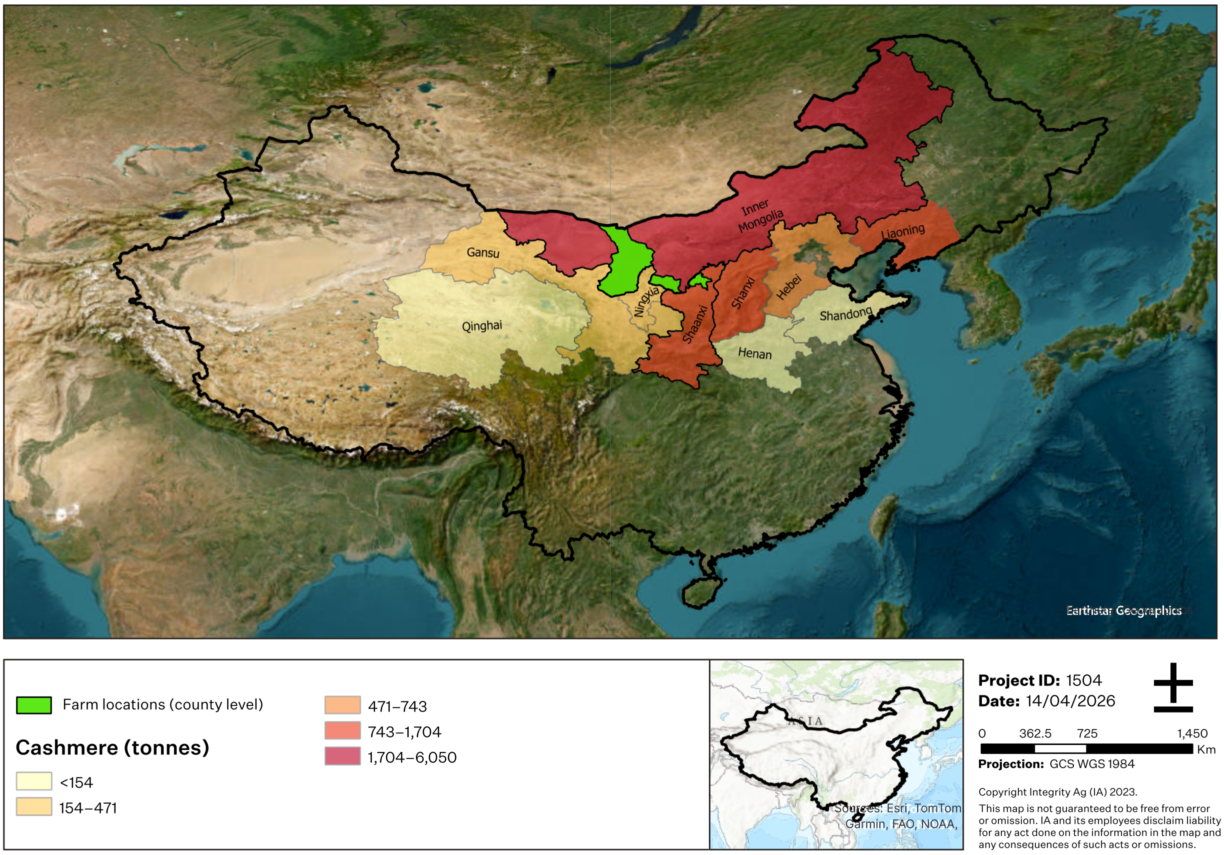
The following process was used for the selection of provinces:

1. Provinces that produced less than 4% of total cashmere production for China were screened out.
2. Provinces that did not produce cashmere for international markets were screened out.
3. The geographical zones for the remaining provinces were compared.

Inner Mongolia and Shaanxi (Figure 3) were the two major regions, which represented 46% of Chinese cashmere production in 2020, and cover geographical zones of cashmere production for international markets. In these two regions, 40 farms were surveyed from Etuokeqian Banner (Inner Mongolia), four farms from Alashanzuo Banner (Inner Mongolia), and 16 farms from Yuyang District (Shaanxi), where existing supply chain relationships enabled engagement with farmers (Table 4). While the sample was not representative of all Chinese cashmere production systems, it reflects some practices typical of the Alashan-Ordos plateau region, which includes desert and desert-steppe transition zones.

Due to the data security law (National People's Congress, 2023), which limited the collection and distribution of spatial data in China, the farms were located only at the county jurisdiction level.

Figure 3: Geographical regional hotspot analysis of cashmere production volumes for international markets in 2023.



The color scale from yellow, orange to red indicates regions from low to high volumes of raw cashmere production. The regions selected in this study include Inner Mongolia and Shaanxi, and are outlined in black. The farms were located in Etuokeqian Banner, Alashanzuo Banner, and Yuyang District, and are highlighted in green.

Table 4: Number of herders surveyed per county for the farmed system

County	Sample size
Etuokeqian Banner	40
Alashanzuo Banner	4
Yuyang District	16

Goat production primary data collection

Field visits were conducted to survey herd inventory numbers and animal weights, herd characteristics, camp locations, grazing areas, estimates of overlap in grazing areas with other herders, crop and fodder production, energy use, water sources, purchased inputs, average price of products sold, goods and services, and transport. All surveys and supporting guidance materials were translated from English and made available in Mongolian and Chinese. For each herder household in Mongolia, a single land assessment visit (rapid assessments as described in Appendix B– Additional information on data collection and modeling) was conducted, during which a minimum of 10 field surveys were completed. These datasets included spatially explicit information on land use classification, land condition score, ground cover, slope, pasture height, and the presence of vegetation. Two herder households per aimag were randomly selected for additional data collection on live weights and animal age, covering a representative sample of their herd. A minimum of 14 goats were weighed, with an even split between males and females across the following age groups: two goats < 1 year of age, four goats 1–2 years of age, four goats 2–4 years of age, and four goats >4 years of age. For each aimag in Mongolia, one herder household was selected, and a more detailed field assessment case study was undertaken. This included collecting additional data on livestock weights and inventories, and land impacts, including pasture and soil samples (Appendix B– Additional information on data collection and modeling). Field visits were completed between August and September 2023 in Mongolia, and from August to October 2024 in China. Hence, data points based on one-time measurements, such as soil samples and land use assessments, represent conditions only at the time they were collected. However, the survey period for which livestock inventories, grazing areas, and purchased inputs were collected covered the 2022–2023 production year in both countries. Respondents were asked to report on herd inventories, production, and management practices for the preceding 12–month period (September 2022 to August 2023). This approach was used to ensure that the data reflected a consistent and recent production cycle across all sites. Field data (pasture, soil, land assessments) was representative of the sampling season, but herd characteristics, production data, and purchased input data was representative of a 12–month period. Although the case study visits were for a limited number of herders, they provided an internal comparison within each region. Case study data collection, weighing of livestock, and field assessments were not possible in China due to the data security law (National People's Congress, 2023), which limited the collection and distribution of spatially explicit data. In the sampling period, Mongolia experienced a dzud event (National Agency Meteorology and Environmental Monitoring, 2023).

The data was reviewed and processed by the research team. All qualitative responses were translated from Mongolian or Chinese into English for analysis. Outliers were identified for each parameter and were removed when they did not comply with the structure of the biological model for goats—for example, when values fell outside the range of biological possibility or violated mass balance principles. In cases where a data point was removed, it was replaced with the normalized mean value for the corresponding production system to maintain consistency in the dataset. The herd data was modeled over one complete production cycle from the inventory of breeding does, replacement does, wethers, bucks, and kids. Inventory data was averaged for each province and then weighted by cashmere production volume (Table 5). The outputs from the modeled herd are shown in Table 6.

5.2. Goat production regional data

Noting recommendations from FAO (2016), a multi-year average was preferred to improve representativeness of the baseline result, particularly to average the impact of the dzud observed in the assessment year in Mongolia with more typical production years. Regionalized datasets were developed by augmenting the model with data from the Mongolian Statistical Information Service (MSIS) (National Statistics Office of Mongolia, 2024a) to generate a representative herd structure and level of production, including representative mortality, kid survival per breeding female, and cashmere production. This provided a dataset reflective of a five-year average performance (Table 5). This was inclusive of the dzud year. Productivity parameters calculated from these national statistics include mortality rate (%), survival of young animals per 100 breeding females (%), cashmere yield per goat (kg), and stocking rate (SU/ha). The model used MSIS values for mortality rate (%) and the survival of young animals per 100 breeding females (%) from 2019 to 2022. For 2023, data from the primary dataset was applied. A five-year average was then calculated by combining the four MSIS-based years with the 2023 dataset value. For cashmere yield per goat (kg), and stocking rate (SU/ha), the MSIS data was averaged over a five-year period (2019–2023). The farmed system dataset was considered temporally representative.

Case study land assessment data was incorporated as a background dataset to inform regional assumptions for the LANCA assessment, and for digestibility and crude protein (CP) parameters. This data was not used as primary input, as it represented spot assessments rather than comprehensive time-series measurements. While the current analysis uses this data only for contextual support, a subsequent paper will undertake further analysis leveraging this dataset more extensively.

5.3. Herd model

A herd model was developed based on the IPCC feed intake model, which was implemented for each individual class of animals in the herd. Classes modeled included breeding does, non-breeding does, replacement does, bucks, wethers, and kids. Province-level inventories were averaged and then weighted by provincial cashmere production volume to generate management system-level LCI reported in Table 5 (inputs), Table 6 (outputs), and Table 7 (ammonia and livestock GHG emissions). Primary data (herd structure, liveweights, sales/output, inputs, water sources, land, and grazing) was compiled from structured field surveys and case-study assessments. Visual vegetation assessments were combined with laboratory analyses of pasture CP, DM, NDF, and ADF to inform the energy quality of diets. For China, diet quality parameters were taken from the literature where case-study sampling was not feasible. Primary data was screened and outlier data points were removed when values fell outside the range of biological possibility or violated mass balance principles. In cases where a data point was removed, it was replaced with the normalized mean value for the corresponding production system to maintain consistency in the dataset. The herd data was modeled over one complete production cycle from the inventory of breeding does, replacement does, wethers, bucks, and kids. Inventory data was averaged for each province and then weighted by cashmere production volume (Table 5). The outputs from the modeled herd are shown in Table 6.

Table 5: Land, water, and herd characteristics averaged for nomadic grazing system (n=110) and farmed systems (n=60). Input parameters were determined from the primary datasets unless otherwise indicated in the footnotes

Parameters	Nomadic grazing system	Farmed system
Land and water resources		
Annual herder's stocking rate [herder's livestock] (SU/ha)[1]	1.1	1.5
Confinement feeding stocking rate (SU per m^2)	n.a.	3.2
Estimated total grazing pressure [livestock + wild herbivores + other herder's livestock] (SU/ha)	2.8	n.a.[2]
Grazing area allocated to goats (ha)	337	174
Total cropped (ha)	n.a.	0.6
Allocation of cropping to goats (%)	n.a.	15%
Number of days of confinement feeding (days/year)	n.a.	155
Irrigation volume (m^3/ha cropped/year)	n.a.	2850
Natural water supply (rivers, lakes, stream, snow) (% of total water supply)	44%	0%
Ground water supply (% of total water supply)	56%	100%
Estimated water supply losses (%)[2]	10%	10%
Goat herd		
Mean herd size (head number) including kids	396	522
Mean herd size (SU) including kids	356	470
Breeding does (number mated)	144	171
Non-breeding does (head number)	43	81
Bucks (head number)	2	7
Wethers (head number)	110	106
Kids weaned (head number)	97	153
Doe mature weight (kg/head)	37	36
Buck mature weight (kg/head)	49	53
Doe cull rate (% of total does)	20%	25%
Wether cull rate (% of total wethers)	37%	no sales[3]
Kid survival as a proportion of breeding females (%)[1]	67%	89%
Adult mortality (%)[1]	6%	5%
Average adult sale age (years)	>4 years	>3 years
Average adult sale weight (kg)	37	36
Kid sale age (months)[3]	no sales	18
Kid sale weight (kg LW)[3]	no sales	27
Feed assumptions		
Crude protein (% of DM)[4]	10%	11%
Digestibility of feed (% of gross energy)[4]	57%	63%
Purchased supplementary feed5		
Wheat (kg/SU/year)	0.6	0.0

Parameters	**Nomadic grazing system**	**Farmed system**
Bran (kg/SU/year)	2.0	0.0
Barley (kg/SU/year)	0.3	0.0
Oats (kg/SU/year)	0.1	0.0
Rice (kg/SU/year)	0.3	0.0
Maize (kg/SU/year)	n.a.	15.1
Alfalfa (kg/SU/year)	n.a.	1.4
Hay/grass/green fodder (kg/SU/year)	1.1	0.4
Protein supplement (kg/SU/year)	0.1	0.0
Liquorice (kg/SU/year)	n.a.	0.2
Purchased inputs for crop production		
Ammonium phosphate fertilizer (kg/ha)	n.a.	2.5
Potassium sulfate fertilizer (kg/ha)	n.a.	1.9
Zinc sulfate fertilizer (kg/ha)	n.a.	0.8
Urea (kg/ha)	n.a.	2.3
Water-soluble fertilizer (kg/ha)[6]	n.a.	11.6
Herbicide (active ingredients: atrazine, mesotrione, nicosulfron)	n.a.	0.2
Energy[7]		
Electricity (kWh/SU/year)[8]	0.0	3.3
Petrol (L/SU/year)	1.0	2.1
Diesel (L/SU/year)	0.6	0.2
Veterinary products		
Average dose of internal and external parasite treatment (mg/SU/year)	16	2258
Number of head treated (internal parasites) (SU/year)	285	474
Average vaccine dose (mg/SU/year)	1111	1111
Number of head vaccinated (SU/year)	285	226

[1] For the nomadic grazing system, stocking rate, adult mortality rate, and kid survival as a proportion of breeding females were calculated from the Mongolian Statistical Information Service (MSIS) (National Statistics Office of Mongolia, 2024a). (Appendix B– Additional information on data collection and modeling). For the farmed system, stocking rate, mortality rate and kid survival as a proportion of breeding females was determined from the primary dataset.

[2] Farmed systems were fenced, preventing grazing by other people's livestock, and land areas were relatively small with minimal reported wild herbivores.

[3] In the nomadic grazing system, kids were not sold but retained in the herd, as retaining kids is a cultural practice and essential to sustain herd numbers due to lower productivity performance. In the farmed systems, kids were sold as part of their income strategy, reflecting a more commercial approach to herd turnover and liveweight production. Hence, the wether class sale was zero as they were sold as "kids" at 18 months of age.

[4] For the nomadic system, crude protein was calculated from Yoshihara et al. (2021). Feed digestibility was initially calculated using primary case study data from a single time point, then extrapolated to represent seasonal variation based on additional insights from Kemp (2019). For the farmed system, crude protein was calculated from the average crude protein values reported (Wang, 2018). Feed digestibility was estimated using the average dry matter digestibility (DMD) of desirable pasture species during non-winter months from Kemp (2019), and the average DMD of maize seed, flaxseed, and sugar beet to reflect the higher digestibility of supplementary winter feed, based on Kemp and Michalk et al. (2008).

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

[6] *The water-soluble fertilizer used was an NPK formulation, assumed to contain equal proportions of nitrogen, phosphorus, and potassium. It was assumed to be a 20-20-20 blend, meaning the fertilizer contains 20% nitrogen, 20% phosphorus (as P_2O_5), and 20% potassium (as K_2O) by weight. These percentages are standard in fertilizer labeling and indicate the relative nutrient composition.*

[7] *Petrol and diesel were used for the transport of goods and services, and transport on farms.*

[8] *Herders self-generated some electricity from solar, which was not metered. There was no usage of grid-supplied electricity.*

n.a. = not applicable to the production system
SU = sheep unit

Table 6: Modeled outputs for nomadic grazing system and farmed system based on the primary datasets and secondary data for temporal representativeness (2019–2023).

Herd outputs	Nomadic grazing system	Farmed system
Raw cashmere per goat (kg/head combed or shorn/year)	0.4	0.8
Total kg liveweight sold or used for consumption (kg LW/year)	3066	4534
Total raw cashmere sold or used for consumption (kg/year)	96	215
Total liters milk sold or used for consumption (L/year)[1]	549	14
Raw cashmere sales per breeding doe (kg/breeding doe/year)	0.7	1.3
Raw cashmere sales per SU (kg /SU/year)	0.3	0.5
Live weight output per breeding doe (kg LW/doe/year)[2]	21.2	26.4
Live weight output per SU (kg LW/SU/year)[2]	8.6	9.7
Milk output per breeding doe (L/doe/year)	3.8	0.1
Milk output per SU (L/SU/year)	1.5	<0.1
Protein allocation to cashmere (%)	11%	15%
Protein allocation to meat (%)	85%	85%
Protein allocation to milk (%)	4%	<0.1%
Protein per SU (kg protein/SU/year)	1.5	1.7
Head sold (head/year)	79	135
Head sold (%)	20%	26%
Total dry matter intake (kg/year)	136174	136689
Total flock water intake (L/year)	408523	410066
Total herd land occupation (ha/year)[3]	337	174

[1] *For the nomadic grazing system, the average milk yield of 549 L per herd per year reflects the full sample of 110 farms within the nomadic grazing system, of which only 27 engaged in milkings. For the farmed system, the average value of 15 L per herd per year reflects the entire sample of 60 farms, of which only four engaged in milking. This limited participation in milk production naturally lowers the overall average, making the figure appear low despite being accurate.*

[2] *Live weight output per SU (kg LW/SU), and live weight output per breeding doe (kg LW/doe), refer to the modeled live weight of animals sold or slaughtered from the system, not the live weight of the animals. These values reflect modeled production outputs leaving the system.*

[3] *Total area allocated to goats. The overall grazing area will be larger when goats are co-grazing with other livestock.*

Table 7: Modeled ammonia and livestock greenhouse gas emissions

Herd outputs	Nomadic grazing system	Farmed system
Total enteric methane (kg CH_4/year)	2453	2419
Total manure methane (kg CH_4/year)	39	31
Total direct nitrous oxide from manure and urine (kg N_2O/year)	7	6
Total indirect nitrous oxide from ammonia volatilization from manure and urine (kg N_2O/year)	2	2
Total ammonia from manure and urine (kg NH_3/year)	380	414

5.4. Primary processing primary data collection

The scouring stage involved the washing of cashmere to remove contaminants such as dirt, organic matter, and grease. The cleaned cashmere is then passed through a dehairing machine to remove the coarse guard hair. There were no other co-products or by-products during these stages. Primary data was collected by surveying 11 primary processing facilities in Ulaanbaatar, Mongolia, and seven primary processing facilities in China across Shaanxi and Inner Mongolia. All surveys and accompanying guidance materials were translated from English and delivered in Mongolian and Chinese, respectively. The data collection captured a sample of facilities that process cashmere for international markets, across a range of production types (scouring only, dehairing only, dehair and scouring, and complex facilities including spinning, dyeing, knitting, manufacturing, and finishing) with small to high production volumes. The survey period for primary processing data was from January 1, 2023, to December 31, 2023. Data collection was completed from January 2024 to June 2024 in Mongolia, and from July 2024 to February 2025 in China; all qualitative responses were subsequently translated from Mongolian and Chinese into English for analysis. The processes included in this analysis were scouring and dehairing, and inputs associated with other processes were omitted. Inventory data included all inputs, outputs, and losses for materials, water, fossil energy, electricity, steam, transport, and wastewater treatment (Table 8). Inventory data was analyzed and validated by comparison with previous studies on wool (Wiedemann et al., 2020). Outlier data points were removed from the inventory. The impact of capital infrastructure and machinery was below the cut-off and was excluded. These impacts were excluded because their environmental contribution was expected to be minimal due to long operational lifespans and low relative significance.

Table 8: Inventory data for primary processing (scouring and dehairing) in Mongolia (n=11) and China (n=6), reported per kg clean, dehaired cashmere

Material/process	Unit	Mongolia	China
Input[1]			
Raw cashmere	kg	1.9	2.5
Water	m^3	0.13	0.04
Electricity	MJ	49.7	4.7
Energy, from natural gas	MJ	0.0	25.2
Process steam	MJ	79.5	60.2
Washing detergent	kg	0.02	0.03
Sodium bicarbonate/carbonate	kg	0.01	0.00
Sodium tripolyphosphate	kg	0.00	0.02
Packaging, cotton fabric	kg	n.a.	0.004
Packaging, HDPE	kg	0.01	0.02
Land occupation, industrial area	m2	0.16	0.18
Staff number	FTE	0.00075	0.00094
Staff travel	km	0.00005	0.00007
Raw cashmere import distance	km	0.0045	0.0037
Product			
Dehaired cashmere	kg	1.00	1.00
Waste[2]			
Water, to wastewater treatment plant	m^3	0.13	0.03
Waste, to landfill	kg	0.07	0.13
Residuals, to recovery[3]	kg	0.51	0.56

[1] *Inputs and outputs are reported per kg of clean, dehaired cashmere. For example, while the per-kg value for the raw cashmere import distance may appear low, this is due to the normalization across the total clean, dehaired output. In this case, the average total clean, dehaired cashmere output was 152,893 kg for Mongolia. Therefore, the estimated average import distance is: 0.0045 km/kg × 152893 kg = 688 km. This reflects the actual transport distance of raw material to the facility. The per-kg normalization is standard practice in LCA reporting.*

[2] *The apparent discrepancy in the mass balance arises because a portion of the mass—primarily dirt and grease—is entrained in the wastewater during processing. For example, for Mongolia, the sum of clean, dehaired cashmere (1.0 kg), waste to landfill (0.07 kg), and residuals to recovery (0.51 kg), totals 1.58 kg, leaving a difference of 0.32 kg. This “missing” mass is accounted for by material lost to the wastewater stream, which is measured on a volume basis and thus not easily visible in the mass balance tables. This phenomenon has been consistently observed across all processing plants studied, and it is nearly impossible to achieve a perfectly closed mass balance from direct measurement.*

[3] *Residuals, to recovery were treated as a product with no economic value and no environmental consequences assumed for its disposal.*

5.5. Validation of data

Primary data collected directly from stakeholders (for example, suppliers, processors, or producers) was validated through the following steps:

1. Cross-checking against published literature and industry benchmarks, where available.
2. Internal consistency checks (for example, 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 was reviewed and processed by the research team, and follow-up questions on the data were reviewed by in-country personnel to ensure the data was complete and properly interpreted. Outliers were identified for each parameter and removed only 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. In the nomadic grazing system, less than 0.03% of data points were outliers, while in the farmed system, 0.34% were outliers. For primary processing in Mongolia, 20% of data points were outliers, and for primary processing in China, 24% were outliers. When a data point was removed, this data point was replaced by the normalized mean value for the production system. No herder household, farm or primary processing facility was completely rejected from the analysis.

Secondary data, sourced from the Ecoinvent 3 database, was 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 was subject to quality assessment using a data quality rating (DQR) framework (see 5.12 Data quality rating method).

5.6. Modeling approaches

5.6.1. Feed intake and livestock greenhouse gas emissions

Herd inventory, liveweights, and growth rates were used to model gross energy and manure production. Gross energy and livestock GHG emissions were modeled using IPCC Tier II equations, emission factors, and uncertainty from the 2019 refinement (IPCC, 2019b, 2019a) (Table 11). The dominant plant communities were assessed visually and pasture characteristics (including crude protein, dry matter %, neutral detergent fiber (NDF), and acid detergent fiber (ADF)) were analyzed 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). Literature values were used for China as case study data collection was not possible (Table 6).

5.6.2. Land use and land use change modeling

LU 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 nomadic grazing systems based on the grazing areas assessed, and statistical LUC methods for the farmed system to within the nearest jurisdiction. The Mongolian National Inventory report identified forest land, remaining forest, and land converted to grassland as the key LU and LUC categories (National Inventory Management Team, 2023). Mongolia's forest land is categorized into boreal forests in the north and saxaul forests in the south. For the assessment of LU and LUC GHG emissions, a boreal forest is defined as all lands where trees were 2 m or more in height and canopy cover was at least 10% per hectare (National Inventory Management Team, 2023). A saxaul forest is defined as all lands with saxaul (dominantly *Haloxylon* spp.) at 1 m, with a minimum area of land of 1.0 ha and a minimum tree crown cover of 4.65% (National Inventory Management Team, 2023). The geospatially referenced land classification data from the field assessments was used to inform the land use for the survey period within Mongolia. The land use types identified included grassland, forest, and shrubland. The major land use types observed from satellite imagery for the regional- based assessment in China 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 in Mongolia and China over the most recent 20-year period (2004–2023) within the grazing regions included in the study. This assessment revealed no material impacts from forest LUC in the studied regions; however, the impacts were included for completeness. The spatial resolution of the freely available satellite imagery was not able to detect saxaul forests. Other studies have indicated the total saxual forest area for Mongolia is 2,048,000 ha (±128,500 ha (Government of Mongolia, 2018)) with no changes between 2005 and 2015, indicating no LUC. For these reasons, this study has assumed no LUC in saxaul forests.

LUC GHG emissions and removals were modeled following the PAS standard (BSI, 2011) (to meet the requirements of PEF and Higg), and ISO14067 (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. Emissions and removals from indirect LUC were excluded. Removals of atmospheric CO_2 from LU and direct LUC were excluded, as measures to address permanence were not in place. Of the six land use categories defined in the IPCC (2006d) guidelines, forestland and grassland were the only land use types identified from the land classification Mongolian primary dataset.

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 and grassland, and for soil organic carbon (SOC) in forestland, because there were no land use or management changes in these land types. For grassland SOC, however, evidence of ongoing rangeland degradation in Mongolia and Inner Mongolia has been observed (Chan et al., 2023; Densambuu et al., 2018; Hilker et al., 2014; Jamsranjav et al., 2018; Sainnemekh & Aduut, 2022; Sheehy & Damiran, 2016), and this constituted a management change under Tier 1. Therefore, Tier 1 SOC stock-change factors for degraded grassland were applied to estimate a net SOC loss, parameterized using the cited literature and validated through consultation with local rangeland experts. However, these losses were not directly attributed to cashmere production for reasons discussed in the following sections.

Soil carbon (grassland remaining grassland)

The Mongolian Second Assessment Report on Climate Change (Dagvadorj et al., 2014) determined SOC loss rates derived from the Century model (Parton et al., 1994), which assessed the impact of climate change on SOC loss but did not examine grazing intensity. This modeling projected a decline in soil organic carbon (SOC) in the forest steppe and steppe regions by 6.4% and 5.8%, respectively, between 2010 and 2020, and by 8.4% and 9.5% by 2050, relative to 2010 levels. In contrast, smaller reductions were modeled in the desert regions (Dagvadorj et al., 2014), which was also consistent with findings from other studies (Dai et al., 2022). Ulgiichimeg (2021) also reported significant variation in SOC stocks across ecological zones, with lower levels observed in desert areas compared to meadow steppe zones. However, estimating changes in SOC remains challenging when relying on data from a single point in time. An updated model result was presented in Mongolia's Third National Communication (2018), which presents modeling results for various future years, reflecting the combined impacts of projected climate change and moderate grazing intensity. However, the uncertainty of the model results has never been assessed, and the impacts of climate change compared to grazing have not been separated in these studies. Application of the Century model in the peer-reviewed literature predicted a decrease in SOC stock in the period of high grazing intensity (1990–2012) in degraded areas of the forest-steppe in Mongolia (Chang et al., 2015).

Table 9: Projected soil organic carbon loss rates modeled using Century and reported in the Mongolian National Inventory Report (0–20 cm)

Natural zones	Soil organic carbon (t C/ha) 1961–2010	Change % (2020)	Change % (2050)	% change per year from 2010–20201	Carbon loss (t C/ha/year) (2010– 2020)[1]
High mountains	29	−1.02	−1.78	−0.10	−0.03
Forest steppe	54	−6.3	−9.47	−0.63	−0.34
Steppe	33	−5.76	−8.4	−0.58	−0.19
Desert, desert steppe	19	−0.32	−1.06	−0.03	−0.01

[1] *Values estimated from reported data.*

Soil carbon loss has also occurred in Inner Mongolia due to long-term heavy grazing (Kemp et al., 2020). Soil carbon stocks in Inner Mongolia were reported to have declined from 78 t C ha^{-1} to 60 t C ha^{-1} (0–100 cm) from 1963 to 2007, with an average SOC loss of 18 t C ha^{-1} or 0.5 t C ha^{-1} yr^{-1} (Xin et al., 2020). Climate change was considered the primary driver for 15.3–34.9% of the total SOC variations, whereas grazing intensity accounted for <9.5% of the changes. The effect of grazing intensity on SOC has been explored in other studies. In the typical steppe of Inner Mongolia, light grazing intensities had significantly higher SOC than under heavy grazing intensities (Liu et al., 2012). Similarly, higher SOC stocks were observed under light and moderate grazing, compared to overgrazed areas in the central Inner Mongolia Plateau (Xie & Wu, 2016). SOC stocks ranged from 59.8 t C ha^{-1} under light grazing conditions to 31.0 t C ha^{-1} (0–20 cm) under extreme heavy grazing conditions (Xie & Wu, 2016). Zou et al. (2007) observed significantly higher SOC under protected sites (92.3 t C ha^{-1}) (0–10 cm) that had not been grazed in over 22 years, compared to heavily degraded sites (16.9 t C ha^{-1}) (0–10 cm) that had been overgrazed for the past 50 years. A general linear decline in soil carbon was observed as grazing intensity increased above 3.0 stocking equivalents per hectare (He et al., 2012). This is approximately the same as a sheep unit. These studies suggest that grazing pressure and historical management were key factors influencing SOC levels. Limited studies exist that have modeled SOC change at the regional level over Inner Mongolia. One study, using a random forest model, predicted soil carbon sequestration of 14.39 t C ha^{-1} (0–100 cm) from 1982 to 2020 across northwestern China (including Inner Mongolia) (Chen et al., 2023). However, this largely contradicts the carbon loss rates observed in Xin et al. (2020) and Chen et al. (2023), and the trend of soil carbon decline under heavy grazing in the studies cited above. Several of the studies cited here are of the typical steppe. The farms sampled in this study are from the desert steppe region.

There are several challenges and limitations associated with modeling soil carbon loss and integrating these estimates into Life Cycle Assessment (LCA). These can be broadly categorized as follows:

1. **Data limitations**—including insufficient availability and quality of site-specific data related to land-use history, changes in soil carbon stocks, and management practices
2. **Attribution complexity**—difficulties in assigning soil carbon loss or sequestration to specific product systems due to external influences such as climate change, and multi-species or multi-enterprise systems

3. **Measurement and monitoring constraints**—challenges in accurately quantifying soil carbon due to its spatial and temporal variability
4. **Model sensitivity and validation issues**—existing soil organic carbon (SOC) models are often highly sensitive to assumptions and are poorly validated at the product scale.

For these reasons, this study has applied the IPCC Tier 1 methodology for soil carbon stock change to assess land use emissions from the grassland category. Research in China and Mongolia indicates likely soil carbon loss in some regions but does not provide sufficient evidence to distinguish whether these impacts are due to broad-scale, long-term climatic factors such as reduced rainfall, or to grazing pressure. These factors are also interrelated and dynamic; reduced rainfall and diminished pasture growth can intensify grazing pressure. As a result, soil carbon loss was assessed and reported on a per hectare basis but was not attributed to cashmere directly until further evidence is available on how to achieve this attribution in these regions.

5.6.3. Modeling land use and land use change greenhouse gas emissions

Of the six land use categories defined in the IPCC 2006, forestland and grassland were the only land use types identified from the land classification primary data for Mongolia (Table 10). Land use change GHG emissions from the carbon pools (biomass, dead organic matter and soils), were assessed following IPCC Tier 1 equations (Table 11). Since the locations of the farms in China were unknown, LUC GHG emissions were assessed over the nearest known jurisdiction. The GHG emissions were calculated per hectare and used as a proxy for the farms. The time period of assessment was the most recent 20-year period (2004–2023), and an equal discounting approach was applied (BSI, 2011). LU and LUC GHG emissions were reported separately as required by ISO 14067 (ISO, 2018).

Table 10: IPCC land use categories that were detected and assessed

	Forest	**Grassland**	**Cropland**	**Wetland**	**Settlement**	**Other land**
Forest	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 No change detected	G → G Detected, assessed	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

Table 11: 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}) Mongolia and China = 50 t C ha^{-1} climate region = Cold template, dry and high activity clay mineral soils (Table 2.3, IPCC 2006, Chapter 2), and as applied in the Mongolian National Inventory Report 2023 Table 6–11 (National Inventory Management Team, 2023) F_{LU} = stock change factor for land-use systems or sub-system for a particular land-use (dimensionless) Mongolia and China = 0.95 ± 13% (Table 6.2, IPCC 2006, Chapter 6, IPCCIPCC), and as applied in the Mongolian National Inventory Report 2023, Table 6–11 (National Inventory Management Team, 2023), representing moderately degraded grassland F_{MG} = stock change factor for management regime (dimensionless) Mongolia and China = 1.0 (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 A = land area (hectares)	Equation 2.25 IPCC 2006, Volume 4, Chapter 2 (IPCC, 2006a)
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/year $^{-1}$) 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	Equation 2.16 IPCC 2006, Volume 4, Chapter 2 (IPCC, 2006a)

Carbon pool	Prediction equation	Reference
	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}) Mongolia and China= 75 t DM ha^{-1} (boreal forests) (Li et al., 2003; Mokany et al., 2006) Table 4.4 IPCC 2006 Chapter 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. Mongolia and China = 0.51 t C t DM^{-1} (uncertainty 0.47 – 0.55) (Li et al., 2003; Mokany et al., 2006) Table 4.4 IPCC 2006 Chapter 4 (IPCC, 2006b)	
Dead organic matter	Annual change in carbon stocks in dead wood and litter due to land conversion $$\Delta\, C_{\text{DOM}} = \frac{(C_n - C_o) \times A_{on}}{T_{on}}$$ **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 $ha^{-1)}$ Mongolia and China= 27 t C ha^{-1} (cold temperate, dry) (Table 2.2 IPCC Volume 4, Chapter 2) (IPCC, 2006a) 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 one year for carbon losses, and hence T_{on} = zero.	Equation 2.23 IPCC 2006 Volume 4, Chapter 2 (IPCC, 2006a)

For the nomadic grazing system, soil degradation levels were classified according to the Fourth National Communication of Mongolia (Ministry of Environment and Tourism of Mongolia, 2024), which reports that 31.1% of the national pasture monitoring area is non-degraded (Level I), 17.7% is slightly degraded (Level II), 22.4% is moderately degraded (Level III), 17.9% is severely degraded (Level IV), and 11.0% is very severely degraded (Level V), indicating complete loss of pasture quality and quantity. Soil organic carbon (SOC) stocks were obtained from the same report, stratified by agroecological zone. IPCC Tier 1 stock change factors (IPCC, 2006c) were applied to estimate SOC loss associated with each degradation level (Table 12). A uniform distribution of degradation levels across all agroecological zones was assumed, which is acknowledged as a limitation of the analysis (UNFCCC, 2023). Soil degradation levels were classified based on a recent study using GIMMS NDVI and MODIS NDVI datasets (1982–2020), which calculated the Fractional Vegetation Cover (FVC) and Grassland Degradation Index (GDI) (Zheng et al., 2024). Soil organic carbon (SOC) stocks reported for China's desert ecosystems in 2020 were 6.3199 billion tonnes across 208.37 million hectares (Government of China, 2023). This corresponds to a carbon stock of 30.33 t C/ha. IPCC Tier 1 stock change factors were applied to estimate SOC loss associated with each degradation level (Table 13).

SOC loss per hectare per year was calculated using the following equation:

Soil carbon loss per ha per year = (current stock – loss factor × current stock)/time period

Where:

- Current stock is the SOC stock (t C/ha) reported in the national inventory.
- Stock change factor is the proportional SOC loss rate from IPCC Tier 1 guidance.
- Time period is set to 20 years.

Table 12: Areas of land degradation in Mongolia (Ministry of Environment and Tourism of Mongolia, 2024) and associated carbon stock change factor (IPCC, 2006c)

Degradation level	% of total land area	IPCC stock change factor	Uncertainty
Improved grassland	n.r.	1.14	+/– 11%
Non-degraded	31%	1	n.r.
Slightly degraded	18%	0.95	+/– 13%
Moderately	22%	0.95	+/– 13%
Severely	18%	0.7	+/– 40%
Very severely degraded	23%	0.7	+/– 40%

n.r. = not reported

Table 13: Areas of land degradation in China (Zheng et al., 2024) and associated carbon stock change factor (IPCC, 2006c)

Description	% of total land area	IPCC stock change factor	Uncertainty
Non-degraded	25%	1	n.r.
Lightly degraded	30%	0.95	+/– 13%
Moderately degraded	27%	0.95	+/– 13%
Severely degraded	22%	0.7	+/– 40%

n.r. = not reported

5.6.4. Resource use, fossil energy, and water use

Demand for fossil fuel energy was assessed by aggregating all fossil fuel energy inputs throughout the system and reporting these as megajoules (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 5.6.2. Historical LUC from forest to pasture was expected to be low risk for cashmere production, and, hence, the impact 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 water sources (including rivers, lakes, streams, and snow) 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. Regionalized characterization factors from Available WAter REmaining (AWARE) (Boulay et al., 2018; UNEP/SETAC, 2016) were selected.

