The International Journal of Life Cycle Assessment (2025) 30:491–510
https://doi.org/10.1007/s11367-024-02411-w

Shifting units, shifting views: how product mass and protein content influence environmental impact of Icelandic lamb

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Received: 18 March 2024 / Accepted: 14 November 2024 / Published online: 4 January 2025

Abstract

Purpose Lamb meat is a crucial protein source in Icelanders' diets. Extensive grazing lands, locally grown hay feed, and traditional farming methods are often used as arguments for Icelandic lamb meat's environmental friendliness. However, no life cycle assessment (LCA) study exists to corroborate these arguments. This study conducts a national-level LCA to evaluate the environmental performance of lamb meat based on two functional units to identify key hotspot processes in its production.

Method This study conducts a cradle-to-farm gate LCA at the national level for two functional units: 1 kg of edible lamb meat (ELM) and 100 g of ELM protein produced in Iceland in 2019. The multifunctionality between wool and meat is handled using mass allocation.

The environmental impacts were estimated using the ReCiPe 2016 v1.1 mid-point (H) impact assessment method, emphasizing selected environmental categories: global warming, fossil resource scarcity, land use, and terrestrial ecotoxicity. In addition, the study conducts a scenario-based variability analysis by taking minimum and maximum values of inventory data to estimate the possible range of environmental impacts. Lastly, an overall uncertainty analysis and a global sensitivity analysis of the key hotspot process shed light on the variability and sensitivity of the LCA results.

Result and discussion For the 18 ReCiPe impact categories, animal and feed (hay) production are the hotspot processes, followed by feed (grazing) as a hotspot for land use. The global warming impact for 1 kg of ELM ranges 41–53 kg CO_2 equivalent, and for 100 g of protein, 19–29 kg CO_2 equivalent. Fossil resource scarcity impact for 1 kg of ELM impact ranges 2.5–3.6 kg oil equivalent, and for 100 g protein, 1–2 kg oil equivalent. Terrestrial ecotoxicity impacts for 1 kg of ELM range 46–69 kg 1,4-DCB, and for 100 g protein, 21–37 kg 1,4-DCB. Lastly, land use impacts for 1 kg of ELM range 562–2448 m^2a crop equivalent, and for 100 g protein, 261–1324 m^2a crop equivalent.

Conclusion With its traditional farming practices, Icelandic lamb meat production is close to an extensive farming system, which is in line with its higher global warming impact per kg ELM. Additionally, due to low hay yield and high fertilization rate, the impact on other impact categories is still higher compared to an extensive system. This perspective shifts when analyzed per 100 g of protein, where it performs close to the global average.

Keywords Life cycle assessment · Icelandic lamb meat · Functional unit · Cradle-to-farm gate · Sheep farming

Communicated by Arnaud Hélias

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1 Introduction

Livestock meat is one of the highly consumed protein sources and plays an essential role in the diets of people around the world. However, the relationship between livestock farming, the production of meat products, and the environment is a local and global concern. The global concerns are due to rising greenhouse gas (GHG) emissions, to which livestock supply chain contributes about 14.5% of total human-induced GHG emissions (Gerber et al. 2013). The local concerns include eutrophication, acidification, biodiversity loss, and land and water use (De Vries et al. 2015; Leip et al. 2015; Ridoutt et al. 2012; Zonderland-Thomassen et al. 2014).

Thus, livestock farming faces an immense challenge in meeting a growing global population's protein requirements and reducing its meat products' environmental pressure. Livestock farming systems vary around the globe based on the type of livestock they farm (beef and dairy, pork, sheep, etc.), farming methods (extensive to intensive), climatic conditions, and other factors. In the simplest sense, the GHG emission intensity of different livestock also varies immensely. For instance, the emission intensity of small ruminants (sheep) production is lower than that of large ruminants (beef) (Caro et al. 2014), but small ruminants production contributes nearly 6% of all livestock emissions globally (Gerber et al. 2013). The environmental impacts also vary within the same livestock species. The GHG emissions among different sheep farming systems range from 3.5 to 25 kg CO_2 eq./kg live weight (LW) of sheep (Bhatt & Abbassi 2021). On a closer look at the constituents of these GHG emissions, they may seem similar across sheep farming systems. However, the proportion to which they contribute to total GHG emissions varies. In particular, enteric methane contributes to 50–75% of the GHG emissions, while about 18–25% arise from manure N_2O, and 10–15% of the GHG emissions arise from feed production (Bhatt & Abbassi 2021). Due to large variability in farming practices, variations in feeding methods, grazing vs. compound feed, manure management strategies, climatic conditions, number of farms, and animal efficiency (lambing percentage, mortality, slaughter weight), and the environmental impacts of sheep farming vary globally.

This heterogeneity within livestock farming systems provides an opportunity for multifaceted interventions that can be explicitly applied to these systems, considering farming methods and region-specific conditions, to reduce environmental pressure. The meat products from livestock farming are a subset of the global food system and integral to many regions and nations' nutrient and food security (Herrero & Thornton 2013; Motteta et al. 2017). In Iceland, until a few decades ago, sheep farming had been a primary contributing factor to the livelihood and well-being of Icelanders. Although sheep are farmed globally for their meat, wool, and milk, in Iceland, sheep is primarily utilized for lamb meat, with wool only used to a limited extent as it does not provide any economic value to farmers due to its coarse texture (Dýrmundsson 2006; Ögmundardóttir 2011).

Although recent trends show poultry as the most consumed meat (2020 onwards), lamb meat products remain the most popular and are an essential part of Icelanders' diets (Statistic Iceland 2019). Sheep farming, as a part of the agriculture sector, contributes both to the nation's 1% gross domestic product (GDP) and about 6% of the country's total GHG emissions (NIR, 2022; Statistic Iceland 2019). Sheep farming practices have remained predominantly unchanged in tradition over the centuries (Ögmundardóttir 2011). Following the tradition, the lambing season is in the spring. During summer, sheep graze freely in Icelandic nature, in private lands but mostly in the commons. In the fall, the farmers collect their sheep from the large groups of herded sheep, and are brought to "réttir," the annual sheep round-up. After the "réttir," all the sheep farmers bring their sheep back to the farms; lambs intended for slaughtering are brought to the slaughterhouse, while ewes and animals for replacement are fed with harvested hay through winter. Grazing land and cultivated hay fields are the primary feed source for the sheep on the island. Sheep resilience and adaptability to withstand the harsh climatic conditions in Iceland, along with abundant grazing land and cultivated hay fields, have made them favorable for farming in Iceland. Due to the unique characteristics of the Icelandic lamb products and their traditional farming practices, the "Icelandic lamb" recently achieved a Protection Designation of Origin (PDO) certification (Íslenskt lambakjöt, EU 2023), which gives it a higher value. Unlike dairy and beef production in Iceland, which have adopted intensive production practices, lamb production is extensive with its use of the common grazing lands. Despite its pre-eminence, estimations of the potential environmental impacts of the lamb meat in Iceland have yet to be documented. Thus, assessing and understanding the environmental impact and hotspots along the production process of lamb meat in Iceland are vital.

One of the tools to assess the environmental impacts of the production system is life cycle assessment (LCA) standardized through ISO (14040) (ISO 2006a) and ISO (14044) (ISO 2006b). LCA is a methodology that captures the environmental impacts of production and consumption activities. It includes all the resources and emissions arising in a given product system at each stage of the product's life cycle, from raw material, production, and use phase up to disposal, providing a cradle-to-grave perspective. LCA also enables the comparison of different products that provide the same functionality; LCA does this by defining a functional unit, which is a quantitative basis for evaluating a product's environmental impact and comparing it with other products that provide the same functionality. In agriculture LCA, especially livestock, there are multiple approaches towards defining the functional unit, including mass (kg of product), energy (MJ), protein (kg), and land area (ha) (Vidergar et al. 2021). The functional unit is a critical parameter that provides what is being studied and influences the outcome of an LCA study (Cooper 2003). Thus, one of the questions that is debated across the agriculture LCA circle is about the functionality of food products (McAuliffe et al. 2018; Pérez et al. 2024). This certainly depends on the goal of the study. One of the critical functions of lamb meat is to fulfill the protein requirement of Icelanders' diet. However, it can be argued that meat products provide protein and other functions such as energy and micro- and macronutrients, but the quantity of protein remains a simplified measure of the nutritional aspect of livestock meat products (Heller et al. 2013; McNicol et al. 2024; Notarnicola et al. 2017; Poore & Nemecek 2018). LCA has been widely used to study the impacts of livestock production systems, such as beef (De Vries et al. 2015), dairy (Üçtuğ, 2019), and pork (Andretta et al. 2021; McAuliffe et al. 2016). However, compared to other livestock, the number of LCA studies investigating sheep production and its products is still limited (Bhatt & Abbassi 2021; Ledgard et al. 2017). Bhatt and Abbassi (2021), providing detailed reviews of the LCA of sheep production. The review indicated that earlier LCA studies on sheep focus on GHG emissions, while only a limited number of studies address additional environmental categories. These include, for instance, Bhatt and Abbassi (2022) who incorporated non-renewable energy demand and water depletion; Zonderland-Thomassen et al. (2014) studied water footprint; Wiedemann et al. (2015a, b), Wiedemann et al. (2016), and Wiedemann et al. (2015a, b) assessed a wide range of impacts, fossil-fuel energy demand, freshwater consumption, and land occupation; Payen and Ledgard (2017) analyzed aquatic eutrophication for dairy, beef, and sheep farming; O'Brien et al. (2016) investigated acidification, eutrophication, fossil fuel energy demand, and land occupation; and lastly, Uusitalo et al. (2019) assessed the impacts of organic sheep farming on planetary boundaries. In the assessed relevant literature, only a few studies applied the ReCiPe life cycle impact assessment (LCIA) method (Huijbregts et al. 2017) to evaluate multiple environmental impacts. Mondello et al. (2018) applied the ReCiPe midpoint method to investigate the impact of cheese production from sheep milk in Italy, while Mohan (2018) applied the method for impact assessment of sheep dairy farms in New Zealand. Sabia et al. (2020) and Vagnoni et al. (2015) assessed the impact of dairy sheep using the ReCiPe endpoint method. No peer-reviewed sources exist, and only one non-peer-reviewed report is available of the assessments of GHG emissions of Icelandic sheep farming. The study was conducted by the consultancy Environice Hallsdóttir and Gíslason (2017) for the farmers' association that followed a greenhouse gas protocol WRI (2004) for their assessment and reported a global warming impact of 28.6 kg CO_2 eq./kg of sheep meat produced. The aims of this paper are thus to evaluate the environmental impacts of lamb meat production in Iceland on a national level and to identify major environmental hotspots by conducting a cradle-to-farm gate LCA. The second aim is to understand the influence of shifting quantitative measures of the functional unit from 1 kg of edible meat to 100 g of protein, and lastly to analyze the sensitivity of the environmental impact assessment of the lamb meat production due to crucial input parameters, and the uncertainty associated with the overall results of the hotspot analysis.