5.6.5. Eutrophication and ammonia-related impact categories

The major sources of nutrients in the cashmere production system were fertilizer, nutrients in purchased feed, and nitrogen in feces and manure. Nutrient flows were calculated using IPCC Tier II equations from the 2019 refinement (IPCC, 2019b) for nutrient runoff, leaching, denitrification, and ammonia volatilization. Characterization and fate factors from ReCiPe were applied (Goedkoop et al., 2009). Eutrophication associated with nutrients in the production of purchased feed at the primary production stage, and purchased chemicals at the primary processing stage, was calculated using background databases. For ammonia-related impact categories, due to the absence of region-specific CFs for Mongolia and China, a European CF (Greece) was selected based on comparable annual rainfall.

5.6.6. Land use

Mongolia's rangelands have been managed using traditional nomadic pastoralism for hundreds, or possibly thousands, of years. Land is generally shared with multiple livestock species, including goats, sheep, cattle, yaks, camels, and horses. Wild herbivores also graze on the same land. Further, due to the absence of clearly delineated land areas, there is a degree of overlap in grazing from one herder to the next. This creates a unique challenge to allocate land use impacts to cashmere production. Total grazing area was mapped during on-site visits and discussions with herder households. Estimates of other livestock species owned by the herder, estimates of small and large ruminants from other herder households that share the same grazing area, and estimates of wild herbivores for each camp location, were used to determine total grazing pressure for the herder's grazing area. Due to data security laws, the exact locations of farms in China were not disclosed, although the total farm area was provided. To estimate the grazing area allocated to goats, livestock species were converted into a standardized unit called a "sheep unit," which represents the feed requirement of a 50 kg sheep. The total grazing area was then divided proportionally, based on the relative share of each livestock species. This approach allows for consistent comparison of grazing pressure across different animal types, sizes, and ages.

Land use impacts include transformation and occupation impacts. Land use change or land-transformation detection was assessed as described in section 5.6.2. Land use change from forest to pasture was assessed to be low risk from regional mapping assessments, and was assumed to be zero. Land use occupation impacts were assessed using the LANd use indicator value CAlculation (LANCA) model version 3.0, which is detailed in (Beck et al., 2010), and updates provided in later publications (Bos, 2019; Bos et al., 2016, 2020; De Laurentiis et al., 2024). However, the biotic production indicator was calculated using model version 2.5, as the updates introducing the soil carbon layer to replace this indicator have not yet been incorporated into the soil quality index (SQI) score for inclusion in PEF. Land use impacts for Mongolia were calculated using spatial data, which is important in the comparison of agricultural products (Beck et al., 2010; Bos, 2019; Bos et al., 2020). For this reason, the most recent publicly available version (LANCA version 2.5) of characterization factors provided by land use type and country (Horn & Maier, 2018) was not applied. Land use impacts were calculated following a GIS framework for LANCA (Bos et al., 2020) to generate regionalized characterization factors for both Mongolia and China (Table 14). The land use survey data and case study data were used as a background dataset to provide regional context and validate assumptions within the LANCA assessment. Specifically, this data informed parameter ranges for land use characterization and helped check the plausibility of digestibility and crude protein (CP) estimates. It was not used as a primary input because it represents spot assessments rather than comprehensive, longitudinal measurements. The main biome identified as a reference site for Mongolia and China used for the calculation of the regionalized characterization factors is a temperate deciduous forest (Bos et al., 2020). This is problematic because (1) areas of land used for agriculture will often have different soil and land characteristics, than remaining natural vegetation on unproductive land, and (2) forest potential is limited to areas above a minimum benchmark of rainfall. If land used for agriculture is compared to a "forest" reference site but does not have the biological potential to establish trees, then this is a biased comparison and an ineffective benchmark. This remains a limitation in the analysis.

Table 14: Regionalized characterization factors and soil quality index score for the calculation of land use impacts

Indicator	Abbreviation	CF name	Unit	Övörkhangai	Bayankhongor	Arkhangai	Khövsgöl	Ömnögovi	Khentii	Inner Mongolia	Shaanxi
Erosion resistance	EW	Erosion potential[1]	$kg/m^2 \cdot a$	-2.8	-13.9	0.8	1.9	-6.3	0.5	0.3	12.5
Mechanical filtration	MF	Infiltration reduction potential	$m^3/m^2 \cdot a$	0.020	0.020	0.068	0.072	0.011	0.047	0.065	0.183
Physicochemical filtration	PCF	Physicochemical filtration reduction potential	mol/m^2	17.4	16.4	14.8	14.2	13.5	17.4	14.1	14.3
Groundwater replenishment	GWN	Groundwater regeneration reduction potential	$m^3/m^2 \cdot a$	0.0026	0.0010	0.0014	0.0061	0.0028	0.0030	0.0040	0.0228
Biotic production	NPP	Biotic production loss potential[2]	$kg\ C/m^2 \cdot a$	30.9	30.9	30.9	30.9	30.9	30.9	0.5	0.5
Soil quality index	SQI	Soil quality index	Pt	31.5	31.1	32.4	35.0	31.5	32.3	36.5	58.3

[1] *The LANCA model calculates erosion potential using RUSLE, comparing actual land use to a reference site. At some sites, a negative characterization factor (CF) for erosion potential was calculated, because the actual land use was determined to have better erosion resistance than the reference land use. In this case, the reference site was defined as a temperate deciduous forest (Bos et al., 2020). This outcome was a limitation of the LANCA model and is discussed in the limitations section.*

[2] *In the LANCA model, the biotic production potential indicator—expressed in kg C/m²a—is not a measure of carbon loss or emission. Rather, it reflects the land's capacity to support biomass production. Therefore, it is conceptually distinct from carbon loss estimates used in climate change impact assessments, and the two values are not directly comparable. The value of 30.9 C/m2 may appear high, but the LANCA biotic production indicator measures the amount of potential biomass that is not produced due to the functional unit, relative to a reference system. In this case, the reference system is a temperate deciduous forest, which naturally has much higher biomass than the grasslands under study. Therefore, the high value (30.9 kg C/m² ≈ 31 t C/ha) reflects the difference between the potential forest biomass and the actual grassland biomass, rather than the actual biomass present on the site.*

5.6.7. Biogenic carbon flows

Biogenic carbon flows were included for completeness and transparency, and to ensure alignment with ISO 14067 (ISO, 2018), clause 6.4.9.3. Biogenic carbon flows were modeled using a simplified carbon (C) balance including pasture, livestock, and soil interactions (Table 15). This balance was based on stoichiometric conversion of different flows and stocks, including complex carbohydrates, proteins, and fat, and gaseous emissions such as carbon dioxide (CO_2) and methane (CH_4), into 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 emissions of methane. Additionally, impacts on climate included non-carbon emissions of nitrous oxide, and fossil-related CO_2-eq, which were calculated as described in other sections of this report, based on primary inventory data.

Temporary carbon storage in cashmere, liveweight, and milk was included in the assessment, with the assumption that 100% of the stored carbon is released back into the atmosphere. This was accounted for during the assessment period, as required by ISO 14067 (ISO, 2018), clauses 6.4.8 and 6.4.9.3, which requires 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 in the ISO method. In practice, carbon stored temporarily in live weight may remain out of the atmosphere for a period of months or even years, and carbon in cashmere will likely remain out of the atmosphere for some years. There are few established ways of determining the effect of this temporary storage on the climate. However, if the model extended to whole-of-life for meat and fiber, and modeled under equilibrium conditions, or over a long time period, the emissions at end-of-life from consumption and disposal processes during use and end-of-life would be expected to approximately equal the removal and temporary storage from meat and fiber.

Table 15: Assumptions used in the modeling of biogenic carbon flows

Parameter	Value	Reference
Pasture utilization rate (%)	20	*(Brown et al., 2021; Cheng et al., 2021)*[1]
Root:shoot ratio	12.7	*Average of (Chen et al., 2006; Kang et al., 2013)*
Plant respiration rate (%)	50	*(Parton et al., 1993)*
Carbon content in dry plant biomass (% of DM)	44.73	*(Ma et al., 2018)*
Carbon content in protein (% of protein)	53	*(Rouwenhorst et al., 1991)*
Carbon content in fat (% of fat)	75	*(Bray & Bouchard, 2003)*
Carbon in clean cashmere (% of clean cashmere)	50	*(Hawkesworth, 1948; Simmonds, 1954, 1958; von Bergen, 1963)*
Carbon in manure (% of volatile solids)	55	*(Natural Resources Conservation Service, 2025)*
Soil respiration rate and organic matter turnover (% of organic material respired)[2]	100	
Proportion of empty body weight (EBW) to liveweight (LW) (% EBW in LW)	89	*(Mahgoub & Lodge, 1998)*
Protein content in EBW (% of EBW)	16.4	*(Sanson et al., 1993)*
Fat content in EBW (% of EBW)	15.38	*(Mahgoub & Lodge, 1998)*
Moisture content (% of scoured cashmere)	15	*(Mongolian Agency for Standardization and Metrology, 2019)*
Dirt content (% of scoured cashmere)	0.9	*(Mongolian Agency for Standardization and Metrology, 2019)*

Parameter	Value	Reference
Vegetable matter content (% of scoured cashmere)	≤ 12	*(Mongolian Agency for Standardization and Metrology, 2019)*
Grease content (% of scoured cashmere) (residual)	0.9	*(Mongolian Agency for Standardization and Metrology, 2019)*
Grease content (% of raw cashmere)	4.27	*(Wang et al., 2024)*
Carbon content in grease (%)	75	*(von Bergen, 1963)*

[1] Pasture utilization rates can vary seasonally and between regions, and may be higher than 50% in overgrazed areas (Gao et al., 2015).

[2] Soil respiration rates are typically reported to be around 90% (Hoyle et al., 2013). The remaining carbon may enter more stable carbon pools. In a steady-state system, the amount of carbon entering those slow pools is roughly balanced by the decomposition of SOC leaving the system, so net SOC stock doesn't necessarily increase.

5.7. Background databases

The background datasets used to estimate the environmental impacts associated with the purchased inputs into the production and processing of cashmere are detailed in Table 16. These datasets were sourced primarily from Ecoinvent 3 databases. The limitations of these datasets in the context of the cashmere LCA are described in the limitations. The data includes inputs for energy, feed production, water use, chemical inputs, transportation, and infrastructure processes, among others.

Table 16: Background databases used to estimate impacts from purchased inputs

Stage	Country	Inputs	Process
Farm (herder)	Mongolia	Bran	Wheat bran (RoW)| market for wheat bran | Cut-off, S
Farm (herder)	Mongolia	Wheat	Wheat grain, feed (RoW)| market for wheat grain, feed | Cut-off, S
Farm (herder)	Mongolia	Barley	Barley grain, feed (GLO)| market for barley grain, feed | Cut-off, S
Farm (herder)	Mongolia	Oats	Oat grain, feed (GLO)| market for oat grain, feed | Cut-off, S
Farm (herder)	Mongolia	Rice/rice bran	Rice, non-basmati (CN)| rice production, non-basmati | Cut-off, S
Farm (herder)	Mongolia	Protein supplement	Protein feed, 100% crude (GLO)| molasses, from sugar beet, to generic market for energy feed | Cut-off, S
Farm (herder)	China	Maize	Maize grain, feed (RoW)| maize grain, feed production | Cut-off, S
Farm (herder)	China	Molasses/ liquorice	Protein feed, 100% crude (GLO)| molasses, from sugar beet, to generic market for energy feed | Cut-off, S
Farm (herder)	China	Ammonium phosphate fertilizer	Diammonium phosphate (CN)| diammonium phosphate production | Cut-off, S
Farm (herder)	China	Zinc sulfate fertilizer	Zinc monosulfate (RoW)| market for zinc monosulfate | Cut-off, S
Farm (herder)	China	Potassium sulphate fertilizer	Potassium sulfate (RoW)| market for potassium sulfate | Cut-off, S
Farm (herder)	China	Urea fertilizer	Urea {CN}| urea production | Cut-off, S
Farm (herder)	China	Chemicals	Atrazine (RoW)| atrazine production | Cut-off, S

Stage	Country	Inputs	Process
Farm (herder)	China	Chemicals	[sulfonyl]urea-compound (RoW)| [sulfonyl]urea-compound production | Cut-off, S
Farm (herder)	China	Chemicals	Dimethyl carbonate (RoW)| dimethyl carbonate production | Cut-off, S
Farm (herder)	China	Purchased hay	Assume hay production is just cutting natural grass manually. Inclusive of transport to consumer. Transport, passenger, car, petrol, small size, EURO 5 (GLO)| market for transport, passenger, car, petrol, small size, EURO 5 | Cut-off, S
Farm (herder)	Mongolia/ China	Petrol and diesel (transport of goods and services and farm/herder logistics)	Transport, passenger, motor scooter, fleet average (GLO)| market for transport, passenger, motor scooter, fleet average | Cut-off, S
Farm (herder)	Mongolia/ China	Petrol (transport of goods and services and farm/herder logistics)	Transport, passenger, car, petrol, small size, EURO 5 (GLO)| market for transport, passenger, car, petrol, small size, EURO 5 | Cut-off, S
Farm (herder)	Mongolia/ China	Diesel (transport of goods and services and farm/herder logistics)	Passenger car, diesel (GLO)| market for passenger car, diesel | Cut-off, S
Farm (herder)/primary processing	Mongolia/ China	Petrol and diesel (transport of goods and services and farm/herder logistics)	Transport, passenger, car, petrol, small size, EURO 5 (GLO)| market for transport, passenger, car, petrol, small size, EURO 5 | Cut-off, S
Farm (herder)/primary processing	China	Electricity	Electricity, low voltage (CN)| market group for electricity, low voltage | Cut-off, S
Primary processing	Mongolia	Electricity	Electricity, low voltage (GLO)| market group for electricity, low voltage | Cut-off, S
Primary processing	Mongolia	Sodium bicarbonate	Sodium bicarbonate (RoW)| market for sodium bicarbonate | Cut-off, S
Primary processing	Mongolia/ China	Detergent	Soap (RoW)| soap production | Cut-off, S
Primary processing	Mongolia	HDPE plastic	Polyethylene, high density, granulate (RER)| polyethylene production, high density, granulate | Cut-off, S
Primary processing	Mongolia	Formic acid	Formic acid (RoW)| formic acid production, methyl formate route | Cut-off, S
Primary processing	Mongolia	Acetic acid	Acetic acid (GLO)| market for acetic acid | Cut-off, S
Primary processing	Mongolia	Steam	Heat, from steam, in chemical industry (RoW)| market for heat, from steam, in chemical industry | Cut-off, S
Primary processing	Mongolia/ China	Truck transport	Transport, freight, lorry, diesel, unspecified (RoW)| transport, freight, lorry, all sizes, EURO 6 to generic market for transport, freight, lorry, unspecified | Cut-off, S
Primary processing	Mongolia	Landfill waste	Municipal solid waste (GLO)| treatment of municipal solid waste, unsanitary landfill, dry infiltration class (100 mm) | Cut-off, S

Stage	Country	Inputs	Process
Primary processing	China	Wastewater treatment	Wastewater from textile production (RoW)| treatment of wastewater from textile production, wastewater treatment | Cut-off, U
Primary processing	China	Natural gas	Heat, central or small-scale, natural gas (RoW)| heat production, natural gas, at boiler modulating <100kW | Cut-off, S

5.8. Sensitivity analysis

5.8.1. Sensitivity to allocation approach

The sensitivity of results to the allocation method was tested by considering energy allocation methods and economic allocation. The economic allocation was determined using the average price multiplied by the modeled output of each co-product (Table 17).

5.8.2. Economic allocation (a)

Table 17: Economic data from the primary dataset used in the sensitivity analysis for handling co-production

Parameters	Nomadic grazing systems	Farmed systems
Cashmere price (USD/kg raw cashmere)[1]	34.8	47.7
Liveweight price (USD/kg LW)[1]	0.9	5.2
Milk price (USD/L of milk)[1]	0.9	4.0
Economic allocation cashmere (%)	52	30
Economic allocation liveweight (%)	41	69
Economic allocation milk (%)	7	<1

[1] *Economic data (cashmere, milk, and live weight prices) was derived from field surveys. Quantities corresponding to these prices are reported in* Table 6 *of the baseline inventory.*

Modeled energy allocation

The sensitivity of results to allocation was performed using the energy allocation method (FAO, 2016). However, the guidance for implementing energy allocation between meat and fiber is not sufficiently specified or operationalized for consistent implementation. Additionally, no data was available on the energy requirements for fiber growth in cashmere goats. Consequently, assumptions were based on wool and mohair data, as outlined in scenarios (d), (e), and (f). A sensitivity analysis was conducted using five alternative approaches to the energy allocation as described below.

Energy allocation (b)

For each animal class, the energy to produce cashmere, for liveweight growth and for lactation, was calculated following the IPCC 2019 Volume 4, Chapter 10 net energy equations (Table 41). Energy for liveweight, growth, and lactation was calculated relative to the output of these products from the herd. Products grown, but not exported from the herd, were considered as part of herd maintenance energy requirements. The energy allocation for cashmere was then determined as follows:

Energy allocation to cashmere % =

$$\frac{\text{Net energy to produce cashmere (MJ)}\times\frac{\text{Cashmere sold (kg)}}{\text{cashmere grown (kg)}}}{\left(\text{Net energy to produce cashmere}\times\frac{\text{Cashmere sold (kg)}}{\text{cashmere grown (kg)}}+\text{net energy for lactation (milk sales)}+\text{net energy for growth}\times\frac{\text{liveweight sold(kg)}}{\text{liveweight gain (kg)}}\right)\text{(MJ)}}$$

Energy allocation to liveweight % =

$$\frac{\text{Net energy for growth}\times\frac{\text{liveweight sold(kg)}}{\text{liveweight gain (kg)}}}{\left(\text{Net energy to produce cashmere}\times\frac{\text{Cashmere sold (kg)}}{\text{cashmere grown (kg)}}+\text{net energy for lactation (milk sales)}+\text{net energy for growth}\times\frac{\text{liveweight sold(kg)}}{\text{liveweight gain (kg)}}\right)\text{(MJ)}}$$

Energy allocation to milk % =

$$\frac{\text{net energy for lactation (milk sales)}}{\left(\text{Net energy to produce cashmere}\times\frac{\text{Cashmere sold (kg)}}{\text{cashmere grown (kg)}}+\text{net energy for lactation (milk sales)}+\text{net energy for growth}\times\frac{\text{liveweight sold(kg)}}{\text{liveweight gain (kg)}}\right)\text{(MJ)}}$$

The net energy to produce cashmere =

$$24\ \text{MJ/kg raw cashmere}^{-1}\times(1-\text{grease content})+38\ \text{MJ/kg raw cashmere}^{-1}\times\text{grease content}$$

Where: grease content = 4.27% of raw cashmere (Table 15).

Energy value of each kg of wool produced = 24 MJ/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, and (2) net energy for growth was not adjusted according to the proportion of liveweight sold. The energy allocation for cashmere was then determined as follows:

Energy allocation to cashmere % =

$$\frac{\text{Net energy to produce cashmere (MJ)}\times\frac{\text{Cashmere sold (kg)}}{\text{cashmere grown (kg)}}}{\left(\begin{array}{c}\text{Net energy to produce cashmere}\times\frac{\text{Cashmere sold (kg)}}{\text{cashmere grown (kg)}}+\text{net energy for lactation (milk sales)}+(\text{Net energy for growth}+\text{net energy for lactation}\\ \text{(excluding milk sales)}+\text{net energy for pregnancy})\end{array}\right)\text{(MJ)}}$$

Energy allocation to liveweight % =

$$\frac{\text{Net energy for growth}+\text{net energy for lactation (excluding milk sales)}+\text{net energy for pregnancy}}{\left(\begin{array}{c}\text{Net energy to produce cashmere}\times\frac{\text{Cashmere sold (kg)}}{\text{cashmere grown (kg)}}+\text{net energy for lactation (milk sales)}+(\text{Net energy for growth}+\text{net energy for lactation}\\ \text{(excluding milk sales)}+\text{net energy for pregnancy})\end{array}\right)\text{(MJ)}}$$

Energy allocation to milk % =

$$\frac{\text{net energy for lactation (milk sales)}}{\left(\begin{array}{c}\text{Net energy to produce cashmere}\times\frac{\text{Cashmere sold (kg)}}{\text{cashmere grown (kg)}}+\text{net energy for lactation (milk sales)}+(\text{Net energy for growth}+\text{net energy for lactation}\\ \text{(excluding milk sales)}+\text{net energy for pregnancy})\end{array}\right)\text{(MJ)}}$$

Energy allocation (d)

This approach followed energy allocation (c), and applied a fixed net energy requirement for cashmere production of 130 MJ/kg raw cashmere. This value was reported in CSIRO (2007), which stated that the ME requirement can be estimated as 0.13 MJ/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 fiber, plus wax and suint). It includes the maintenance energy required for skin and follicle growth. As no alternative value was available for cashmere, this estimate was applied and incorporated into the sensitivity analysis.

Energy allocation (e)

This approach followed energy allocation (c) and applied a fixed net energy requirement for cashmere production of 157 MJ/kg raw cashmere. 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). As no alternative value was available for cashmere, this estimate was applied and incorporated into the sensitivity analysis.

Energy allocation (f)

This approach followed energy allocation (c), and applied a fixed net energy requirement for cashmere production of 59.3 MJ/kg raw cashmere. 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 fiber growth beyond maintenance requirements and was included to provide an indication of "fiber only" requirements. A merino sheep for wool production on average produces 4 kg of wool per year, equivalent to approximately 11 g per day. This yields an ME for wool (MJ/d) = 0.13(11–6) = 0.65 MJ/day equivalent to 59.3 MJ/kg greasy wool. This example illustrates the implementation of the equation when maintenance energy requirements are excluded. The equation cannot be directly applied to cashmere because cashmere growth rates are far below the 6 g/day threshold, meaning the model falls outside its valid range. However, as no cashmere-specific energy requirement values were available, this wool-based estimate was used as a proxy and included in the sensitivity analysis to explore its potential influence.

5.8.3. Sensitivity to seasonal and regional impacts

At the production stage, the dataset included different agroecological regions, aggregated to the management system level by the proportion of cashmere produced in each province (see section 5.1 Stratification). Cashmere production data was available at the province level, while agroecological zones represented a finer-scale spatial unit that often intersected multiple provinces. To test the accuracy of these weightings by province, a sensitivity analysis was conducted to compare these weightings to those by agroecological zones. This analysis used an area-weighted spatial disaggregation approach, assuming a uniform spatial distribution of cashmere production within each province, due to the absence of more spatially explicit data. This analysis represents a reweighting of existing life cycle inventory data. The sensitivity of the results to the handling of the temporal representativeness of the nomadic grazing system was also tested by analyzing the surveyed inventory data from the survey year (September 2022 to August 2023), which was impacted by the dzud event (National Statistics Office of Mongolia, 2024a). This was compared to the baseline result.

5.8.4. Sensitivity to key parameters

The sensitivity of the model to key assumptions, data input parameters (Table 18, Table 19) and methodological decisions was 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 most reduce 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 behavior when multiple parameters change simultaneously. Instead, they indicate relative importance for prioritizing data refinement. To explore combined effects, scenario analyses were also conducted, which demonstrate that simultaneous improvements across multiple productivity parameters can lead to non-linear reductions in environmental impacts, particularly from a low-productivity baseline.

Table 18: Sensitivity analysis to key parameters for the nomadic grazing system

Parameters	Nomadic grazing system (baseline value)	Low range	Upper range
Crude protein (% of DM) (+/−25%)	10%	7%	12%
Digestibility of feed (+/−10%)	57%	51%	63%

Parameters	Nomadic grazing system (baseline value)	Low range	Upper range
Average weights (kg LW) (+/−25%)	37	28	46
Raw cashmere (kg/hd/year) (+/−25%)	0.37	0.28	0.46
Mortality rate (%) (+/−50%)	6%	3%	9%
Kid survival as a proportion of breeding females (%) (+/−50%)	67%	33%	100%
Clean cashmere scoured yield (% raw cashmere) (+/−10%)	82%	74%	90%
Wether inclusion rate (+/−50%)[1]	76%	38%	114%
Sheep units per hectare (+/−50%)	1.1	0.6	1.7
LANCA SQI (+/−50%)	32	16	48

[1] Wether inclusion rate (%) = the proportion of wethers to breeding does. If the wether inclusion rate is greater than 100% that means there are more wethers than breeding does in the herd. The authors refer to a wether as a castrated goat.

Table 19: Sensitivity analysis to key parameters for the farmed system

Parameters	Farmed system (baseline value)	Low range	Upper range
Crude protein (% of DM) (+/−25%)	11%	8%	14%
Digestibility of feed (+/−10%)	63%	56%	69%
Average weights (kg LW) (+/−25%)	30	23	38
Raw cashmere (kg/head/year) (+/−25%)	0.8	0.6	1.0
Mortality rate (%) (+/−50%)	5%	3%	8%
Kid survival as a proportion of breeding females (%) (+/−50%)	89%	45%	134%
Clean cashmere scoured yield (% raw cashmere) (+/−10%)	74%	67%	82%
Wether inclusion rate (+/−50%)	62%	31%	93%
Sheep units per hectare (+/−50%)	1.5	0.8	2.3
LANCA SQI (+/−50%)	43	22	65

5.8.5. Sensitivity analysis: Soil carbon

Impacts from soil carbon loss were not attributed to cashmere in the baseline results because of the difficulty in separating climate-induced effects and grazing impacts. Climate change effects, including reduced rainfall and increased temperature variability, are known to significantly affect soil carbon stocks in rangeland systems (>90%) (Henry et al., 2024), independent of grazing pressure or herd size. However, the study explored the attribution in a sensitivity analysis (Table 20).

Table 20: Soil carbon stock changes with an estimated attribution to livestock for sensitivity analysis

Soil carbon change (kg $Cha^{-1}yr^{-1}$)[1]	Attribution to livestock		
	10%	20%	30%
−150	−15	−30	−45
−100	−10	−20	−30
−50	−5	−10	−15
50	5	10	15

[1] *Negative values indicate soil carbon loss rates.*

5.9. Uncertainty analysis

Alpha and beta uncertainties were assessed via Monte Carlo analysis (1,000 iterations) using SimaPro™ 9.6.0.1 (Pré Consultants, 2024). Results were presented using the mean ± 2S.D, and both alpha and beta uncertainties were used to calculate the 95% confidence interval. As beta uncertainty was shared between both management systems, comparison of the mean results between systems was based on alpha uncertainties only, and significant differences were determined using the equation of Wiltshire et al. (2009) in Appendix D–Uncertainty analysis.

5.10. Statistical analysis

5.10.1. Regression model of individual herds

For climate change (excluding LU and LUC), a statistical analysis was conducted by analyzing each herd individually. A regression model was fitted and grouped by management practice. The dependent variable was climate change impacts (excluding 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 (excluding LU and LUC). To assess the normality of the data distribution, a Shapiro-Wilk test was conducted. If the assumption of normality was violated, the non-parametric Kruskal-Wallis test was applied to compare differences between management practices. Post-hoc comparisons were performed using Dunn's test with Bonferroni correction to identify significant differences between management practices. Furthermore, an effect size analysis was conducted to provide a measure of practical significance independent of p-values. Effect sizes were calculated using eta-squared (η^2) for the Kruskal-Wallis test. Statistical analyses were conducted using RStudio (version 2024.12.1+563). The threshold for statistical significance was set at $\alpha = 0.05$. Data visualization was performed using the "ggplot2" package to illustrate group differences and distributions. Assumptions and model fits were assessed through residual diagnostics.

5.11. 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 (ISO, 2006b), 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.

5.11.1. Allocation at the primary production stage

At the primary production stage, there are a number of co-products produced, including milk, live animals for meat consumption, and raw cashmere. Cashmere herders typically operate mixed species herds, which can include sheep, cattle, yaks, horses and/or camels, and, in China, herders may also produce grains or other crops. The presence of multiple production systems was handled by system subdivision and accounting for the cashmere goat production system separately where possible. Shared inputs between livestock species, including land area and energy use, were divided and attributed to each system based on stocking rates. Manure deposited on grazing land was an internal flow, and impacts (emissions) were attributed to the grazing system. Handling co-production of cashmere, liveweight for meat consumption, and milk for dairy products, was modeled using the protein allocation method (Wiedemann et al., 2015). For comparison, energy allocation methods and economic allocation were used in the sensitivity analysis.

5.11.2. Protein allocation

The protein allocation method involves calculating the amount of protein in each product (Table 21).

Table 21: Calculation of protein in livestock products

Parameter	Equation
Total protein in liveweight[1]	Total liveweight sold × proportion of EBW in LW/100 × protein content in EBW
Clean dry fiber (% of clean, scoured cashmere yield)[1, 2]	1 - (moisture_content + grease_content + dirt_content + vm_content) contents are expressed as a % of scoured cashmere3
Protein in clean, dry scoured fiber (% of clean dry fiber)	100%
Total protein in clean fiber (kg)	Total raw cashmere (kg) × clean, scoured cashmere yield (%) × clean dry fiber (%) × protein in clean dry fiber (%)
Total protein in milk sold or consumed (kg)[3]	Milk sold (or consumed) (L) × density of goat milk (kg/L) × protein in milk (%)4

[1] Assumptions provided in Table 15.

[2] The scoured cashmere yield (% of raw cashmere) for the nomadic grazing system and farmed system was 82% and 74%, respectively.

[3] Density of goat milk is 1.032 kg per liter (ICAR, 2018) and protein in milk was 4.11% (Narangerel et al., 2016).

5.11.3. Allocation in processing

At the primary processing stage, the output product was fine, dehaired cashmere. This process removes coarse fibers, suint, grease, and contaminants such as dirt and vegetable matter. The modeling assumed that suint and grease were removed in the wastewater, contaminants were disposed of as solid waste, and coarse hair was treated as a residual on account of its low value, and no allocation of impacts was made to this product. All impacts were allocated to the clean, dehaired fiber.

5.11.4. Allocation for secondary data

All background processes were sourced from the Ecoinvent 3 database, using the allocation cut-off by classification model (Table 16). The allocation approaches documented in the respective datasets were retained. No user modifications to allocation procedures were made.

5.12. Data quality rating method

5.12.1. 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 (ISO, 2006b), and aligned with the ILCD Handbook (European Commission—Joint Research Centre—Institute for Environment and Sustainability, 2010). 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).

5.12.2. 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 Appendix C–Data quality rating method and criteria (ILCD compliant).

5.12.3. Scope of assessment

Key unit processes assessed:

1. Goat production unit process, including farm services, drinking water model, and herd production model.
2. Primary processing unit process, including wastewater management, scouring, and dehairing.

This covers all unit processes in the system boundary.

6. Results

6.1. Overall results

6.1.1. Environmental impacts per kg of clean, dehaired cashmere

The environmental impacts per kg of clean, dehaired cashmere are reported for all impact categories (Table 22). The results presented in section 6.1 follow the protein allocation method as described in section 5.11. The PEF method applies a normalization and weighting approach to produce a single overall score that was used here to indicate environmental priorities in Europe, where large volumes of cashmere are sold in garments. We note the Technical Advisory Board (TAB) and the Environmental Footprint (EF) Steering Group have recommended that the single score for business-to-consumer communication should not be permitted in the context of the PEFCR for apparel and footwear. Given that cashmere is primarily used in apparel, this guidance is relevant to the interpretation of fiber-level results in this study. Although this study does not fully conform to all PEF methodological requirements, the PEF normalization and weighting approach was applied solely as a contextual indicator to support the interpretation of the results. The contributions that individual environmental impact categories make to the PEF single score for the nomadic grazing and farmed systems, were land use (68% and 56%), climate change (16% and 20%), particulate matter (10% and 13%), acidification (1% and 1%), terrestrial eutrophication (1% and 2%), ecotoxicity (<1% and <1%), water use (1% and 3%), and fossil resource use (1% and 1%), respectively (Figure 4). Ammonia volatilized from livestock manure contributed >90% of particulate matter impacts and >69% terrestrial eutrophication impacts across both management systems and was, therefore, a dominant sub-process.

The role of ammonia losses, which arise from animal manure excretion, was considered more relevant for industrialized western Europe than for Mongolia and northern China, where diffuse ammonia losses from low-density grazing in semi-arid environments are less likely to result in high environmental impacts via particulate matter, atmospheric acidification, or terrestrial eutrophication. While required for a PEF-compliant analysis, regional characterization factors and regional weighting are required to improve the interpretation of these results. The material impacts for these production systems were climate change and land impacts, both of which were considered material in the production countries. Other impacts, including marine eutrophication, freshwater eutrophication, human toxicity, ionizing radiation, ozone depletion, photochemical ozone formation, minerals, and metals resource use (Figure 4), had low reportable impacts either because of low emission rates or low weightings, or a combination of these two factors.

Impacts associated with fossil energy resources and water stress, while not material in the PEF single score, were, nonetheless, useful comparators between the production systems studied. Ecotoxicity also provided a comparison indicator between the production systems to assess the effect of intensification. Results for these indicators are shown in Table 22.

Table 22: The environmental impacts reported for the impact categories assessed in the Product Environmental Footprint (PEF) per kg of clean, dehaired cashmere for the nomadic grazing systems and farmed systems

Impact category (PEF)	Unit	Nomadic grazing system	Farmed system
Acidification	mol H^+ eq	0.2	0.2
Climate change	kg CO_2 eq	185	156
Climate change—(excluding LULUC)	kg CO_2 eq	183	155
Climate change—biogenic	kg CO_2 eq	145	111
Climate change—fossil	kg CO_2 eq	38	43
Climate change—LULUC (excluding soil carbon loss from LU)[1]	kg CO_2 eq	1.5	1.5
Ecotoxicity, freshwater	CTUe	415	535
Particulate matter	disease incidence	2.2E-05	2.0E-05
Eutrophication, marine	kg N eq	0.04	0.06
Eutrophication, freshwater	kg P eq	8.7E-03	6.6E-03
Eutrophication, terrestrial	mol N eq	1.7	1.8
Human toxicity, cancer	CTUh	8.3E-09	1.1E-08
Human toxicity, cancer—inorganics	CTUh	3.0E-09	2.8E-09
Human toxicity, cancer—organics	CTUh	5.2E-09	8.1E-09
Human toxicity, non-cancer	CTUh	5.3E-07	4.5E-07
Human toxicity, non-cancer—inorganics	CTUh	2.6E-07	2.1E-07
Human toxicity, non-cancer—organics	CTUh	2.7E-07	2.4E-07
Ionizing radiation	kBq U-235 eq	1.7	0.8
Land use	Pt	233313	127992
Ozone depletion	kg CFC11 eq	6.4E-08	1.1E-07
Photochemical ozone formation	kg NMVOC eq	0.1	0.2
Resource use, fossils	MJ	144	109
Resource use, minerals and metals	kg Sb eq	2.4E-04	2.8E-04
Water use	m^3 deprived	46	83

[1] *Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which is reported elsewhere in section 6.1.10.*

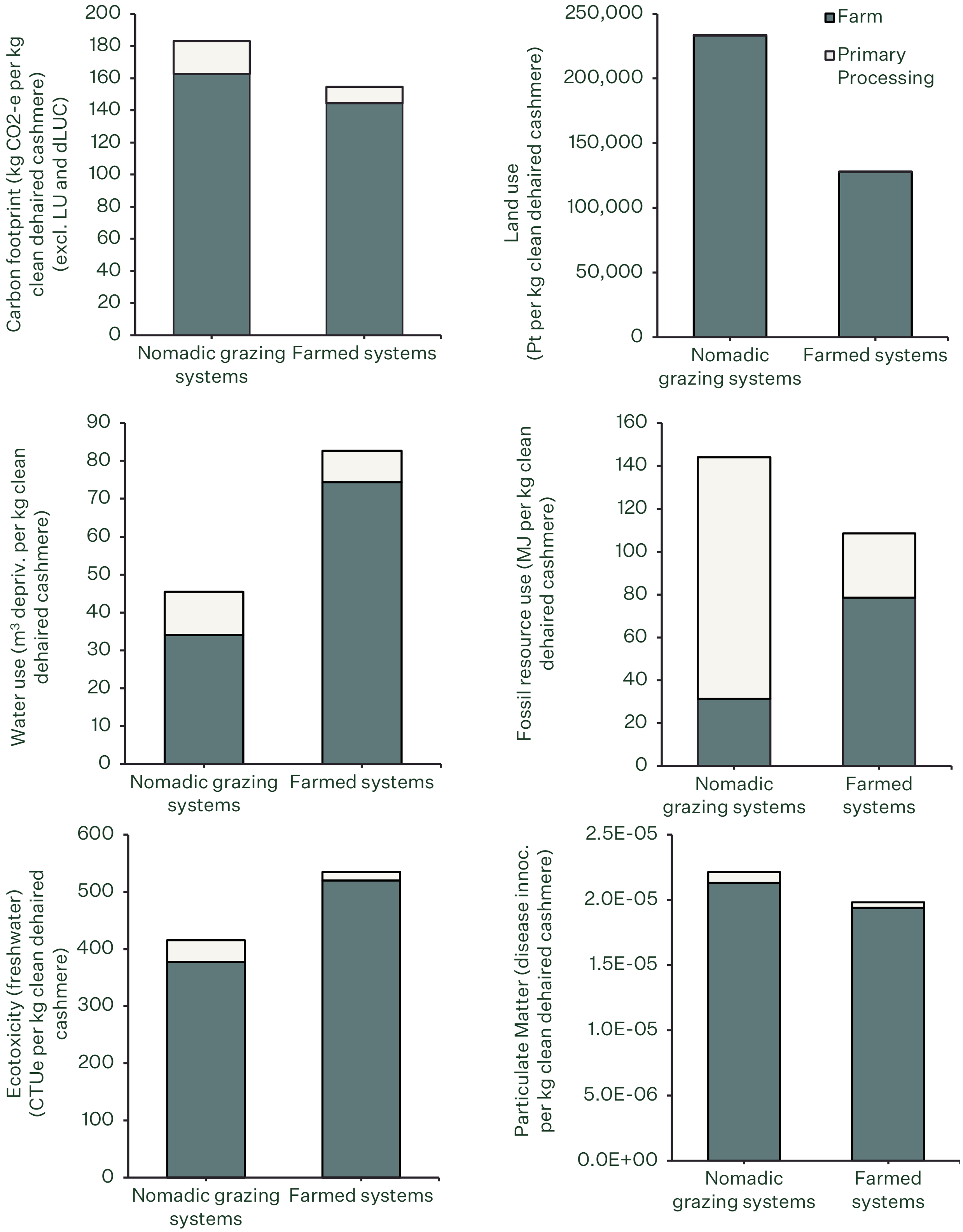
Figure 4: The contribution of environmental impacts to the PEF single score for the nomadic grazing system (green) and farmed system (yellow)

6.1.2. Most relevant environmental impacts per kg of clean, dehaired cashmere

The most relevant impact categories were determined from the impact categories identified through the PEF weighting and normalization. The contributions from different stages of the supply chain varied according to the impact category (Figure 5). The primary production stage accounted for over 75% of the total impact across climate change, water use, ecotoxicity, particulate matter, and land use (Figure 5). The occupation of livestock grazing contributed >99% of land use impacts. The climate change impacts (excluding LU and LUC) were dominated by methane (80% and 74%), followed by carbon dioxide (15% and 20%), and nitrous oxide (5% and 5%) emissions, for the nomadic grazing and farmed system, respectively. Methane emissions were dominated by enteric methane emitted as a by-product of ruminant digestion, and nitrous oxide emissions were primarily from livestock manure and, to a smaller extent, purchased feed. The contribution of carbon dioxide from different stages of the supply chain varied between production systems. Carbon dioxide emissions at the primary production stage were very low in the nomadic grazing systems, representing only <5% of impacts from GHG emissions (excluding LU and LUC). This reflected the low level of purchased inputs to the system. In contrast, carbon dioxide emissions at the primary production stage in farmed systems represented 15% of impacts from GHG emissions, which was reflective of their higher input system with supplementary feed, fertilizer, and chemicals. The remaining impacts from carbon dioxide emissions occurred at the primary processing stage, mainly from electricity and energy use. Impacts from LU from livestock grazing were reported per hectare and were substantial, but could not be attributed directly to goats

A similar trend was observed for fossil resource use, with 22% of impacts coming from the primary production stage for the nomadic grazing systems compared to 72% impacts for the farmed system. The remaining impacts were from electricity and energy use at the primary processing stage. Livestock drinking water, and associated supply losses at the primary production stage, were the most significant contributors to water use, while much smaller proportions were used in primary processing and irrigation for crop production within the farmed system. This trend was most prominent when analyzed from cradle to farm gate (Figure 6), as here the farmed system showed significantly higher impacts in water use, fossil resource use, and climate change (fossil), compared to the nomadic system. This highlights a trade-off, where farmed systems have greater resource intensity, while nomadic systems are associated with higher land use and climate change impacts related to land-based emissions.

Figure 5: Climate change (excluding LU and LUC), land use, water use, fossil resource use, freshwater ecotoxicity, and particulate matter for the nomadic grazing and farmed system per kg of clean, dehaired cashmere.



The dark segments represent the contribution from the farm, and the light segments indicate the contribution from the primary processing stage.

6.1.3. Environmental impacts per kg of raw cashmere (cradle to primary production gate)

The environmental impacts per kg of raw cashmere (cradle to primary production gate) are reported in Table 23. Impacts were lower at the primary production stage because the product mass was greater before dehairing, meaning impacts were distributed over a larger quantity of material. These values also exclude impacts from primary processing. When the product was dehaired, the mass losses resulted in higher reported impacts to the lower mass of product post-processing.

Table 23: Environmental impacts per kg of raw cashmere for nomadic grazing systems and farmed systems (cradle-to-primary production gate)

Impact category (PEF)	Unit	Nomadic grazing system	Farmed system
Acidification	mol H^+ eq	<0.1	0.1
Climate change	kg CO_2 eq	85	59
Climate change—(excluding LULUC)	kg CO_2 eq	84	59
Climate change—biogenic[1]	kg CO_2 eq	74	45
Climate change—fossil	kg CO_2 eq	10	13
Climate change—LULUC (excluding soil carbon loss from LU)[2]	kg CO_2 eq	0.8	0.6
Ecotoxicity, freshwater	CTUe	195	211
Particulate matter	disease incidence	1.1E-05	7.9E-06
Eutrophication, marine	kg N eq	0.011	0.023
Eutrophication, freshwater	kg P eq	1.4E-03	2.3E-03
Eutrophication, terrestrial	mol N eq	0.8	0.7
Human toxicity, cancer	CTUh	2.6E-09	3.8E-09
Human toxicity, cancer—inorganics	CTUh	8.7E-10	9.6E-10
Human toxicity, cancer—organics	CTUh	1.7E-09	2.8E-09
Human toxicity, non-cancer	CTUh	2.1E-07	1.7E-07
Human toxicity, non-cancer—inorganics	CTUh	7.1E-08	7.1E-08
Human toxicity, non-cancer—organics	CTUh	1.4E-07	9.6E-08
Ionizing radiation	kBq U-235 eq	0.2	0.3
Land use	Pt	120568	51858
Ozone depletion	kg CFC11 eq	2.5E-08	4.4E-08
Photochemical ozone formation	kg NMVOC eq	4.9E-02	5.8E-02
Resource use, fossils	MJ	16	32
Resource use, minerals and metals	kg Sb eq	9.1E-05	1.1E-04
Water use	m^3 deprived	18	30

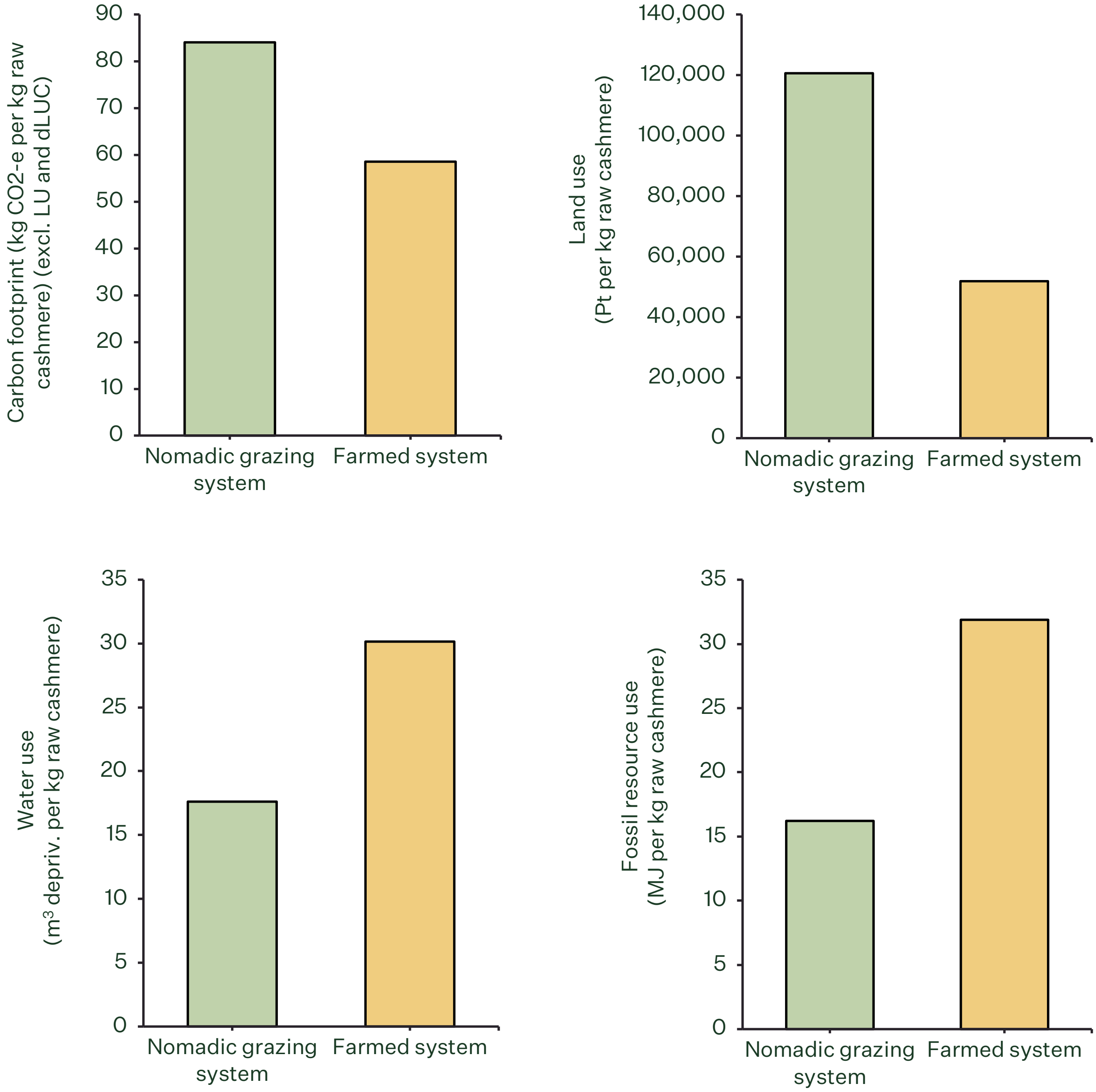
[1] *The biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.*

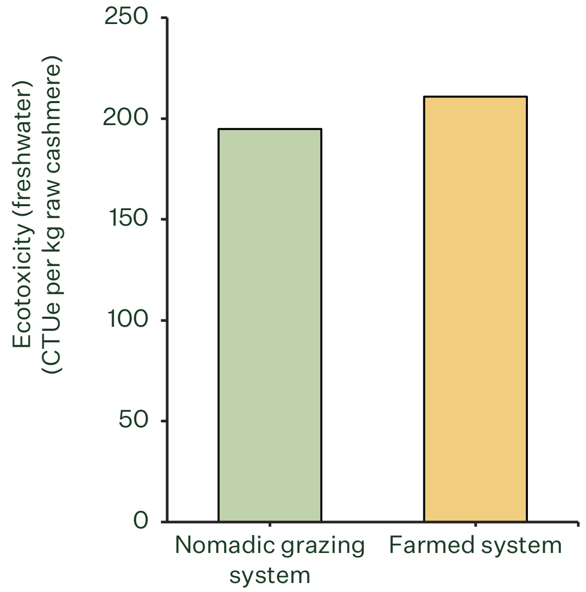
[2] *Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which is reported elsewhere in section 6.1.10.*

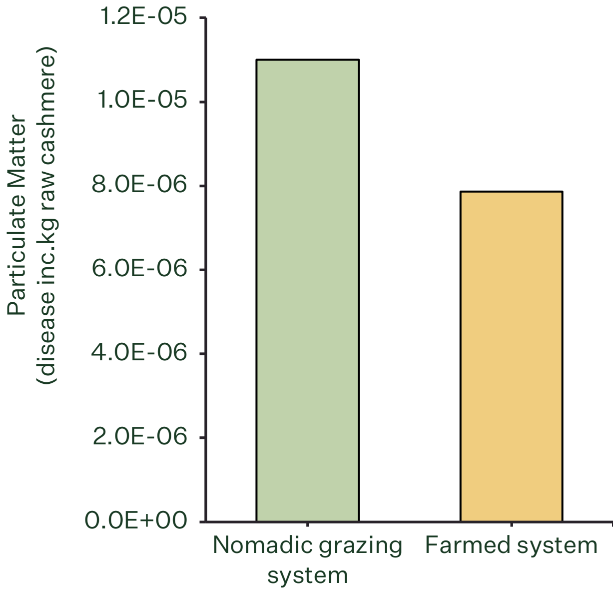
6.1.4. Relevant environmental impacts per kg of raw cashmere (cradle to primary production gate)

Impacts reported at the primary production stage are shown in Figure 6 for the selected indicators. The results showed a trend in higher impacts for climate change and land use (assessed using LANCA) for the nomadic grazing system, while water, energy, and freshwater ecotoxicity impacts were higher in farmed systems, largely in response to the higher inputs used for feeding goats while confined.

Figure 6: Climate change (excluding. LU and LUC), land use, water use, fossil resource use, freshwater ecotoxicity, and particulate matter for the nomadic grazing (yellow bars) and farmed system (green bars) per kg of raw cashmere (cradle to primary production gate)







6.1.5. Environmental impacts per kg of clean, dehaired cashmere by life cycle stage

The contributions from different stages of the supply chain varied according to the impact category (Table 24). Primary production was the largest contributor to most impact categories, with the exception of those related to fossil fuel energy use and some toxicity indicators.

Table 24: The contribution of environmental impacts by life cycle stage to each Product Environmental Footprint (PEF) impact category for the nomadic grazing systems and farmed systems. Percentages represent the share of each life cycle stage to the impact category.

		Nomadic grazing system		Farmed system	
Impact category (PEF)	**Unit**	**Primary production**	**Primary processing**	**Primary production**	**Primary processing**
Acidification	mol H^+ eq	45%	55%	84%	16%
Climate change	kg CO_2 eq	89%	11%	93%	7%
Climate change—(excluding LULUC)	kg CO_2 eq	89%	11%	93%	7%
Climate change—biogenic[1]	kg CO_2 eq	99%	1%	100%	0%
Climate change—fossil	kg CO_2 eq	48%	52%	77%	23%
Climate change—LULUC (excluding soil carbon loss from LU)[2]	kg CO_2 eq	97%	3%	97%	3%
Ecotoxicity, freshwater	CTUe	91%	9%	99%	1%
Particulate matter	disease incidence	96%	4%	98%	2%
Eutrophication, marine	kg N eq	46%	54%	90%	10%
Eutrophication, freshwater	kg P eq	32%	68%	84%	16%
Eutrophication, terrestrial	mol N eq	91%	9%	97%	3%
Human toxicity, cancer	CTUh	61%	39%	86%	14%
Human toxicity, cancer—inorganics	CTUh	56%	44%	86%	14%
Human toxicity, cancer—organics	CTUh	64%	36%	86%	14%
Human toxicity, non-cancer	CTUh	76%	24%	92%	8%

		Nomadic grazing system		Farmed system	
Impact category (PEF)	**Unit**	**Primary production**	**Primary processing**	**Primary production**	**Primary processing**
Human toxicity, non-cancer—inorganics	CTUh	54%	46%	83%	17%
Human toxicity, non-cancer—organics	CTUh	97%	3%	99%	1%
Ionizing radiation	kBq U-235 eq	17%	83%	84%	16%
Land use	Pt	100%	0%	100%	0%
Ozone depletion	kg CFC11 eq	75%	25%	96%	4%
Photochemical ozone formation	kg NMVOC eq	63%	37%	85%	15%
Resource use, fossils	MJ	22%	78%	72%	28%
Resource use, minerals and metals	kg Sb eq	74%	26%	97%	3%
Water use	m^3 deprived	75%	25%	90%	10%

[1] The biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.

[2] Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which is reported elsewhere in section 6.1.10.

6.1.6. Environmental impacts per kg of clean, dehaired cashmere by process contribution

When reported per process, goat production was the largest impact source for land, climate change, and water, while purchased feed was also a material source of impact, particularly in the farmed system (Table 25). Electricity and water use were material for primary processing (Table 25).

Table 25: Process contribution to hotspot impact categories by life cycle stage for the nomadic grazing systems and farmed systems. Percentages represent the share of each impact category per kilogram of clean, dehaired cashmere.

Life cycle stage	Process	Project	Land use	Climate change	Water use	Ecotoxicity	Fossil resource use	Particulate matter
Nomadic grazing system								
Primary production	Goat production	Foreground process	100%	83.2%	41%	28.0%	n.a.	93.6%
Primary processing	Electricity, low voltage (GLO)| market group for electricity, low voltage | Cut-off, S	Ecoinvent 3	<0.1%	5.2%	2.3%	3.5%	59.6%	1.9%
Primary production	Transport, passenger, car, petrol, small size, EURO 5 (GLO)| market for transport, passenger, car, petrol, small size, EURO 5 | Cut-off, S	Ecoinvent 3	<0.1%	3.4%	0.4%	6.1%	8.0%	1.1%
Primary production	Passenger car, diesel (GLO)| market for passenger car, diesel | Cut-off, S	Ecoinvent 3	<0.1%	1.4%	0.6%	8.7%	11.7%	0.8%
Primary processing	Heat, from steam, in chemical industry (RoW)| market for heat, from steam, in chemical industry | Cut-off, S	Ecoinvent 3	<0.1%	5.5%	0.4%	2.6%	18.3%	1.9%
Primary production	Rice, non-basmati (CN)| rice production, non-basmati | Cut-off, S	Ecoinvent 3	<0.1%	<0.1%	6.4%	0.5%	0.2%	<0.1%
Primary production	Wheat bran (RoW)| market for wheat bran | Cut-off, S	Ecoinvent 3	<0.1%	0.4%	15.9%	1.6%	1.0%	0.3%
Primary production	Wheat grain, feed (RoW)| market for wheat grain, feed | Cut-off, S	Ecoinvent 3	<0.1%	0.2%	8.6%	0.8%	0.5%	0.2%
Primary production	Protein feed, 100% crude (GLO)| molasses, from sugar beet, to generic market for energy feed | Cut-off, S	Ecoinvent 3	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	n.a.
Primary production	Oat grain, feed (GLO)| market for oat grain, feed | Cut-off, S	Ecoinvent 3	<0.1%	<0.1%	<0.1%	0.1%	<0.1%	n.a.
Primary production	Veterinary products	Agricultural LCA with	n.a.	<0.1%	<0.1%	44.4%	<0.1%	n.a.

Life cycle stage	**Process**	**Project**	**Land use**	**Climate change**	**Water use**	**Ecotoxicity**	**Fossil resource use**	**Particulate matter**
		ecoinvent 3.8 and Agri-footprint 6.0						
Primary processing	Scouring water use	Foreground process	n.a.	n.a.	22.4%	n.a.	n.a.	n.a.
Farmed system								
Primary production	Goat production	Foreground process	99.2%	75.6%	60.0%	18.7%	n.a.	89.9%
Primary production	Transport, passenger, car, petrol, small size, EURO 5 (GLO)| market for transport, passenger, car, petrol, small size, EURO 5 | Cut-off, S	Ecoinvent 3	<0.1%	11.0%	0.6%	12.9%	29.0%	3.2%
Primary production	Passenger car, diesel (GLO)| market for passenger car, diesel | Cut-off, S	Ecoinvent 3	<0.1%	0.7%	0.1%	2.7%	6.3%	0.4%
Primary production	Maize grain, feed (RoW)| maize grain, feed production | Cut-off, S	Ecoinvent 3	0.6%	4.7%	16.2%	61.4%	17.3%	3.5%
Primary production	Hay production	Ecoinvent 3	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Primary production	Electricity, low voltage (CN)| market group for electricity, low voltage | Cut-off, S	Foreground process	n.a.	1.4%	0.4%	1.3%	19.4%	0.9%
Primary production	China crop irrigation	Ecoinvent 3	n.a.	<0.1%	12.5%	<0.1%	n.a.	n.a.
Primary processing	Electricity, low voltage (CN)| market group for electricity, low voltage | Cut-off, S	Ecoinvent 3	n.a.	0.7%	0.2%	0.7%	9.8%	0.5%
Primary processing	Heat, central or small-scale, natural gas (RoW)| heat production, natural gas, at boiler modulating <100kW | Cut-off, S	Ecoinvent 3	n.a.	1.3%	n.a.	0.3%	0.8%	n.a.
Primary processing	Heat, from steam, in chemical industry (RoW)| market for heat, from steam, in chemical industry | Cut-off, S	Ecoinvent 3	n.a.	4.4%	n.a.	1.4%	16.6%	1.5%
Primary processing	Scouring water use	Foreground process	n.a.	n.a.	9.7%	n.a.	n.a.	n.a.

6.1.7. Environmental impacts per kg of clean, dehaired cashmere by elementary flows

Further disaggregating impacts revealed land occupation for grazing, enteric methane, and manure emissions were the major elementary flows from primary production (Table 26), while water from livestock drinking and irrigation were major contributors to water impacts. Energy impacts were primarily associated with coal use for electricity production. Ecotoxicity impacts were associated with purchased inputs into the system.

Table 26: Elementary flows to the hotspot impact categories for the nomadic grazing systems and farmed systems. Percentages represent the share of each impact category per kilogram of clean, dehaired cashmere.

Life cycle stage	Process	Elementary flow	Land use	Climate change	Water use	Fossil resource use	Particulate matter	Ecotoxicity
Nomadic grazing systems								
Primary production	Occupation, grassland/pasture/meadow for livestock grazing	SQI	100%	n.a.	n.a.	n.a.	n.a.	n.a.
Primary production	Enteric methane	CH_4 emissions	n.a.	77%	n.a.	n.a.	n.a.	n.a.
Primary production	Manure methane	CH_4 emissions	n.a.	1.2%	n.a.	n.a.	n.a.	n.a.
Primary production	Direct manure nitrous oxide emissions	N_2O emissions	n.a.	3.6%	n.a.	n.a.	n.a.	n.a.
Primary production	Indirect manure nitrous oxide emissions from the volatilization of ammonia	N_2O emissions	n.a.	1.0%	n.a.	n.a.	n.a.	n.a.
Primary production	Indirect manure nitrous oxide emissions from the leaching of nitrogen	N_2O emissions	n.a.	0.0%	n.a.	n.a.	n.a.	n.a.
Primary production	Carbon dioxide emissions from forest to grassland conversion	CO_2 emissions	n.a.	0.7%	n.a.	n.a.	n.a.	n.a.
Primary production	Carbon dioxide emissions, land transformation from background processes	CO_2 emissions	n.a.	0.1%	n.a.	n.a.	n.a.	n.a.

Life cycle stage	Process	Elementary flow	Land use	Climate change	Water use	Fossil resource use	Particulate matter	Ecotoxicity
Primary production	Carbon dioxide emissions, fossil	CO_2 emissions	n.a.	4.7%	n.a.	n.a.	n.a.	n.a.
Primary processing	Carbon dioxide emissions, fossil	CO_2 emissions	n.a.	9.8%	n.a.	n.a.	n.a.	n.a.
Primary production	Ammonia volatilization from livestock manure	NH3 emissions	n.a.	n.a.	n.a.	n.a.	94%	n.a.
Primary processing	Particulates from process steam from hard coal	particulates, < 2.5 um	n.a.	n.a.	n.a.	n.a.	3%	n.a.
Primary production	Irrigation water for supplementary feed	Water	n.a.	n.a.	34%	n.a.	n.a.	n.a.
Primary production	Livestock drinking water	Water	n.a.	n.a.	41%	n.a.	n.a.	n.a.
Primary processing	Water for primary processing	Water	n.a.	n.a.	25%	n.a.	n.a.	n.a.
Primary production	Energy	Uranium	n.a.	n.a.	n.a.	3.3%	n.a.	n.a.
Primary production	Energy	Peat	n.a.	n.a.	n.a.	<0.1%	n.a.	n.a.
Primary production	Energy	Oil, crude	n.a.	n.a.	n.a.	<0.1%	n.a.	n.a.
Primary production	Energy	Coal, hard	n.a.	n.a.	n.a.	16.8%	n.a.	n.a.
Primary production	Energy	Coal, brown	n.a.	n.a.	n.a.	1.6%	n.a.	n.a.
Primary processing	Energy	Uranium	n.a.	n.a.	n.a.	15.8%	n.a.	n.a.
Primary processing	Energy	Peat	n.a.	n.a.	n.a.	<0.1%	n.a.	n.a.
Primary processing	Energy	Oil, crude	n.a.	n.a.	n.a.	<0.1%	n.a.	n.a.
Primary processing	Energy	Coal, hard	n.a.	n.a.	n.a.	54.8%	n.a.	n.a.
Primary processing	Energy	Coal, brown	n.a.	n.a.	n.a.	7.6%	n.a.	n.a.
Primary production	Veterinary products	Avermectin B1	n.a.	n.a.	n.a.	n.a.	n.a.	44.4%
Primary production	Ammonia volatilization from livestock manure	NH3 emissions	n.a.	n.a.	n.a.	n.a.	n.a.	27.6%
Primary production	Purchased inputs	Chlorpyrifos	n.a.	n.a.	n.a.	n.a.	n.a.	<0.1%
Primary production	Purchased inputs	Chloride	n.a.	n.a.	n.a.	n.a.	n.a.	3.7%

Life cycle stage	**Process**	**Elementary flow**	**Land use**	**Climate change**	**Water use**	**Fossil resource use**	**Particulate matter**	**Ecotoxicity**
Primary production	Purchased inputs	Benzene, 1,2-dichloro-	n.a.	n.a.	n.a.	n.a.	n.a.	2.4%
Primary processing	Purchased inputs	Iron, ion	n.a.	n.a.	n.a.	n.a.	n.a.	1.2%
Primary processing	Purchased inputs	Chloride	n.a.	n.a.	n.a.	n.a.	n.a.	4.2%
Primary processing	Purchased inputs	Hydrogen sulfide	n.a.	n.a.	n.a.	n.a.	n.a.	1.3%
Farmed systems								
Primary production	Occupation, grassland/pasture/meadow for livestock grazing	SQI	99%	n.a.	n.a.	n.a.	n.a.	n.a.
Primary production	Enteric methane	CH_4 emissions	n.a.	71%	n.a.	n.a.	n.a.	n.a.
Primary production	Manure methane	CH_4 emissions	n.a.	0.9%	n.a.	n.a.	n.a.	n.a.
Primary production	Direct manure nitrous oxide emissions	N_2O emissions	n.a.	2.9%	n.a.	n.a.	n.a.	n.a.
Primary production	Indirect manure nitrous oxide emissions from the volatilization of ammonia	N_2O emissions	n.a.	1.0%	n.a.	n.a.	n.a.	n.a.
Primary production	Indirect manure nitrous oxide emissions from the leaching of nitrogen	N_2O emissions	n.a.	0.0%	n.a.	n.a.	n.a.	n.a.
Primary production	Carbon dioxide emissions from forest to grassland conversion	CO_2 emissions	n.a.	0.2%	n.a.	n.a.	n.a.	n.a.
Primary production	Carbon dioxide emissions, land transformation from background processes	CO_2 emissions	n.a.	0.7%	n.a.	n.a.	n.a.	n.a.
Primary production	Carbon dioxide emissions, fossil	CO_2 emissions	n.a.	14.4%	n.a.	n.a.	n.a.	n.a.
Primary processing	Carbon dioxide emissions, fossil	CO_2 emissions	n.a.	5.9%	n.a.	n.a.	n.a.	n.a.
Primary production	Ammonia volatilisation from livestock manure	NH3 emissions	n.a.	n.a.	n.a.	n.a.	90%	n.a.
Primary production	Particulates from purchased inputs	Particulates, < 2.5 um	n.a.	n.a.	n.a.	n.a.	5%	n.a.

Life cycle stage	Process	Elementary flow	Land use	Climate change	Water use	Fossil resource use	Particulate matter	Ecotoxicity
Primary processing	Particulates from process steam from hard coal	Particulates, < 2.5 um	n.a.	n.a.	n.a.	n.a.	1%	n.a.
Primary production	Crop irrigation	Water	n.a.	n.a.	13%	n.a.	n.a.	n.a.
Primary production	Irrigation water for supplementary feed	Water	n.a.	n.a.	17%	n.a.	n.a.	n.a.
Primary production	Livestock drinking water	Water	n.a.	n.a.	60%	n.a.	n.a.	n.a.
Primary processing	Water for primary processing	Water	n.a.	n.a.	10%	n.a.	n.a.	n.a.
Primary production	Energy	Coal, brown	n.a.	n.a.	n.a.	3.8%	n.a.	n.a.
Primary production	Energy	Coal, hard	n.a.	n.a.	n.a.	58.8%	n.a.	n.a.
Primary production	Energy	Oil, crude	n.a.	n.a.	n.a.	0.1%	n.a.	n.a.
Primary production	Energy	Uranium	n.a.	n.a.	n.a.	9.7%	n.a.	n.a.
Primary processing	Energy	Coal, brown	n.a.	n.a.	n.a.	0.6%	n.a.	n.a.
Primary processing	Energy	Coal, hard	n.a.	n.a.	n.a.	25.0%	n.a.	n.a.
Primary processing	Energy	Uranium	n.a.	n.a.	n.a.	1.9%	n.a.	n.a.
Primary production	Purchased inputs	Lambda-cyhalothrin	n.a.	n.a.	n.a.	n.a.	n.a.	0.6%
Primary production	Purchased inputs	Chlorpyrifos	n.a.	n.a.	n.a.	n.a.	n.a.	1.5%
Primary production	Purchased inputs	Chloride	n.a.	n.a.	n.a.	n.a.	n.a.	7.3%
Primary production	Purchased inputs	Acetochlor	n.a.	n.a.	n.a.	n.a.	n.a.	26.1%
Primary production	Purchased inputs	Terbuthylazin	n.a.	n.a.	n.a.	n.a.	n.a.	9.9%
Primary production	Purchased inputs	Atrazine	n.a.	n.a.	n.a.	n.a.	n.a.	4.2%
Primary production	Purchased inputs	Hydrogen sulfide	n.a.	n.a.	n.a.	n.a.	n.a.	6.7%
Primary production	Purchased inputs	Tebupirimphos	n.a.	n.a.	n.a.	n.a.	n.a.	3.0%
Primary production	Ammonia volatilization from livestock manure	NH3 emissions	n.a.	n.a.	n.a.	n.a.	n.a.	18.4%
Primary processing	Purchased inputs	Chloride	n.a.	n.a.	n.a.	n.a.	n.a.	7.3%
Primary processing	Purchased inputs	Strontium (II)	n.a.	n.a.	n.a.	n.a.	n.a.	0.6%

6.1.8. Environmental impacts per kg of clean, dehaired cashmere HIGG MSI impact categories

The impacts reported in the HIGG MSI were more narrowly focused than those in PEF. Aside from a measure of land use impact, they aligned with the indicators most relevant to the production regions, namely, climate change, fossil fuel use, and water use. Eutrophication was considered less relevant in the semi-arid and arid zone production in Mongolia and northern China than this indicator is in Europe or other industrialized nations that use large volumes of fertilizer.

Table 27: The environmental impacts reported for the impact categories assessed in the Higg MSI per kg of clean, dehaired cashmere for the nomadic grazing systems and farmed systems

Impact category (Higg MSI)	Unit	Nomadic grazing system	Farmed system
Climate change—(excluding LULUC)	kg CO_2 eq	183	155
Climate change—LUC (excluding soil carbon loss from LU)[1]	kg CO_2 eq	1.5	1.5
Abiotic depletion (fossil fuels)	MJ LHV	144	109
Water use	m^3 deprived	46	83
Eutrophication	kg PO_4 eq	0.1	0.1
Ecotoxicity	CTUe[1]	301	436

[1] The ecotoxicity values (CTUe) will be converted to Higg's semi-quantitative assessment, based on chemistry units, by the Cascale team. Higg does not share the calculation process used to determine the normalization factors for the calculation of the MSI scores.

6.1.9. Biogenic carbon flows

The biogenic carbon flows are reported in Table 28. The net carbon balance was zero, indicating no transfer of carbon flows to or from permanent carbon stocks (temporary stocks in livestock products were treated as resulting in equivalent emissions). Potential changes in soil carbon stocks are discussed in section 6.1.10. As a result, the only carbon flow that contributed to the climate change indicator was methane arising from enteric and manure processes.

Table 28: Modeled inputs and outputs associated with biogenic carbon flows for the nomadic grazing and farmed system (units in kg C per year)

Carbon balance	Nomadic grazing	Farmed system
Plant		
Plant CO_2 assimilation (CO_2-C)	8334021	8365503
Autotrophic respiration (plant respiration)	4167010	4182751
Annual dry matter production	304554	305704
Livestock dry matter intake	60911	61141
Senesced leaf, stem	243643	244563
Senesced root material	3862457	3877047
Livestock		
Animal respiration	25717	30020
Enteric methane as carbon	1840	1814
Manure methane as carbon	29	23
Manure excreted as carbon	32741	28402
Carbon embedded in liveweight	552	816
Carbon embedded in wool	32	65

Carbon balance	**Nomadic grazing**	**Farmed system**
Soil		
Carbon added in the soil	4138841	4150013
Soil respiration	4138841	4150013
Carbon balance		
Annual plant uptake of carbon	−8334021	−8365503
Autotrophic respiration (plant respiration)	4167010	4182751
Respired by livestock as CO_2	25717	30020
Eructated as methane (CH_4-C)	1840	1814
Manure methane (CH_4-C)	29	23
Embedded in livestock products (live weight and wool)	583	881
Soil respiration	4138841	4150013
Carbon balance	**0**	**0**

6.1.10. Environmental impacts: Soil carbon per hectare

The estimated soil carbon loss in grassland remaining grassland calculated using the IPCC method varied, depending on the level of land use pressure and from region to region. The proportion of areas and associated soil carbon stock change factors, and uncertainty, are shown in Table 29, Table 30 and Figure 7. The probability density plots of IPCC stock change factors under varying degradation levels reveal substantial differences in both the magnitude and uncertainty of potential soil carbon outcomes (Figure 9, Figure 10). Slightly degraded soils exhibited a narrow, sharply peaked distribution center, indicating small to no changes in soil carbon stocks. In contrast, moderately to degraded soils presented a broader and more variable distribution. Notably, severely and very severely degraded soils demonstrated the highest sensitivity, largely due to the uncertainty over whether these systems have reached a new equilibrium or are still undergoing soil carbon loss. These results reflect not only the heightened uncertainty but also the greater potential for carbon sequestration, depending on how land is managed.

Under the IPCC framework, stock change factors are assigned according to degradation status. The predicted carbon stock change takes into consideration lands that are currently improving in productivity. When the uncertainty was considered, the stock change factor exceeded 1, implying a net SOC gain relative to a degraded baseline. This outcome reflected recovery from prior degradation (see Figure 10).

Table 29: Soil organic carbon stocks in Mongolia (Ministry of Environment and Tourism of Mongolia, 2024) and estimated soil carbon loss rate using IPCC Tier 1 factors (IPCC, 2006c)

Natural zones	Current content, t C/ha	**Estimated SOC loss t C/ha/year**
High mountain	59.08	0.32
Forest steppe	47.47	0.25
Steppe	44.06	0.24
Desert steppe[1]	41.65	0
Desert[1]	28.24	0

[1] Supporting evidence from Mongolian field studies and Century model simulations indicates minimal to no change in soil organic carbon stocks under current land use in desert and semi-desert regions.

Table 30: Areas of land degradation in China (Zheng et al., 2024) and associated carbon stock change factor (IPCC, 2006c)

Description	% of total land area	Soil carbon change (t C/ha/year)	Uncertainty
Non-degraded	25%	0.00	n.r.
Lightly degraded	30%	0.08	+/- 13%
Moderately degraded	27%	0.08	+/- 13%
Severely degraded	22%	0.45	+/- 40%

n.r. = not reported

Figure 7: Application of the IPCC stock change factors to soil carbon stock change (t C/ha/year) for the nomadic grazing system. Negative values indicate soil carbon loss

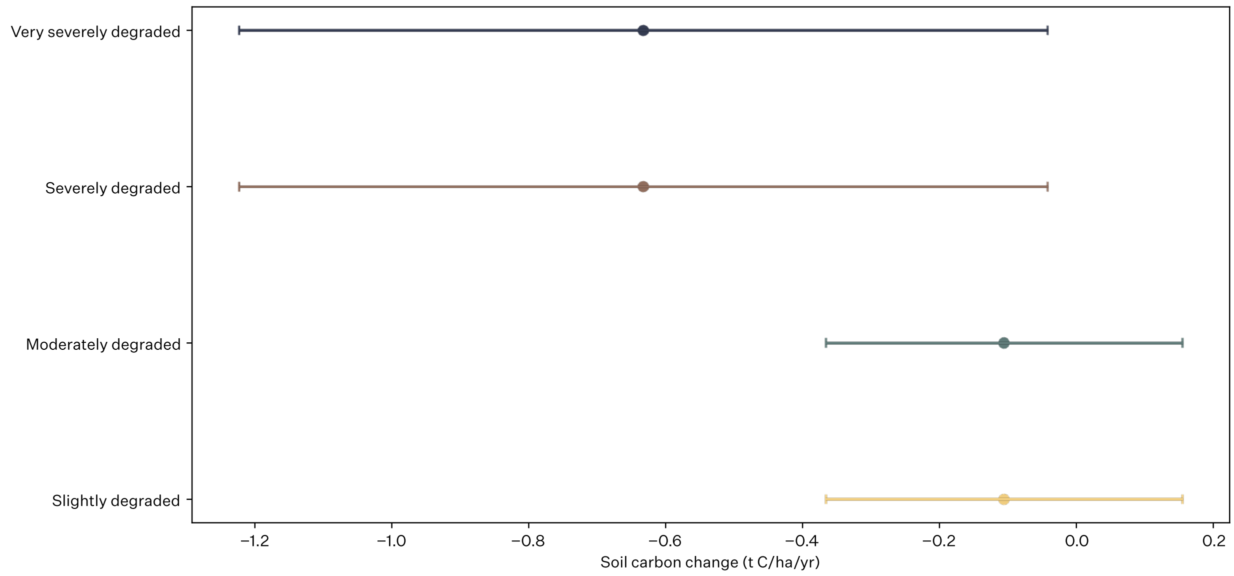


Figure 8: Application of the IPCC stock change factors to soil carbon stock change (t C/ha/year) for the farmed system. Negative values indicate soil carbon loss.