2 Material and methods

2.1 Life cycle assessment

In this study, a cradle-to-farm gate LCA was conducted, encompassing all materials and energy inputs, as well as all other activities necessary for lamb meat production in Iceland. The system boundaries (graphically shown in Fig. 1) include feed cultivation (hay), grazing, pasture, and animal production at a farm, as well as electricity and fuel usage at the farm.

Post-farm activities, such as transport to the slaughterhouse, slaughtering, treatment of slaughter waste, and meat processing, are not included due to a lack of data. From an overall environmental perspective, it is essential to investigate these activities, which should be explored at a later stage. As Wiedemann et al. (2015a, b) demonstrated, these activities have a proportionally small effect on the overall system. However, lamb meat processing could potentially contribute about 6% to the total global warming impact and about 31% to the total fossil fuel demand of the supply chain. In the studies reviewed by Ledgard et al. (2017) that extend beyond the farm gate, an additional 5–25% increase in cradle-to-farm gate GHG emissions was observed, with processing contributing to about 3%, transportation 5%, and 12% originating from the retail, consumer, and waste stages (Ledgard et al. 2011).

The functional units (FU) of the current assessment are defined as "1 kg of edible lamb meat" and "100 g of edible lamb meat protein produced in Iceland in 2019." These FU are then scaled to estimate the national-level environmental impact, with an estimated total production output of 8489 tonnes of edible lamb meat in 2019. Although the study does not include post-farm activities in this assessment, it

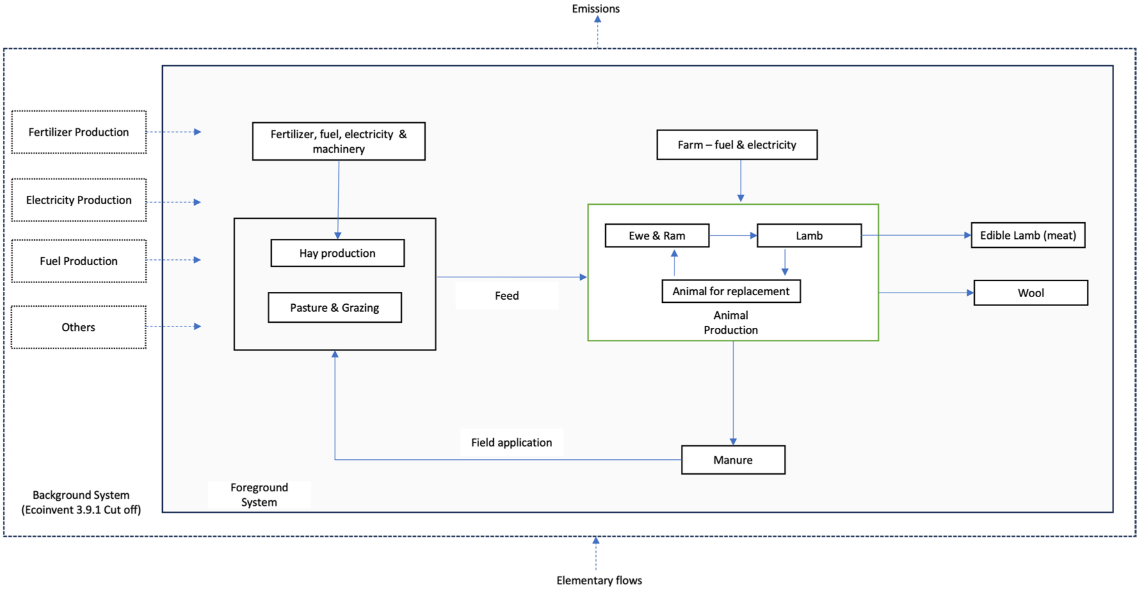


Fig. 1 System boundary of cradle-to-farm gate assessment of lamb production in Iceland

assesses the environmental impacts based on four common production outputs to compare the performance of Icelandic lamb meat at different production stages and with other studies. First, at the farm gate as per kilogram of live weight (LW); second, as kilogram of carcass weight (CW), the CW of Icelandic lamb is about 42% of LW (Hilmarsson and Einarsson 2019); third, for ready-to-retail as per kilogram of edible lamb meat, based on a meat conversion ratio of 39% of LW (Hilmarsson et al. 2023). Lastly, the impacts are based on protein content, ranging from 18.5 to 21.5 g of protein per 100 g of edible Icelandic lamb meat. The reason for including two functional units is twofold. Firstly, assessing impacts per *1 kg of edible lamb meat* makes it possible to compare the study results to pre-existing literature and benchmark Icelandic lamb products in comparison to other lamb products worldwide. Secondly, by assessing impacts per *100 g of edible lamb meat*, this study supports the ongoing efforts towards assessing the environmental impacts of sustainable healthy diets compared to more conventional dietary patterns in Iceland (Guðmannsdóttir et al. 2024). In addition, by providing the analysis with two functional units, the study provides insights upon which environmental sustainability element can be added to the mainstream nutrition discussion and dietary guidelines, which enable alignment of dietary guidelines with other Nordic countries.

The assumptions for these functional units are that the term "edible product" includes all the parts of edible lamb meat for consumption, i.e., meat, fat, and bones, adding up to 39% of LW and generalizes all cuts as edible parts (Hilmarsson and Einarsson 2019; Hilmarsson et al. 2023). The remaining part of the live weight is either discarded or utilized as fertilizer. Due to a lack of data on waste stream utilization, they are excluded in this study. In the lamb production, wool is collected only as a side product and has little economic value to the farmers due to its coarse texture. Although ewes are slaughtered after birthing lambs, the ewe meat only makes up 14% of the sheep slaughtered over the last 5 years (Statistic Iceland 2019). Since information on what ewe meat is used for is not available in Iceland, the impact of the ewes is not included in this study. In short, all impacts occurring from cradle-to-farm gate are allocated to the edible parts of the lambs. The protein content of edible lamb meat is obtained from The Icelandic database on the chemical content of food (ÍSGEM) (Matis 2024) based on two products LAMBALÆRI, með fitu, hrátt (lamb leg, raw, ID-0215) containing 18.5 g of protein per 100 g of edible lamb meat, and LAMBAHRYGGVÖÐVAR, án fitu, hráir (Lamb, tenderloin and striploin, tri, ID-0821) with 21.5 g of protein per 100 g of edible lamb meat. These two products encompass the different ranges of raw lamb products and their protein content and provide an estimate of the protein content of edible lamb meat cuts available in the Icelandic market.

The LCA of the lamb meat production was conducted following the ISO (14040) (ISO 2006a) and ISO (14044) (ISO 2006b) standards, with an attributional approach. SimaPro version 9.5 (PRé Sustainability 2023) was used for conducting the LCA along with Activity Browser version 3 (Steubing et al. 2020) to conduct a global sensitivity analysis for the hay production process. The background and secondary data for the study are based on ecoinvent data 3.9.1 cut-off criteria (FitzGerald & Sonderegger 2022; Nemecek & Kägi 2007). The multifunctionality between wool and meat production was addressed using mass allocation. As wool in

Iceland has marginal to no economic value to the farmers, the allocation factor for economic allocation for meat is estimated to be 99% in comparison to 97% in the case of mass allocation. This leads to similar results, irrespective of which allocation method is used. The environmental impacts are assessed using the ReCiPe 2016 v1.1 midpoint, hierarchist (H) perspective (Huijbregts et al. 2017). The study applies the ReCiPe midpoint assessment, as it aligns with the goal of this study to perform the first LCA study of lamb meat in Iceland. Furthermore, the ReCiPe midpoint assessment allows diverse coverage of environmental categories, providing a comprehensive overview of potential environmental impacts within the life cycle.

2.2 Life cycle inventory

The data for this study is compiled and estimated using multiple sources available at either the national level or extrapolated from farm-level data. Table 1 provides the national-level inventory used in this study, as well as their sources. A detailed per animal inventory is provided in (Supplementary materials (SM), Sect. 1, Table S1). The national data sources in this study include Statistics Iceland (Statistics Iceland 2020), the National Inventory Report (NIR, 2022), and the GróLind project data (GróLind 2020). The farm-level data originates from a sheep farm associated with the Agricultural University of Iceland that reflects the state-of-the-art in Iceland, encompassing the best practices, and with a size reflecting an average sheep farm in Iceland. Where national-level information was unavailable, such as fuel usage of machinery, electricity usage, and manure application rate, the farm data was extrapolated to the national level. The data from the farm was collected via a questionnaire, answered through email communications (Correspondence: Eyjólfur Kristinn Örnólfsson, October 2022–February 2023), and during a visit to the farm in October 2022. Where data was unavailable within national data sources, and where farm data extrapolation was not feasible, estimations were made, e.g., including estimating the number of lambs, land area used for hay production, pasture and grazing land area, fertilizer application, and all the emissions associated with sheep.

This study's sheep population comprises ewes (female—mature sheep more than one year old), rams (male—mature

Table 1 National lamb meat production inventory, based on total number of ewes, rams, animals for replacement, and lambs produced in Iceland in 2019

Data	Amount	Source
Animal		
Total number of animals	1,053,104	E and NIR
Live weight (tonnes) (AF: 97%)	51,019	E and NIR
Wool production (tonnes) (AF: 3%)	1755	NIR
Lamb product		
Edible lamb meat 39% of LW (tonnes)	8489	E
Edible lamb meat protein (18.5 to 23.1 g) per 100 g of meat (tonnes)	1570–1961	ÍSGEM
Feed		
Hay at housing (tonnes dry matter (dm))	133,344	NIR
Hay at pasture (tonnes dm)	12,501	NIR
Grass at pasture (tonnes dm)	52,777	NIR
Grass at grazing (tonnes dm)	119,486	NIR
Arable land, hay cultivated (ha)	30,076	E, SI, NIR
Arable land, pasture (ha)	24,018	SI
Non-arable land, grazing (ha)	2,402,367	E, SI, Grolínd, NIR
On-farm activities		
Fuel agricultural machinery (m^3)	7161	FD
Electricity (GWh)	39.702	FD
Fertilizer–hay production		
N (tonnes)	5019	E, SI
P (tonnes)	730	E, SI
K (tonnes)	1194	E, SI
Manure (tonnes)	2271	E, FD

AF, mass allocation factor; *E*, estimate; *NIR*, National Inventory Report (NIR, 2022); *SI*, Statistic Iceland (Statistic Iceland 2010 , 2015 , 2019); *ÍSGEM*, The Icelandic database on the chemical content of food (Matis 2024); *FD*, farm data; Grolínd, GróLind (2020) sheep more than 1 year old), animals for replacement (1-year-old lambs, AFR), and lambs (living up to 4.5 months from spring to fall). The information on the population of ewes, rams, and AFR is taken from the National Inventory Report (NIR, 2022), for the year 2019, compiled by the Environmental Agency of Iceland. For comprehensive information on sheep population and its characteristics, please refer to SM1, Sect. 1 Table S2b for inventory data and SM2, Section S1.1 for description of animal characteristics.