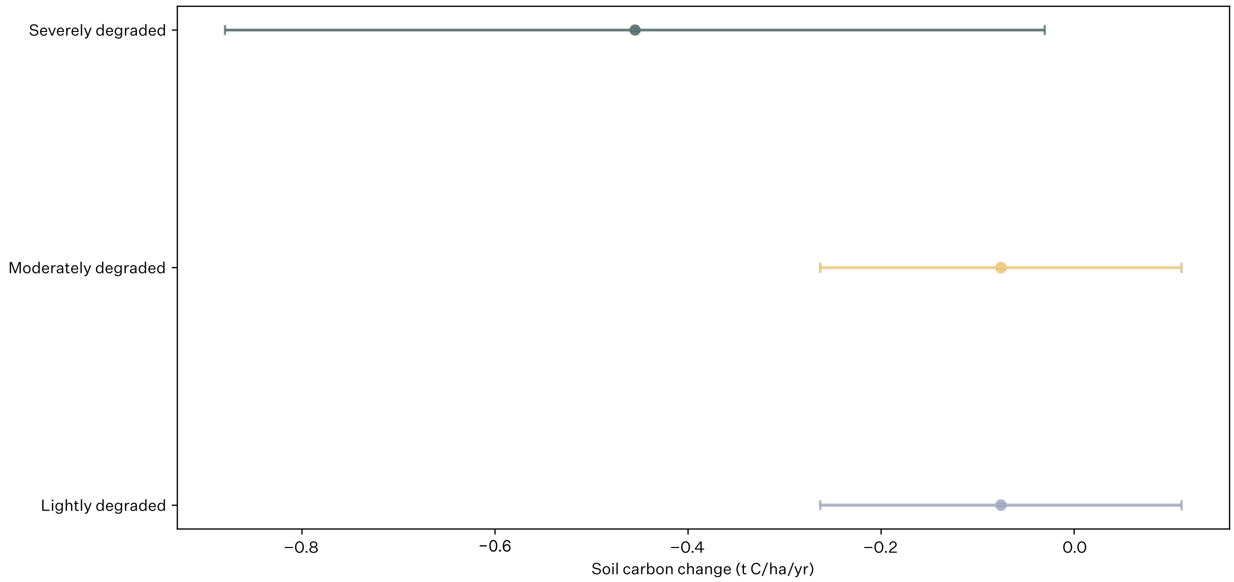


Figure 9: Application of the IPCC stock change factors based on the proportion of degradation levels in the nomadic grazing system. Values less than 1 indicate soil carbon loss.

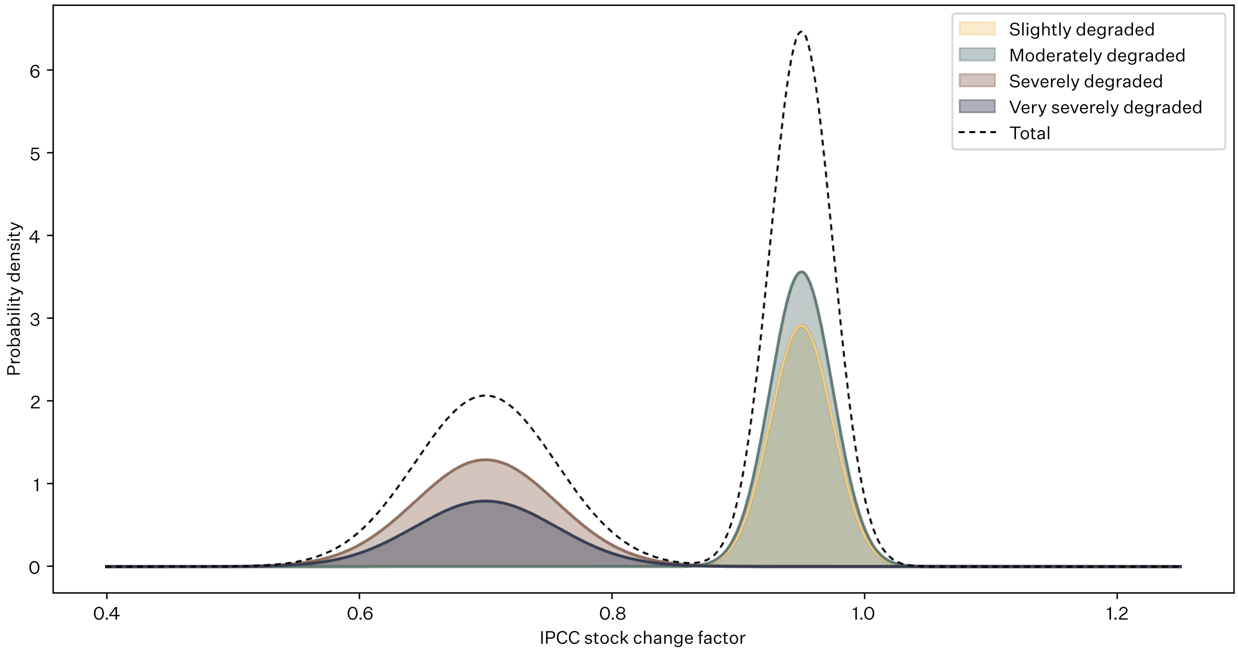
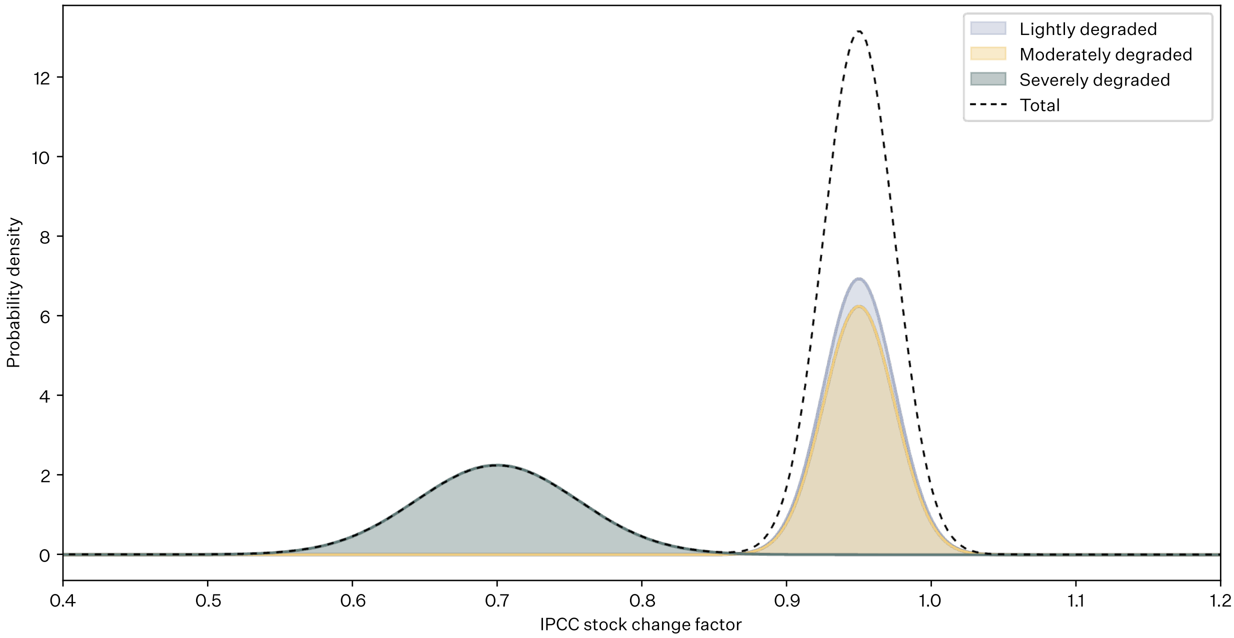


Figure 10: Application of the IPCC stock change factors based on the proportion of degradation levels in the farmed system. Values less than 1 indicate soil carbon loss.



6.2. Sensitivity analysis

6.2.1. Sensitivity to allocation approach

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

6.2.2. Economic allocation

The sensitivity analysis, using an economic allocation for the handling of co-production of cashmere, liveweight for meat consumption, and milk for dairy products, substantially increased the environmental impacts for cashmere compared to the baseline results (Table 22), by up to a factor of 5 for nomadic grazing systems and by up to a factor of 2 for farmed systems. This varied depending on the impact category (see Table 33). The larger increase in impacts observed in nomadic grazing systems reflected the lower economic value for live weight and meat sales in Mongolia compared to China. Mongolian herders have fewer livestock market options, and the product is in less demand compared to China, affecting prices received by herders. In addition, the presence of livestock diseases in Mongolia restricts access to international markets. It could be postulated that these market conditions influenced primary production output differently in Mongolia and China. This combined impact of lower sales numbers and lower sales price had a compounding effect on allocation impacts in Mongolia. The inventory data (Table 5) showed significantly higher liveweight output from the farmed system compared to the nomadic system, including higher numbers and weight of sales of younger animals. This suggested the increased sale value induced more sales from these herds, though climate factors also influenced the total number and weight of animals available for sale in Mongolia compared to China.

6.2.3. Energy allocation

The sensitivity analysis of energy allocation methods for the handling of co-production of cashmere, liveweight for meat consumption, and milk for dairy products, resulted in lower and higher allocations to cashmere 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 raw cashmere (less the grease content) and 38 MJ in grease, showed impacts were higher for fiber using the protein method, because fiber has a very high proportion of protein (clean, dry fiber 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 protein 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 cashmere was increased to 59.3 MJ, 130 MJ, and 157 MJ per kg of raw cashmere, the impacts on cashmere were up to four times higher than the protein allocation method. These values were based on wool (sheep) energy estimates, of which the 130 MJ and 157 MJ figures included maintenance energy requirements. Further investigation into the appropriate energy allocation method is therefore needed, along with dedicated research into the specific energy demands of cashmere growth. The results of these allocation approaches are reported per kg of raw cashmere in Table 31 and Table 32, and the results of the energy allocation (b) are also reported per kg of clean, dehaired cashmere in Table 34.

Table 31: Sensitivity analysis of economic and energy allocation approaches per kg of raw cashmere for the nomadic grazing systems to handle the co-production of cashmere, liveweight for meat consumption, and milk for dairy products

Farm gate	Unit	Protein	(a) Economic	(b) Energy	(c) Energy	(d) Energy	(e) Energy	(f) Energy
Total greenhouse gas emissions (excluding LU and LUC)[1]	kg CO_2-eq	75958				78755	79471	76880
Total raw cashmere sold or used for consumption	kg	96						
Total kg liveweight sold or used for consumption	kg	3066						
Total liters milk sold or used for consumption	L	549						
% cashmere	%	11%	52%	6%	5%	22%	25%	11%
% meat	%	85%	41%	90%	92%	75%	72%	85%
% milk	%	4%	7%	4%	4%	3%	3%	3%
Climate change (excluding LU and LUC)—cashmere	kg CO_2-eq/kg raw cashmere	84	410	45	39	180	210	91
Climate change (excluding LU and LUC)—meat	kg CO_2-eq/kg liveweight	21	10	22	23	19	19	21
Climate change (excluding LU and LUC)—milk	kg CO_2-eq/L milk	6	10	6	5	4	4	5

[1] The total greenhouse gas emissions increased with the increase in the energy required to produce cashmere from 24 MJ to (d) 130 MJ/kg raw cashmere, (e) 157 MJ/kg raw cashmere, and (f) 59.3 MJ/kg raw cashmere). These assumptions are used in the calculation of the gross energy that is used to predict livestock greenhouse gas emissions.

Table 32: Sensitivity analysis of economic and energy allocation approaches per kg of raw cashmere for the farmed system to handle the co-production of cashmere, liveweight for meat consumption, and milk for dairy products

Farm gate	Unit	Headline Protein	(a) Economic	(b) Energy	(c) Energy	(d) Energy	(e) Energy	(f) Energy
Total greenhouse gas emissions (excluding LU and LUC)[1]	kg CO_2-eq	85711				92442	94166	87928
Total raw cashmere sold or used for consumption	kg	215						
Total kg liveweight sold or used for consumption	kg	4534						
Total liters milk sold or used for consumption	L	14						
% cashmere	%	15%	30%	9%	9%	34%	38%	19%

% meat	%	85%	69%	91%	91%	66%	62%	81%
% milk	%	0.1%	0.2%	0.1%	0.1%	0.1%	0.0%	0.1%
Climate change (excluding LU and LUC)—cashmere	kg CO_2-eq/kg raw cashmere	59	121	37	34	144	166	76
Climate change (excluding LU and LUC)—meat	kg CO_2-eq/kg liveweight	16	13	17	17	14	13	16
Climate change (excluding LU and LUC)—milk	kg CO_2-eq/L milk	5	10	5	4	3	3	4

[1] The total greenhouse gas emissions increased with the increase in the energy required to produce cashmere from 24 MJ to (d) 130 MJ/kg raw cashmere, (e) 157 MJ/kg raw cashmere, and (f) 59.3 MJ/kg raw cashmere). These assumptions are used in the calculation of the gross energy that is used to predict livestock greenhouse gas emissions.

Table 33: Environmental impacts per kg of clean, dehaired cashmere for nomadic grazing systems and farmed systems using an economic allocation to handle the co-production of cashmere, liveweight for meat consumption, and milk for dairy products

Impact category (PEF)	Unit	Nomadic grazing system	Farmed system
Acidification	mol H^+ eq	0.4	0.4
Climate change	kg CO_2 eq	821	312
Climate change—(excluding LU and LUC)	kg CO_2 eq	814	309
Climate change—biogenic[1]	kg CO_2 eq	704	231
Climate change—fossil	kg CO_2 eq	110	78
Climate change—(excluding soil carbon loss from LU)[2]	kg CO_2 eq	7.2	3.0
Ecotoxicity, freshwater	CTUe	1877	1092
Particulate matter	disease incidence	1E-04	4E-05
Eutrophication, marine	kg N eq	0.1	0.1
Eutrophication, freshwater	kg P eq	2.0E-02	1.3E-02
Eutrophication, terrestrial	mol N eq	7.8	3.6
Human toxicity, cancer	CTUh	2.8E-08	2.1E-08
Human toxicity, cancer—inorganics	CTUh	9.6E-09	5.3E-09
Human toxicity, cancer—organics	CTUh	1.8E-08	1.5E-08
Human toxicity, non-cancer	CTUh	2.1E-06	8.9E-07
Human toxicity, non-cancer—inorganics	CTUh	7.9E-07	4.0E-07
Human toxicity, non-cancer—organics	CTUh	1.3E-06	4.9E-07
Ionizing radiation	kBq U-235 eq	2.9	1.5
Land use	Pt	1137942	265212
Ozone depletion	kg CFC11 eq	2.5E-07	2.3E-07
Photochemical ozone formation	kg NMVOC eq	0.5	0.3
Resource use, fossils	MJ	266	193
Resource use, minerals and metals	kg Sb eq	9.2E-04	5.6E-04
Water use	m^3 deprived	178	163

[1] Biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.

[2] Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which is reported elsewhere in section 6.1.10.

Table 34: Environmental impacts per kg of clean, dehaired cashmere for nomadic grazing systems, and farmed systems, using a biophysical energy allocation method to handle the co-production of cashmere, liveweight for meat consumption, and milk for dairy products

Impact category (PEF)[1]	Unit	Nomadic grazing	Farmed system
Acidification	mol H^+ eq	0.1	0.1
Climate change	kg CO_2 eq	109	103
Climate change—(excluding LULUC)	kg CO_2 eq	108	103
Climate change—biogenic[2]	kg CO_2 eq	79	71
Climate change—fossil	kg CO_2 eq	30	31
Climate change—LUC (excluding soil carbon loss from LU)[3]	kg CO_2 eq	0.8	1.0
Ecotoxicity, freshwater	CTUe	242	347
Particulate matter	disease incidence	1E-05	1E-05
Eutrophication, marine	kg N eq	0.0	0.0
Eutrophication, freshwater	kg P eq	7.4E-03	4.6E-03
Eutrophication, terrestrial	mol N eq	1.0	1.2
Human toxicity, cancer	CTUh	5.9E-09	7.5E-09
Human toxicity, cancer—inorganics	CTUh	2.3E-09	1.9E-09
Human toxicity, cancer—organics	CTUh	3.7E-09	5.6E-09
Human toxicity, non-cancer	CTUh	3.4E-07	3.0E-07
Human toxicity, non-cancer— inorganics	CTUh	1.9E-07	1.5E-07
Human toxicity, non-cancer— organics	CTUh	1.5E-07	1.5E-07
Ionizing radiation	kBq U-235 eq	1.6	0.5
Land use	Pt	126057	81942
Ozone depletion	kg CFC11 eq	4.2E-08	7.4E-08
Photochemical ozone formation	kg NMVOC eq	0.1	0.1
Resource use, fossils	MJ	130	80
Resource use, minerals and metals	kg Sb eq	1.6E-04	1.8E-04
Water use	m3 deprived	30	56

[1] The results presented here follow the energy allocation approach described in section 5.8 energy allocation (b).

[2] Biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.

[3] Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which is reported elsewhere in section 6.1.10.

6.2.4. Sensitivity to seasonal and regional impacts

Impacts in a dzud year were, on average, four times higher than the baseline results (Table 22), depending on the impact category (Table 35). The primary contributing factor was the dramatic reduction in product output in these years. During the dzud year covered in this study, almost no sales of animals or meat occurred because of the high mortalities observed. This pattern is not unique to this year. When mortality rates are high, herders typically cannot maintain a self-replacing herd, which prevents sales in order to prioritize herd recovery. This had the effect of shifting almost all primary production impacts to cashmere, as there was very low output of meat and milk from the system. These results also indicated that intermittent dzud events influence the long-term performance of the goat herd in Mongolia and highlight the opportunity to mitigate effects through management of these events.

The area-weighted spatial disaggregation approach by agroecological zone had minimal impact on the overall results, with less than a 2.5% difference across all impact categories. This suggests that the stratification approach and aggregation by cashmere volume effectively captured the weightings by agroecological zone.

Table 35: Environmental impacts per kg of clean, dehaired cashmere for nomadic grazing systems for a dzud impacted year

Impact category (PEF)	Unit	Nomadic grazing systems (dzud impacted year)
Acidification	mol H^+ eq	0.5
Climate change	kg CO_2 eq	826
Climate change—(excluding LULUC)	kg CO_2 eq	817
Climate change—biogenic[1]	kg CO_2 eq	701
Climate change—fossil	kg CO_2 eq	116
Climate change—(excluding soil carbon loss from LU)[2]	kg CO_2 eq	9.7
Ecotoxicity, freshwater	CTUe	2099
Particulate matter	disease incidence	1E-04
Eutrophication, marine	kg N eq	0.2
Eutrophication, freshwater	kg P eq	0.0
Eutrophication, terrestrial	mol N eq	8.2
Human toxicity, cancer	CTUh	3.2E-08
Human toxicity, cancer—inorganics	CTUh	1.1E-08
Human toxicity, cancer—organics	CTUh	2.1E-08
Human toxicity, non-cancer	CTUh	2.2E-06
Human toxicity, non-cancer—inorganics	CTUh	9.3E-07
Human toxicity, non-cancer—organics	CTUh	1.3E-06
Ionizing radiation	kBq U-235 eq	3.1
Land use	Pt	889662
Ozone depletion	kg CFC11 eq	3.1E-07
Photochemical ozone formation	kg NMVOC eq	0.5
Resource use, fossils	MJ	288
Resource use, minerals and metals	kg Sb eq	0.0
Water use	m^3 deprived	210

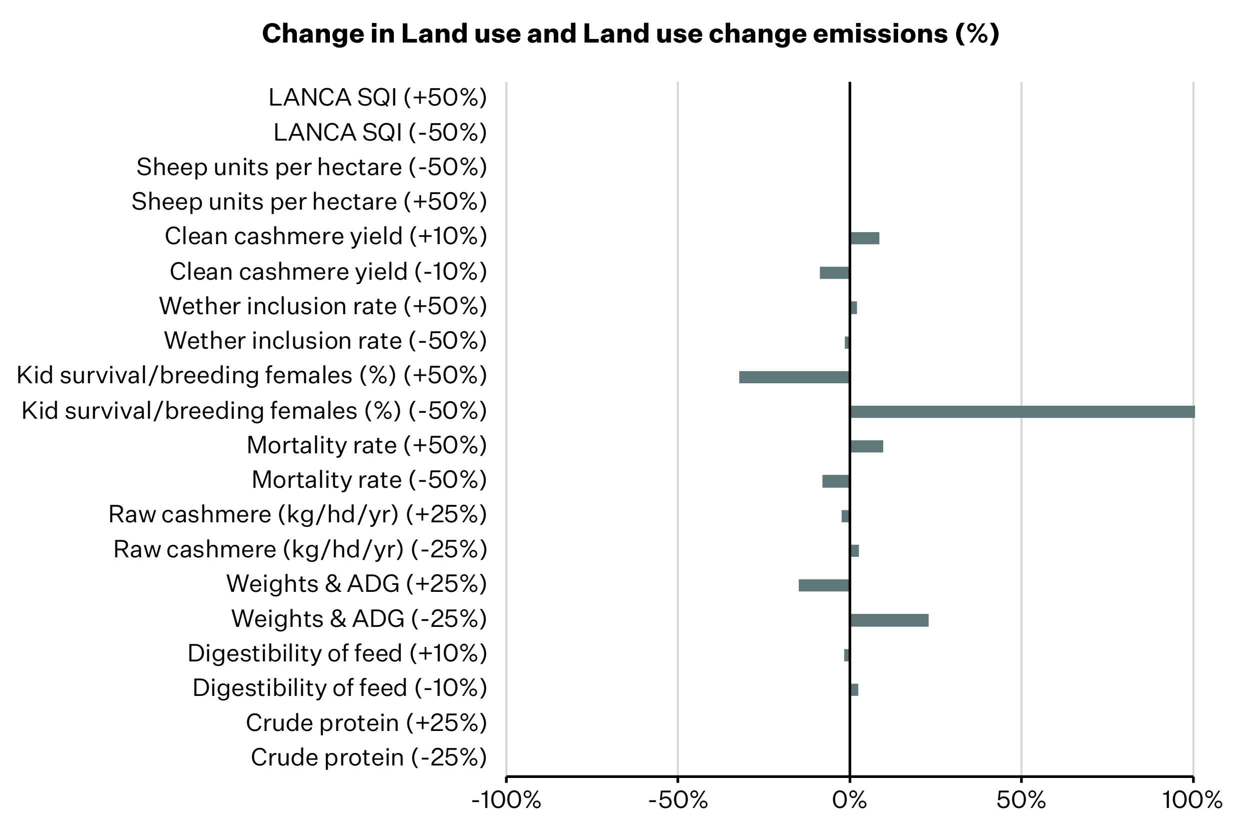
[1] Biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.

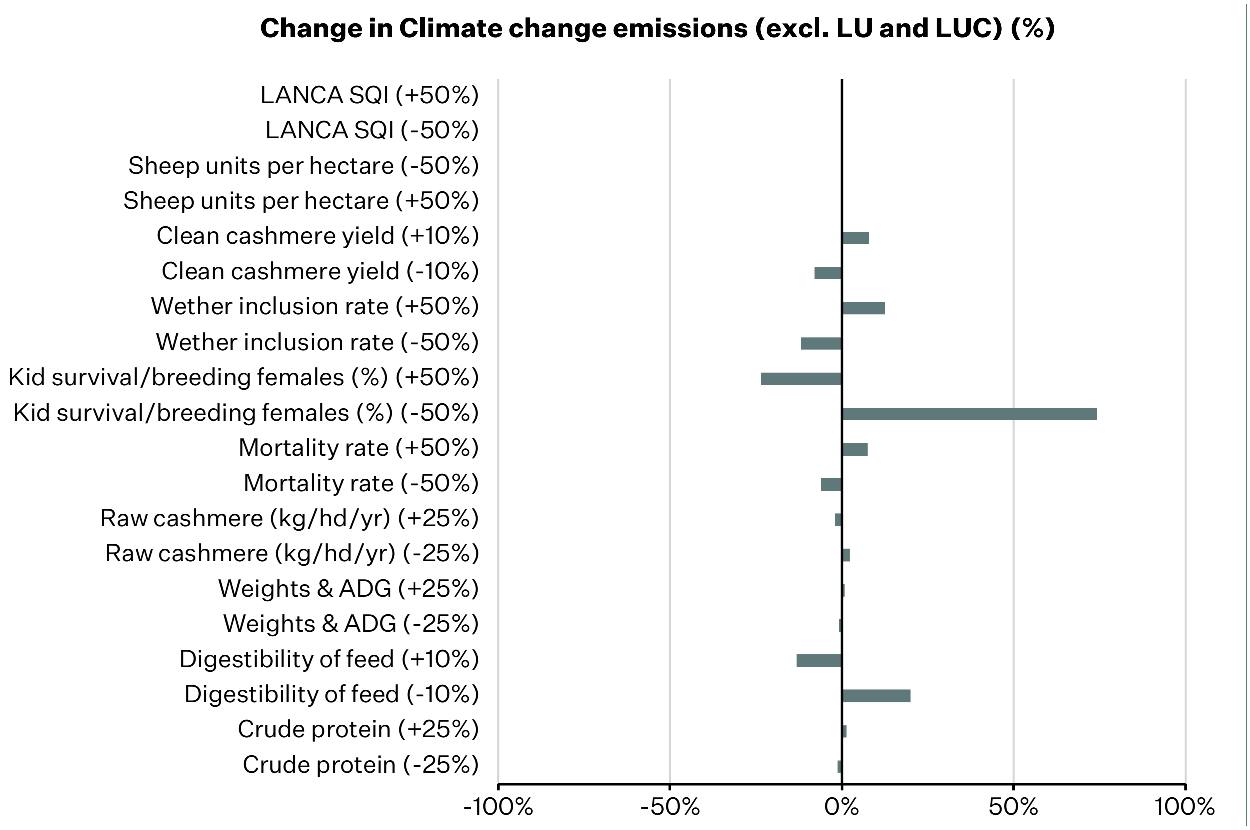
[2] Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which is reported elsewhere in section 6.1.10.

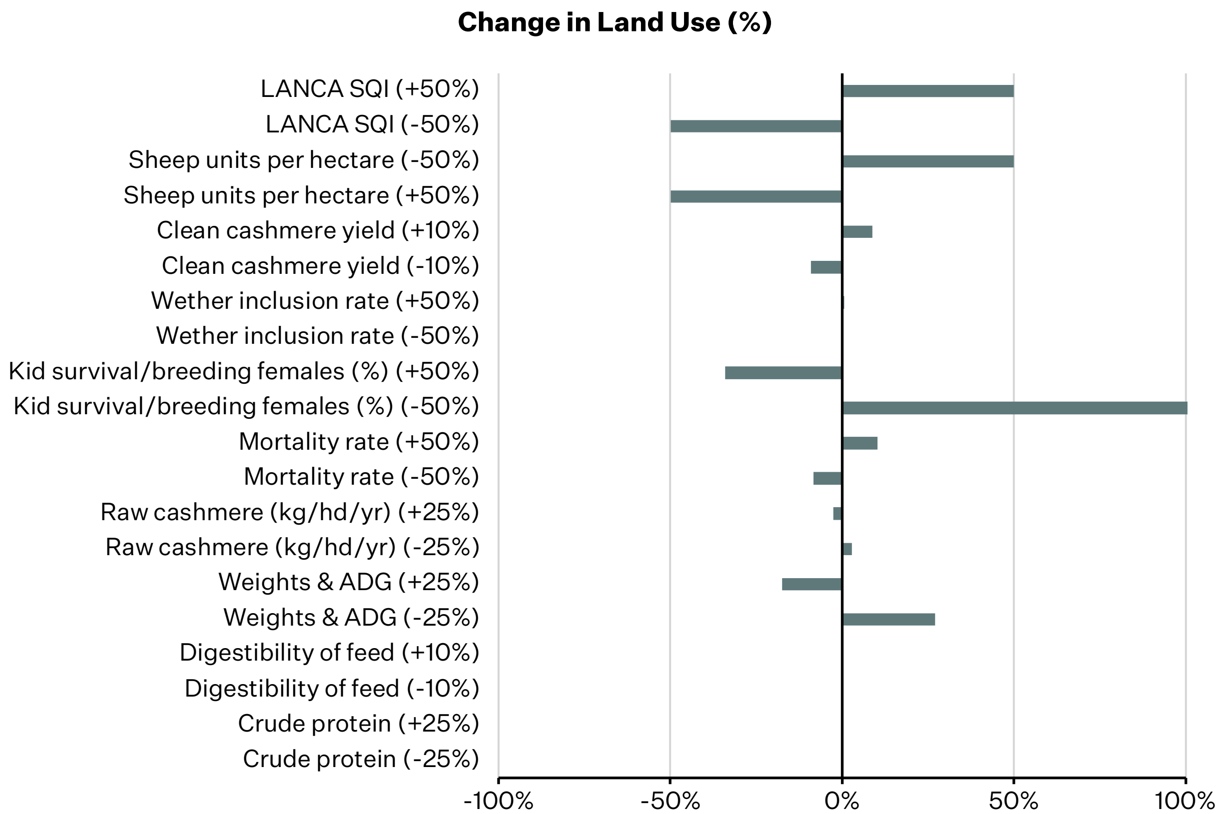
6.2.5. Sensitivity analysis: Key parameters

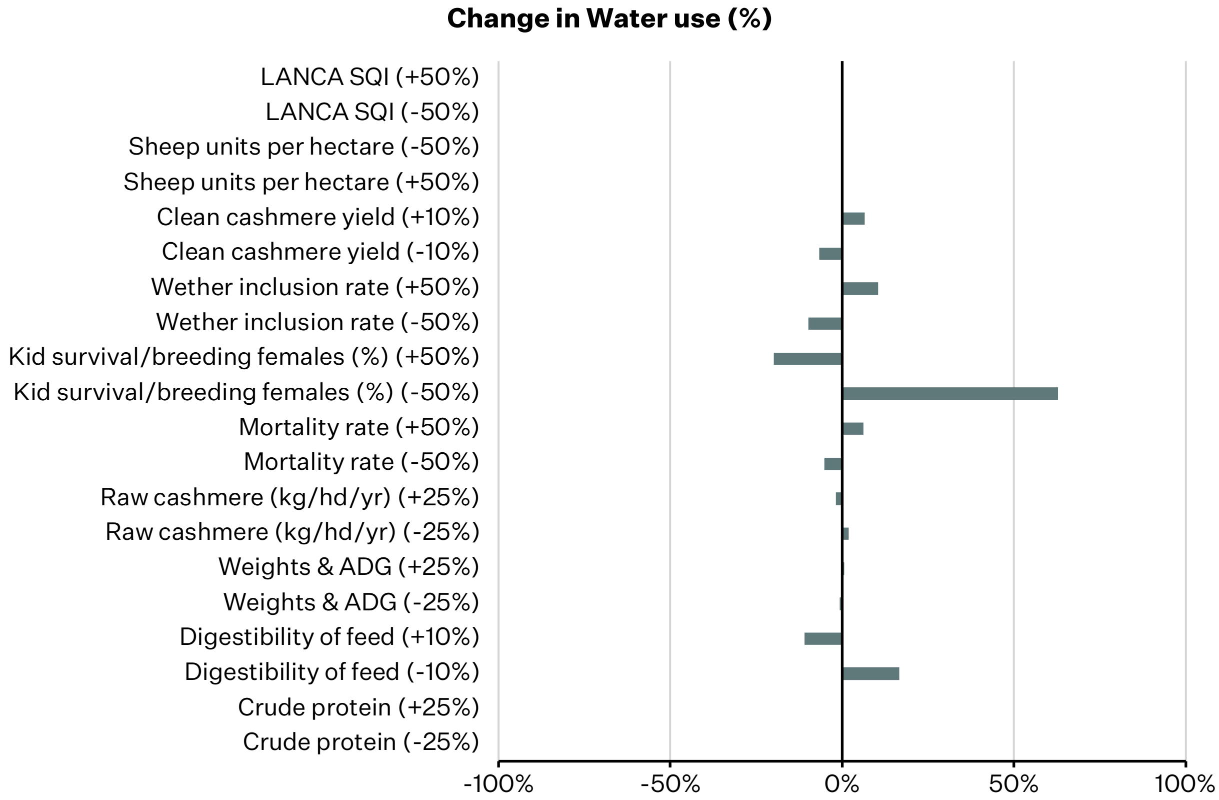
A sensitivity analysis was performed on key model parameters. Herd productivity parameters, including kid survival as a proportion of breeding females, were identified as one of the most influential factors affecting environmental impacts (Figure 11, Figure 12). Increasing kid survival as a proportion of breeding females from 67% to 100% (+50% change) reduced climate change impacts (excluding LU and LUC) by 24% in the nomadic grazing system. Due to the model's non-linear structure, reductions in kid survival led to exponential increases in environmental impacts for raw cashmere, primarily driven by a substantial decline in overall protein output. This trend is also evident under the dzud scenario. 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 kid 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, are functions 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 11: Sensitivity analysis of key parameters as a proportion of the baseline environmental impacts per kg of clean, dehaired cashmere for the nomadic grazing system




Change in Climate change emissions (excl. LU and LUC) (%)
LANCA SQI (+50%)
LANCA SQI (-50%)
Sheep units per hectare (-50%)
Sheep units per hectare (+50%)
Clean cashmere yield (+10%)
Clean cashmere yield (-10%)
Wether inclusion rate (+50%)
Wether inclusion rate (-50%)
Kid survival/breeding females (%) (+50%)
Kid survival/breeding females (%) (-50%)
Mortality rate (+50%)
Mortality rate (-50%)
Raw cashmere (kg/hd/yr) (+25%)
Raw cashmere (kg/hd/yr) (-25%)
Weights & ADG (+25%)
Weights & ADG (-25%)
Digestibility of feed (+10%)
Digestibility of feed (-10%)
Crude protein (+25%)
Crude protein (-25%)
-100%
-50%
0%
50%
100%


Change in Land Use (%)
LANCA SQI (+50%)
LANCA SQI (-50%)
Sheep units per hectare (-50%)
Sheep units per hectare (+50%)
Clean cashmere yield (+10%)
Clean cashmere yield (-10%)
Wether inclusion rate (+50%)
Wether inclusion rate (-50%)
Kid survival/breeding females (%) (+50%)
Kid survival/breeding females (%) (-50%)
Mortality rate (+50%)
Mortality rate (-50%)
Raw cashmere (kg/hd/yr) (+25%)
Raw cashmere (kg/hd/yr) (-25%)
Weights & ADG (+25%)
Weights & ADG (-25%)
Digestibility of feed (+10%)
Digestibility of feed (-10%)
Crude protein (+25%)
Crude protein (-25%)
-100%
-50%
0%
50%
100%


Change in Water use (%)
LANCA SQI (+50%)
LANCA SQI (-50%)
Sheep units per hectare (-50%)
Sheep units per hectare (+50%)
Clean cashmere yield (+10%)
Clean cashmere yield (-10%)
Wether inclusion rate (+50%)
Wether inclusion rate (-50%)
Kid survival/breeding females (%) (+50%)
Kid survival/breeding females (%) (-50%)
Mortality rate (+50%)
Mortality rate (-50%)
Raw cashmere (kg/hd/yr) (+25%)
Raw cashmere (kg/hd/yr) (-25%)
Weights & ADG (+25%)
Weights & ADG (-25%)
Digestibility of feed (+10%)
Digestibility of feed (-10%)
Crude protein (+25%)
Crude protein (-25%)
-100%
-50%
0%
50%
100%