Domestic hay and vegetation (pasture and grazing) are the primary feed sources for sheep in Iceland (NIR, 2022). In this study, pasture is defined as the land area close to farms controlled by farmers, while the grazing areas are open vast land of Icelandic commons, both of which are not fertilized, and vegetation grows naturally. This study estimated the hay, grazing and pasture, land area under sheep farming using averages from these multiple sources. SM1 Sect. 1, Tables S3–S6 contain the complete data and estimates for feed types used in this study. Additionally, the rationale and calculation approach for different feed production used in this study are provided in SM2 Section S1.2.

In this study, on-farm activities include electricity and fuel usage. The data for electricity and fuel use was extrapolated from data from the Agricultural University farm to the national level. SM1 Sect. 1, Table S7 provides the estimates of on-farm activities, and SM 2Section S1.3 provides description of the electricity mix and fuel use in Iceland.

The environmental emissions from animal production are estimated using the Intergovernmental Panel on Climate Change (IPCC) guidelines for GHG inventories (IPCC 2019) and the EMEP/EEA air pollutant emission inventory Guidebook (Amon et al. 2019). The estimated environmental emissions per animal is provided in SM1 Sect. 2, Table S1–S7. Additionally, the details on the emission estimates are provided in SM 2Section S1.4.

2.3 Variability and uncertainty analysis

This study addresses variability and uncertainty separately. The variability of the input parameters arises from different values reported by different sources. The foreground system input parameters that lead to variability in this study are animal gross energy intake; feed and emissions from animal production; grazing, pasture, and hay land area; and on-farm activities. The input parameter and their variability, along with reason for the variability in the reported values, are provided in SM 1Sect. 3 Tables S1–S5 and the rationales behind the scenarios are provided in SM 2 Sects. 2.1–2.3. The base case (S_b) is constructed using the average of the inventory data, compiled from the multiple references described in Sect. 2.2 (Table 1). Due to observed variability in the input data, two additional inventory scenarios were introduced to rigorously test the influence of these inputs on the overall LCA results. The reason for addressing this variability as the minimum scenario (S_{min}) using the lower set of the input parameter value, and the maximum scenario (S_{max}) using the higher set of input parameter value is that in Iceland there is no alignment in these values among different inventory data sources.

The parameter values in all three variability scenarios have individual parameter uncertainty (Huijbregts 1998). The parameter uncertainty originates due to various reasons, to name a few, lack of measured data, such as feed intake estimate of rams, and animals for replacement. These parameter uncertainties are dealt with through uncertainty propagation using Monte Carlo analysis. An uncertainty analysis was thus performed using the Monte Carlo analysis with 10,000 runs of the foreground system, for the base case (S_b) and the variability scenarios (S_{min} and S_{max}), respectively, with a 95% confidence interval using the pedigree matrix approach (Ciroth et al. 2016; Rosenbaum et al. 2018). The reason for conducting uncertainty analysis using the foreground system is that it allows to capture the influence of input parameter data that is localized to Iceland. The uncertainty factor of the foreground system data was established using the pedigree matrix method following a log-normal distribution as provided in SM1 Sect. 3, Table S6. Additionally, the combined (foreground and background) uncertainty analysis, with background data, using the pre-defined uncertainty values already available in the ecoinvent database (Nemecek and Kägi 2007) was also carried out as presented in SM3 Sect. 1, Table S10. Furthermore, local sensitivity analysis or one-at-the-time sensitivity analysis of a single parameter fails to capture the LCA model sensitivity when the goal is to identify essential input parameters (Cucurachi et al. 2016; Groen et al. 2017), underlining the importance of performing this global multifactorial analysis to give a more holistic sensitivity assessment. Therefore, the study applies global sensitivity analysis (GSA) to the critical hotspot process following Cucurachi et al. (2022). Procedure and additional information on variability, uncertainty analysis, and GSA is provided in SM 2Sects. 3.1–3.2.

3 Results and discussion

The characterized impacts for all ReCiPe 2016 v1.1 midpoint (H) impact categories for the 1 kg of edible lamb meat (ELM) are provided in Table 2 as well as total impacts of lamb production at the national level. The results for 100 g of protein (for products ranging between 18.5 and 21.5 g protein per 100 g meat) follow the same proportional contribution, and are provided in SM3 Sect. 1, Tables S1–S6. Among the 18 impact categories, the processes of animal and feed (hay) production stand out as hotspots for most of the impact categories. The other processes, such as

Table 2 Impact assessment results: All ReCiPe 2016 v1.1 midpoint (H) categories for the base case (S_b) per kilogram edible lamb meat (ELM) showing the contribution of each process and at national level for a total production output of 8489 tonnes of ELM. The hotspot process for each impact category is shown with red followed by the second most contributing process in orange, while the other processes with contribution between 1 and 2% are in green, and less than 1% in light green. The processes with no contribution are not highlighted with color

Impact categories	Life cycle process						Total per kg ELM	Total at national-level
	Animal production	Hay production	On-Farm Fuel	On-Farm Electricity	Feed-Pasture	Feed-Grazing		
Global warming (kg CO_2 eq)	3.5E+01 (76%)	1.0E+01 (22%)	6.1E-01 (1%)	2.4E-01 (1%)	9.1E-03 (0%)	0.0E+00 (0%)	4.6E+01	3.9E+08
Stratospheric ozone depletion (kg CFC11 eq)	1.0E-04 (46%)	1.2E-04 (54%)	1.5E-07 (0%)	2.8E-07 (0%)	1.1E-07 (0%)	0.0E+00 (0%)	2.2E-04	1.9E+03
Ionizing radiation (kBq Co-60 eq)	0.0E+00 (0%)	3.4E-01 (97%)	2.6E-03 (2%)	3.3E-03 (1%)	6.2E-03 (0%)	0.0E+00 (0%)	3.6E-01	3.1E+06
Ozone formation, Human health (kg NOx eq)	1.1E-02 (15%)	6.0E-02 (82%)	1.9E-03 (3%)	1.8E-04 (0%)	3.0E-05 (0%)	0.0E+00 (0%)	7.3E-02	6.2E+05
Fine particulate matter formation (kg PM2.5 eq)	4.8E-02 (60%)	3.1E-02 (39%)	7.4E-04 (1%)	1.3E-04 (0%)	1.4E-05 (0%)	0.0E+00 (0%)	8.0E-02	6.8E+05
Ozone formation, Terrestrial ecosystems (kg NOx eq)	2.7E-02 (17%)	1.3E-01 (82%)	2.3E-03 (1%)	1.9E-04 (0%)	3.1E-05 (0%)	0.0E+00 (0%)	1.6E-01	1.4E+06
Terrestrial acidification (kg SO_2 eq)	3.7E-01 (69%)	1.7E-01 (31%)	2.1E-03 (0%)	2.8E-04 (0%)	5.6E-05 (0%)	0.0E+00 (0%)	5.4E-01	4.6E+06
Freshwater eutrophication (kg P eq)	0.0E+00 (0%)	1.5E-02 (100%)	3.7E-05 (0%)	3.5E-05 (0%)	2.1E-06 (0%)	0.0E+00 (0%)	1.5E-02	1.3E+05
Marine eutrophication (kg N eq)	0.0E+00 (0%)	2.3E-02 (100%)	5.5E-05 (0%)	1.9E-06 (0%)	2.7E-05 (0%)	0.0E+00 (0%)	2.3E-02	1.9E+05
Terrestrial ecotoxicity (kg 1,4-DCB)	0.0E+00 (0%)	5.2E+01 (95%)	1.3E+00 (2%)	1.2E+00 (2%)	4.3E-02 (0%)	0.0E+00 (0%)	5.5E+01	4.6E+08
Freshwater ecotoxicity (kg 1,4-DCB)	0.0E+00 (0%)	5.1E-01 (95%)	5.6E-03 (1%)	2.3E-02 (4%)	4.2E-04 (0%)	0.0E+00 (0%)	5.4E-01	4.6E+06
Marine ecotoxicity (kg 1,4-DCB)	0.0E+00 (0%)	6.7E-01 (95%)	9.5E-03 (1%)	2.8E-02 (4%)	5.4E-04 (0%)	0.0E+00 (0%)	7.1E-01	6.0E+06
Human carcinogenic toxicity (kg 1,4-DCB)	0.0E+00 (0%)	5.8E-01 (92%)	2.2E-02 (4%)	2.6E-02 (4%)	4.5E-04 (0%)	0.0E+00 (0%)	6.3E-01	5.4E+06
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.0E+00 (0%)	8.8E+00 (96%)	1.7E-01 (2%)	2.3E-01 (3%)	4.8E-03 (0%)	0.0E+00 (0%)	9.2E+00	7.8E+07
Land use (m^2a crop eq)	0.0E+00 (0%)	2.4E+01 (2%)	1.6E-02 (0%)	1.6E-03 (0%)	1.5E+01 (1%)	1.5E+03 (97%)	1.5E+03	1.3E+10
Mineral resource scarcity (kg Cu eq)	0.0E+00 (0%)	1.1E-01 (98%)	1.1E-03 (1%)	1.7E-03 (0%)	4.7E-05 (0%)	0.0E+00 (0%)	1.1E-01	9.8E+05
Fossil resource scarcity (kg oil eq)	0.0E+00 (0%)	2.1E+00 (71%)	8.3E-01 (28%)	1.2E-02 (0%)	1.8E-03 (0%)	0.0E+00 (0%)	2.9E+00	2.5E+07
Water consumption (m^3)	0.0E+00 (0%)	9.9E-02 (50%)	2.1E-03 (1%)	9.8E-02 (49%)	8.5E-05 (0%)	0.0E+00 (0%)	2.0E-01	1.7E+06

on-farm fuel, electricity, and feed (grazing), are hotspots for fossil resource scarcity, water consumption, and land use, respectively.