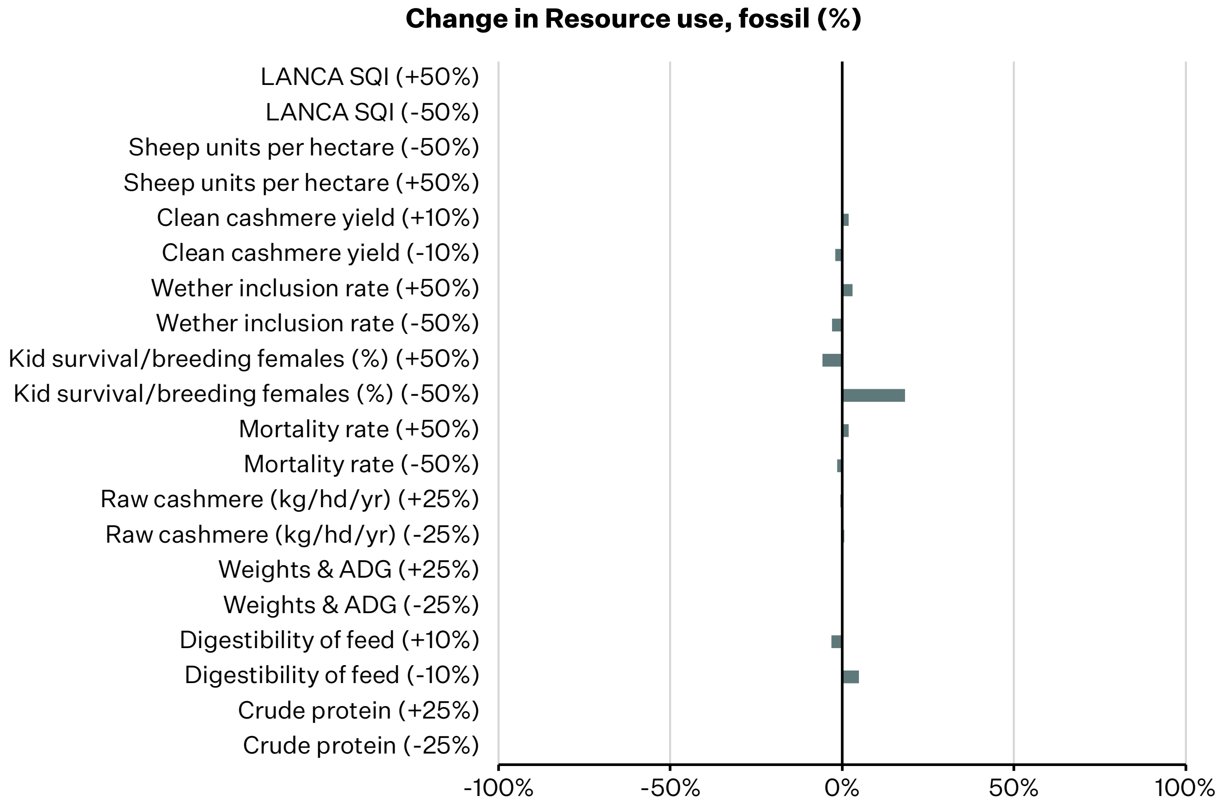
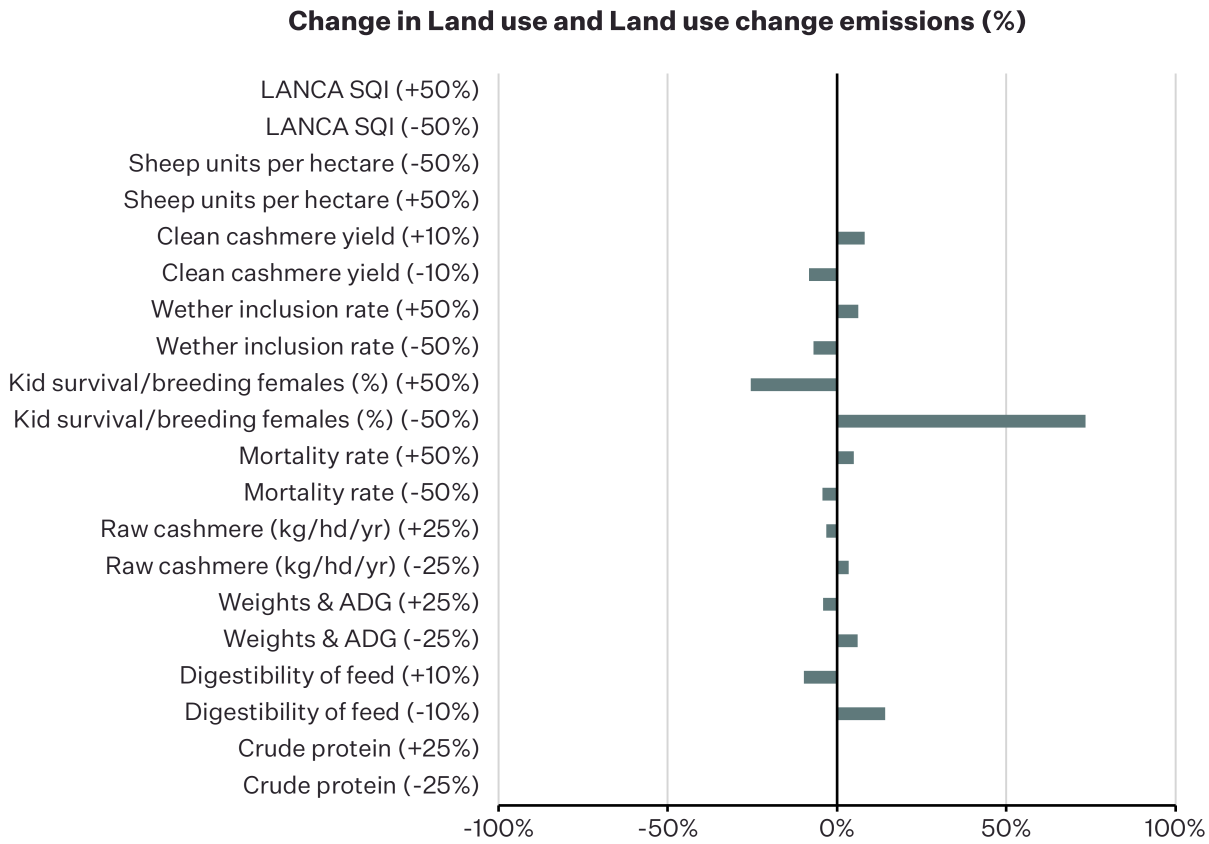
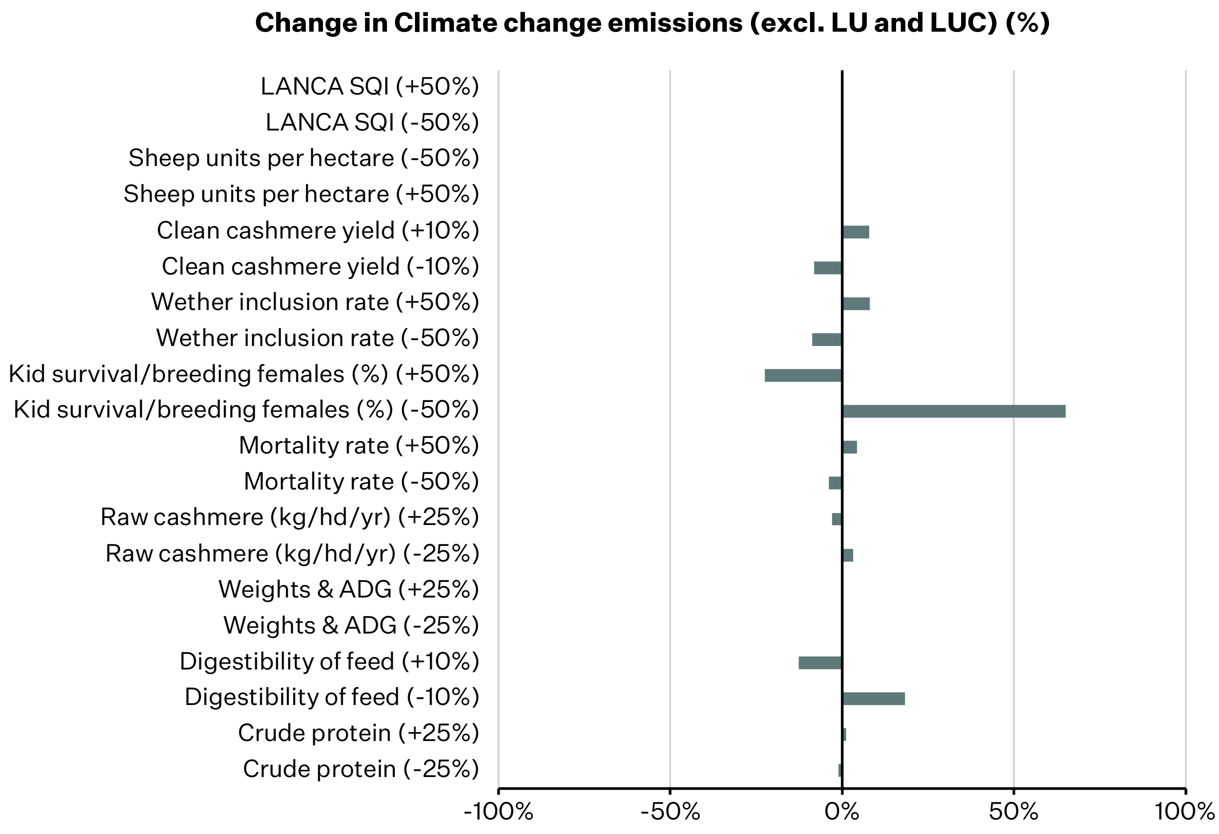
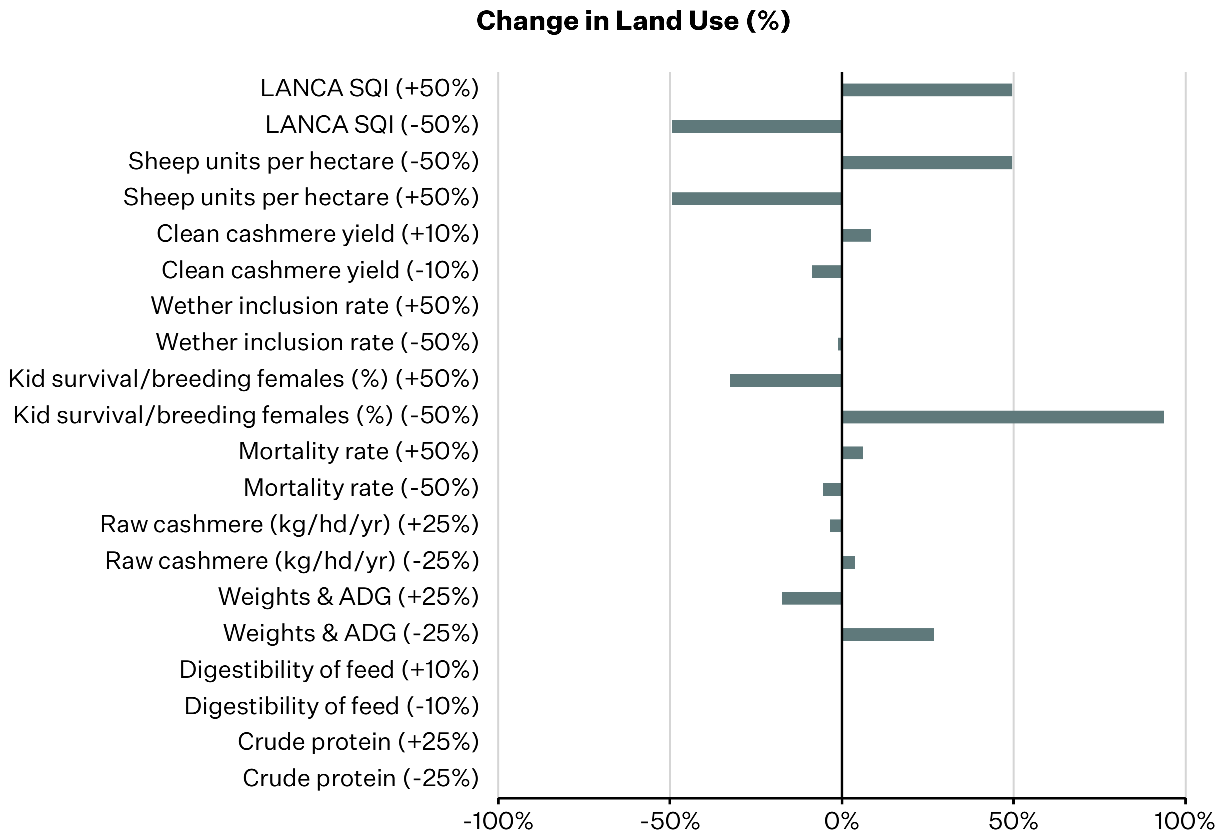
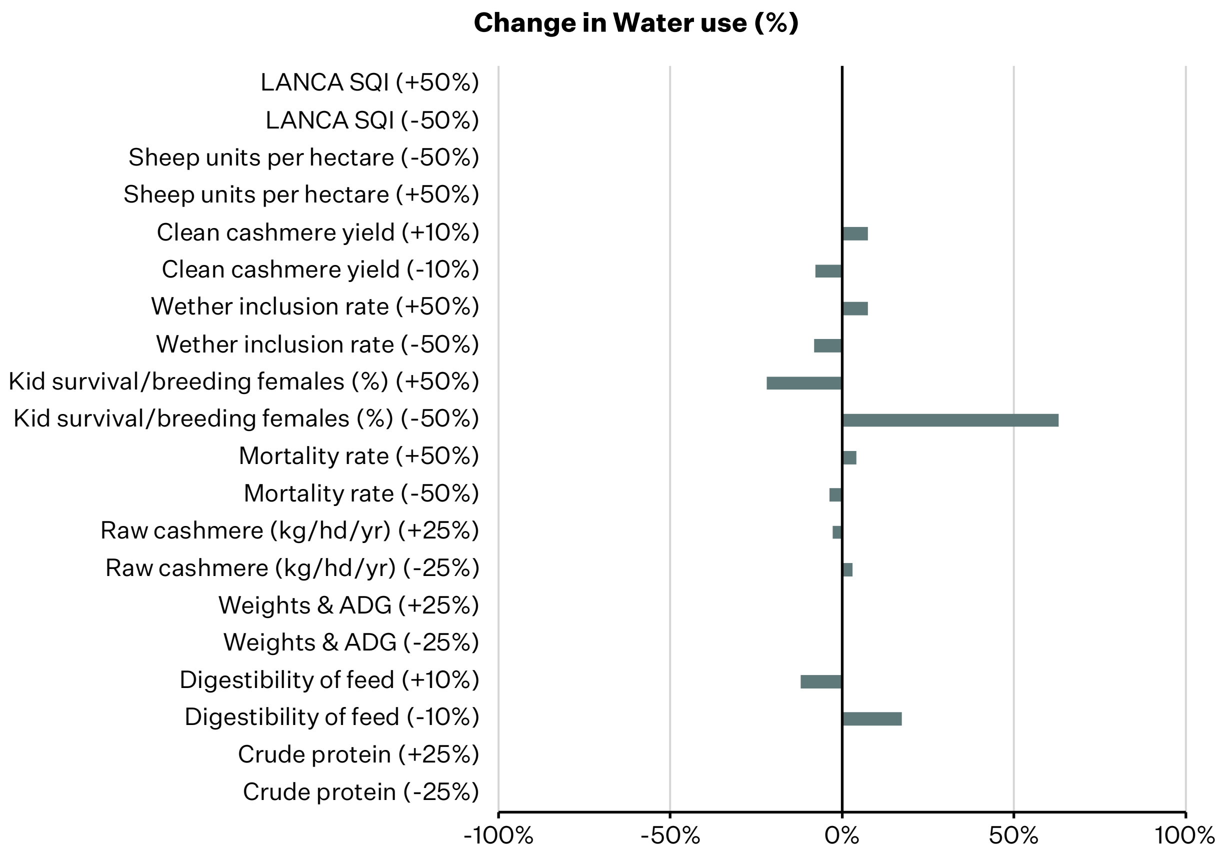

Change in Resource use, fossil (%)
LANCA SQI (+50%)
LANCA SQI (-50%)
Sheep units per hectare (-50%)
Sheep units per hectare (+50%)
Clean cashmere yield (+10%)
Clean cashmere yield (-10%)
Wether inclusion rate (+50%)
Wether inclusion rate (-50%)
Kid survival/breeding females (%) (+50%)
Kid survival/breeding females (%) (-50%)
Mortality rate (+50%)
Mortality rate (-50%)
Raw cashmere (kg/hd/yr) (+25%)
Raw cashmere (kg/hd/yr) (-25%)
Weights & ADG (+25%)
Weights & ADG (-25%)
Digestibility of feed (+10%)
Digestibility of feed (-10%)
Crude protein (+25%)
Crude protein (-25%)
-100%
-50%
0%
50%
100%

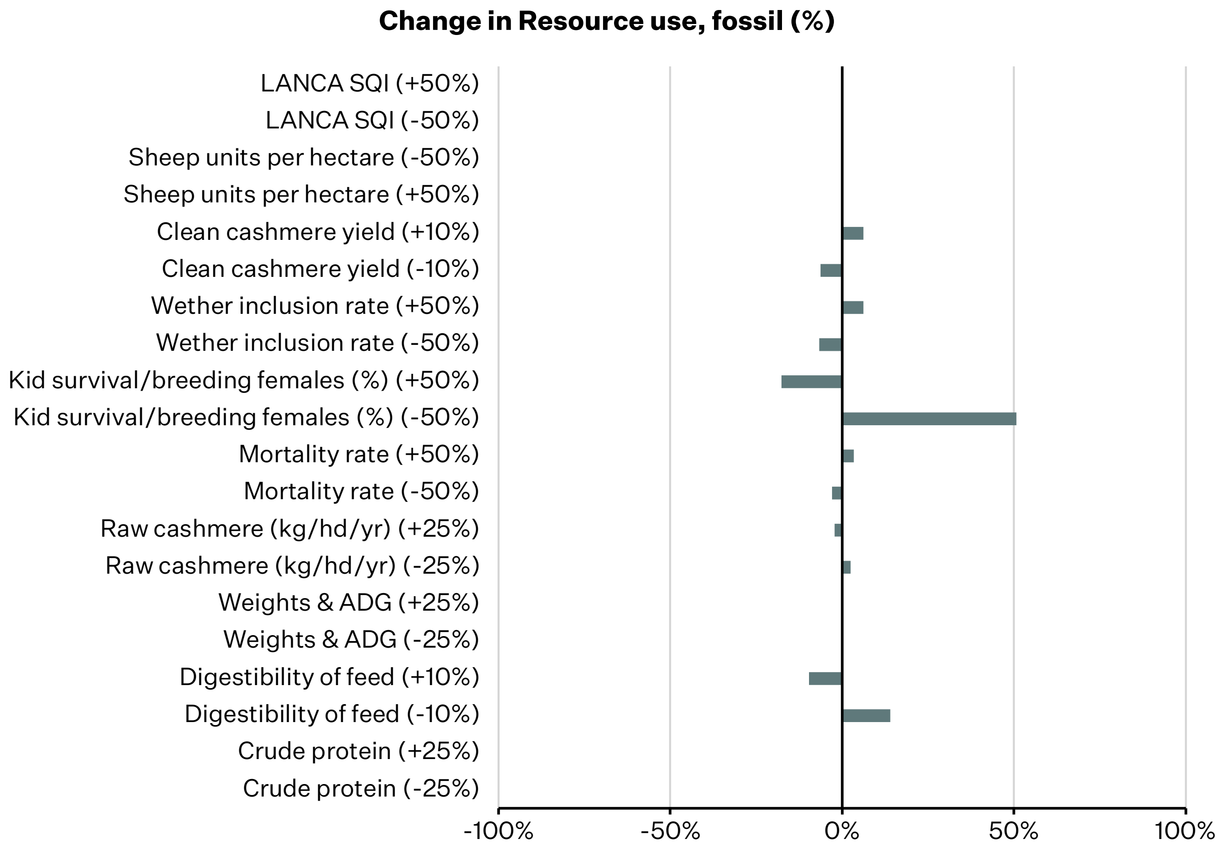
Figure 12: Sensitivity analysis of key parameters as a proportion of the baseline environmental impacts per of clean, dehaired cashmere for the farmed system






Change in Land Use (%)
LANCA SQI (+50%)
LANCA SQI (-50%)
Sheep units per hectare (-50%)
Sheep units per hectare (+50%)
Clean cashmere yield (+10%)
Clean cashmere yield (-10%)
Wether inclusion rate (+50%)
Wether inclusion rate (-50%)
Kid survival/breeding females (%) (+50%)
Kid survival/breeding females (%) (-50%)
Mortality rate (+50%)
Mortality rate (-50%)
Raw cashmere (kg/hd/yr) (+25%)
Raw cashmere (kg/hd/yr) (-25%)
Weights & ADG (+25%)
Weights & ADG (-25%)
Digestibility of feed (+10%)
Digestibility of feed (-10%)
Crude protein (+25%)
Crude protein (-25%)
-100%
-50%
0%
50%
100%


Change in Water use (%)
LANCA SQI (+50%)
LANCA SQI (-50%)
Sheep units per hectare (-50%)
Sheep units per hectare (+50%)
Clean cashmere yield (+10%)
Clean cashmere yield (-10%)
Wether inclusion rate (+50%)
Wether inclusion rate (-50%)
Kid survival/breeding females (%) (+50%)
Kid survival/breeding females (%) (-50%)
Mortality rate (+50%)
Mortality rate (-50%)
Raw cashmere (kg/hd/yr) (+25%)
Raw cashmere (kg/hd/yr) (-25%)
Weights & ADG (+25%)
Weights & ADG (-25%)
Digestibility of feed (+10%)
Digestibility of feed (-10%)
Crude protein (+25%)
Crude protein (-25%)
-100%
-50%
0%
50%
100%



6.2.6. Sensitivity analysis: Soil carbon

The sensitivity analysis showed that changes in soil carbon stocks could have a notable effect on the carbon footprint of clean, dehaired cashmere for both production systems. For the nomadic grazing system, soil carbon loss ranging from 50 to 150 kg C/ha/year with an attribution to livestock in the range 10–30%, increased impacts by 7–64% relative to the baseline (Table 36). Conversely, a soil carbon stock gain (sequestration) of 50 kg C/ha/year, with an attribution to livestock in the range 10 to 30%, reduced the footprint by 7–21% of the baseline. For the farmed system, the effect was less pronounced but followed the same trend: soil carbon stock losses increased the footprint by 3–31%, while a soil carbon stock gain (sequestration) reduced it by 3–10% (Table 37). Higher attribution levels consistently amplified the sensitivity in both systems.

Table 36: Sensitivity analysis of the carbon footprint (per kg of clean, dehaired cashmere) to soil carbon stock changes under different livestock attribution scenarios for the nomadic grazing system

Soil carbon change (kg C/ha/year)	Attribution to livestock		
	10%	20%	30%
–150	+21%	+43%	+64%
–100	+14%	+29%	+43%
–50	+7%	+14%	+21%
50	–7%	–14%	–21%

Table 37: Sensitivity analysis of the carbon footprint (per kg of clean, dehaired cashmere) to soil carbon stock changes under different livestock attribution scenarios for the farmed system

Soil carbon change (kg C/ha/year)	Attribution to livestock		
	10%	20%	30%
−150	+10%	+20%	+31%
−100	+7%	+14%	+21%
−50	+3%	+7%	+10%
50	−3%	−7%	−10%

6.3. Uncertainty analysis

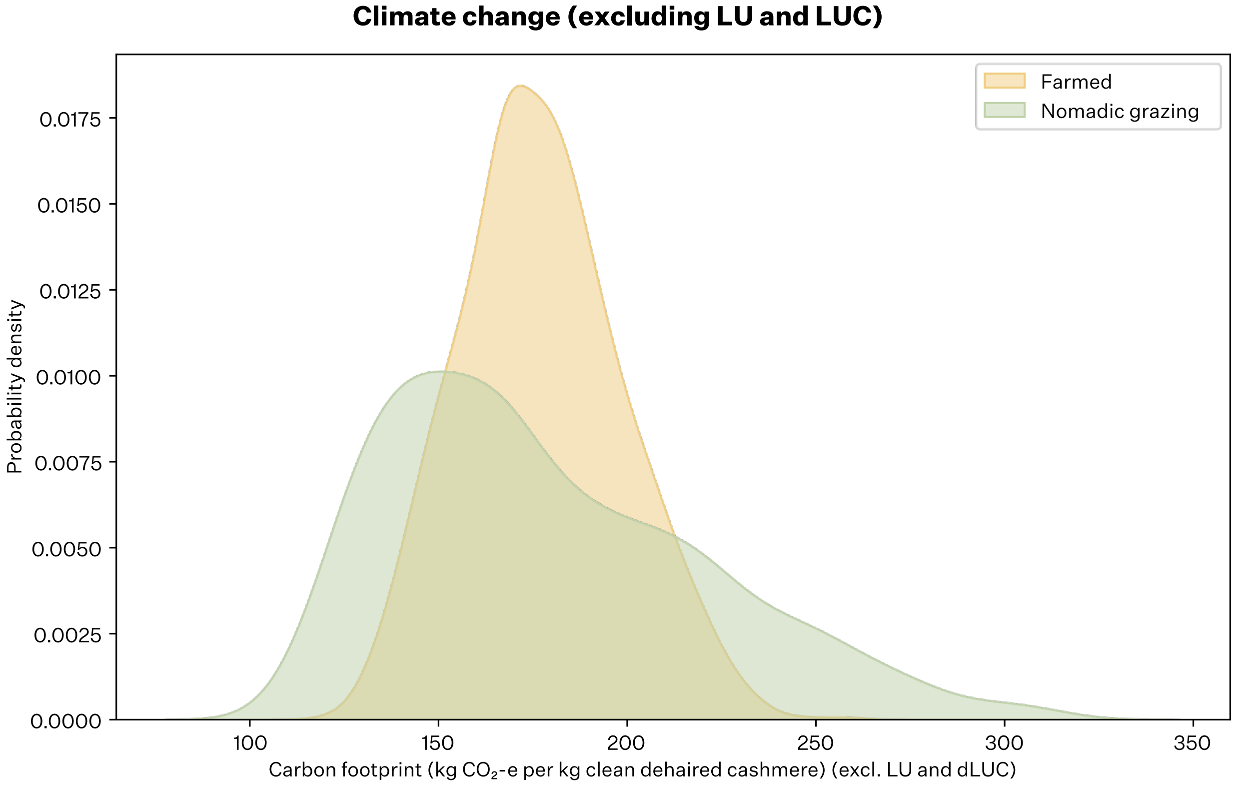
An uncertainty analysis was run using Monte Carlo simulation (n = 1,000) to investigate variability in the impact assessment results across all categories (see Appendix D–Uncertainty), and to evaluate the significance of differences between production systems. Uncertainty was reasonably high, which was associated with variation in inputs, and goat herd performance and attributes. Coefficients of variation ranged from 8–127% between impact categories, and confidence intervals did not reflect normal distributions for most impact categories. Key contributors to uncertainty included parameter uncertainty in the livestock model associated with variation in production across the surveyed farms and regions, soil carbon loss assumptions, purchased supplementary feed, clean cashmere yield, and fossil resource use at the primary processing stage and in the farm system. While uncertainty distributions for both primary production and primary processing were included, variance in total results was largely driven by primary production parameters because this stage dominates overall impacts, with the exception of fossil resource use. This reflects the biological complexity and variability of livestock systems relative to the more standardized industrial processes in primary processing.

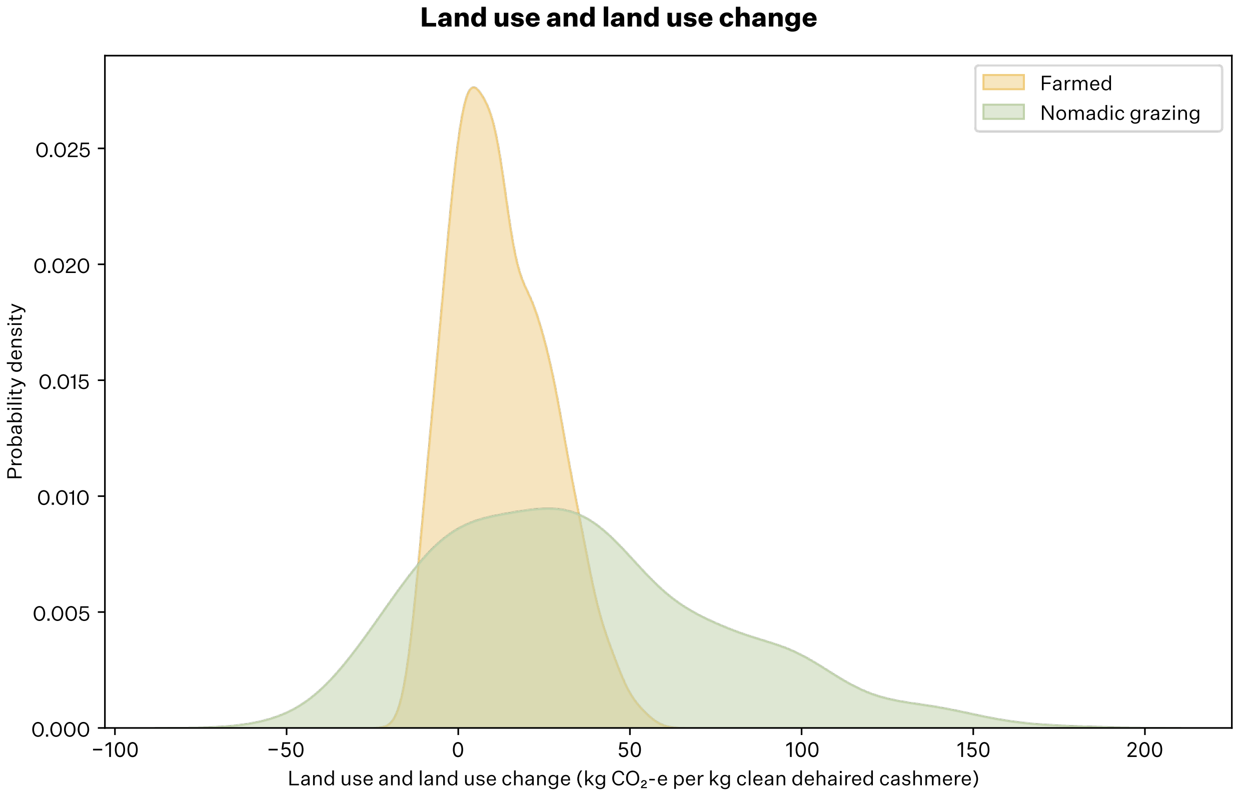
When analyzed per kg of clean, dehaired cashmere, there was substantial overlap in the uncertainty distributions between the nomadic grazing system and farmed systems for the climate change and fossil resource impact categories, and mean values were not statistically significantly different (Figure 13). This was further confirmed by the application of the Wiltshire et al. (2009) equation, which revealed no significant differences between the nomadic grazing and farmed systems in the climate change and fossil resource impact categories when reported per kg of clean, dehaired cashmere.

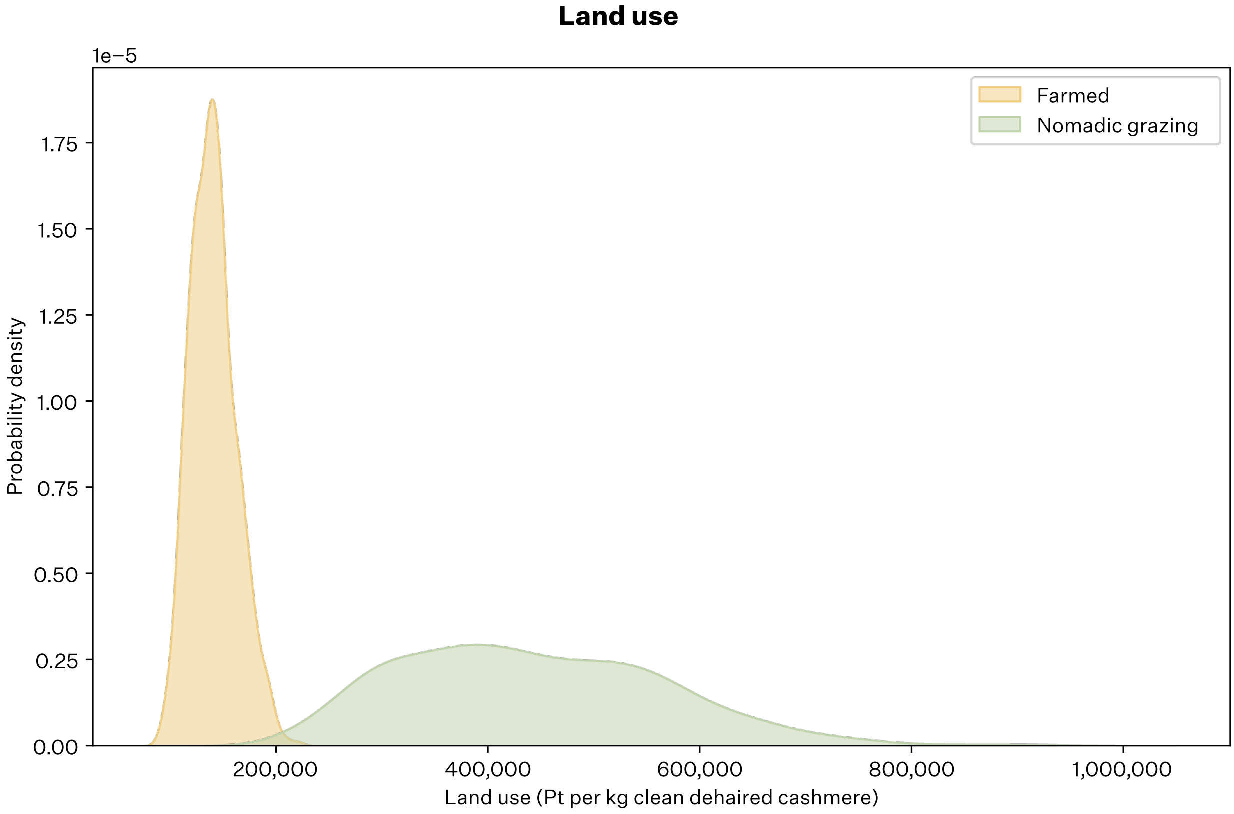
However, there were significant differences between production systems in the water use and the land use impact categories per kg of clean, dehaired cashmere. In the climate change and land use impact categories, the nomadic grazing system distribution was broader and more dispersed, reflecting greater variability in these systems (see also Figure 15).

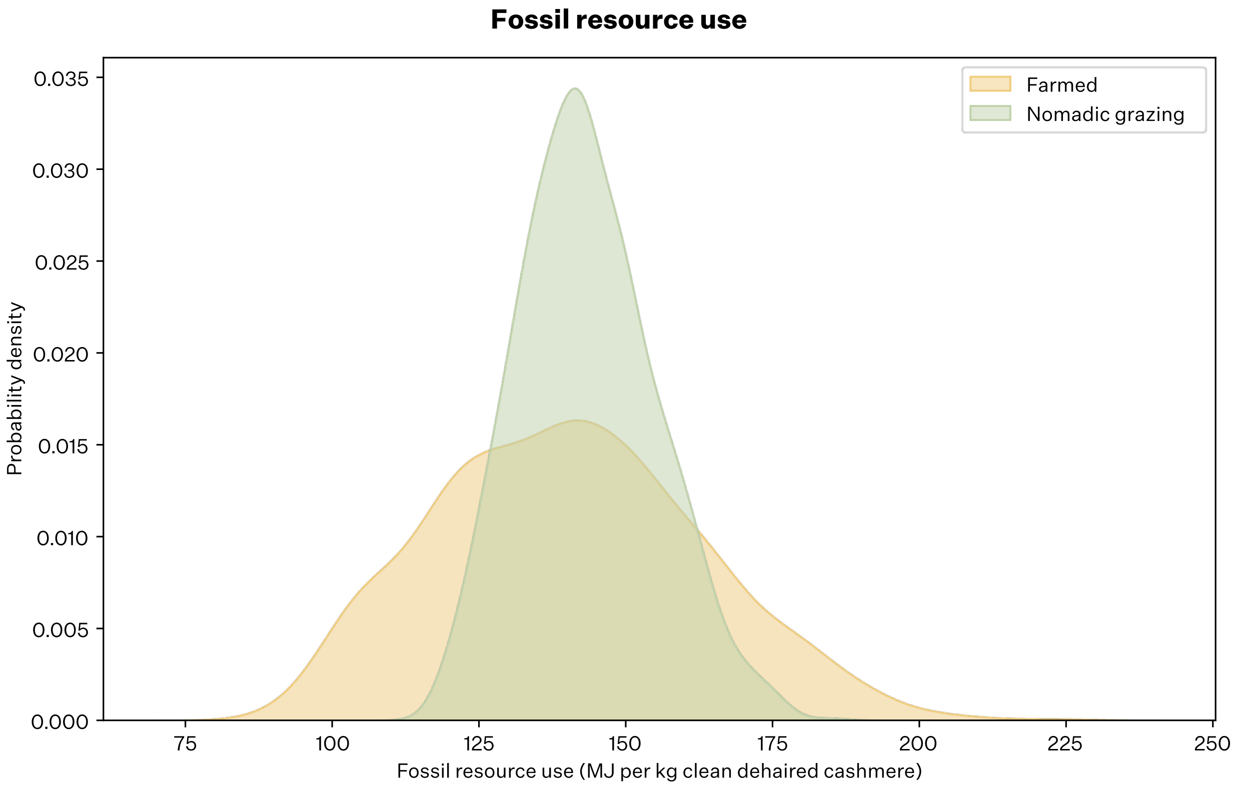
However, when analyzed at the primary production stage, the land use, fossil resource, and water use were statistically significant with minimal overlap (Figure 14), and confirmed by the application of the Wiltshire et al. (2009) equation. It is important to acknowledge the limitations that may result in an underestimation of uncertainty, particularly for the farmed system. The sampling approach for the farmed system, while pragmatic, may not have fully captured the diversity of production systems, management practices, or regional conditions. Consequently, the relatively narrow uncertainty bounds shown in Figure 13 should not be interpreted as being of high precision.

Figure 13: Uncertainty distribution (excluding beta uncertainty) for climate change (excluding LU and LUC), land use and land use change, freshwater ecotoxicity, water use, and fossil resource use, for the nomadic grazing and farmed system reported per kg of clean, dehaired cashmere

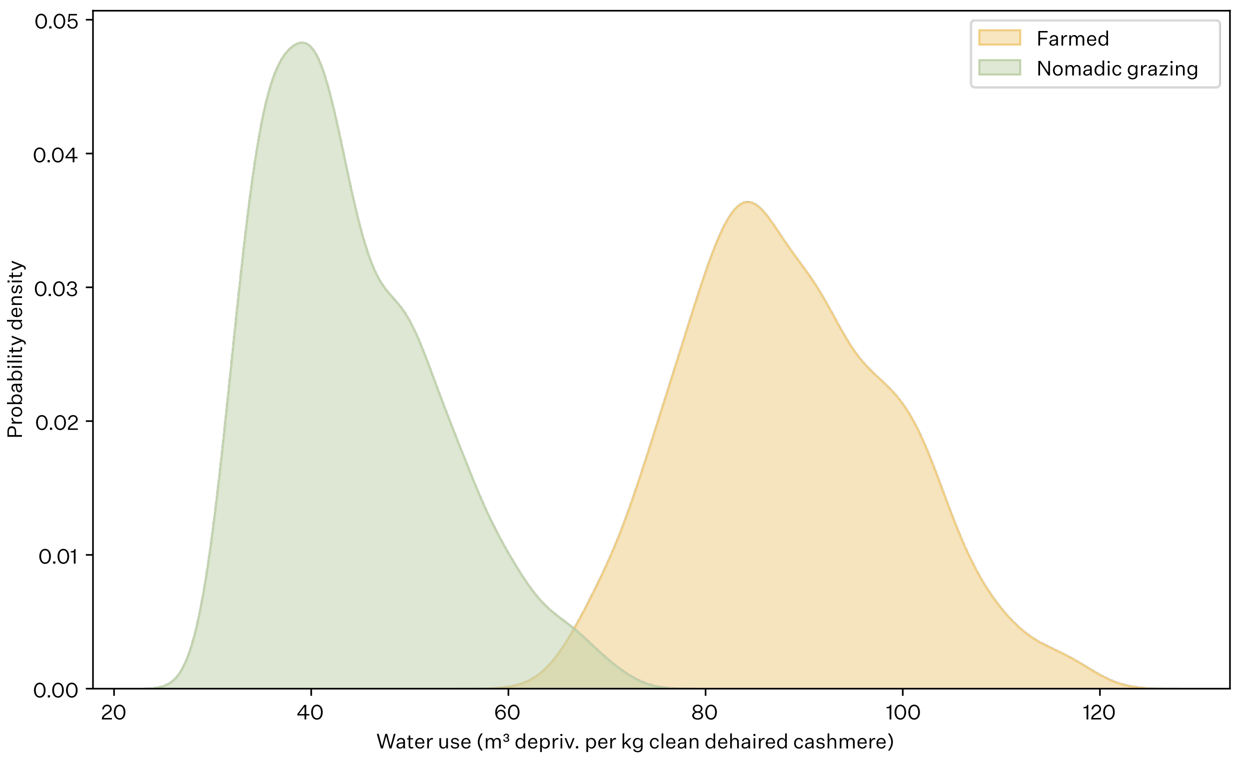




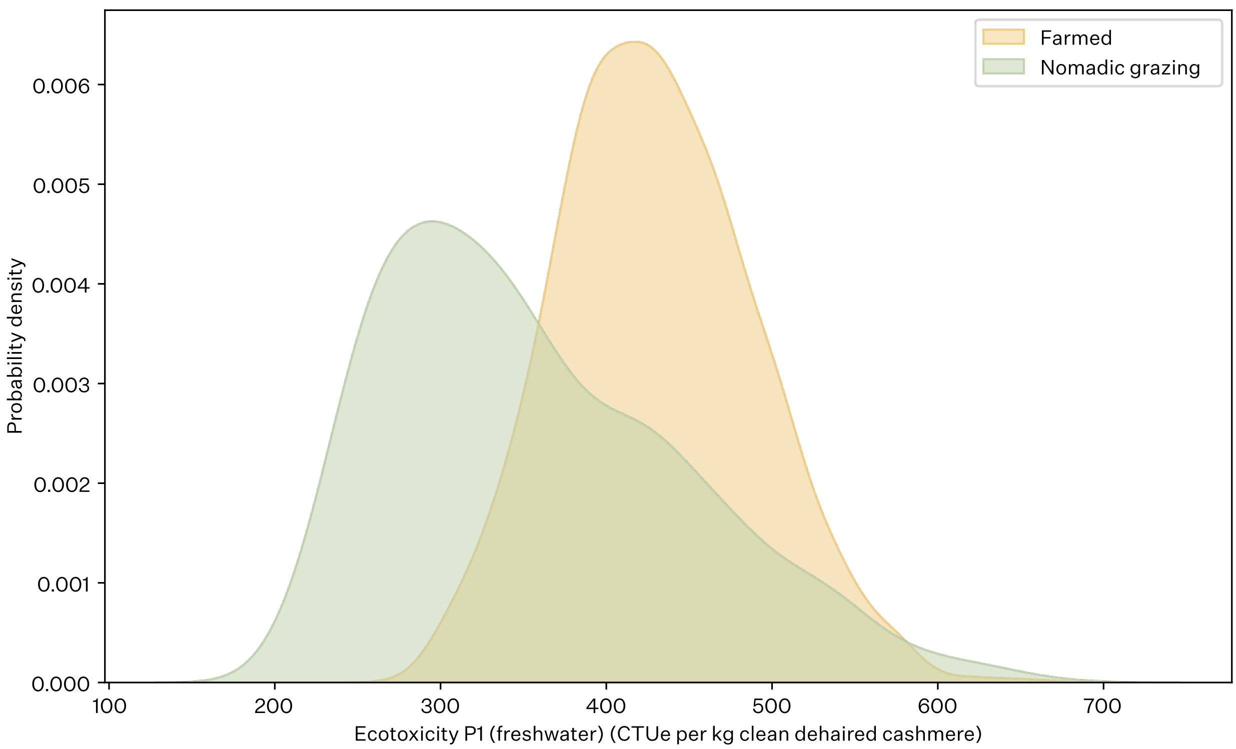

Land use
1e−5
Farmed
Nomadic grazing
Probability density
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
200,000
400,000
600,000
800,000
1,000,000
Land use (Pt per kg clean dehaired cashmere)


Fossil resource use
Farmed
Nomadic grazing
Probability density
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
75
100
125
150
175
200
225
250
Fossil resource use (MJ per kg clean dehaired cashmere)

Water use



Freshwater ecotoxicity P1



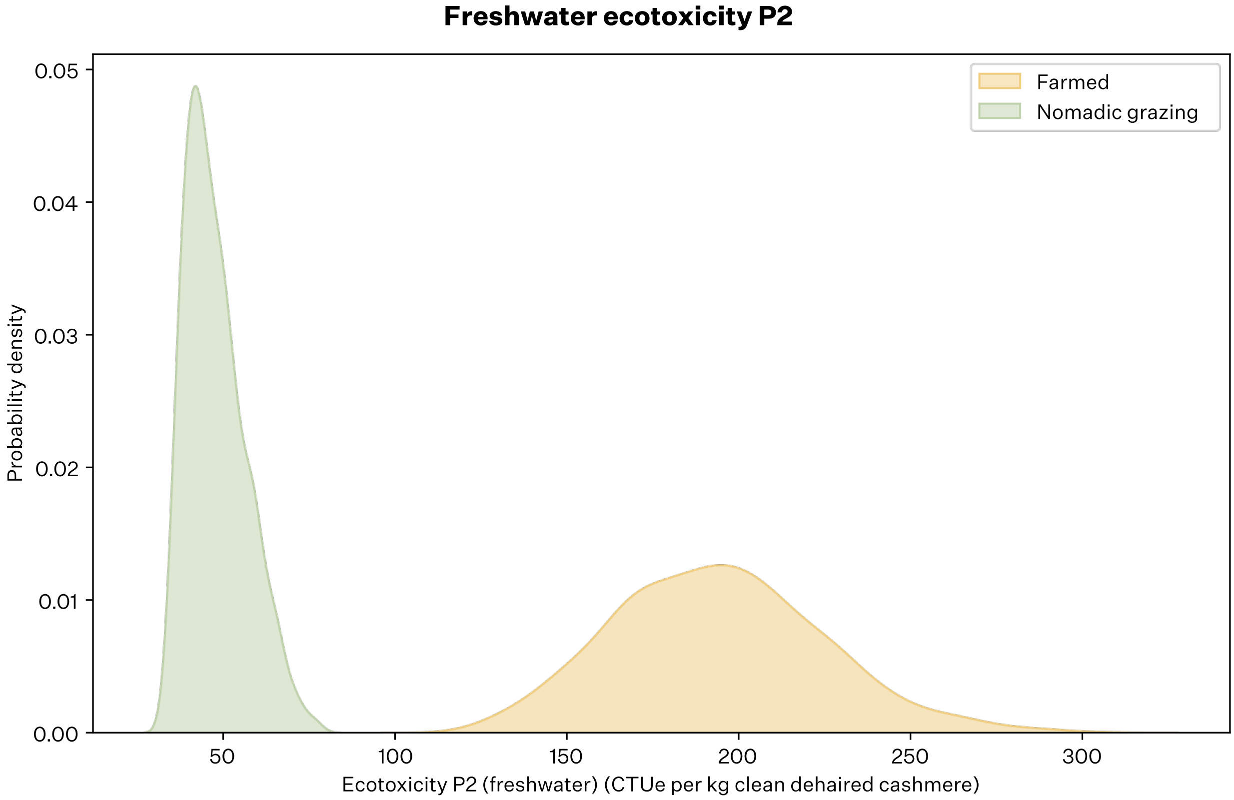
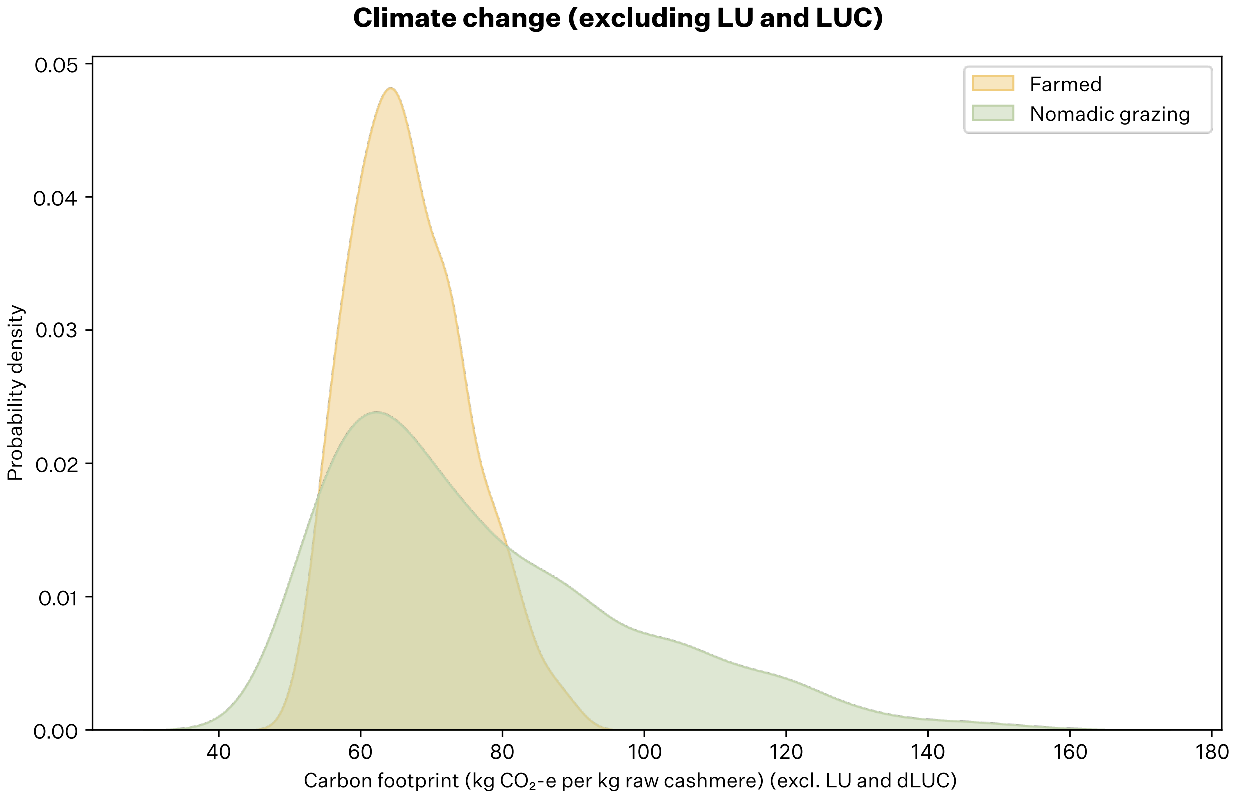
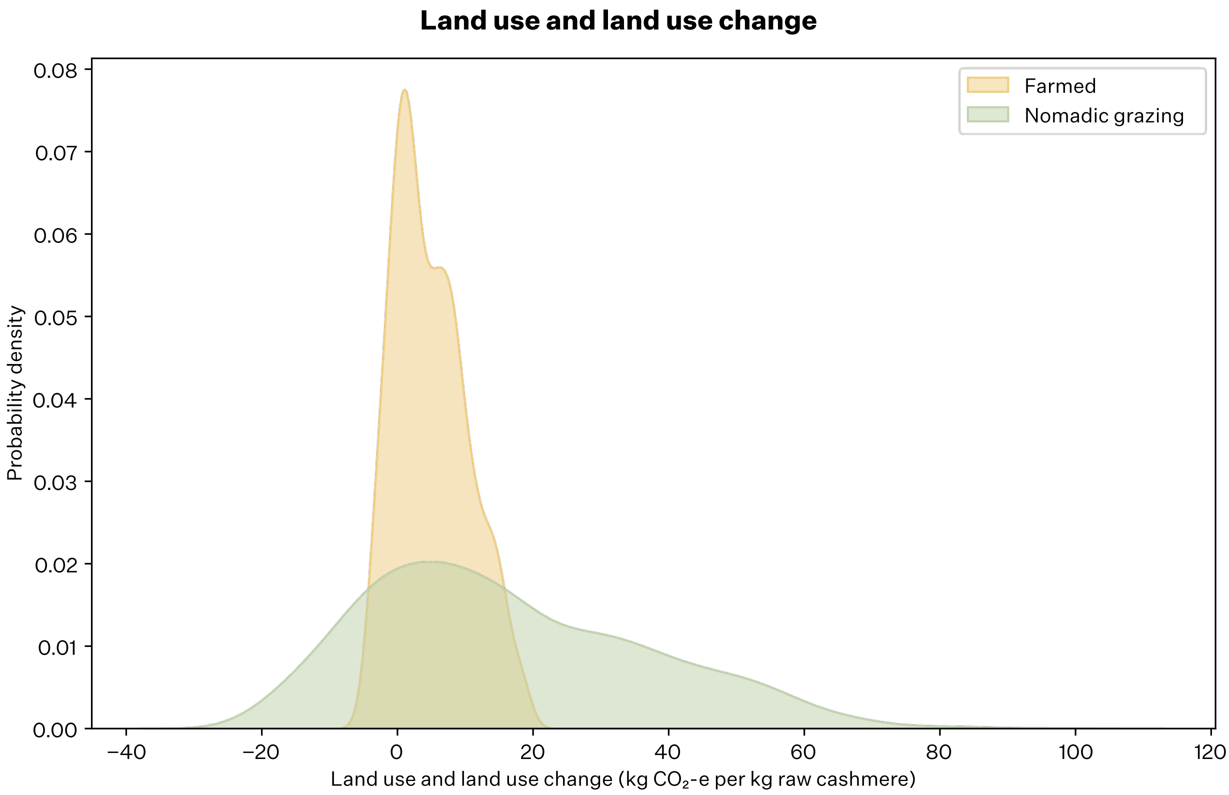
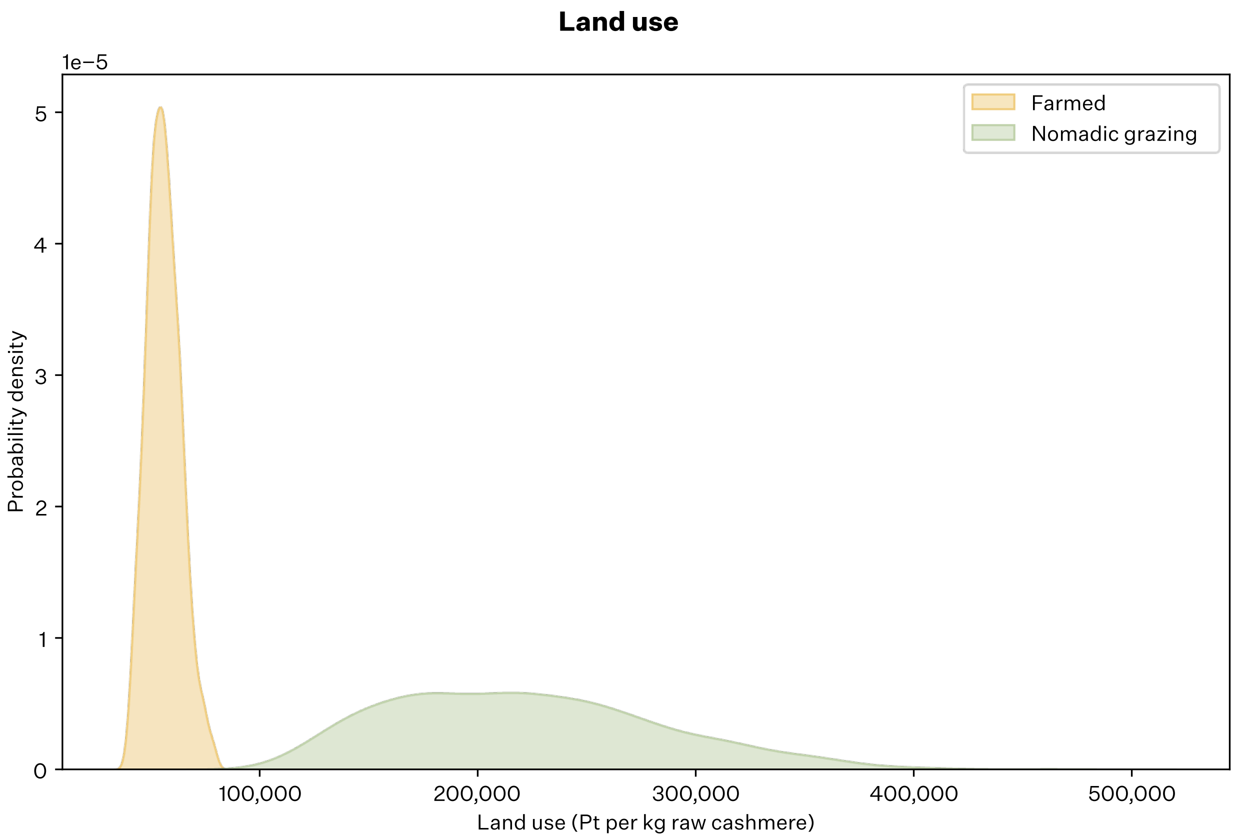
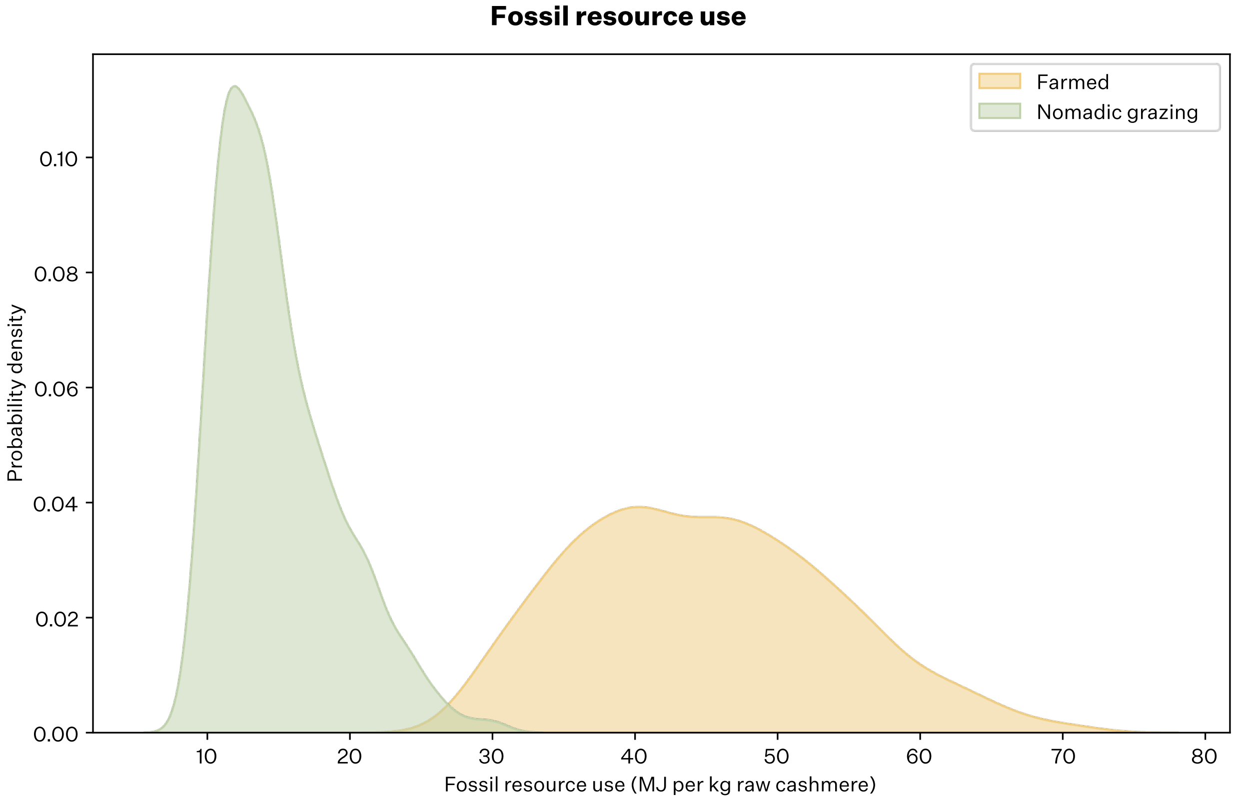


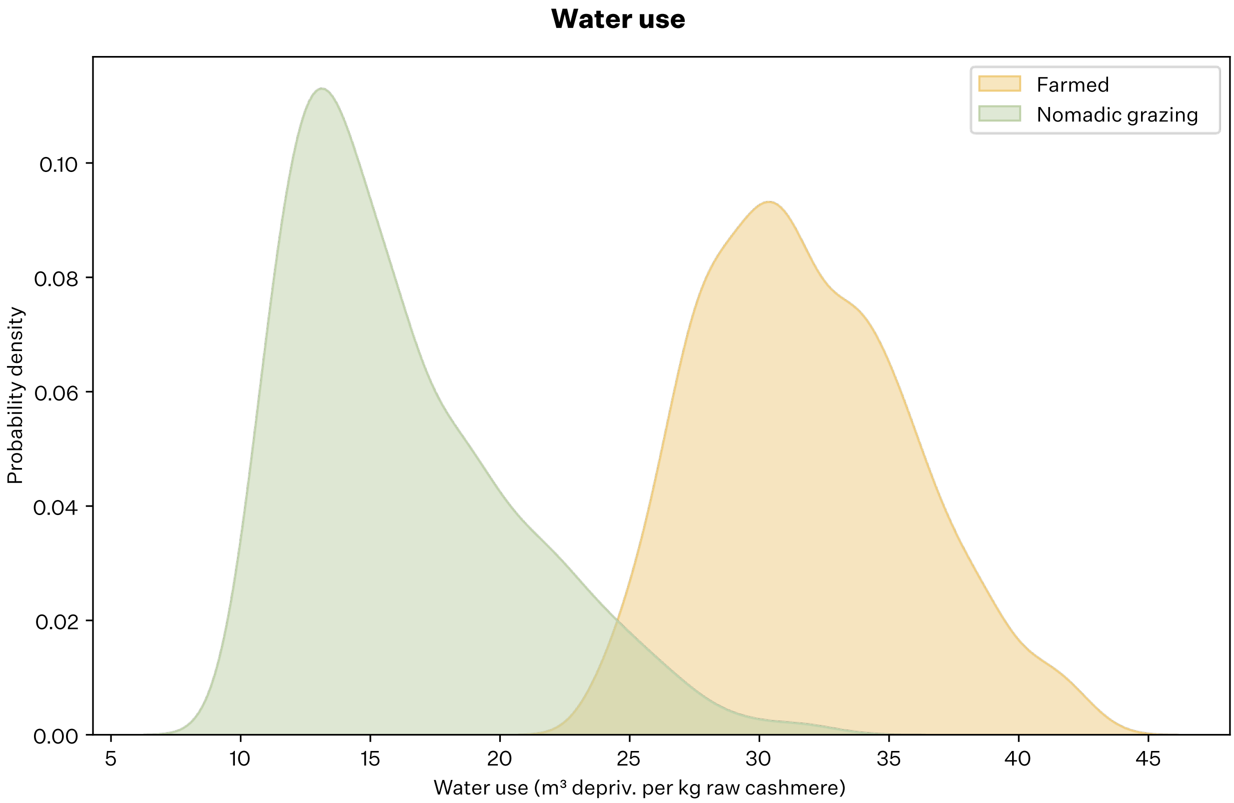
Figure 14: Uncertainty distribution (excluding beta uncertainty) for climate change (excluding LU and LUC), land use and land use change, freshwater ecotoxicity, water use, and fossil resource use, for the nomadic grazing and farmed system reported per kg of raw cashmere (cradle to primary production gate)

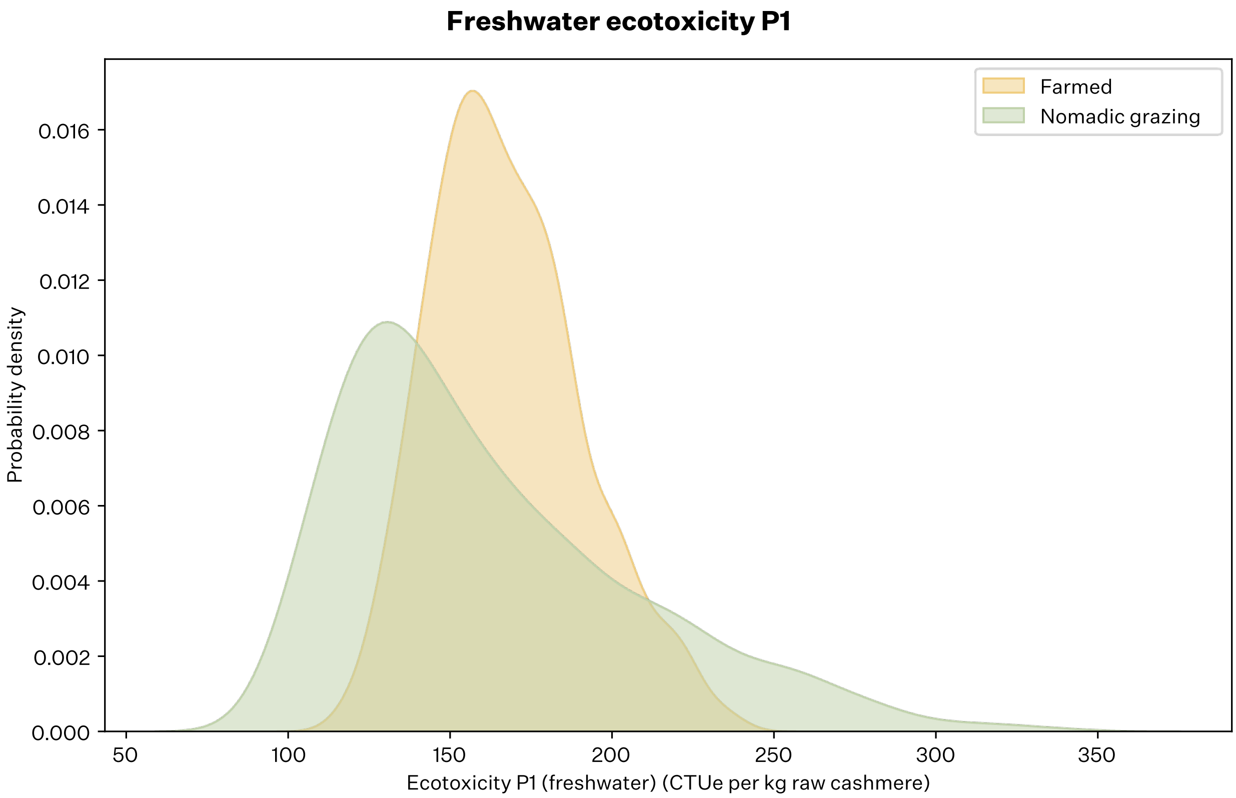


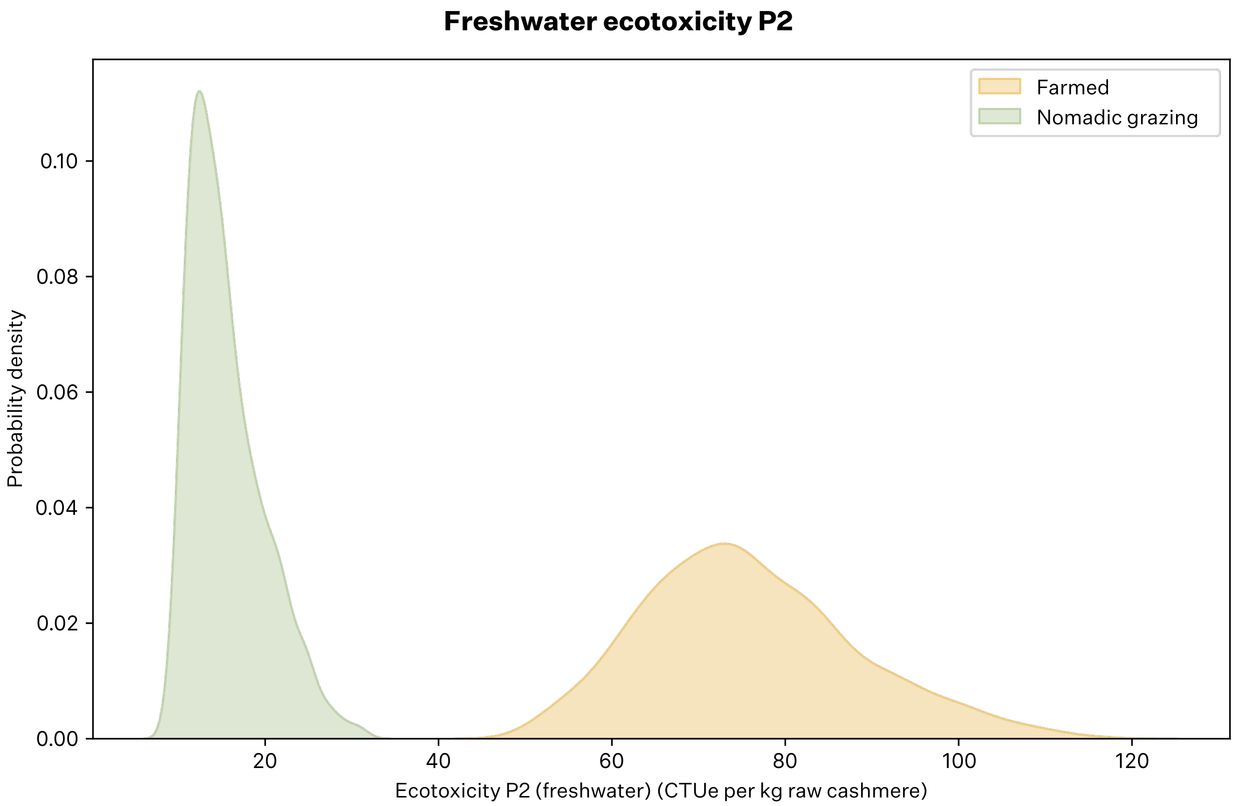

Land use and land use change
Farmed
Nomadic grazing
Probability density
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−40
−20
0
20
40
60
80
100
120
Land use and land use change (kg CO_2-e per kg raw cashmere)


Land use
1e−5
Farmed
Nomadic grazing
Probability density
5
4
3
2
1
0
100,000
200,000
300,000
400,000
500,000
Land use (Pt per kg raw cashmere)


Fossil resource use
Farmed
Nomadic grazing
Probability density
0.00
0.02
0.04
0.06
0.08
0.10
10
20
30
40
50
60
70
80
Fossil resource use (MJ per kg raw cashmere)


Water use
Farmed
Nomadic grazing
Probability density
0.00
0.02
0.04
0.06
0.08
0.10
5
10
15
20
25
30
35
40
45
Water use (m³ depriv. per kg raw cashmere)

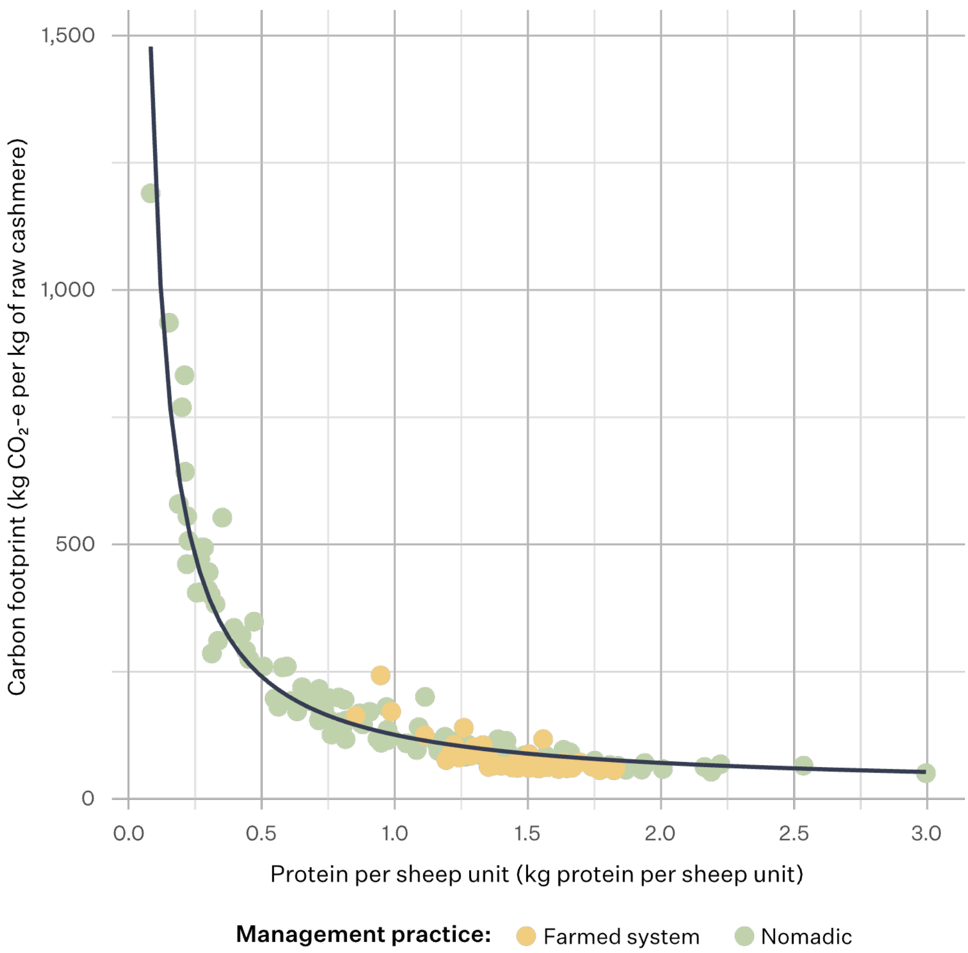

Freshwater ecotoxicity P1
Farmed
Nomadic grazing
Probability density
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
50
100
150
200
250
300
350
Ecotoxicity P1 (freshwater) (CTUe per kg raw cashmere)


Freshwater ecotoxicity P2
Farmed
Nomadic grazing
Probability density
0.10
0.08
0.06
0.04
0.02
0.00
20
40
60
80
100
120
Ecotoxicity P2 (freshwater) (CTUe per kg raw cashmere)

6.4. Statistical analysis of individual producers

Climate change impacts (excluding LU and dLUC) per kg of raw cashmere for each herder and farm were plotted against the total protein output standardized per livestock unit (sheep unit). A fitted power model was created demonstrating this relationship, with the equation: $y = 120.07 \times x^{-1.05}$, where x = protein per sheep unit (adjusted R^2 = 0.93) (Figure 15). The model was estimated using a log-log regression, and the residual analysis confirmed the appropriateness of the model. The regression analysis shows that the carbon footprint exponentially increased with decreasing protein output per livestock unit. The results show a strong correlation between total protein per SU and climate change impact (excluding LU and dLUC), indicating that systems producing more protein per SU tend to have lower climate change impacts per unit of protein. This showed that herd productivity, measured in terms of output per sheep unit, was the primary determinant of variation in carbon footprint between farms. This analysis showed high impacts from some, but not all, nomadic production systems, with significant overlap between nomadic and farmed production, and a much higher level of variation in the nomadic production results compared to the farm results. The higher impacts per kilogram of raw cashmere observed in the nomadic systems were largely driven by lower productivity, rather than inherent differences in the management systems themselves. This suggests that both nomadic and farmed systems have the potential to reduce impacts through improvements such as enhanced winter nutrition and better genetics. While nomadic systems are naturally more variable, due to fewer management controls, even modest productivity gains in either system could lead to significant reductions in impact

Figure 15: Regression of protein per sheep unit and carbon footprint (excluding LU and LUC) (cradle-to-primary production gate) from the results of individual herds analyzed in this study. Orange dots represent farmed herds and green dots represent nomadic grazing herds



6.5. Data quality summary and evaluation

This study met ISO 14040/14044 (ISO, 2006a, 2006b) data quality requirements using region-specific, up-to-date, and methodologically consistent data. Primary data was collected from the countries (Mongolia and China) that make the highest contribution to international cashmere production, with technological relevance to current cashmere production systems and processing practices. Secondary data was sourced from peer-reviewed literature and the Ecoinvent 3 database, and was assessed for temporal (within the past 10 years), geographical, and technological relevance. All data was checked for completeness, internal consistency, and transparency, ensuring the study can be reproduced and verified in line with ISO 14044 (ISO, 2006b), Section 4.2.3.6.