Animal production contributes to > 40% to four out of 18 impact categories, including global warming (76%), stratospheric ozone depletion (46%), fine particulate matter formation (60%), and terrestrial acidification (69%) (Table 2). The global warming impacts from the animal production process due to various GHG emissions from the sheep are presented in subsection 3.1. The contributions towards stratospheric ozone depletion were due to N_2O emissions, and NH_3 and particulate matter (PM 2.5) originating from the manure from the animal production process towards terrestrial acidification and fine particulate formation.

Feed (hay) production contributes to > 40% to 14 out of 18 impact categories (Table 2), contributing towards stratospheric ozone depletion (54%) entirely due to N_2O emissions from fertilizers and manure field applications. Ozone formation (82%) is mostly due to nitrogen monoxide (NO) emissions from applying fertilizers. Ionization radiation (97%), fossil resource scarcity (71%), mineral resource scarcity (98%), human carcinogenic and non-carcinogenic toxicity (92 and 96%), and ecotoxicity (95%) are due to fertilizer and agricultural operations.

Eutrophication (~99%) is mainly due to phosphorus, phosphate, and nitrate emissions to water bodies. Lastly, feed (hay) production contributes to 50% of the water consumption. In earlier LCA studies of agricultural systems, only a limited number of environmental impacts, such as global

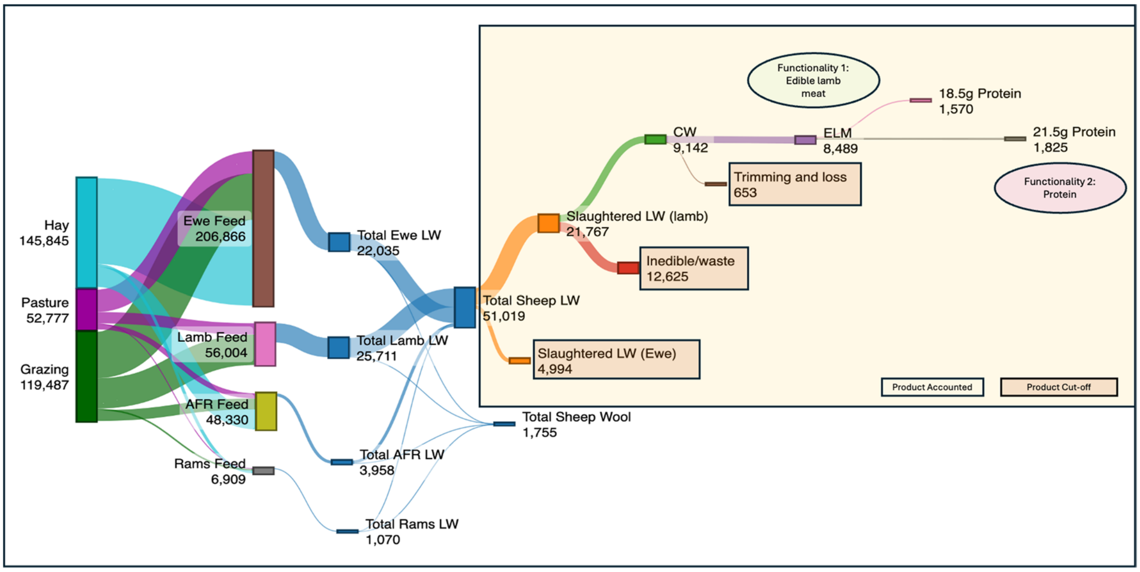


Fig. 2 Mass flow analysis of national-level feed to lamb meat products at different production stages. LW, live weight; CW, carcass weight; ELM, edible lamb meat and protein. All values are in tonnes

warming, acidification, eutrophication, ozone depletion, and energy use, are included (Dijkman et al. 2018). Global warming, eutrophication, acidification, and ecotoxicity are relevant environmental categories for the agricultural system and have been studied in sheep environmental studies (Ögmundarson et al. 2020; Roma et al. 2015). However, this study focuses in detail on global warming, fossil fuel scarcity, terrestrial ecotoxicity, and land use.

This is because these impact categories are of special concern in Iceland. For instance, climate change is a primary concern both locally and globally, along with reducing dependence on fossil fuels. Land use associated with sheep grazing is highly debated in the policy and political arena in Iceland due to land degradation and soil erosion (Arnalds & Barkarson 2003). Furthermore, terrestrial ecotoxicity impacts have not yet been widely studied in Iceland. This study does not focus in detail on acidification and eutrophication mainly because a previously conducted field study at the Agricultural University sheep farm concluded that eutrophication from fertilizer in grassland is not a concern (Thorsteinsson et al. 2019). Next, a chemical water quality study conducted over different regions in Iceland indicated that the amount of nitrate from fertilizer application in the agricultural region complied for all the samples, indicating little impacts from agriculture in Iceland (Gunnarsdottir et al. 2016). The main impact category results are presented in the following order: global warming, fossil fuel scarcity, terrestrial ecotoxicity, and land use. The presented results are reported for the two functional units, “1 kg of edible lamb meat” and “100 g edible lamb meat protein produced in Iceland in 2019. (See Fig. 2). All results for these two functional units are provided as mean ± standard deviation, along with their percentile ranges (2.5th–97.5th percentile) based on the uncertainty analysis of the foreground system. The Monte Carlo analysis outputs for all 18 impact categories for both functional units, along with all the results for both foreground, combined foreground, and background systems, are summarized in SM3Sect. 1, Tables S7–S10. Furthermore, comparisons with existing literature are discussed, although such comparisons should be interpreted with caution due to differences in system boundaries, functional units, databases, and environmental impact methods. The characterized impacts for the same impact category may therefore differ slightly between studies, due to differences in modeling approaches employed by the different impact assessment methods applied.

3.1 Global warming

The output of lamb meat at different production stages, from feed to products (live weight, carcass weight, edible lamb meat (ELM)), and total ELM protein output based on two protein contents 18.5 and 21.5 g/100 g meat is shown in Fig. 3a. The global warming impact for the base case (S_b) is 46.2 ± 7.4 kg CO_2 eq./kg ELM, 25 ± 4.1 kg CO_2 eq./100 g of protein for the lower protein content (18.5 g/100 g meat), and 21.5 ± 3.5 kg CO_2 eq./100 g of protein for the higher protein concentration (21.5 g/100 g meat) (Fig. 3b). Furthermore, animal and feed (hay) production are the two main hotspot processes contributing 76% and 22%, respectively, to the global warming of lamb meat at the different production

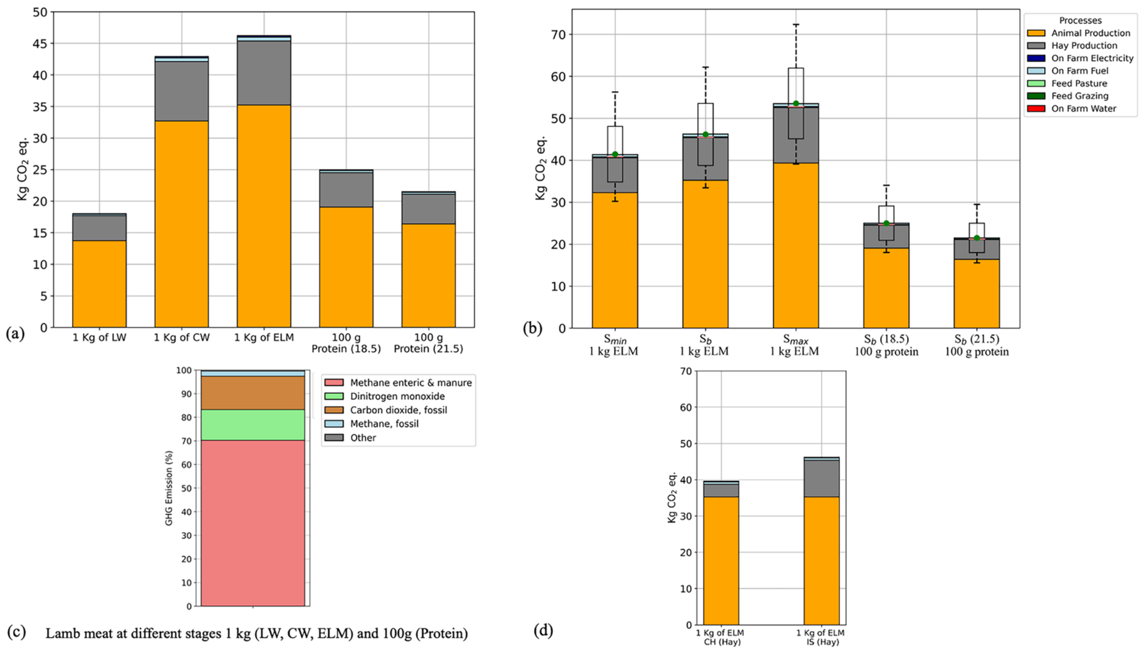


Fig. 3 **a** Impact of 1 kg of lamb meat product at different production stages (LW, CW, ELM, and protein). **b** Results per 1 kg of ELM for the three scenarios (S_b, S_{min}, and S_{max}) and S_b for 100 g protein based on 18.5 g/100 g meat and 21.5 g/100 g meat. The box plot provides the associated uncertainty of each scenario, using the Monte Carlo analysis, mean (green dot), median (light coral line). The standard deviation is represented by the height of the box, and the whisker with caps represents the range between 2.5 and 97%. **c** Distribution of GHG emissions of 1 kg of lamb meat products at different production stages. **d** Comparison of 1 kg of ELM obtained with the hay production process in Iceland (IS) and the ecoinvent hay Switzerland process (CH)

stages. This observation corroborates the review of sheep LCA studies conducted by Bhatt and Abbassi (2021), which stated that feed and animal production are the two main hotspot processes in the LCA of sheep.

On delving into GHG emissions constituents of the global warming impact (Fig. 3c), methane (CH_4) emitted during the animal production process contributes to about 70% of the total GHG emissions of the lamb meat products. Enteric and manure CH_4 account for 66% and 4% of the total GHG emissions, respectively. In the literature, enteric CH_4 contributions to the total GHG emission vary from 50 to 75% (Bhatt & Abbassi 2021) to as high as 90% CH_4 of the total GHG emissions (Biswas et al. 2010). In the case of Icelandic sheep, the enteric methane is observed to be on the higher side of the contribution. This could be due to multiple factors, including effects from feed, sheep genetics, and climatic conditions (Gerber et al. 2013; IPCC 2019). Enteric methane can only be reduced to a certain extent since it is inherent to the sheep's anatomy.