6.5.1. Data quality rating

The data quality rating (DQR) scores for the major system processes are summarized in Table 38. 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. Across the system, individual process scores ranged from 2.1 to 2.5, resulting in a study-wide average of 2.3. 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 C–Data quality rating method and criteria (ILCD compliant).

Table 38: Summary table of scores against each quality criterion, and global quality score

Process/Dataset	TeR	GR	TiR	C	P	DQR (avg)
Nomadic grazing system	2.5	2.5	2	2	3	2.4
Farmed system	2	3	2	2	3.5	2.5
Mongolia primary processing	1	2	2	2	3.5	2.1
China primary processing	2	1	2	2	3.5	2.1
Study average						2.3

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

7. Interpretation

7.1. Identification of relevant findings

Herders have managed livestock in Mongolia and Inner Mongolia for centuries, demonstrating resilience when practiced within ecological carrying capacity. However, recent increases in livestock numbers and land-use pressures have raised concerns about the long-term sustainability of these systems. Although exact records are not available, estimates suggest that livestock numbers in Mongolia around 72 BC were approximately 28 million head (Bold, 1998), indicating that the pastoral system has been sustained for over two thousand years Considering the very long-term management, grazing ruminants could be viewed as endemic and part of the biosphere, seeing that extensive grasslands globally are populated with ruminant herbivores. However, the increase in livestock numbers beyond the long-term carrying capacity of rangelands has arguably disrupted the ecological state, leading to increased environmental impacts. These impacts could be reduced or even reversed by reducing stocking numbers, but this may conflict with herder values and economic aspirations. This conflict in objectives is one challenge for cashmere that must be resolved to decrease environmental impacts from the sector. Farmed systems have been introduced in some regions, notably in China, to help reduce grazing pressure and support the restoration of degraded rangelands. However, these systems rely on more intensive inputs to meet feed requirements, which introduces trade-offs in other environmental impact categories. This study is the first cashmere LCA to quantify impacts across multiple environmental impact categories, assessing two major production systems used in nomadic and farmed systems, and revealing new insights and trade-offs between different impacts.

7.1.1. Productivity and herd dynamics

Opportunities for impact reduction across multiple impact categories can be achieved by producing more output with the same or fewer inputs. With respect to the dominant impact categories of climate change and land use, the main inputs were feed and land. The nomadic grazing systems in this study had lower productivity compared to the farmed systems, and both systems were substantially less productive than extensive grazing systems in developed countries when considered on the basis of total meat, fiber, and milk per livestock unit (FAO, 2025). However, the large variation between producers, which overlapped across systems, indicates that the production system alone did not explain the differences in environmental impact.

Two main factors contributed to the variation in productivity: management of livestock nutrition during winter, and high stocking rates that exceed the capacity of an area to meet the optimal nutritional requirements of the herd. These factors directly influenced herd productivity, which, in turn, affected LCA results. For example, poor winter nutrition and high mortality rates reduced meat and milk outputs, increasing the impact per unit of product. Impacts of severe seasonal variation on livestock have been documented by multiple studies: animals have been found to lose 20–30% of their body weight during winter, experience high mortality rates, and exhibit low reproductive performance (Jargalsaihan et al., 2021; Kemp, 2019). Consequently, the output of milk and meat per animal is low. One additional factor was the higher output of cashmere in the farmed systems, which may also have been supported by higher yielding genetics.

Goats in these systems are typically of low birth weight, reach maturity at twice the age of small ruminants in other developed countries, and herds are managed with disproportionately high numbers of male and older goats (Kemp et al., 2011). This management strategy, which prioritizes a higher proportion of older, castrated goats, is predicated on their greater resilience, enhancing overall herd survival while maintaining relatively high cashmere yields, but reduces the potential for liveweight production via reproduction. Long-term livestock statistics show that herd dynamics in Mongolia are strongly influenced by seasonal weather conditions (National Statistics Office of

Mongolia, 2024b). Herd productivity significantly declines in poor seasons, and then numbers rebound in good seasons when above-average numbers of animals are born to rebuild the herd. These herd characteristics were observed in this current study. The overall effect is a reduction in long-term outputs, particularly of milk and meat.

Housing and confinement of livestock are common in many northern-hemisphere countries to manage severe winter conditions and limit negative effects on livestock, and may be considered a reasonable level of intensification to manage seasonal conditions and animal energy requirements. While housing was used in both countries, the duration was longer, and livestock was fully contained and provided with higher levels of feed in the farmed system. In the nomadic grazing system, containment occurred during the most severe weather, but animals were also allowed to graze during winter, and supplementary feed was used to a lesser extent. Management practices in the farmed system had the effect of reducing weight loss, and improving production and output of cashmere and meat, over the whole year. Containment duration varied widely in the farmed systems, between 90 days and up to 300 days. This resulted in varying degrees of intensification. Intensification has been reported to contribute to lower carbon footprints in ruminant livestock (Capper, 2011; Escribano et al., 2020; Hermansen & Kristensen, 2011; Wiedemann et al., 2017), largely through reductions to enteric methane per unit of feed intake and significant increases in production and outputs, reducing overall impact per unit of product. Confinement has been found to improve livestock production in Inner Mongolia compared to allowing grazing during winter (Zheng et al., 2013) because animals expend less energy walking. Increased dietary energy is, therefore, available for maintaining live weight, increasing survival and reproduction. This result suggested that the environmental performance of cashmere could be improved through improved winter management, and this could be successfully implemented in either system, though the potential for improvement would be greater in the nomadic grazing systems. This would be particularly impactful for mitigating the significant negative effects of intermittent dzud events, and would also improve animal welfare. Compared to other extensive ruminant grazing regions, such as Australia, both the farmed and nomadic grazing systems had the advantage of regular contact between herders and the livestock. With the right logistics and economic incentives, this suggests that targeted supplementation, including the use of supplements that reduce methane, could be implemented and could result in better animal outcomes and lower methane emissions. While testing this was beyond the scope of the project, it represents a useful direction for follow-up work.

Herders are now part of a market economy, and have increased opportunities to optimize productivity to supply animal products (Kemp & Michalk, 2011). This presents opportunities to potentially reduce environmental impacts without reducing income, particularly in China where livestock can be sold at relatively favorable market prices. For example, in their study of Chinese grasslands, Kemp & Michalk (2011) and Kemp (2019) found that, in a feed-limited system, a 50% reduction in livestock numbers (achieved by culling unproductive older animals, especially prior to the harsh winters), and retaining only the better animals, would result in the same net income. This is because the remaining livestock has increased feed availability and consequently higher production and lower mortalities. Additionally, providing supplementary feed, improved fodder management, an objective breeding program of selecting better animals, and sufficiently sized, weather-proof sheds to reduce maintenance energy requirements during the winter, have been identified as key strategies to improve livestock productivity in both China and Mongolia (Jargalsaihan et al., 2021; Kemp, 2019). While this has the effect of lowering overall impacts to both meat and fiber because total protein production increases in these scenarios, the effect is disproportionately skewed toward higher live weight, not higher fiber. In the case of reducing the overall livestock numbers cited above, this may maintain income but fiber production will generally decrease if the number of adult animals is reduced.

Depending on the region of production, several challenges need to be addressed and considered to implement management change. For example, reducing livestock numbers in nomadic grazing systems must be a collective effort at the community level for nomadic herders (for example, bagh or soum level in Mongolia). If one herder reduces their livestock numbers, the benefits will not be realized if neighboring herds sharing the grazing lands subsequently increase their livestock numbers. Sustainable intensification through increased use of supplementary feed is constrained unless feed is imported, because only a small proportion of the landscape is suitable for cropping due to topography and climate constraints. However, opportunities still exist to improve winter supplementation to improve animal performance and reduce grazing pressure. Culling unproductive animals and selling animals at a younger, heavier weight would be incentivized by improving meat market access in Mongolia. It is reasonable to expect that the lower price offered for meat in the nomadic grazing systems than in the farmed systems (Table 17) had the effect of disincentivizing livestock sales. Without better access to meat markets and improved product prices, there is little incentive to enhance herd productivity.

7.1.2. Management of dzuds

The sensitivity analysis revealed significantly higher environmental impacts in the dzud year compared to average years. This can largely be explained by the following factors: (1) the harsh conditions reduced feed availability, thereby reducing body condition, leading to (2) significantly increased mortalities, and (3) reduced weaning rates. As a result, (4) there were minimal to no sales of goats for meat consumption because herders focused on maintaining the current herd size. In these years, almost all impacts were allocated to cashmere as there were very low or negligible outputs of meat or milk, resulting in very high reportable environmental impacts. This did not translate into fundamentally higher emissions or land impacts, but higher reportable impacts on an intensity basis, because of the lower productivity levels. Nonetheless, the effect was significant and highlighted that, with better dzud management, it may be possible to maintain smaller herds with lower total land and emission impacts while maintaining the same output. Further to this, improving dzud management provides an opportunity to also improve animal welfare through lower mortality rates. As noted in the following section, improving productivity and dzud management is also related to the production system and intensification.

7.1.3. Land use impacts

Land use impacts were significantly higher for nomadic grazing systems compared to farmed systems when measured per kilogram of clean, dehaired cashmere. This outcome reflects the fact that, due to large grazing areas per sheep unit and lower productivity, the results represent the environmental impact per unit of product (impact intensity), not the total environmental impact (absolute impact) of the system as a whole. When analyzed per hectare, land use impacts were reversed between the production systems—impacts were significantly higher for the farmed system due to higher stocking rates (Table 46).

The land use impacts reported in this study should be interpreted with caution, as the LANCA model used to assess these impacts in the PEF method is currently undergoing updates. The known challenges associated with the LANCA model, which are discussed below, need to be addressed and tested in agricultural systems. While LANCA allows for the global application and characterization of land use impacts, simplifications had to be made to quickly adapt to LCA requirements (Beck et al., 2010). Such simplifications include the method used to calculate the reference site, and the methods and data for determining net primary productivity, humus content, crop management factor, conservation practice factor, and cation exchange capacity, are look up values that have been simplified and defined to a limited number of classes based on the underlying relationship between soil type, slope, precipitation, and land use type. These often refer to Central European conditions and do not use internationally recognized models (Bos, 2019). Additionally, the background factors have very low sensitivity to agricultural management practices, which does not allow differences to be accounted for between different management practices, which may show better land management than the average. All the spatial inputs into LANCA have limited temporal coverage. Without annual calculation and reporting of these inputs, trend analyses will be limited to land area and production yields (i.e., land use efficiency). This presents an incomplete measure of environmental impacts and could misleadingly suggest that intensifying land use, such as by increasing stocking rates, will reduce land impacts. This is a perverse outcome as higher stocking rates in rangelands are often associated with increased environmental pressure (Dashbal, 2010;

Densambuu, Sainnemekh et al., 2018; Li et al., 2024; Munkhzul et al., 2021; Sainnemekh & Aduut, 2022).

Due to these simplifications and data limitations, this study found LANCA was not currently an effective monitoring tool to measure and show changes or improvements in land use impacts over time. At a minimum, the parameters influenced by anthropogenic changes, including net primary productivity, soil organic carbon %, cover management factor, and sealing factor, require spatial and temporal resolution. Future research is required to determine whether LANCA accurately reflects land impacts measured using assessment techniques more common in rangelands, such as land condition scoring (Densambuu et al., 2018) and remote sensing techniques (Retallack et al., 2024), before it would be considered suitable for the characterization of extensive grazing systems. The findings here suggest it is more appropriately considered as a screening indicator at the present time.

7.1.4. Soil carbon impacts

Soil organic carbon losses were estimated in this study based on IPCC Tier 1 methodology, and were highly uncertain. Variability between regions was substantial. The analysis revealed that the total (aggregated) distribution of carbon values showed extended tails, which underscored the inadequacy of using a single average value to represent diverse grazing landscapes, particularly in regions like Mongolia and northern China, with varied agroecological zones.

Given the wide sensitivity range observed, there is potential for both underestimation and overestimation of greenhouse gas impacts from soil carbon stock change in the cashmere supply chain. The sensitivity analysis underscores the need for higher-resolution degradation data, and improved monitoring of land condition in pastoral systems. The analysis highlights the significance of capturing spatial heterogeneity and site-specific data in influencing carbon sequestration, or loss within the grazing systems associated with cashmere production. It also supports the adoption of spatially explicit models when assessing the environmental impacts of grazing, especially when soil carbon is a key contributor to total emissions or potential mitigation.

Impacts from soil carbon loss were not attributed to cashmere in the baseline results because of the difficulty in separating climate-induced effects and grazing impacts. Climate change effects, including reduced rainfall and increased temperature variability, are known to significantly affect soil carbon stocks in rangeland systems, with climate factors (rainfall and temperature) accounting for more than 80% of the variation in SOC stocks (Henry et al., 2024), independent of grazing pressure or herd size. These climate-driven changes often occur over large spatial and temporal scales, making it difficult to isolate the specific contribution of cashmere production to observed soil carbon losses. As a result, while grazing systems may influence soil carbon dynamics, a portion of the modeled change may reflect other environmental factors rather than direct impacts of the cashmere production itself. While it was not appropriate to allocate impacts to cashmere for the baseline results because the climate and grazing interactions could not be determined separately, the sensitivity analysis showed that it was nonetheless evident that soil carbon loss may contribute large sources of emissions or removals to cashmere production systems, depending on land management. Soil carbon loss has been linked to overstocking in numerous studies (Deng et al., 2023; Dlamini et al., 2016; Huang et al., 2025; Wang et al., 2011), pointing to this being a major concern for the sustainability of the production system.

Reversing these impacts via reduced stocking rates has also been examined. Chang et al. (2015) conducted measurement and modeling of Mongolian grasslands and concluded that grasslands with degraded soil carbon content, as a result of historical over-grazing, could be restored through changed management. This finding has been supported by research in Inner Mongolia (Liu et al., 2012; Xie & Wu, 2016; Zhao et al., 2017; Zou et al., 2007). Significant potential exists to reverse soil carbon losses. Chang et al. (2015) concluded that accumulation rates of 22–36.9 g C m-2 were possible in Mongolia, which could result in >0.8t CO2-eq removal per hectare. Compared to the impact rates per hectare (Table 46), this indicates that climate change effects could be improved through this mitigation. While this is a large opportunity, practically reducing stocking rates must be achieved not only with changes in goat management, but also through management of sheep, cattle, camels, yaks, and wild ruminants. This must also be done through collective action, where multiple herders, who may have overlapping grazing areas, agree to reduce stocking rates. Nonetheless, reversing soil carbon losses would represent a highly impactful change in the overall outcomes for cashmere. As soil carbon levels and overgrazing are major contributions to land impacts measured by LANCA, mitigating these impacts would also reduce and potentially reverse the two largest impacts associated with cashmere production in Mongolia and China.

7.1.5. Ammonia-related impacts

Particulate matter, acidification and terrestrial eutrophication were largely driven by ammonia volatilization from livestock manure. These results should be interpreted with caution for three reasons. As noted previously, these impacts have been determined to be significant in Western Europe because of the large nitrogen inputs from fertilizer and animal manure in agricultural systems, which can create a high nitrogen surplus. Large nitrogen surpluses were not apparent in Mongolia or northern China, where chemical fertilization is not used on pastures in these regions and systems. In the case of particulate matter, the significance is primarily related to the high population density in Europe. Ammonia in grazing environments is released in regions with very low human population density, in an open and well-ventilated environment, which promotes the rapid dispersion of gases. This reduces the incidence of ammonia building up to high concentrations, leading to high deposition rates to sensitive ecosystems or atmospheric reactions. The impact of ammonia from this source on particulate matter, typically a measure of air pollution in cities from fossil fuel burning, is likely to be lower than the characterization factor suggests, resulting in likely over-reporting of this impact category. New characterization factors for the remote release of ammonia from livestock are needed before these results are compared with industrialized systems, or considered to materially contribute to poor environmental outcomes.

7.2. 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.

7.2.1. Sampling limitations

The selection of provinces and, subsequently, herder households and farms for data collection, considered a balance between a representative sample and the cost, time, and logistics of travelling large distances required for primary data collection. However, this reduced the size of the dataset and introduced limitations around the representativeness of the results. For China, the study was limited to the farms and regions that the in-country personnel had established relationships within their supply chain, which may not have been representative of the full population. This could be tested by collecting data from larger sample sizes, from a diverse number of regions or supply chains, in the future. For this reason, the results should not be interpreted as being representative of either Mongolia or China, and should not be used for comparison between these countries.

7.2.2. Translation and data quality

The data collection survey was translated into the native language by local 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 in the translation of technical or scientific terminology may have impacted the data quality. Additionally, most herders had no form of record keeping, and, consequently, survey responses were estimated. This could have introduced bias in the survey responses as herders may have been inclined to provide answers that led to more favorable results. The research team worked to mitigate this risk by verifying the plausibility of the data using first principles in considering herd performance, population, and dynamics.

7.2.3. Data security and legal constraints

Due to the data security law in China (National People's Congress, 2023), differences existed in the data collection approach between the two countries. Specifically, case studies could not be completed in China, and spatial data could not be supplied. For this reason, the results should not be interpreted as being representative of either Mongolia or China, and should not be used for comparison between these countries. Implementing the case study field visit methodology in China with local researchers would provide a more detailed dataset, and reduce the uncertainty in the calculations of the LANCA land use impact model and the assessments of LU and LUC GHG emissions.

7.3. Data quality assessment

The data quality of this study was assessed across all major processes using the ILCD-recommended data quality rating (DQR) method. Scores across the system ranged from 2.1 to 2.5, reflecting generally moderately high-quality data.

Primary data from both Mongolia and China was gathered in consultation with key value chain stakeholders and reflects current practices, while secondary data from national statistical sources was used to support, verify, and adjust inventory estimates. However, some uncertainty remains in regard to the quantity, type, and origin of purchased inputs and supplementary feed requirements in both the nomadic grazing and farmed systems.

To manage practical constraints and improve transparency, data quality was assessed and reported at the process level rather than at the level of individual flows. This approach was selected due to the integrated nature of inventory development, where multiple raw datasets (including secondary time series data from MSIS) informed a single modeled inventory.

Slightly lower completeness and precision scores (particularly in the processing stages) reflect limited access to on-site data and the use of expert judgement or literature values to fill gaps. These limitations are not expected to materially affect the comparative results or the conclusions drawn, but should be considered when using the results for decision-making. Future work should prioritize improving the precision of activity data, focusing on the parameters shown to be influential in the sensitivity analysis, and emission factors used in processing stages, particularly in China.

The study also considered the representativeness of data collected during an extreme climatic year (2023, a known dzud year). A multi-year average was applied to key livestock inventory parameters using long-term statistical datasets to ensure that the results reflect an average production cycle rather than a one-off shock event. This approach mitigates temporal bias and improves the robustness of the farming system inventories.

7.4. Allocation

The sensitivity analysis demonstrated that the results were highly sensitive to allocation methods. Goat production systems generate fiber, meat, and, in the case of Mongolia, milk. All products are important, but cashmere has important attributes that enable international trade, i.e., it is non-perishable and has no trade barriers with respect to animal disease. In contrast, goat meat had relatively low value in economic terms but was important as a local food source.

The protein method (a biophysical approach) applied in this study apportioned the majority of environmental impacts to meat. While not the focus of the study, the corresponding carbon footprint of goat meat was similar to alternative meat products available in the region (for example, cattle or sheep) (Wang et al., 2024, 2025; Zhao et al., 2019).

Economic allocation, by contrast, shifted most impacts to cashmere, given its high market value, and resulted in very low impacts for meat, particularly in Mongolia. Goat meat impacts were well below the impacts reported for alternative red meat products in the same regions. In contrast, reported impacts for cashmere were more than an order of magnitude greater than those for other natural fibers such as wool (Wiedemann et al., 2015, 2016). Part of the reason for the high allocation to cashmere was the relatively low value of meat in Mongolia, where there were limited local marketing options and restricted access to world meat markets. If this market access problem was overcome, it is reasonable to expect much higher values would be observed for goat meat, which would materially alter reported impacts for cashmere using economic allocation.

Given these dynamics, and considering the functional relationship between cashmere, meat, and milk in these production systems, as well as guidance from international standards and sector organizations, the choice to use protein as the basis for allocation was considered the most suitable and documented method for interpreting environmental performance in cashmere LCA studies. Ultimately, while allocation affects numerical results, the critical insight is that interventions, rather than allocation choices, drive meaningful reductions in environmental impact.

We acknowledge that economic allocation reflects consumer-driven impacts and is relevant for downstream users. At the same time, biophysical allocation aligns with international guidance for representing multifunctionality and avoids artefacts from volatile or context-specific market conditions. In this study, the choice of protein allocation was guided by documented methodology in peer-reviewed literature rather than market dynamics. Our intention in this paper, however, is not to resolve the allocation debate but to provide sufficient context for interpreting results. While allocation influences the distribution of impacts, the overarching message remains that interventions to improve production efficiency and reduce emissions are far more important than the allocation method applied.

8. Conclusions and recommendations

This study addressed the growing need to understand the environmental impacts of cashmere production in textile supply chains using LCA, representing a significant step forward through the development of the first regionally specific life cycle inventory for cashmere production. Cashmere and other animal fibers have been produced by nomadic herders for thousands of years, in systems that have sustainably delivered fiber, meat, and milk. In recent decades, however, rising livestock numbers have prompted growing concern over the environmental impacts of production, highlighting the need for robust, context-specific research. Farmed systems have been introduced in some regions to help reduce grazing pressure and support the restoration of degraded rangelands. However, these systems rely on more intensive inputs to meet feed requirements, which introduces trade-offs in other environmental impact categories. This study found no significant differences in climate change impacts between management systems when assessed per kilogram of clean, dehaired cashmere, suggesting that both nomadic and farmed systems can achieve comparable outcomes. The findings highlighted that the primary production stage is the most significant contributor across the key indicators of climate change, water, energy use (farmed system only), and land use.

At the primary production stage, higher impacts per kilogram of raw cashmere were observed in the nomadic systems, largely due to lower productivity. Importantly, this is not an inherent characteristic of the nomadic grazing system; rather, it reflects the greater variability and exposure to weather events, and fewer management controls implemented. This was mostly related to the management of winter conditions, where animals were provided with higher feed inputs in the farmed systems. While this contributed to higher energy and water use via feed inputs, it significantly reduced the carbon footprint and land impacts per unit of production. The results showed that even modest productivity gains in either system could lead to significant reductions in environmental impacts in both production systems.

Enhancing the productivity and efficiency of cashmere production in herding communities was one of the most significant opportunities to reduce environmental impacts. The sensitivity analysis of dzud events demonstrated the impact on the long-term performance of the goat herd in Mongolia, and highlighted opportunities to improve outcomes through better dzud management. While this suggests that productivity in nomadic systems could be improved through greater use of supplementary feed during the winter and dzud events, we recognize that this is not a simple intervention. Although winter feeding has historical precedent in Mongolia, particularly during the Soviet era, and is widely practiced in other cold-climate regions to support animal welfare and survival, its adoption today is shaped by complex social, economic, and logistical factors. These considerations must be taken into account when exploring pathways to improve resilience and reduce environmental impact. Support for improved access to feed, when co-designed with herders and grounded in the local context, could offer meaningful gains to improve resilience and environmental impacts. For this increase in productivity to also reduce absolute impacts (on a per hectare or per stocking unit basis), this would also need to be accompanied by reduced stocking rates. The findings underscore the importance of targeted interventions to improve on-farm productivity and resilience, such as herd management and improved supplementary feed.

The second most significant opportunity to reduce environmental impacts identified in this study was increasing soil carbon sequestration by reversing soil carbon loss. Modeling from other studies suggests that this strategy could potentially reverse climate change impacts. While impacts were high and uncertain from the present study, these opportunities suggest significant change could be achieved through practice change.

8.1.1. Responsible use of results

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

- Data from certain regions was either unavailable or had to be modeled based on proxies, limiting granularity. The results presented do not support comparisons between Mongolia and China, particularly because of limitations in the representativeness of the dataset for China.
- SOC change and its contribution to the carbon footprint of cashmere is highly uncertain and impacted by numerous factors. Further research is needed to quantify these impacts across major production regions (see recommendations). Considering the high levels of uncertainty, we recommend using the carbon footprint results without amalgamating these with the emissions from soil carbon until a higher degree of certainty in the findings can be achieved through further research. Climate change (excluding 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 modeling. These results should be used for indicative purposes only, and not for procurement decisions nor choices between production systems.
- The LANCA model has not been standardized and will change in response to new development activities underway. The land use impact results should be used for indicative purposes only, and not for procurement decisions nor choices between production systems. The application of the land use LANCA impact model requires further development and research applications in grazing systems to verify true impacts.
- Animal welfare and social outcomes were not assessed in this report. Social outcomes and livelihood impacts will be qualitatively explored in a separate study.
- The results presented in this study are based on biophysical allocation, specifically using protein allocation at the primary production stage, to allocate impacts between the main co-products: liveweight, raw cashmere, and milk. This approach follows established LCA guidance, and the methods are documented in the peer-reviewed literature. A sensitivity analysis, using economic and energy allocation methods, revealed differing trends in some impact categories and, in some cases, lower and higher reportable impacts for cashmere, highlighting the significant influence that allocation choice can have on comparative outcomes.

Given the identified limitations, results from this study should be used with caution and viewed as a first step in understanding cashmere impacts. While the findings offer valuable insights into environmental hotspots and system-level dynamics, they are not suited for direct comparison with other fiber LCA studies unless methodological alignment is ensured. Stakeholders are encouraged to interpret the results in context and avoid overgeneralization or fiber substitution decisions based on isolated values without considering the broader sustainability profile and uncertainties involved.

8.1.2. Recommendations for decision-makers

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

Herders and producers:

They can benefit from strategies that enhance herd productivity, manage stocking rates relative to land condition, and improve animal nutrition. Achieving these outcomes often depends on supportive conditions such as improved access to animal feed during winter, reliable market access, and economic incentives that align with and respect existing cultural practices. These measures are particularly relevant during dzud events, where supplementary feeding can improve animal welfare and survival. However, adoption is shaped by barriers such as feed cost and availability, as well as infrastructure limitations.

Industry organizations:

They should facilitate targeted training programs for herders and extension agents on herd nutrition, grazing management, and winter preparedness. They should support farm-level data collection on feed use, stocking rates, and animal performance to enable benchmarking across production systems. Benchmarks should be used to guide evidence-based practice change.

Brands and retailers:

Brands and retailers play a critical role in enabling positive change within supply chains. The results highlight the importance of sourcing transparency and long-term supplier engagement to encourage supply chain development initiatives that reduce environmental and social risk. This study indicated that significant opportunities exist to improve environmental outcomes in both nomadic grazing and farm systems, but this requires market support for transition. Supporting higher returns for herders and farmers, combined with supply chain requirements around stocking rate and winter management, could dramatically improve environmental outcomes. Impact reductions are achievable in either system, and actions by brands should prioritize supplier support and targeted interventions in both systems, and should not withdraw from one system in favor of the other.

8.1.3. Recommendations for future research and development

This study revealed the considerable complexity in assessing impacts from cashmere using multi-indicator LCA, and represented a first step in building this knowledge base. Further research is needed as follows:

- Expand regional coverage of farm-level data, particularly in underrepresented production systems in China.
- Quantify and improve soil carbon modeling, and evaluate soil carbon sequestration under improved grazing practices.
- Research and extension to demonstrate cost-effective winter livestock management to improve nutrition, animal performance, and economic outcomes. While winter supplementary feeding is a well-established practice in many cold-climate regions, and was institutionalized in Mongolia during the Soviet era, there are a range of social, cultural, and economic barriers that need to be considered in contemporary Mongolian herding systems.
- Integrated assessments that include socio-economic factors alongside environmental impacts.
- Collaborative research with stakeholders to improve access to processing and market data, especially post-dehairing.
- Development of regionally relevant characterization factors for acidification, eutrophication, and particulate matter.
- Development of regionally relevant weighting and normalization for PEF single score assessment so that the single score reflects material priorities in semi-arid rangeland contexts.

Appendix A–Critical review statement

This Life Cycle Assessment (LCA) report underwent a critical review process to ensure compliance with ISO 14044, and to verify the robustness of the methodology, data quality, and the interpretation of results. The review was conducted by a panel of expert reviewers and assessed the following aspects of the study:

- **Methodology:** Evaluation of the goal and scope, data collection methods, and life cycle impact assessment approach.
- **Data quality:** Review of data sources, consistency, and reliability.
- **Impact assessment:** Assessment of how results are interpreted, including the handling of assumptions, limitations, and scenarios.
- **Transparency and clarity:** Evaluation of the report's clarity in communicating the results, assumptions, and limitations.

Summary of major themes from the critical review and how they were addressed

The critical review process for this cashmere LCA report identified several themes, including allocation methodology, data quality and representativeness, handling of co-products and residuals, and sensitivity and uncertainty analyses.

1. Allocation methodology

Theme: Reviewers discussed the application of allocation methods (biophysical: protein and energy, economic) for attributing environmental impacts among cashmere, meat, and milk.

How this was addressed: The allocation method applied was protein allocation, with energy and economic allocation used in the sensitivity analysis. The report clarified the rationale for using biophysical (protein) allocation as the primary method, consistent with ISO 14044 and LEAP guidelines. Energy and economic allocation were included as a sensitivity analysis, with results transparently presented for comparison. The methodology section was expanded to detail calculation approaches, and the implications of allocation choices were discussed.

2. Data quality, representativeness, and averaging

Theme: Reviewers sought further explanation regarding the sources, structure, and representativeness of primary and regional data, the averaging of multi-year datasets (including dzud years), and the merging of farm-level and regional statistics.

How this was addressed: Further details were provided regarding the methodology, and the appendix was updated to explain data collection, survey structure, and the integration of case study and regional data. Footnotes and glossary entries were added for transparency.

3. Handling of co-products and residuals

Theme: Reviewers identified coarse hair, suint, and grease in the primary processing allocation.

How this was addressed: The report clarified that coarse hair is treated as a residual, not a waste, in line with LEAP terminology, and described its typical uses. Suint and grease were treated as waste.

4. Sensitivity and uncertainty analysis

Theme: Reviewers requested more detail on sensitivity analysis (especially for allocation, soil carbon loss, and productivity parameters).

How this was addressed: Sensitivity analysis was expanded to include soil carbon loss, allocation methods, and key productivity parameters. Further detail was provided on the uncertainty analysis, specifically the distinction between alpha and beta uncertainties. The report clarified that uncertainty is dominated by production-stage parameters, and provided guidance on interpreting confidence intervals.

Critical review statement for the study: Life Cycle Assessment (LCA) of Cashmere

Commissioned by Textile Exchange and prepared by Integrity Ag

February 9, 2026

Review panel:	Greg Thoma, Ph.D. (Panel Chair) Sandra Eady, Ph.D. Mireille Faist, Ph.D. Managing Director Research Scientist Principal Sustainability Expert Resilience Services, PLLC. Lifecycles Quantis The members of the critical review panel were chosen to ensure the required LCA competence and expertise in the scientific and technical aspects of the studied product system.
References:	International Organization for Standardization. (2006). *Environmental management—Life cycle assessment—Principles and framework* (ISO 14040:2006). https://www.iso.org/standard/37456.html International Organization for Standardization. (2006). *Environmental management—Life cycle assessment—Requirements and guidelines* (ISO 14044:2006). https://www.iso.org/standard/38498.html International Organization for Standardization. (2014). *Environmental management—Life cycle assessment—Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006.* (ISO/TS 14071:2014). https://www.iso.org/standard/86264.html

The scope of the critical review

The review panel has the task of assessing whether:

- The methods used to carry out the LCA are consistent with the international standards ISO 14040 (2006) and ISO 14044 (2006)
- The methods used to carry out the LCA are scientifically and technically valid
- The data used is appropriate and reasonable in relation to the goal of the study
- The interpretations reflect the limitations identified and the goal of the study, and
- The study report is transparent and consistent.

The full analysis of individual datasets and calculations underlying the results was outside the scope of this review. Nonetheless, the panel included an evaluation of the modeling and methods used for the study.

This review statement is valid for the final version of the report dated January 30, 2026.

The process and outcome of the review

The review was performed in five rounds of comment and response. There were approximately 300 individual comments which covered a range of issues from grammatical and structural suggestions to important points on both technical and methodological aspects, which could influence the communication around the conclusions of the study. There were vigorous discussions, including several virtual meetings between the panel and practitioners, regarding these issues. As a result of the discussions, panel comments, and practitioner responses, the report has an appropriate level of transparency regarding both data and methodology. Recommendations for use of the information provided to the report's audience are based on the strengths and limitations inherent in LCA studies. The practitioners have provided, as an annex to the report, a summary of the main topics raised by the panel and their corrective action.

General remarks

The study uses LCA to perform a quantitative analysis of the environmental impacts of Cashmere production in Mongolia and China. The practitioner collected primary data from both nomadic systems and confinement systems in Mongolia and China, respectively. The primary data was augmented with regional datasets from agricultural statistics, and a representative production model was produced from the combination of this information, and emissions were estimated using standard relationships from IPCC and other recognized sources.

The panel strongly recommended that, because the determining product in the production system is the high value-fiber, the choice of protein allocation alone was not sufficient to document the potential range of outcomes. An investigation of energy and economic allocation was necessary to demonstrate sensitivity to methodological choice to ensure a comprehensive view of potential outcomes, along with the applicability of results for different environmental sustainability frameworks. This also aligns with the LEAP guidelines, which recommend using economic allocation as a second approach when the markets for the co-products differ strongly. The practitioners have included these alternate allocations. The baseline biophysical (protein-based) allocation is in conformance with the ISO standards.

Overall, the analysis is adequate and the sensitivity and uncertainty analysis satisfactory to substantiate the conclusions regarding the environmental impacts of the categories defined in the goal and scope.

Conformance Statement

Overall, the critical review panel found the final report's methodology and its application in the analysis to be satisfactory for the defined goal and scope of the study. The reporting, methodology, and study results are acceptably transparent. The discussion of the results covers the relevant aspects following the goal of the study, and the conclusions are clearly expressed in relation to the results and in accordance with the defined goal. The study is determined to be in conformance with the applicable ISO standards.

GThoma — Sandra Eady — MFaist

Greg Thoma, Ph.D. | Sandra Eady, Ph.D. | Mireille Faist, Ph.D

Appendix B– Additional information on data collection and modeling

Simplified and case study survey design

Data collection was split into simplified and case study surveys (Table 39). Case study data collection was completed by researchers from the Mongolian Academy of Sciences, following collaboration with the research team on the first case study farm.