Nitrous oxide (N_2O) from the lamb meat products contributes to about 13% of the total GHG emissions, whereof 46% of the total N_2O emissions are emitted during the animal production process, while 54% originate from the feed (hay) process. N_2O emissions during the process of animal production are due to manure storage and deposited during grazing and pasture. However, for the feed (hay) production process, N_2O emissions are emitted from inorganic fertilizers (predominately nitrogen) and sheep manure.

Likewise, in the literature, the N_2O contribution to the total GHG emissions also varies. Gerber et al. (2013) observed N_2O emissions around 28% of the total GHG emission, while other studies show varying contributions to the total GHG emissions, e.g., 9–11% (Wiedemann et al. 2016), 8.9–16.3% (Biswas et al. 2010), and 16% (Batalla et al. 2015). These variations are observed due to different crude protein contents of the feed and manure handling strategies, and for the product which sheep are farmed for (wool, milk or meat) (Hristov et al. 2013). Carbon dioxide (CO_2) from the lamb meat products contributes to 14% of the total GHG emissions, whereas 91% of the total CO_2 is emitted from feed (hay) and 5% from on-farm fuel usage. The CO_2 emission from the feed (hay) production process is mainly from the fertilizer production, and 70% and 30% can be traced to agriculture operations and machinery, respectively. About 2.5% of the total GHG emissions are due to methane (fossil), and other gases emitted during the feed (hay) production process, and from on-farm electricity usage. The previously conducted Environice study (Hallsdóttir & Gíslason 2017) in Iceland reported a global warming impact of 28.6 kg CO_2 eq./kg of sheep meat produced. The study applied the GHG protocol to estimate the global warming impacts in the year 2015, and reported the total impact of the lamb meat production system to be 2.91×10^8 kg CO_2 eq. In their assessment, Hallsdóttir and Gíslason (2017) allocated the lamb meat production system impact of 2.91×10^8 kg CO_2 eq. to 10,185 tonnes of (mutton and lamb) production output as reported by Statistic Iceland (2015). However, when allocated to the production output of only lamb meat, which was 8807 tonnes in 2015 (Statistic Iceland 2015), the global warming impact based on Hallsdóttir and Gíslason (2017) estimate becomes about 33 kg CO_2 eq./kg of lamb meat. A direct comparison with the Hallsdóttir and Gíslason (2017) study is not possible due to differences in modelling approaches, animal populations, production outputs, and temporal variations compared to this study. This demonstrates the influences of methodological choices on the outcomes in relative terms.

In comparison to the European average of 19–28 kg CO_2 eq./kg carcass meat (Weiss & Leip 2012), the impact of 1 kg of ELM in this study is higher by a factor of 1.6 since the processing yield between CW and ELM is 39%. Ripoll-Bosch et al. (2013) estimated the GHG impact to be 51.7 kg CO_2 eq./kg of lamb meat for a pasture-based system in Spain, where the lamb had a LW of 22 kg and an average dressing percentage of 50%, which is lower than the live weight of the Icelandic lamb.

While the current study focuses on the impacts of the ELM and protein content of the meat, other studies have used lamb live weight (LW) and carcass weight (CW) as basis for their assessment of the global warming impact. Based on LW, the global warming impact of 1 kg of Icelandic lamb meat for the base case (S_b) is 18.0 kg CO_2 eq. (Fig. 3a). This value is in line with the pre-existing literature. Bhatt and Abbassi (2022) conducted an LCA on sheep farming in Ontario, Canada, which indicated that for 90% of the studied 23 farms, the global warming impact ranged from 8.4 to 18.6 kg CO_2 eq./kg LW. Edwards-Jones et al. (2009) assessed the carbon footprint of lamb across England and Wales and estimated that the global warming impact ranged from 10.85 to 17.86 kg CO_2 eq./kg LW lamb. Ripoll-Bosch et al. (2013) estimated that for different grazing system types, the global warming impact ranged from 19.5 to 25.9 kg CO_2 eq./kg LW lamb. These results are in line with other published LCA studies assessing impact per kg LW, e.g., 6–20 kg CO_2 eq./kg LW (Bhatt & Abbassi 2021; Ledgard et al. 2017).

On the basis of CW, the global warming impact of 1 kg of Icelandic lamb meat for the base case (S_b) is 43 kg CO_2 eq./kg CW (Fig. 3a). Studies assessing global warming impacts for global production of small ruminants estimate 23.8 kg CO_2 eq./kg CW (Gerber et al. 2013), and 21.7–23.3 kg CO_2 eq./kg CW (Farrell et al. 2022). In contrast to LW, the impacts per kg CW of the Icelandic sheep are higher than seen in other studies assessing impact per kg CW.

However, when the focus is shifted towards the protein content of the edible lamb meat, the comparison shifts from the relative product mass impacts (LW, CW, and ELM) having higher global warming impact compared to other studies, to an impact on a protein basis that is close to the global average. Poore and Nemecek (2018) estimated the environmental impact of multiple food products per 100-g protein basis, indicating a mean global warming impact of lamb and mutton of about 20 kg CO_2 eq./100 g protein, including post-farm activities, retail, and transportation.

When adjusted for processing and packaging with 0.96 kg CO_2 eq. based on mean value of 710 g CO_2 eq. for processing and 270 g CO_2 eq. for packaging from Poore and Nemecek (2018), the comparison with the global average becomes more evident for the higher concentration of protein (21.5 g protein per 100 g of meat) from this study.

The current study's global warming impacts per kg LW are consistent with the literature, but the impacts per kg edible lamb meat (ELM) are higher than reported literature. This is due to two reasons: First, the impact of the Icelandic production system is allocated only to the total lamb meat output, whereas in the pre-existing literature, sheep meat in addition to lamb meat is part of the assessed product output (Gerber et al. 2013; Weiss & Leip 2012). Second, the results per kg ELM in this study are derived from a total production output (8489 tonnes), i.e., the average of the total edible lamb meat production in Iceland in the year 2019. The study does, therefore, not account for variation in for example annual number of animals, animal weight, LW, and in the processing yield to edible meat.

3.2 Fossil resource scarcity

The fossil resource scarcity for the base case (S_b) is 2.9 ± 0.6 kg oil eq./kg ELM and 1.6 ± 0.3 kg oil eq./100 g of protein for the lower protein content (18.5 g/100 g meat), and 1.4 ± 0.3 kg oil eq./100 g of protein for the higher protein concentration (21.5 g/100 g meat) (Fig. 4). Feed (hay) and on-farm fuel are the main processes contributing to 71% and 28% of fossil resource scarcity, respectively. Of the 71% designated to the feed (hay) production, about 70% is due to fertilizer production, while 30% is emitted due to agriculture operations and machinery fuel usage. When comparing to pre-existing literature, only a few studies have estimated the fossil fuel energy demand in their analysis of different sheep products, and the average use across farms for these studies. For instance, O'Brien et al. (2016) estimated for the average Irish average lowland farm the fossil fuel energy demand is 15.4 MJ/kg LW, and for an average hill farm is 21.4 MJ/kg LW, with most of the fossil fuel (75–89%) consumed off-farm as part of the fertilizer production (57–71%). In comparison, the fossil resource scarcity for this study is 1.1 kg oil eq./LW (49 MJ/kg LW based on conversion factor of

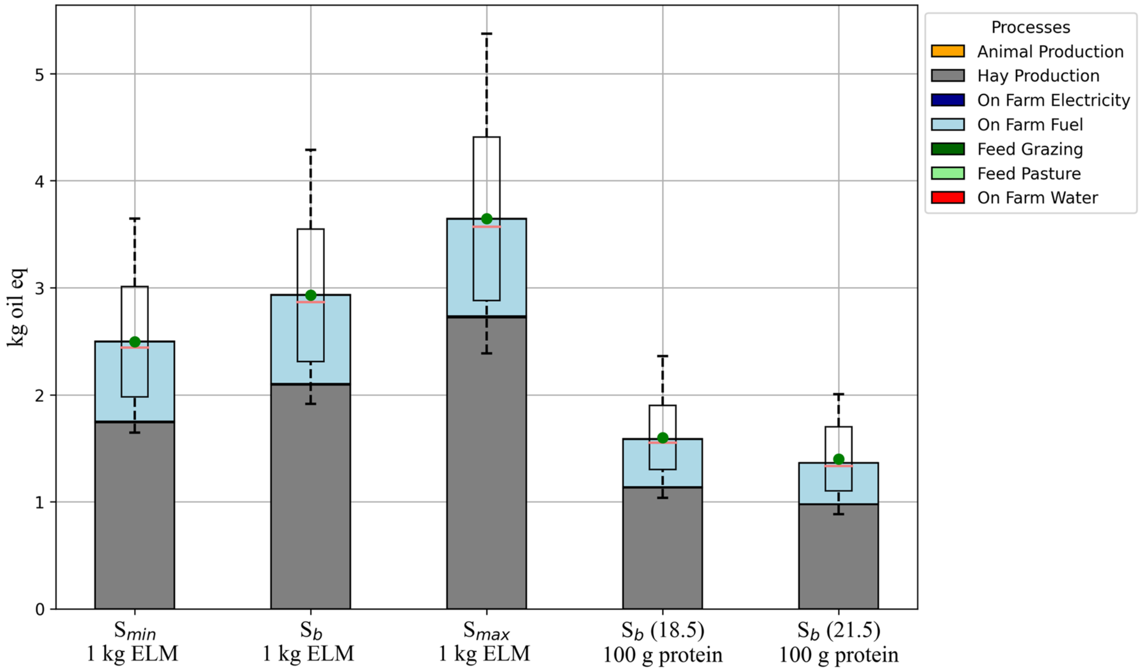


Fig. 4 Fossil resource scarcity impacts, per 1 kg of edible lamb meat (ELM) for the three scenarios (S_b, S_{min}, and S_{max}) and S_b for 100 g protein based on 18.5 g/100 g meat and 21.5 g/100 g meat. The box plot provides the associated uncertainty of each scenario, using the Monte Carlo analysis, mean (green dot), median (light coral line), the standard deviation is represented by height of the box, and the whisker with caps represent the range between 2.5 and 97.5%

42.8 MJ/kg). Wiedemann et al. (2015a, b) estimated for the lamb meat, in Australia, that the fossil energy demand was between 2.5 and 7 MJ/kg LW with fertilizer production contributing to 9–15%, while on-farm energy use contributed to 38–72%. Wallman et al. (2011) estimated an average energy use of 36 MJ/kg CW for the Swedish lamb production system; in comparison, the impact in this study is about 1.9 kg oil eq./CW (83 MJ/kg LW based on a conversion factor of 42.8 MJ/kg).

3.3 Terrestrial ecotoxicity

The terrestrial ecotoxicity impact for the base case (S_b) is 54.5 ± 14.7 kg 1,4-dichlorobenzene (DCB)/kg ELM, 29.5 ± 8 kg 1,4-DCB/100 g of protein for the lower protein content (18.5 g/100 g meat), and 25 ± 6.9 kg 1,4-DCB/100 g of protein for the higher protein concentration (21.5 g/100 g meat) (Fig. 5). Feed (hay) production is the main process contributing 95% to terrestrial ecotoxicity. Of the 95% impact originating from feed (hay), 61% is due to fertilizer production (N 48%, P3%, K9%), or arising from heavy metal emissions, while the remaining 38% is due to agriculture operations. The prominent agricultural operation that contributes the most towards terrestrial ecotoxicity is dried roughage storage (22% of feed (hay)). This process could be an additional estimate to the total terrestrial ecotoxicity impact. However, as it is not clear if dried roughage storage is done in a similar manner in Iceland, the process accounts for construction of a storage area for hay and may not be representative of Icelandic conditions. Only one study has calculated the terrestrial ecotoxicity impacts for sheep production. Mohan (2018) showed an impact of 36.5 kg 1,4-DCB/ha land use for a sheep farm in New Zealand, whereof about 86% of the total impacts were due to pesticide use, with barley feed production contributing to about 14%. In Iceland, pesticide use is very limited, and their use in hay production is not known (Worldometers.info 2024). Its potential minor contribution to the terrestrial ecotoxicity impact was therefore neglected in the study. Additionally, due to differences in the functional unit used in the Mohan (2018) study, it is not feasible to make direct comparisons of results with this study.

3.4 Land use

The land use impact for the base case (S_b) is 1544 ± 205 m^2a crop eq./ELM, 834 ± 111 m^2a crop eq./100 g of protein for the lower protein content (18.5 g/100 g meat), and 717 ± 97 m^2a crop eq./100 g of protein for the higher protein concentration (21.5 g/100 g meat) (Fig. 6). Feed (grazing) (contributing 97%) is the leading process contributing to land use impact. Among pasture-based sheep production, different estimates are available in the pre-existing literature, ranging between 82 and 98% of land

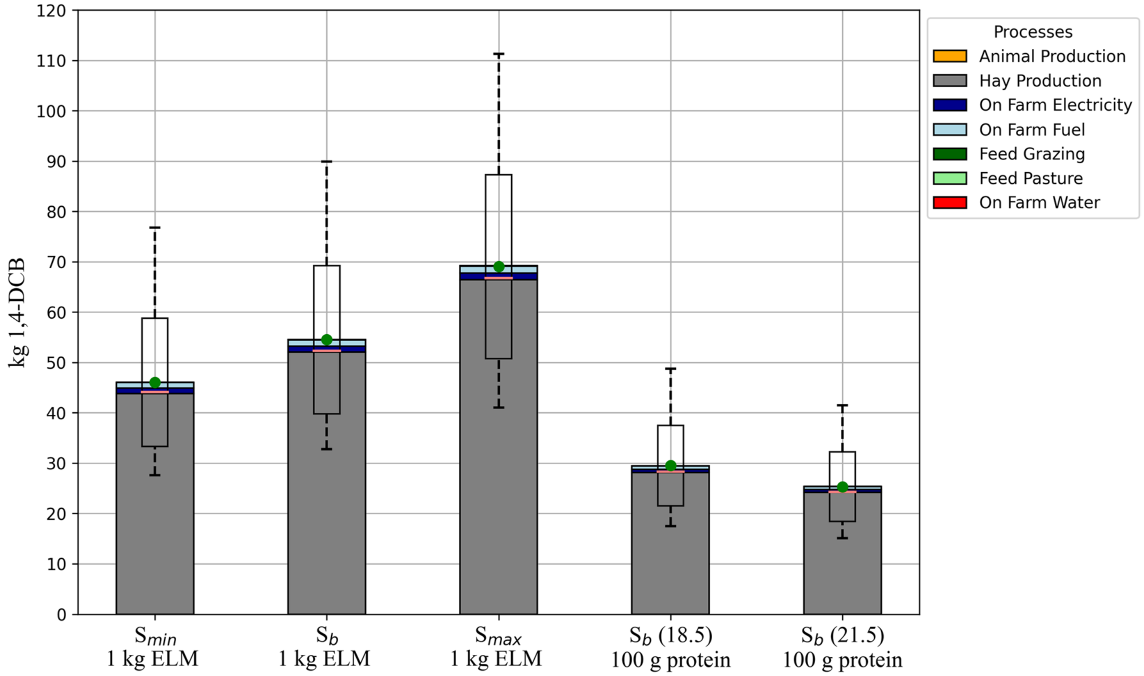
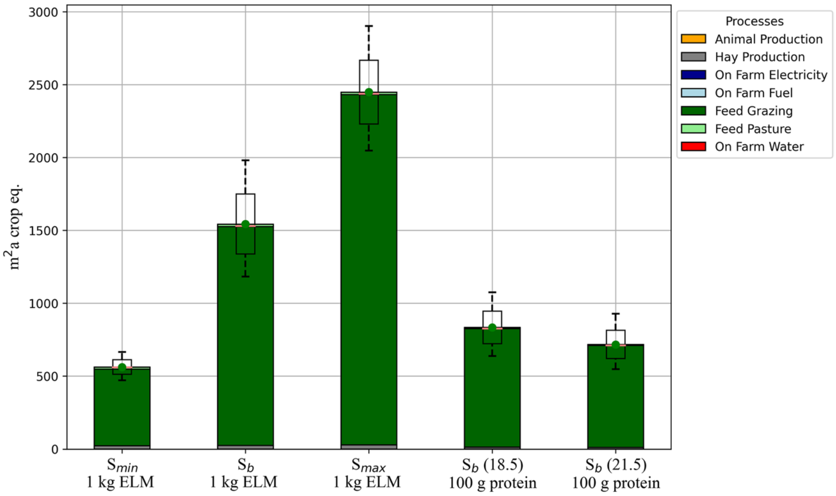


Fig. 5 Terrestrial ecotoxicity impacts, per 1 kg of edible lamb meat (ELM) for the three scenarios (S_b, S_{min}, and S_{max}) and S_b for 100 g protein based on 18.5 g/100 g meat and 21.5 g/100 g meat. The box plot provides the associated uncertainty of each scenario, using the Monte Carlo analysis, mean (green dot), median (light coral line), the standard deviation is represented by height of the box, and the whisker with caps represent the range between 2.5 and 97.5%

Fig. 6 Land use impacts, per 1 kg of edible lamb meat (ELM) for the three scenarios (S_b, S_{min}, and S_{max}) and S_b for 100 g protein based on 18.5 g/100 g meat and 21.5 g/100 g meat. The box plot provides the associated uncertainty of each scenario, using the Monte Carlo analysis, mean (green dot), median (light coral line), the standard deviation is represented by the height of the box, and the whisker with caps represent the range between 2.5 and 97.5%



occupation for on-farm forage (O'Brien et al. 2016), 118 m^2a/kg carcass weight (CW) (Wallman et al. 2011), 94% on non-arable pasture (Wiedemann et al. 2015a, b), and an average of 90.3% non-arable land and 7% arable pasture land per kg LW (Wiedemann et al. 2015a, b). However, a parallel cannot be drawn with Iceland, as most of these studies estimate the impact for a limited number of farms, while in Iceland about 62% of the country's area is used for sheep grazing (GróLind 2020).

3.5 Variability and uncertainty analysis

Due to data quality and utilization of multiple sources (Sect. 2) for the foreground data, the impact results of this study should be interpreted along with the uncertainty analysis. The uncertainty analysis for the foreground system for all impact categories is provided in SM3Sect. 1, Tables S7–S9, while the combined uncertainty analysis considering ecoinvent background data is provided in

Table 3 Differences between the base case (S_b) and variability scenarios (S_{min} and S_{max}) for different processes. The hotspot process for each impact category is shown with red followed by second most contributing process in light red, while the other processes with the least contribution in blue

	Global warming (kg CO_2 eq.)				
	S_b	% Change S_b to S_{min}	S_{min}	% Change S_b to S_{max}	S_{max}
Total	100%	↓-11%	100%	↑+16%	100%
Animal Production	76%	-8%	78%	+12%	74%
Hay Production	22%	-18%	20%	+30%	25%
On Farm - Electricity	1%	-10%	1%	+11%	0%
On Farm - Fuel	1%	-10%	1%	+10%	1%
Feed - Grazing	0%	x	0%	x	0%
Feed - Pasture	0%	0%	0%	0%	0%

	Terrestrial ecotoxicity (kg 1,4-DCB)				
	S_b	% Change S_b to S_{min}	S_{min}	% Change S_b to S_{max}	S_{max}
Total	100%	↓-15%	100%	↑+27%	100%
Animal Production	0%	x	0%	x	0%
Hay Production	95%	-16%	95%	+28%	96%
Electricity	2%	-10%	2%	+11%	2%
On Farm - Fuel	2%	-10%	2%	+10%	2%
Feed - Grazing	0%	x	0%	x	0%
Feed - Pasture	0%	0%	0%	0%	0%

	Land use (m^2 a crop eq.)				
	S_b	% Change S_b to S_{min}	S_{min}	% Change S_b to S_{max}	S_{max}
Total	100%	↓-64%	100%	↑+59%	100%
Animal Production	0%	x	0%	x	0%
Hay Production	2%	-5%	4%	+15%	1%
Electricity	0%	-10%	0%	+11%	0%
On Farm - Fuel	0%	-10%	0%	+10%	0%
Feed - Grazing	97%	-65%	94%	+60%	98%
Feed - Pasture	1%	-13%	2%	+9%	1%

	Fossil resource scarcity (kg oil eq.)				
	S_b	% Change S_b to S_{min}	S_{min}	% Change S_b to S_{max}	S_{max}
Total	100%	↓-15%	100%	↑ +24%	100%
Animal Production	0%	x	0%	x	0%
Hay Production	71%	-17%	70%	+30%	75%
Electricity	0%	-10%	0%	+11%	0%
On Farm - Fuel Feed	28%	-10%	30%	+10%	25%
- Grazing Feed -	0%	x	0%	x	0%
Pasture	0%	0%	0%	0%	0%

The values are rounded to the nearest whole number. In the S_{max} scenario, on-farm water use was also considered but contribute to < 1% and not provided here

SM3Sect. 1, Table S10. The only added insight from the combined uncertainty analysis is the increase in interquartile ranges for each impact category, while the mean and standard deviation remain the same within margins of the foreground system uncertainty analysis. Animal population and live weight, along with daily feed, gross energy requirement, and the total production output, are variables that influence the estimated global warming impacts. Additionally, the fertilizer input and operation of agricultural machinery strongly add to other assessed environmental impacts. The variability scenarios S_{min} and S_{max} consider the variability in the data sources for these inputs attributed to different processes to assess how much the lamb meat production environmental impacts deviate from S_b.