Table 39: Simplified and case study survey design

	Simplified survey	Case study survey
Part 1, farm survey	One farm survey per herder household/farm	One farm survey per herder household/farm
Part 2, rapid assessments[1,2]	A minimum of 10 rapid assessments per herder household	A minimum of 40 rapid assessments per herder household
Part 3, livestock weights1	A minimum of two herder households per aimag	All case study herder households
Part 4a, plot assessments	Not applicable	A minimum of 16 plots (four plots per camp)
Part 4b, transect assessments	Not applicable	A minimum of seven transects per plot

[1] *Case study data collection, weighing of livestock and rapid assessments did not occur in China due to the data security law (National People's Congress, 2023), which limits the collection of spatially explicit data.*

[2] *These datasets included spatially explicit information on land use classification, land condition score, ground cover, slope, pasture height, and the presence of vegetation.*

Regional data—Mongolian Statistical Information Service (MSIS)

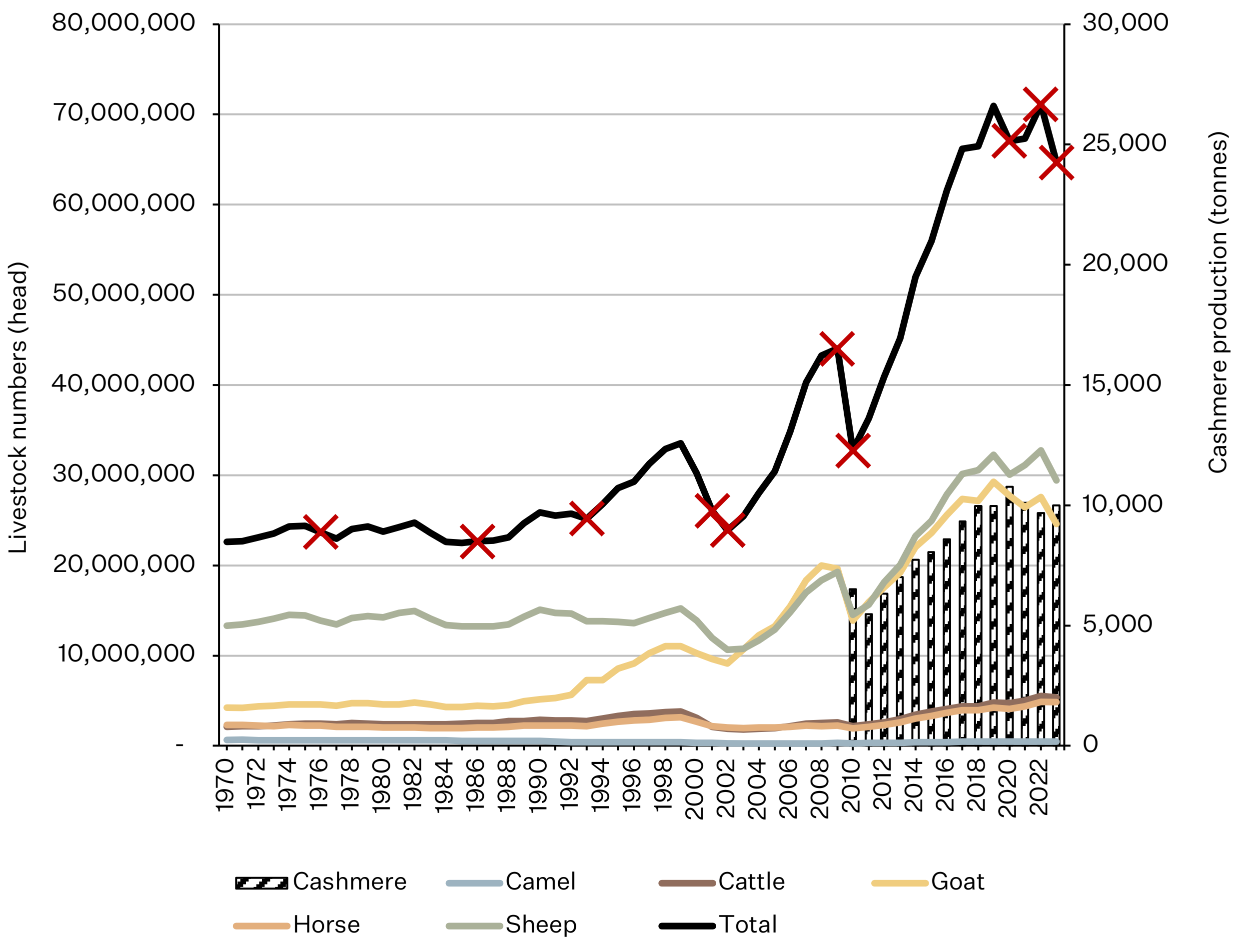
To conduct an LCA study on a product, it is important that the inventory reflects a "steady state" condition, as livestock production is often variable from season to season. This was achieved by modeling a self-replacing herd over one complete production cycle of animal inventories. A five-year average of the key productivity parameters from the Mongolian Statistical Information Service (MSIS), (National Statistics Office of Mongolia, 2024a), was used to remove the effect of inter-annual variability (Table 40). This included the productivity performance of the dzud year. The dzud events were identified as 1976, 1986, 1993, 2002, 2010, 2020, 2022, and 2023 using datasets from the Mongolian Statistical Information Service (MSIS) (Figure 16), and NAMEM (National Agency Meteorology and Environmental Monitoring, 2023), and confirmed by the National Federation of Pasture User Groups (personal communication).

Table 40: Datasets downloaded from the Mongolian Statistical Information Service (MSIS)

Dataset	Description	Temporal coverage	Download date
Number of livestock, by type, region, bag, soum, aimags, and the Capital	Livestock refers to all animals, birds, and insects kept or reared in captivity mainly for agricultural purposes. This includes cattle, buffaloes, sheep, goats, and pigs, as well as poultry and bees. Domestic animals, such as cats and dogs, are excluded unless they are raised for food or other agricultural purposes.	1970–2023	09/23/2024

Dataset	Description	Temporal coverage	Download date
Number of herder households, by region, bag, soum, aimags, and the Capital	Households with livestock	1991–2023	10/10/2024
Production of agriculture, by type, region, aimags, and the Capital	Includes tons of cashmere produced	2010–2023	09/04/2024
Number of breeding stock, by region, bag, soum, aimags, and the Capital	Female animals up to two years old and capable of reproduction	1991–2023	09/16/2024
Number of barren female animals, by region, bag, soum, aimags, and the Capital	Female animals not producing or incapable of producing offspring	1991–2023	09/16/2024
Losses of adult animals, by region, quarter, aimags, and the Capital	Loss of animals due to natural disasters, such as dzud, heavy rain, fire, lightning, infectious and non-infectious diseases, and others (wild animal depredation and accidents).	2011–2023	09/04/2024
Survival of young animals, by region, by bag, soum, aimags, and the Capital	Refers to a young animal being reared	1991–2023	09/16/2024

Figure 16: Number of livestock by species (primary vertical axis) and total cashmere production (tons) (secondary vertical axis), where szud events are identified by a red cross (X)



Calculation of key productivity parameters from the Mongolian Statistical Information Service (MSIS) datasets

A five-year average (2019–2023) of the following key productivity parameters was used in the herd model for the nomadic grazing system.

Equation 1

$$\text{Mortalities (\%)} = \frac{\text{Natural losses of adult animals}}{\text{Number of goats}}$$

Equation 2

$$\text{Survival of young animals per 100 breeding females (\%)} = \frac{\text{Number of survivals of young animals}}{\text{Number of breeding stock}}$$

Equation 3

$$\text{Cashmere yield per goat (kg)} = \frac{\text{Tonnes of cashmere } \times 1000}{\text{Number of goats}}$$

Equation 4

$$\text{Proportion of breeding females (\% of herd)} = \frac{\text{Number of breeding stock}}{\text{Number of goats}}$$

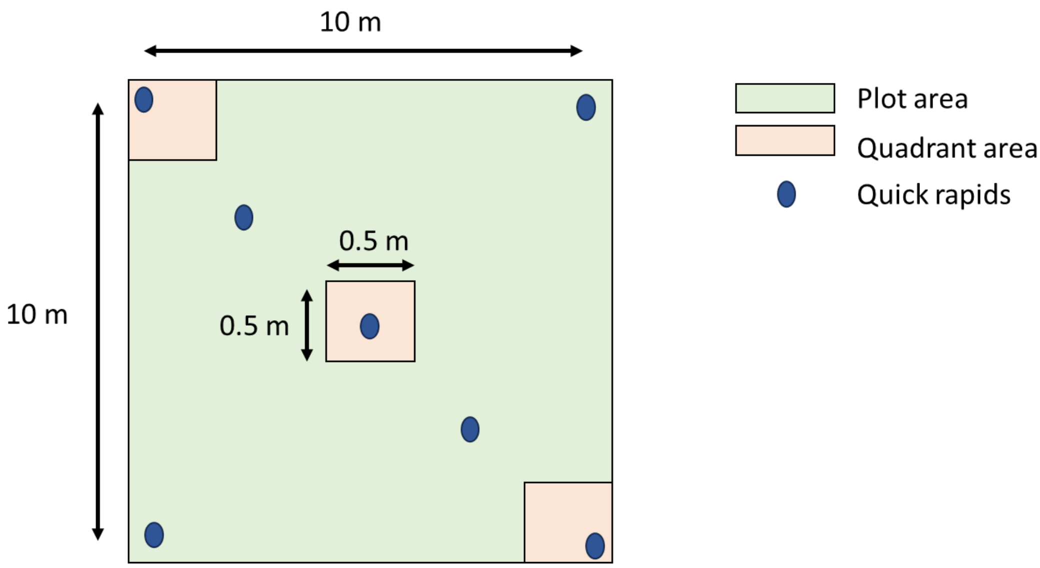
Equation 5

$$\text{Stocking rate (SU/ha)} = \frac{\text{Total sheep units}}{\text{Total hectares for agriculture}}$$

Plot and transect assessments

The completion of the rapid assessments was used to select plot assessments that captured a range in land use type, topography, soil type, and grazing pressure across the camp areas. All plot locations were at least 50 m away from high-traffic areas, water points, roads, and tracks. A 10 m × 10 m area was marked, and photographs were taken at the middle of the plot in all four directions (Figure 17). Land use type, land condition score, slope %, and average canopy width and tree height (if present), were recorded for each plot. Three 50 cm × 50 cm quadrants per plot were selected for further analysis. The quadrants were evenly spaced across the plot, one in each far corner and one in the middle of the plot following a transect (Figure 17). Estimates of ground cover %, dry matter production (kg/ha), dry matter %, unpalatable species %, green fraction %, pasture depth (cm), dominant plant community, and a photograph of the quadrant at elbow height, were collected. The pasture was then cut to ground level within each quadrant and separated into palatable and unpalatable species. The pasture samples were weighed immediately on kitchen scales. A soil core was extracted for each quadrant to a depth of 30 cm using a T-bar hand sampler with a 38 mm diameter, and the latitude and longitude of each sample were recorded. The sampling depth was recorded when a 30 cm core could not be extracted. Seven quick rapids were completed along transects in the plot (Figure 17). A photograph of the groundcover and additional estimates on ground cover % and pasture height were recorded for each quick rapid assessment.

Figure 17: Diagram of part 4a and 4b plot assessment



Laboratory testing on pasture and soil samples was completed at the National University of Mongolia Laboratory of Environmental Chemistry and Geochemistry.

Prediction equations

Feed intake and livestock GHG emissions were modeled using IPCC Tier II equations from the 2019 refinement (IPCC, 2019b, 2019a) (Table 41).

Table 41: Feed intake, livestock greenhouse gas, and livestock drinking water prediction methods

Prediction method	Factor/prediction equation	Reference
Net energy for maintenance (MJ day^{-1})	$NE_m = 0.315 \times$ average liveweight$^{0.75}$	Equation 10.3 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Net energy for activity (MJ day^{-1})	$NE_a = C_a \times$ average liveweight For nomadic grazing system: C_a = 0.024 MJ d^{-1} kg^{-1}. This is reflective of goats grazing open range pasture. For farmed system: C_a = 0.019 MJ d^{-1} kg^{-1} for goats grazing and 0.0067 MJ d^{-1} kg^{-1} for goats during confinement feeding.	Equation 10.4 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Net energy for lactation (MJ day^{-1})	$NE_l = \frac{5 \times WG_{wean}}{365} \times EV_{milk}$ **Where:** WG_{wean} = the weight gain of the kid between birth and weaning (kg) EV_{milk} = the energy required to produce 1 kg of milk (MJ/kg^{-1}). Assumed 3 MJ/kg^{-1} for goats and 3 months lactating	Equation 10.10 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Net energy to produce cashmere (MJ/day)	$NE_{wool} = \frac{EV_{wool} \times PR_{wool}}{DOF}$ **Where:** EV_{wool} = the energy value of each kg of cashmere produced. = 24 MJ/kg^{-1} × protein content in raw cashmere + 38 MJ/kg^{-1} × grease content in dry, raw cashmere (energy content has been modified from the IPCC to include energy in grease). PR_{wool} = annual cashmere production per goat kg yr^{-1}	Equation 10.12 IPCC Volume 4, Chapter 10 (IPCC, 2019a)

Prediction method	Factor/prediction equation	Reference
	DOF = days in each animal class	
Net energy for pregnancy (MJ/day)	$Ne_p = C_{pregnancy} \times NE_m$ **Where:** $C_{pregnancy}$ = 0.077. Assumed all goats are 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)	Equation 10.13 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Net energy for growth (MJ/day)	$NE_g = \frac{WG \times (5.0 + 0.5 \times 0.33(BW_i + BW_f))}{DOF}$ **Where:** $WG = BW_f - BW_i$ kg yr^{-1} BW_i = live bodyweight at weaning kg yr^{-1} BW_f = live bodyweight at 1yr, or at slaughter if slaughtered prior to 1 year of age, kg DOF = days in each animal class This equation was modified from Equation 10.7 IPCC Volume 4, Chapter 10, to model the net energy for growth in each animal class.	Equation 10.7 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Gross energy (MJ/day)	$GE = \frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM}\right) + \left(\frac{NE_g + NE_{wool}}{REG}\right)}{DE}$ **Where:** GE = gross energy intake MJ $head^{-1}$ day^{-1} 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} 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 cashmere (Equation 10.12) MJ day^{-1} DE = digestibility of feed expressed as a fraction of gross energy (digestible energy/gross energy)	Equation 10.16 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Ratio of net energy available for maintenance in a diet to digestible energy consumed	$REM = 1.123 - (4.092 \times 10^{-3} \times DE) + (1.126 \times 10^{-5} \times (DE)^2) - (\frac{25.4}{DE})$ **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)

Prediction method	Factor/prediction equation	Reference
Dry matter intake	$$\mathrm{DMI} = \frac{\mathrm{GE}}{18.45}$$ **Where:** 18.45 = assumption of the gross energy content of cellulose fibers (MJ/kg DM^{-1})	(CSIRO, 2007)
Enteric methane	$$\mathrm{EF} = \frac{\mathrm{GE} \times \left(\frac{Y_m}{100}\right)}{55.65}$$ **Where:** EF = emission factor, kg CH_4 $head^{-1}$ day^{-1} GE = gross energy intake MJ $head^{-1}$ day^{-1} Y_m = methane conversion factor, percent of gross energy in feed converted to methane. Y_m = 5.5 The factor 55.65 (MJ/kg CH_4) is the energy content of methane.	Equation 10.21 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Volatile solid excretion rates	$$VS = [\mathrm{GE} \times (1 - \mathrm{DE}) + (\mathrm{UE} \times \mathrm{GE})] \times [\frac{1 - \mathrm{ASH}}{18.45}]$$ **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. 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.	Equation 10.24 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Methane emissions from manure	$$EF = (\mathrm{VS} * 365) * [B_0 \times 0.67 \times \sum \frac{\mathrm{MCF}_{S,k}}{100} \times \mathrm{AWMS}_{(T,S,K)}]$$ **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 kilograms 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. When goats are from low productivity systems: B_0 = 0.13 m^3 CH_4 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% "Dry lot/composted/solid storage"MCF = 1.0% "Daily spread" MCF = 0.10%	Table 10.17 IPCC Volume 4, Chapter 10 (IPCC, 2019a)
Animal waste management system (AWMS)	For the nomadic grazing system: • 96% of animal waste is deposited on pasture/range/paddock • 4% of animal waste is stockpiled (winter)	

Prediction method	Factor/prediction equation	Reference
	For the farmed system: • 57% of animal waste is deposited on pasture/range/paddock • 5% of animal waste is stockpiled/solid storage • 3% of animal waste is spread across grassland • 15% of animal waste is composted • 19% of animal waste is dry lot This considered a weighted average between the time goats spent grazing the pasture and the time goats were in confinement feeding systems.	
Nitrogen intake (kg N hd^{-1} day^{-1})	$$\text{N intake} = \frac{\text{GE}}{18.45} \times \left(\frac{\frac{\text{CP\%}}{100}}{6.25}\right)$$ **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 the 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)
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	$$\text{N retention} = \frac{\text{P cashmere} + \text{P liveweight} + \text{P milk}}{6.25}$$ **Where:** N retention = total N that is retained in the animal for the production of meat, cashmere, and milk. P cashmere = amount of protein contributing to raw cashmere production (kg protein hd^{-1} day^{-1}). Assumption that 100% scoured cashmere is protein. P liveweight = amount of protein contributing to liveweight growth (kg protein hd^{-1} day^{-1}). P milk = amount of protein contributing to milk production (kg protein hd^{-1} day^{-1}). Assumption that 4.11% of goat milk is protein, and Mongolian goats produce 60–70 liters per lactation (Narangerel et al., 2016).	
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.	Equation 10.25 IPCC Volume 4, Chapter 10 (IPCC, 2019a) Table 11.1 IPCC Volume 4, Chapter 11 (IPCC, 2019b)

Prediction method	Factor/prediction equation	Reference
	• Daily spread, during storage and treatment, are assumed to be zero. Emissions from land application then use the emission factor for pasture/range/paddocks. • Solid storage/stockpiled = 0.010 (kg N_2O – N (kg N)$^{-1}$). • Composting = 0.010 (kg N_2O – N (kg N)$^{-1}$). • Dry lot = 0.02 (kg N_2O – N (kg N)$^{-1}$). Uncertainty range for manure management emission factors +/100%. $\frac{44}{28}$= conversion of N_2O – N to N_2O	
Indirect N_2O emissions due to volatilization of N from manure management	$$\mathrm{iN_2O} = \mathrm{N\ volatilzation} \times \mathrm{EF_4} \times \frac{44}{28}$$ **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 and for wet climates = 0.014. Mongolia and China were characterized as a dry climate.	Equation 10.28 IPCC Volume 4, Chapter 10 (IPCC, 2019a) Table 11.3 IPCC Volume 4, Chapter 11 (IPCC, 2019b)
N_2O from atmospheric deposition of N volatilized from managed soils	$$\mathrm{N\ volatilisation} = \sum_S [\mathrm{Nex} \times \mathrm{AWMS(s)} \times \mathrm{Frac_{GASM}}]$$ **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. • Fraction of N excreted from drylot that volatilizes as NH_3 and NO_x (kg N volatilized) = 0.30. Uncertainty range = 0.20–0.50. • Fraction of N excreted from stockpile that volatilizes as NH_3 and NO_x (kg N volatilized) = 0.12. Uncertainty range = 0.05–0.20. • Fraction of N excreted from daily spread that volatilizes as NH_3 and NO_x (kg N volatilized) = 0.07. Uncertainty range = 0.05–0.60. • Fraction of N excreted from stockpile that volatilizes as NH_3 and NO_x (kg N volatilized) = 0.12. Uncertainty range = 0.05– 0.20. • Fraction of N excreted from compost that volatilizes as NH_3 and NO_x (kg N volatilized) = 0.20. Uncertainty range = 0.05–0.24.	Equation 11.9 IPCC Volume 4, Chapter 11 (IPCC, 2019b)
Indirect N_2O emissions from leaching	$$iN_2O_{leach} = Nex \times Frac_{leach} \times EF_5 \times \frac{44}{28}$$ **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 = 0.24. The $Frac_{leach}$ only applies to wet climates. For dry climate, the default $Frac_{leach}$ is zero. Uncertainty 0.00–0.31.	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)

Prediction method	**Factor/prediction equation**	**Reference**
	Uncertainty range is based on the 2.5th to 97.5th percentile. For Mongolia's and China's dry arid climate where our study sites were located, $Frac_{leach}$ is assumed to be zero. 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.	
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. 1.215 = conversion factor from NH_3-N to NH_3	Table 8A.1 IPCC Volume 4, Chapter 11 (IPCC, 2019b)
Livestock drinking water intake	$$3 \times \mathrm{DMI}$$ **Where:** DMI = dry matter intake (kg DMI hd^{-1} day^{-1}). 2–4 L water/kg DMI for goats at temperatures < 15°C.	INRA 1978 Alimentation des Ruminants (Ed.) R. Jarriage (INRA publications: Versailles), as cited in CSIRO 2007 Nutrient Requirements of Domesticated Ruminants (CSIRO, 2007)

Appendix C–Data quality rating method and criteria (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 the ILCD Handbook (European Commission—Joint Research Centre—Institute for Environment and Sustainability, 2010). Each dataset was scored based on its performance in line with ISO, p. (2006b, p. 10), 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.

Rationale for process-level data quality rating

In this study, data quality ratings (DQR) were assigned at the process level, encompassing distinct supply chain stages, including goat 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 (ISO, 2006b) guidelines, which do not mandate a specific level of granularity for data quality assessment, and with ILCD and PEF recommendations that encourage detailed evaluation where feasible but allow flexibility based on study goals and constraints.

Time-related representativeness and dzud events

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. The primary data was collected during a dzud year, an extreme weather event known to cause significant fluctuations in livestock productivity, representing an atypical production state.

To ensure the LCA inventory reflects typical production conditions, rather than an anomaly, a complete production cycle was modeled and adjusted for changes in inventory. This adjustment was informed by secondary datasets from the Mongolian Statistical Information Service (MSIS), which provide long-term averages of key productivity parameters. Dzud years were identified through multiple data sources (MSIS, NAMEM, and expert consultation). Dzud years were included in the five-year average to ensure the analysis reflects the full range of production conditions. Averaging over this period helps smooth out inter-annual variability while still capturing the impact of extreme events such as dzuds. This approach enhances the time-related representativeness of the inventory data by aligning it with steady-state production conditions.

Mean DQR score

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

Data quality ratings

The following table presents DQR scores for each major process included in the LCA, based on the final inventory data as used in the model. These scores reflect the overall quality of the inventory after integration of primary and secondary data, including any adjustments (for example, for time-related representativeness).

Table 42: Data quality rating for unit processes

Process	Technological representativeness	Geographical representativeness	Time-related representativeness	Completeness	Precision/ uncertainty	DQR
Goat production nomadic grazing systems	Data collected from the exact farms in the study (some secondary data used); however, the dataset may not reflect the true population	Data directly from Mongolia; however, the dataset may not be representative of all geographical areas	Data collected within the last two years	High completeness; administration and overheads were excluded	Limited sample size, moderate variability	
	2.5	2.5	2	2	3	2.4
Mongolia primary processing	Data collected from 11 processing facilities, of which ~50 % of cashmere processing sites in Mongolia	Data specific to Mongolia	Data collected within the last two years	Includes key inputs and outputs; minor uncertainties on chemical usage; administration and overheads excluded	Large sample size, moderate uncertainty	
	1	2	2	2	3.5	2.1
Goat production farmed system	Data collected from the exact farms in the study (some secondary data used)	Data collected from China (Inner Mongolia and Shaanxi); however, data may not be representative of all cashmere producing regions for international markets	Data collected within the last two years	High completeness; includes key inputs and outputs; minor uncertainties on chemicals and purchased inputs; administration and overheads were excluded	High variability in farm practices; limited sample size	
	2	3	2	2	3.5	2.5
China primary processing	Data from seven cashmere processing plants in China; however, may not be completely representative of the entire population	Data specific to China	Data collected within the last two years	Includes key inputs and outputs; minor uncertainties chemicals and purchased inputs; administration and overheads were excluded	Medium sample size; moderate uncertainty	
	2	1	2	2	3.5	2.1
Study average						2.3

Appendix D–Uncertainty analysis

Two types of uncertainty were distinguished: α (alpha) uncertainty, which represents variation between farm (herder) 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), is reported for the nomadic grazing system (Table 43), and for the farmed system (Table 44). As beta uncertainty was shared by all systems, comparison of the mean results between production systems was based on alpha uncertainties only, and significant differences were determined using the following equation of Wiltshire et al. (2009):

$$z = \frac{100 \times |A - B|}{\sqrt{CV_A^2 \times A^2 + CV_B^2 \times B^2}}$$

Where:

A and B are the mean values, and CV_A and CV_B are the coefficients of variance of the two systems compared. In Life Cycle Assessment (LCA), the presence of non-linear relationships between input parameters and impact results, and skewed input data distributions, can lead to differences between the deterministic and probabilistic mean. Specifically, the result obtained by evaluating the model using mean input values (the deterministic mean) often differs from the mean of the output distribution generated through Monte Carlo simulation (the probabilistic mean). This phenomenon arises because, in non-linear systems, the function of an average input does not generally equal the average of the function's outputs—an effect formally described by Jensen's Inequality (Jensen, 1906). Additionally, in this study, the deterministic mean was weighted by the cashmere production volumes by region to create a more representative result of the two production systems.

Uncertainty in the Monte Carlo analysis is expressed as a 95% confidence interval, defined by the 2.5% and 97.5% percentiles of the simulated results. For example, the estimated climate change (excluding LULUC) impacts were 169 [median value] kg CO_2-e per kg clean, dehaired cashmere, with a 95% confidence interval ranging from 120–278 kg CO_2-e kg clean, dehaired cashmere for the nomadic grazing system (Table 43). This means that, based on the input uncertainties included in the model, there is a 95% probability that the true impact lies within this range. Similarly, the estimated climate change (excluding LULUC) impacts were 176 [median value] kg CO_2-e per kg clean, dehaired cashmere, with a 95% confidence interval ranging from 139–222 kg CO_2-e kg clean, dehaired cashmere for the farmed system.

Table 43: Uncertainty analysis excluding beta uncertainties (shared model uncertainties) for the nomadic grazing system per kg of clean, dehaired cashmere

Impact category (PEF)	Unit	Probabilistic mean	Median	Standard deviation	Coefficient variation	2.5%	97.5%
Acidification	mol H^+ eq	0.2	0.1	0.02	13	0.1	0.2
Climate change	kg CO_2 eq	214	207	60	28	117	345
Climate change—(excluding LULUC)	kg CO_2 eq	179	169	43	24	120	278

Impact category (PEF)	Unit	Probabilistic mean	Median	Standard deviation	Coefficient variation	2.5%	97.5%
Climate change—biogenic[1]	kg CO_2 eq	141	132	37	26	89	227
Climate change—fossil	kg CO_2 eq	38	37	5	14	30	50
Climate change—LULUC[2]	kg CO_2 eq	35	30	42	122	−32	133
Ecotoxicity, freshwater—part 1	CTUe	358	340	92	26	229	563
Ecotoxicity, freshwater—part 2	CTUe	48	46	9	19	35	68
Ecotoxicity, freshwater—inorganics	CTUe	196	187	46	24	133	300
Ecotoxicity, freshwater—organics—p.1	CTUe	201	192	54	27	125	325
Ecotoxicity, freshwater—organics—p.2	CTUe	8	8	2	24	5	13
Particulate matter	disease incidence	2E-05	2E-05	6E-06	29	1E-05	4E-05
Eutrophication, marine	kg N eq	4.4E-02	4.3E-02	5.7E-03	13	3.4E-02	5.6E-02
Eutrophication, freshwater	kg P eq	8.7E-03	8.6E-03	8.7E-04	10	7.2E-03	1.1E-02
Eutrophication, terrestrial	mol N eq	1.7	1.6	0.5	27	1.0	2.7
Human toxicity, cancer	CTUh	8.2E-09	8.0E-09	1E-09	17	6.2E-09	1.1E-08
Human toxicity, cancer—inorganics	CTUh	3.0E-09	3.0E-09	5E-10	15	2.4E-09	4.1E-09
Human toxicity, cancer— organics	CTUh	5.2E-09	5.0E-09	9E-10	18	3.8E-09	7.3E-09
Human toxicity, non-cancer	CTUh	5.2E-07	5.0E-07	1E-07	20	3.7E-07	7.6E-07
Human toxicity, non-cancer—inorganics	CTUh	2.6E-07	2.5E-07	4E-08	15	2.0E-07	3.4E-07
Human toxicity, non-cancer—organics	CTUh	2.6E-07	2.5E-07	7E-08	26	1.7E-07	4.2E-07
Ionizing radiation	kBq U-235 eq	1.8	1.8	0.1	8	1.5	2.1
Land use	Pt	443553	430904	125404	28	243767	712361
Ozone depletion	kg CFC11 eq	6.4E-08	6.2E-08	1.3E-08	20	4.6E-08	9.4E-08
Photochemical ozone formation	kg NMVOC eq	0.1	0.1	0.0	17	0.1	0.2
Resource use, fossils	MJ	143	142	12	8	123	168
Resource use, minerals, and metals	kg Sb eq	2.4E-04	2.3E-04	4.9E-05	2.0E+01	1.7E-04	3.5E-04
Water use	m^3 deprived	44	42	9	20	31	65

[1] Biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.

[2] Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which are reported elsewhere in section 6.1.10.

Table 44: Uncertainty analysis, excluding beta uncertainties (shared model uncertainties), for the farmed system per kg of clean, dehaired cashmere

Impact category (PEF)	Unit	Probabilistic mean	Median	Standard deviation	Coefficient variation	2.5%	97.5%
Acidification	mol H^+ eq	0.3	0.3	0.0	15	0.2	0.3
Climate change	kg CO_2 eq	190	188	26	14	141	245
Climate change—(excluding LULUC)	kg CO_2 eq	177	176	21	12	139	222
Climate change—biogenic[1]	kg CO_2 eq	117	116	13	11	94	143
Climate change—fossil	kg CO_2 eq	60	60	12	19	40	84
Climate change—LULUC[2]	kg CO_2 eq	13	11	14	113	–10	43
Ecotoxicity, freshwater—part 1	CTUe	430	426	60	14	319	553
Ecotoxicity, freshwater—part 2	CTUe	194	193	31	16	138	262
Ecotoxicity, freshwater—inorganics	CTUe	275	273	46	17	191	370
Ecotoxicity, freshwater—organics—p.1	CTUe	240	237	36	15	176	317
Ecotoxicity, freshwater—organics—p.2	CTUe	109	108	17	15	80	145
Particulate matter	disease inc.	2.1E-05	2E-05	3E-06	16	2E-05	3E-05
Eutrophication, marine	kg N eq	0.1	0.1	0.0	14	0.1	0.1
Eutrophication, freshwater	kg P eq	8.9E-03	8.9E-03	1.6E-03	18	6.2E-03	1.2E-02
Eutrophication, terrestrial	mol N eq	2.0	1.9	0.3	14	1.4	2.5
Human toxicity, cancer	CTUh	1.6E-08	1.6E-08	3E-09	22	1.0E-08	2.3E-08
Human toxicity, cancer—inorganics	CTUh	4.4E-09	4.3E-09	1E-09	24	2.6E-09	6.5E-09
Human toxicity, cancer—organics	CTUh	1.2E-08	1.2E-08	2E-09	21	7.5E-09	1.6E-08
Human toxicity, non-cancer	CTUh	5.8E-07	5.8E-07	9E-08	16	4.2E-07	7.8E-07
Human toxicity, non-cancer—inorganics	CTUh	3.2E-07	3.2E-07	7E-08	23	2.0E-07	4.6E-07
Human toxicity, non-cancer—organics	CTUh	2.6E-07	2.6E-07	3E-08	11	2.1E-07	3.2E-07
Ionizing radiation	kBq U-235 eq	1.1	1.1	0.2	21	0.7	1.6
Land use	Pt	141126	139270	21819	15	103776	189604
Ozone depletion	kg CFC11 eq	1.5E-07	1.5E-07	2.6E-08	18	1.0E-07	2.0E-07

Impact category (PEF)	Unit	Probabilistic mean	Median	Standard deviation	Coefficient variation	2.5%	97.5%
Photochemical ozone formation	kg NMVOC eq	0.2	0.2	0.0	19	0.2	0.3
Resource use, fossils	MJ	140	140	23	16	101	187
Resource use, minerals, and metals	kg Sb eq	4.4E-04	4.4E-04	1.1E-04	2.5E+01	2.5E-04	6.6E-04
Water use	m^3 deprived	89	88	11	12	69	111

[1] *Biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.*

[2] *Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which are reported elsewhere in section 6.1.10.*

Appendix E–Supplementary results

Environmental impacts per sheep unit (cradle to primary production gate)

Environmental impacts were reported per sheep unit (Table 45). Reporting impacts per sheep unit is useful for comparing systems with different stocking densities, eliminates the need to allocate emission between co-products, and considers animal-level GHG emissions. However, it does not accurately reflect the system's productivity. These are provided as supplementary information only.

Table 45: Environmental impacts per sheep unit for nomadic grazing systems and farmed systems (cradle-to-primary production gate)

Impact category (PEF)	Unit	Nomadic grazing system	Farmed system
Acidification	mol H^+ eq	0.1	0.2
Climate change	kg CO_2 eq	215	184
Climate change—(excluding LULUC)	kg CO_2 eq	213	183
Climate change—biogenic[1]	kg CO_2 eq	189	141
Climate change—fossil	kg CO_2 eq	24	42
Climate change—LUC (excluding soil carbon loss from LU)[2]	kg CO_2 eq	1.9	1.8
Ecotoxicity, freshwater	CTUe	494	657
Particulate matter	disease incidence	3E-05	2E-05
Eutrophication, marine	kg N eq	0.0	0.1
Eutrophication, freshwater	kg P eq	3.7E-03	7.1E-03
Eutrophication, terrestrial	mol N eq	2.1	2.2
Human toxicity, cancer	CTUh	6.6E-09	1.2E-08
Human toxicity, cancer—inorganics	CTUh	2.2E-09	3.0E-09
Human toxicity, cancer—organics	CTUh	4.4E-09	8.7E-09
Human toxicity, non-cancer	CTUh	5.3E-07	5.2E-07
Human toxicity, non-cancer—inorganics	CTUh	1.8E-07	2.2E-07
Human toxicity, non-cancer—organics	CTUh	3.4E-07	3.0E-07
Ionizing radiation	kBq U-235 eq	0.4	0.8
Land use	Pt	305829	161696
Ozone depletion	kg CFC11 eq	6.3E-08	1.4E-07
Photochemical ozone formation	kg NMVOC eq	0.1	0.2
Resource use, fossils	MJ	41	99
Resource use, minerals, and metals	kg Sb eq	2.3E-04	3.4E-04
Water use	m^3 deprived	45	94

[1] Biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.

[2] Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which are reported elsewhere in section 6.1.10.

Environmental impacts per hectare (cradle to primary production gate)

Environmental impacts were reported per hectare and were significantly higher for the farmed system (Table 46). This reflects the trade-off between land sparing and land sharing (grazing). When impacts are reported per hectare, they primarily reflect the stocking rate or intensity of the production system, which can be misleading if considered alone. Reporting impacts per kilogram of product normalizes these impacts by productivity, and reduces variability caused by differences in stocking rates.

Table 46: Environmental impacts per hectare for nomadic grazing systems and farmed systems (cradle-to-primary production gate)

Impact category (PEF)	Unit	Nomadic grazing system	Farmed system
Acidification	mol H^+ eq	0.1	0.6
Climate change		227.4	497.5
Climate change—(excluding LULUC)	kg CO_2 eq	225.4	492.8
Climate change—biogenic[1]	kg CO_2 eq	199.7	380.3
Climate change—fossil	kg CO_2 eq	25.7	112.4
Climate change—LUC (excluding soil carbon loss from LU)[2]	kg CO_2 eq	2.0	4.8
Ecotoxicity, freshwater	CTUe	523	1775
Particulate matter	disease inc.	3E-05	7E-05
Eutrophication, marine	kg N eq	0.0	0.2
Eutrophication, freshwater	kg P eq	0.0	0.0
Eutrophication, terrestrial	mol N eq	2.2	5.9
Human toxicity, cancer	CTUh	7.0E-09	3.2E-08
Human toxicity, cancer—inorganics	CTUh	2.3E-09	8.1E-09
Human toxicity, cancer—organics	CTUh	4.7E-09	2.4E-08
Human toxicity, non-cancer	CTUh	5.6E-07	1.4E-06
Human toxicity, non-cancer—inorganics	CTUh	1.9E-07	6.0E-07
Human toxicity, non-cancer—organics	CTUh	3.6E-07	8.1E-07
Ionizing radiation	kBq U-235 eq	0.4	2.2
Land use	Pt	323379	436555
Ozone depletion	kg CFC11 eq	6.7E-08	3.7E-07
Photochemical ozone formation	kg NMVOC eq	0.1	0.5
Resource use, fossils	MJ	43	268

Impact category (PEF)	**Unit**	**Nomadic grazing system**	**Farmed system**
Resource use, minerals, and metals	kg Sb eq	2.4E-04	9.1E-04
Water use	m^3 deprived	47	254

[1] Biogenic climate change impacts reported here are inclusive of carbon and non-carbon emissions, specifically methane and nitrous oxide.

[2] Climate change LU and LUC included emissions associated with forestland to grassland, and LU and LUC impacts embedded within the background datasets used in the modeling. It excluded emissions associated with grassland remaining grassland, which are reported elsewhere in section 6.1.10.

Document information

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