The hotspot analysis and differences between the base case S_b and S_{min} and S_{max} per kg ELM are provided in Table 3 and follow the same trend of per 100 g of protein, as provided in SM3 Sect. 1. Despite the variation in inputs from the different data sources, the identified main hotspot processes in S_b maintain the same relative contribution to the impact categories in the variability scenarios. This observation is not surprising as the input variables were linearly varied when designing the scenarios, i.e., the minimum and maximum of all inputs, while keeping the same animal population. However, how much the total environmental impacts deviate from S_b due to variation in the contributing processes is a key insight from the variability scenarios.

In the case of animal production, variations in gross energy intake and feed intake are the key parameters that influence the total global warming impacts. Specifically, these variations are assumed to be about −5% for S_{min} and +15% for S_{max}. As a direct consequence, compared to S_b, CH_4 and N_2O emissions from the animal production decreased by 8% in the S_{min}, and increased by 12% in the S_{max} (Table 3). Furthermore, the variation in feed intake is focused only on feed (hay). The variation in feed (hay) consequently leads to variation in the associated material inputs, such as inorganic fertilizers, sheep manure, operations, and use of agricultural machinery in hay production. These changes influence the CO_2 and N_2O emissions, resulting in a reduction of 18% in the S_{min}, and an increase of 30% in the S_{max} from the hay production to the total global warming impacts (Table 3). Incorporating the combined effects of changes in the animal and hay production processes, along with other processes, the total global warming impacts for S_{min} and S_{max} are 41.4 ± 6.6 kg CO_2 eq./kg of ELM and 53.5 ± 8.4 kg CO_2 eq./kg ELM, respectively (Fig. 3b). This translates to a 10% reduction (S_{min}), and a 16% increase (S_{max}) compared to the S_b (Table 3). Although the correlation between the inputs influencing the GHG emissions in the variability scenarios is well established in the literature (Bhatt & Abbassi 2021; Gerber et al. 2013; Ledgard et al. 2017), the variability analysis demonstrates the range to which these inputs vary in the Icelandic lamb meat production.

Along with earlier mentioned variation related to feed (hay) and its material inputs, other input parameters that were varied in the variability scenarios include a ± 10% change in on-farm fuel usage compared to S_b. These changes in feed (hay) resulted in a 17% reduction in S_{min}, and 30% increase in S_{max} from the hay production process to the fossil resource scarcity impacts (Table 3). Variations in the on-farm fuel usage resulted in proportional ± 10% to total fossil resource scarcity impacts (Table 3). As a result of the changes in these two processes, the fossil resource scarcity impacts in the S_{min} and S_{max} are 2.4 ± 0.5 kg oil eq./kg ELM and 3.6 ± 0.7 kg oil eq./kg ELM, respectively (Fig. 4). This equates to a 15% reduction in S_{min} and a 24% increase in S_{max} compared to S_b (Table 3). Simultaneously, changes in feed (hay) also influence terrestrial ecotoxicity impact with a 16% reduction in S_{min} and a 28% increase for S_{max}. As a direct result of these changes, the terrestrial ecotoxicity impacts in the S_{min} and S_{max} are 46 ± 13 kg 1,4-DCB/kg ELM and 69 ± 18 kg 1,4-DCB/kg ELM, respectively (Fig. 5), leading to an overall 15% reduction (S_{min}) and a 27% increase (S_{max}) compared to the S_b terrestrial ecotoxicity impact (Table 3).

The land use impacts are 562 ± 49 m^2a crop eq./kg ELM and 2448 ± 219 m^2a crop eq./kg ELM, for the S_{min} and S_{max}, respectively (Fig. 6). A 64% reduction (S_{min}) and a 59% increase (S_{max}) are observed from the S_b for the total land use impact (Table 3). This variability is mainly due to a 65% reduction (S_{min}) and a 60% increase (S_{max}) in the contribution of feed process (grazing) and is induced by the data sources used for the variability analysis (Table 3). The land use estimates differentiate between lambs and other sheep based on their feed intake requirements (SM1, Sect. 1, Tables S3 and S6). Furthermore, the grazing area is also assumed to be fully vegetated to provide this feed requirement. This might not be the case due to uneven vegetation patterns (GróLind 2020; Marteinsdóttir et al. 2017). Therefore, this assumption influences the overall land use impact. A better approach to estimate the total land area here would be to consider only the vegetated grazing area, but such data is not currently available, but is under development (GróLind 2020). Simultaneously, sheep grazing in Iceland has long been associated with land degradation and soil erosion.

Various gray literature have addressed this issue and other environmental concerns including vast land use for sheep grazing (Marteinsdóttir et al. 2017). Additionally, this study does not estimate the soil carbon emissions and sequestration associated with land use, as a national average of soil carbon emission and sequestration is currently being investigated, which could further influence the total global warming impacts of the lamb meat production (Arnalds and Guðmundsson 2020).

Though animal population is not considered in the variability scenarios, it is an important deterministic factor in total environmental impacts and therefore induces uncertainty towards the overall results. For instance, the number of lambs produced determines the amount of total edible lamb meat produced and the protein output at the national level, which in this study was estimated using the birth fraction of ewes and AFR (NIR, 2022). This provided 8489 tonnes of edible lamb meat at the national level. In comparison, Statistic Iceland (2019) reports 8375 tonnes of edible lamb meat. This production output difference for lamb is associated with an assessment of 10% fewer lambs slaughtered compared to the estimates used in this study, resulting in a 10% increase in the environmental impact per kg ELM compared to S_b. Therefore, it is vital that data from the lamb meat production at the national level on the animal population, especially lamb produced and slaughtered, is collected at the time of census. Simultaneously, more comprehensive daily feed intake data must be collected for ewes, rams, and AFR, along with their gross energy intake for more detailed assessments. As the daily feed intake links to the total CH_4 and N_2O emissions obtained, this parameter induces a high uncertainty for the overall global warming impact. The input data (on-farm electricity and fuel used) is based on estimates from the Agricultural University farm and proxy data for

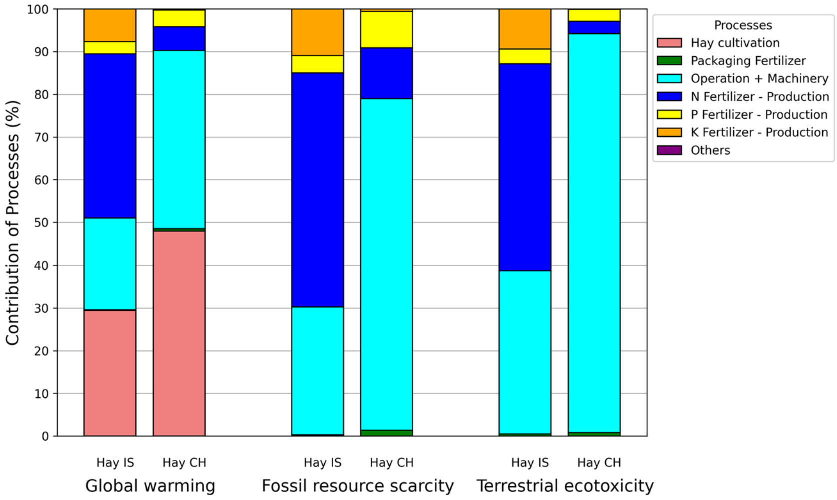


Fig. 7 Comparison of the hay production processes, Hay Iceland (Hay IS), adapted from Switzerland hay conditions (CH) from ecoinvent, compared to the original Switzerland hay ecoinvent process (Hay CH) for global warming, fossil resource scarcity, and terrestrial ecotoxicity. The characterized midpoint impacts of these two processes for 1 kg of hay are global warming (IS 0.61, and CH 0.21) kg CO_2 eq., fossil resource scarcity (IS 0.13, and CH 0.03) kg oil eq., and terrestrial ecotoxicity (IS 3.12, and CH 1.88) kg 1,4-DCB

animal drinking water. The influence of these parameters on the overall impacts must be interpreted cautiously, and for the lamb meat production they might not be representative of the national average due to the variety in farm sizes, numbers of animals, and edible lamb meat yield. Additionally, distances of each farm to the grazing area are a missing link in this assessment, and the environmental impacts from transport of the animals to and from the grazing area are not included due to a lack of national representative data.

In the feed (hay) process, fertilizer production and agricultural operations and machinery are the hotspot input parameters influencing multiple impact categories. The high fertilizer uses in Iceland, predominately nitrogen (S_{min}, 100 kg/ha; S_{b}, 121 kg/ha; and S_{max}, 141 kg/ha) for hay cultivation is due to a low hay yield (4849 kg/ha), as discussed earlier. The estimated amount of fertilizer used for this study is influenced by the following assumptions: first, the total land area under hay cultivation was divided between cattle (72%) and sheep (28%) and based on the annual feed demand from these production systems, based on which estimates of hay yield were made. Second, based on the very minimal utilization of cropland for other vegetation, it was assumed that 90% of the total fertilizer imports are utilized for hay cultivation. Furthermore, this study adapted the feed (hay) life cycle from the ecoinvent process (hay production, Swiss integrated production, extensive CH) due to a lack of data surrounding hay cultivation in Iceland. This needs to be further investigated and cross-checked with on-farm data. Adapting this process allowed the integration of fertilizer and manure emissions. Instead, if an ecoinvent process for hay is used as a proxy, the global warming impact would be 39.6 kg CO_2 eq./kg ELM (Fig. 3d), and the fossil fuel scarcity and terrestrial ecotoxicity 1.3 kg oil eq./kg ELM and 34 kg 1,4- DCB/kg ELM, respectively, for the S_{b}. Simultaneously, the agriculture operation (dried roughage storage) is another hotspot input that adds towards the terrestrial ecotoxicity impact. This input needs to be further investigated for its representatives of the Icelandic hay cultivation process by respective parties. A comparison between the adapted hay production (Hay IS), used in this study, with the Swiss ecoinvent integrated, intensive hay process (Hay CH) is given in Fig. 7. The characterized midpoint score for both processes is provided in SM 3,Sect. 1, Table S11. One key difference that stands out for the assessed three impact categories in Fig. 7 is the significant contribution of nitrogen fertilizer at the Icelandic conditions. In contrast, for the Swiss conditions, most of the contribution comes from the operation and machinery in the hay production process. This difference is primarily due to the high fertilization needed to grow hay in Iceland due to climatic conditions, followed by low hay yield compared to the Swiss case. The intensification of hay production in Switzerland, which has a higher yield (11,603 kg/ha) (Nemecek & Kägi 2007), thus leads to lower environmental impacts.

3.6 Global sensitivity analysis

A global sensitivity analysis (GSA) was conducted for the hay production process to understand the influence of input parameters that are most sensitive, and thus leads to high uncertainty associated with the adaptation of the process. In the GSA using the Activity Browser (Steubing et al. 2020), the two primary metrics used to analyze the results are the (δ) estimate[1] and the first-order sensitivity index (S1)[2] (Cucurachi et al. 2022). The results of the GSA are provided in SM3 Sect. 2.

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[1] The δ: estimate is a measure of the effect an input parameter with a fixed particular value has on the output distribution.

[2] The S1 index provides information on the contribution of an input parameter to the output variance.

For the global warming impact, the most sensitive parameter is NPK (15–15-15) to the nutrient supply with (δ−0.18, S1-0.24), followed by N_2O emissions from nitrogen fertilizers and manure application (δ−0.16, S1-0.21), and inorganic nitrogen fertilizer- N (INF-N) to market INF-N, IS (δ−0.16, S1- 0.24). In the subsequent analysis with the parameterized inorganic N, P fertilizer, N_2O, and nickel emissions with (20%) reduction, the NPK (15–15-15) to nutrient supply remains the most sensitive parameter (δ−0.33, S1-0.56). These parameters provide the influence of using a market activity to model the nitrogen fertilizer input in the hay production process. Additionally, the influence of N_2O emissions further demonstrates the high emission intensity from significant fertilization in Iceland. In the case of fossil resource scarcity, the most sensitive parameter is NPK (15–15-15) to nutrient supply (δ−0.21, S1-0.33), and in the subsequent analysis with (δ−0.32, S1-0.55). This further assessment provides the influence of using a market activity to model nitrogen fertilizers in the hay production process. Similarly, the influence of N_2O emissions further demonstrates the high emission intensity from the heavy fertilization in Iceland.

For terrestrial ecotoxicity, the most sensitive parameter is related to multi-story building constructions for fertilizers (δ−0.13, S1-0.05), followed by dried roughage storage (δ−0.12, S1-0.38), while in the subsequent analysis, dried roughage storage (δ−0.13, S1-0.03) further highlights the sensitivity regarding the representatives of this process in Icelandic hay cultivation, as discussed in subsection 3.3. The Monte Carlo results for initial analysis along with subsequent analysis are provided in SM3 Sect. 2.

3.7 Interplay between variability and uncertainty

The variability analysis in this study provides the possible ranges of the environmental impacts of 1 kg of ELM, which is based on the variability in the input parameters available from different sources. As summarized in Table 3, the influence of these differences in data sources results in three possible ranges of the total environmental impact, with a decrease from S_b to S_{min} and an increase for S_{max}. In contrast, the relative contribution of the life cycle process in each variability scenario remains similar. If only the deterministic results were considered, the potential environmental impacts of 1 kg of ELM are likely to occur within these variability scenario ranges, based on the available data sources. However, such an interpretation is incomplete, as whatever data source may be most accurate still consists of some uncertainty for the reasons discussed in previous sections. The variability scenarios provide the possible ranges of the result, while the uncertainty analysis provides additionality to deterministic results by providing a probability distribution of the variability scenarios. Thus, if there is a decrease in total environmental impact from S_b to S_{min}, the uncertainty analysis provides the possible range or confidence interval of this variation from S_b. Furthermore, as hay production is one of the hotspots for multiple environmental impact categories, the GSA of this process helps to identify the most influential input parameters that contribute to the uncertainty. Thus, for each variability scenario and their uncertainty ranges, hay production is one of the hotspots, making hay production highly influential in its contribution towards this uncertainty. By conducting the analysis this way, the study provides insight that might not be possible with deterministic analysis. However, there are still many limitations to this approach, such as not incorporating variability regarding animal populations, animal LW, slaughtered animal LW to edible meat ratios, fertilizer sub-types used in hay production, uncertainties regarding the characterization factor of the environmental impact method for the Iceland-based study, and spatial variability across different regions in Iceland, to suggest a few. These, however, are to be addressed in future research for a more comprehensive environmental assessment of lamb production in Iceland.

3.8 General discussion

In the LCA of livestock meat products, the choice of a functional unit is a crucial parameter. Including other functions apart from product mass could provide a more well-rounded analysis (Salou et al. 2017). In this study, a shift from product mass to protein content shifts the focus from production efficiency, which is captured by the environmental impacts of product mass, to product quality (gram protein). This broadens the perspective to incorporate other livestock meat functionality in LCA, in addition to traditional eco-efficiency characteristics that are considered in product mass–based LCAs. Icelandic lamb meat production is based on traditional farming methods and the utilization of vast grassland. It is characterized as close to an extensive farming system with higher environmental impacts on a product-mass basis. Extensive livestock meat farming systems often have higher global warming impacts and land use impacts, due to lower overall productivity and lower terrestrial ecotoxicity and fossil fuel usage than intensive farming systems (Nemecek et al. 2011; Ogino et al. 2016; Ripoll-Bosch et al. 2013). However, this generalization may not be consistent with the high terrestrial ecotoxicity impact of Icelandic lamb meat per kg ELM.

The primary function of lamb meat is to fulfill protein requirements in diets. Evaluation of the global warming impact of Icelandic lamb meat per gram protein is close to the global average estimates, encompassing different production methods. This is not to say that the Icelandic lamb meat has a higher protein content compared to lamb of other breeds. Rather, it emphasizes the importance of considering the primary function of the meat—its protein content—in concurrence with the efficiency of the production system for a more complete environmental impact assessment. However, making a comparison for other environmental impacts is not directly feasible due to the lack of available studies that include the protein content as a base for calculations on multiple environmental categories. In addition to the inherent variability and uncertainty in the input data, this study has several limitations. Firstly, the LCA is conducted for a production output of 8489 tonnes of edible lamb meat. This analysis allocates all the impacts towards the lamb meat, not considering the 14% of cull ewes, as no documentation on the utilization of ewe meat is publicly available in Iceland. Next, the LW to CW conversion does not account for the 12,625 tonnes of inedible/waste co-products resulting from the lamb meat production due to lack of data. More detailed data collection and better understanding of these side streams would further allocate the impacts between valuable side products and CW of lamb meat at this production stage. These streams are not currently used for anything. Therefore, including them would not give a realistic view of the lamb meat production system as a whole. Similarly, the protein content of edible lamb meat basis is assumed to be 18.5–21.5 g protein per 100 g meat since they represent the main parts and cuts consumed. However, the protein content may show more variation if the analysis is done for different lamb meat cuts and products. Furthermore, the study is limited by the extrapolation of farm-level data for electricity and fuel use data to the national level. These on-farm inputs were a hotspot for water use and fossil resource scarcity and could thus benefit from multiple farm-level samples of different sizes. Additionally, analyzing the environmental impacts using different impact assessment methods could provide a more holistic assessment of convergence of results and need to be investigated in future work. Lastly, this study considers the national-level dataset as one homogeneous system which only provides a snapshot of the potential environmental impact of the Icelandic lamb meat production. The next iteration of LCA studies in Iceland could benefit from these identified hotspots. Direct data collection efforts can then also be made in the direction of addressing this study's data input gaps and the resulting associated uncertainty in the assessment.

4 Conclusion

This study is the first detailed cradle-to-gate LCA-based environmental impact assessment of the Icelandic lamb meat production, which looks beyond the global warming impacts. By employing LCA, the study offers insights into the environmental impacts of lamb meat products at different production stages and pinpoints environmental hotspots. When paired with a nutritional functional unit (the protein content of the meat), it provides insight into the role of product quality over the production efficiency of an extensive livestock meat production system. This dual approach, achieved by combining the product mass and protein content, showcases that including other functions of lamb meat provides a more comprehensive assessment. Furthermore, the applied scenario-based variability and uncertainty analyses provide potential ranges of environmental impacts on the lamb meat production system. The study further highlights the lack of quality input data and low or non-existent access to data in English, which could enhance international and interdisciplinary research on the subject. These insights provide direction for relevant stakeholders for future work to direct data-gathering efforts needed for such analysis. In addition, for the national-level data sources, the Icelandic government needs to initiate work compiling relevant data for assessing food systems' sustainability. Ensuring consistency and transparency among data sources and addressing missing links are essential for thorough environmental sustainability assessments. Direct comparison with other sheep LCA studies should be interpreted carefully due to differences in the production systems, animal breeds, feed, methodological approaches for solving multifunctionality issues within the lamb meat production system, and environmental impact assessment used and levels of modeling. Animal production and feed (hay and grazing) are the critical processes in lamb meat production that contribute to most of the assessed environmental impacts for both functional units. Based on the results of this study, the farming community is advised to prioritize their effort to reduce environmental impacts from lamb meat production by optimizing fertilizer input and feeding strategies that can potentially reduce GHG emissions. Furthermore, there is a need of examining biodiversity effects (positive or negative) of Icelandic sheep grazing flocks and extensive management practices. Future studies should focus their effort to assess these impacts. The endeavor toward environmentally sustainable lamb meat production requires a multi-faceted intervention focusing on increasing production efficiency and product quality in Iceland, and this work provides a first high-level snapshot of the current status of the lamb meat production system.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-024-02411-w.

Acknowledgements The authors acknowledge the assistance of Eyjólfur Kristinn Örnólfsson and Erla Sturludóttir in providing data and access to the Agricultural University of Iceland's sheep farm. We also thank Vincent Elijiah Merida for proofreading the manuscript and providing valuable feedback.

Funding This work has been supported by Rannsóknamiðstöð Íslands (Rannís) in relation to the Sustainable Healthy Diets project (grant no. 200221–5601).

Data availability All data generated in this work is attached as supplementary materials 1, 2, and 3.

Declarations

Conflict of interest The authors declare no competing interests.

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